

[Document Type] Specification

[Title of the Invention] DISPLACEMENT ESTIMATION DEVICE, BUCKLING
STRESS ESTIMATION DEVICE, DISPLACEMENT ESTIMATION METHOD,
BUCKLING STRESS ESTIMATION METHOD, DISPLACEMENT ESTIMATION
PROGRAM, AND BUCKLING STRESS ESTIMATION PROGRAM

[Technical Field of the Invention]

[0001]

The present invention relates to a displacement estimation device, a buckling stress estimation device, a displacement estimation method, a buckling stress estimation method, a displacement estimation program, and a buckling stress estimation program.

Priority is claimed on Japanese Patent Application No. 2019-120970, Japanese Patent Application No. 2019-120971, Japanese Patent Application No. 2019-120972, Japanese Patent Application No. 2019-120980, Japanese Patent Application No. 2019-120981, Japanese Patent Application No. 2019-120982, and Japanese Patent Application No. 2019-120983, all filed June 28, 2019, the contents of which are incorporated herein by reference.

[Background Art]

[0002]

Conventionally, as a method of estimating the out-of-plane displacement (first out-of-plane displacement) of an elastic element such as a beam, it is common to use the Fourier series represented by Formula (1) (for example, refer to Non-Patent Document 1). Incidentally, the value of Y in Formula (1) is a value made dimensionless by dividing the coordinate of the elastic element in a direction along the y -axis by the length of the elastic element in the direction along the y -axis.

[0003]

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos n\pi Y + b_n \sin n\pi Y) \quad \cdot \cdot (1)$$

[0004]

Since the basis of the Fourier series has orthogonality, it is possible to accurately approximate a larger number of curves with the Fourier series.

[Prior Art Document]

[Non-Patent Document]

[0005]

Non-Patent Document 1: Stephen P. Timoshenko and James M. Gere, "Theory of Elastic Stability" Second Edition

[Disclosure of the Invention]

[Problems to be Solved by the Invention]

[0006]

However, there is a problem in that the convergence of approximation is slow in the Fourier series. For example, in the case of attempting to approximate buckling distortion that is caused in a member of a building or a flat sheet-shaped elastic element constituting a member, approximately the 15th partial sum of the Fourier series is required, that is, it is necessary to set N in Formula (1) to approximately 15. In this case, the approximate function includes 30 trigonometric terms in addition to the undetermined coefficient a_0 .

As described above, in the Fourier series, a number of terms are required for the convergence of approximation, which makes it impossible to perform an analysis by the Fourier series by manual calculation and creates a need for numerical calculation using a calculator. Furthermore, in conventional displacement estimation methods, there has been a technical problem in that estimation results cannot be formulated to be

easily understood physically.

[0007]

The present invention has been made in view of such problems, and an object of the present invention is to provide a displacement estimation device, a buckling stress estimation device, a displacement estimation method, a buckling stress estimation method, a displacement estimation program, and a buckling stress estimation program which make it possible to simplify calculation necessary for estimation compared with a case where the Fourier series is used and to formulate estimation results to be easily understood physically.

[Means for Solving the Problem]

[0008]

Means for solving the above-described problems include the following aspects.

[0009]

<1> A displacement estimation device that estimates a first out-of-plane displacement w_w of an elastic element directed in a direction along a z-axis, which is a sheet thickness direction of the elastic element being formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis, the displacement estimation device including a first displacement estimation portion that, when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line, estimates the first out-of-plane displacement w_w from Formula (1) in a case where the first out-of-plane displacement w_w is estimated to

be symmetrical in the direction along the y-axis with respect to the reference line and estimates the first out-of-plane displacement w_w from Formula (2) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, in which, in Formula (1) and Formula (2), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed support.

Here, a value of Y in Formula (1) and Formula (2) is a value for which a coordinate of the y-axis is made dimensionless using the length of the elastic element in the direction along the y-axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

[0010]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot (2)$$

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (3)$$

[0011]

<2> The displacement estimation device according to <1>, in which N is 2.

[0012]

<3> A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation device according to <1>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange

sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v -axis that is the y -axis of the web sheet element, the compressive force acts on the end surface of the H-section steel in a direction along a u -axis that is the x -axis of the web sheet element, a w -axis is defined as an axis in the direction along the z -axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y -axis and is along the x -axis of the web sheet element, a central position of the first flange sheet element in the direction along the v -axis is defined as an origin of the v -axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v -axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v -axis is indicated by b_w , and a half wavelength in the direction along the u -axis of the web sheet element that is displaced in a positive orientation of the w -axis and a negative orientation of the w -axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u -axis is indicated by a , the first out-of-plane displacement w_w of the H-section steel is estimated to be symmetrical in the direction along the v -axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w -axis in the web sheet element from Formula (4) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v -axis in the first flange sheet element and the second flange sheet element from each of Formula (5) and Formula (6) using the first out-of-plane displacement w_w estimated by the first

displacement estimation portion; and a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (4) to Formula (6).

Here, N is a natural number of 2 or more.

[0013]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (4)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (5)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (6)$$

[0014]

<4> The buckling stress estimation device according to <3>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (11), using Formula (7) to Formula (10).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0015]

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (7)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du$$

$$\cdot \cdot (8)$$

$$C = \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (9)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du$$

$$\cdot \cdot (10)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (11)$$

[0016]

<5> A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation device according to <1>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (12); and a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (12).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0017]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (12)$$

[0018]

<6> The buckling stress estimation device according to <5>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (15), using Formula (13) and Formula (14).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0019]

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (13)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\cdot \cdot (14)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (15)$$

[0020]

<7> A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation device according to <1>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v -axis that is the y -axis of the web sheet element, the bending moment acts on the end surface of the H-section steel about a w -axis that is the z -axis of the web sheet element, a u -axis is defined as an axis in the direction along the x -axis of the web sheet element, the reference line is defined as a line that passes through a central position of a

length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, the first flange sheet element is assumed to receive a tensile force due to the bending moment, a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a , the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the H-section steel becomes asymmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (16) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (17) and Formula (18) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (16) to Formula (18).

Here, N is a natural number of 2 or more.

[0021]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (16)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (17)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (18)$$

[0022]

<8> The buckling stress estimation device according to <7>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (23), using Formula (19) to Formula (22).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0023]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (19)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \quad \cdot \cdot (20)$$

$$C = \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (21)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \quad \cdot \cdot (22)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (23)$$

[0024]

<9> A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about

the z-axis using the displacement estimation device according to <1>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes asymmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (24) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (24).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0025]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w^n} + b_n \sin \frac{\pi y^n}{b_w^n} \right) \right] \quad \cdot \cdot (24)$$

[0026]

<10> The buckling stress estimation device according to <9>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (27), using Formula (25) and Formula (26).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0027]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (25)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

· · (26)

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A} \quad \cdot \cdot (27)$$

[0028]

<11> A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a shear force acting as the external force using the displacement estimation device according to <1>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the shear force acts on the end surface of the H-section steel in the direction along the v-axis, a u-axis is defined as an axis in the direction along the x-axis of the web sheet element, a w-axis is defined as an axis in the direction along the z-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis

alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a, the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (28) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (29) and Formula (30) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (28) to Formula (30).

Here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

[0029]

$$W_w = \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (28)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (29)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (30)$$

[0030]

<12> The buckling stress estimation device according to <11>, in which the stress calculation portion obtains the buckling stress τ_{cr} based on the a_n , the b_n , the λ , and the half wavelength a, which are real numbers that impart a minimum positive value

to the buckling stress τ_{cr} represented by Formula (34), using Formula (31) to Formula (33).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0031]

$$\begin{aligned}
 A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (31) \\
 B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad \cdot \cdot (32) \\
 C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
 &\quad \cdot \cdot (33) \\
 \tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2 \sum_{i=1}^2 C_i}{b_f^2 t_w A} \quad \cdot \cdot (34)
 \end{aligned}$$

[0032]

<13> A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation device according to <1>, in which when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation device includes a second displacement estimation portion that estimates a

second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (35); and a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (35).

Here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

[0033]

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (35)$$

[0034]

<14> The buckling stress estimation device according to <13>, in which the stress calculation portion obtains the buckling stress τ_{cr} based on the undetermined coefficients a_n , b_n , and λ and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (38), using Formula (36) and Formula (37).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0035]

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (36)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (37)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (38)$$

[0036]

<15> The buckling stress estimation device according to any one of <3> to <14>, in which N is 2.

[0037]

<16> A displacement estimation method of estimating a first out-of-plane displacement w_w of an elastic element directed in a direction along a z-axis, which is a sheet thickness direction of the elastic element being formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis, the displacement estimation method including a first displacement estimation step of, when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line, estimating the first out-of-plane displacement w_w from Formula (41) in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the direction along the y-axis with respect to the reference line and estimating the first out-of-plane displacement w_w from Formula (42) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, in which, in Formula (41) and Formula (42), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed support.

Here, a value of Y in Formula (41) and Formula (42) is a value for which a

coordinate of the y-axis is made dimensionless using the length of the elastic element in the direction along the y-axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

[0038]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot (4.1)$$

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (4.2)$$

[0039]

<17> The displacement estimation method according to <16>, in which N is 2.

[0040]

<18> A buckling stress estimation method of estimating a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation method according to <16>,

in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the compressive force acts on the end surface of the H-section steel in a direction along a u-axis that is the x-axis of the web sheet element, a w-axis is defined as an axis in the direction along the z-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-

axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a , in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to be symmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (43) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (44) and Formula (45) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (43) to Formula (45).

Here, N is a natural number of 2 or more.

[0041]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (43)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (44)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (45)$$

[0042]

<19> The buckling stress estimation method according to <18>, in which, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (50), using Formula (46) to Formula (49).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0043]

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (46)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du$$

· · (47)

$$C = \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (48)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du$$

· · (49)

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (50)$$

[0044]

<20> A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation method according to <16>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward

a first end of the sheet element in the direction along the x-axis is indicated by a, in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to be symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (51); and a stress calculation step of obtaining the buckling stress of the sheet element based on an energy method using Formula (51).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0045]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (51)$$

[0046]

<21> The buckling stress estimation method according to <20>, in which, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (54), using Formula (52) and Formula (53).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0047]

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (5.2) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
&\quad \cdot \cdot (5.3) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (5.4)
\end{aligned}$$

[0048]

<22> A buckling stress estimation method of estimating a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation method according to <16>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the bending moment acts on the end surface of the H-section steel about a w-axis that is the z-axis of the web sheet element, a u-axis is defined as an axis in the direction along the x-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, the first flange sheet element is assumed to receive a tensile force due to the bending moment, a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet

element in the direction along the u-axis is indicated by a, in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to become asymmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (55) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (56) and Formula (57) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (55) to Formula (57).

Here, N is a natural number of 2 or more.

[0049]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (55)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (56)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (57)$$

[0050]

<23> The buckling stress estimation method according to <22>, in which, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (62), using Formula (58) to Formula

(61).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0051]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2\nu}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (58)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du$$

· · (59)

$$C = \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (60)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du$$

· · (61)

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (62)$$

[0052]

<24> A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about the z-axis using the displacement estimation method according to <16>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet

element directed in the direction along the z-axis from Formula (63); and a stress calculation step of obtaining the buckling stress of the sheet element based on an energy method using Formula (63).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0053]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w} + b_n \sin \frac{\pi y^n}{b_w} \right) \right] \quad \cdot \cdot (63)$$

[0054]

<25> The buckling stress estimation method according to <24>, in which, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (66), using Formula (64) and Formula (65).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0055]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (64)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (65)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A} \quad \cdot \cdot (66)$$

[0056]

<26> A buckling stress estimation method of estimating a buckling stress of an H-section steel that buckles due to a shear force acting as the external force using the displacement estimation method according to <16>, in which, when the H-section steel

includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the shear force acts on the end surface of the H-section steel in the direction along the v-axis, a u-axis is defined as an axis in the direction along the x-axis of the web sheet element, a w-axis is defined as an axis in the direction along the z-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a , in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to be symmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (67) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first

flange sheet element and the second flange sheet element from each of Formula (68) and Formula (69) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (67) to Formula (69).

Here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

[0057]

$$W_w = \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (67)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (68)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (69)$$

[0058]

<27> The buckling stress estimation method according to <26>, in which, in the stress calculation step, the buckling stress τ_{cr} is obtained based on the a_n , the b_n , the λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (73), using Formula (70) to Formula (72).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0059]

$$\begin{aligned}
A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (70) \\
B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (71) \\
C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (72) \\
\tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{t_f \sum_{i=1}^2 C_i}{t_w A} \quad \cdot \cdot (73)
\end{aligned}$$

[0060]

<28> A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation method according to <16>, in which, when the sheet element is the elastic element, an axis that extends in the sheet thickness direction of the sheet element is defined as the z-axis, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to be symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation method includes a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (74); and a stress calculation step of obtaining the buckling stress of the sheet element based on an energy method using Formula (74).

Here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

[0061]

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (74)$$

[0062]

<29> The buckling stress estimation method according to <28>, in which, in the stress calculation step, the buckling stress τ_{cr} is obtained based on the undetermined coefficients a_n , b_n , and λ and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (77), using Formula (75) and Formula (76).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0063]

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (75)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (76)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (77)$$

[0064]

<30> The buckling stress estimation method according to any one of <18> to <29>, in which N is 2.

[0065]

<31> A sheet-shaped body design method of designing a sheet-shaped body that is at least one of an H-section steel and a sheet element using the displacement estimation method according to <16> or <17>.

[0066]

<32> A displacement estimation program for an estimation device that estimates a first out-of-plane displacement w_w of an elastic element directed in a

direction along a z-axis, which is a sheet thickness direction of the elastic element being formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis, in which, when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line, the displacement estimation program causes the estimation device to function as a first displacement estimation portion that estimates the first out-of-plane displacement w_w from Formula (81) in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the direction along the y-axis with respect to the reference line and estimates the first out-of-plane displacement w_w from Formula (82) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, and, in Formula (81) and Formula (82), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed support.

Here, a value of Y in Formula (81) and Formula (82) is a value for which a coordinate of the y-axis is made dimensionless using the length of the elastic element in the direction along the y-axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

[0067]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot (8.1)$$

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (8.2)$$

[0068]

<33> The displacement estimation program according to <32>, in which N is 2.

[0069]

<34> A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation program according to <32>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the compressive force acts on the end surface of the H-section steel in a direction along a u-axis that is the x-axis of the web sheet element, a w-axis is defined as an axis in the direction along the z-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction

along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a, with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (83) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (84) and Formula (85) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (83) to Formula (85).

Here, N is a natural number of 2 or more.

[0070]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (83)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (84)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (85)$$

[0071]

<35> The buckling stress estimation program according to <34>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (90), using Formula (86) to Formula (89).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0072]

$$\begin{aligned}
 A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (86) \\
 B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad \cdot \cdot (87) \\
 C &= \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (88) \\
 D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
 &\quad \cdot \cdot (89) \\
 \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (90)
 \end{aligned}$$

[0073]

<36> A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation program according to <32>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a , with the displacement estimation program, the first displacement

estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (91) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (91).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0074]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (91)$$

[0075]

<37> The buckling stress estimation program according to <36>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (94), using Formula (92) and Formula (93).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0076]

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (92)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (93)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (94)$$

[0077]

<38> A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation program according to <32>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the bending moment acts on the end surface of the H-section steel about a w-axis that is the z-axis of the web sheet element, a u-axis is defined as an axis in the direction along the x-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, the first flange sheet element is assumed to receive a tensile force due to the bending moment, a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a , with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes asymmetrical in the direction along the v-axis with respect to the reference line, and the

buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (95) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (96) and Formula (97) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (95) to Formula (97).

Here, N is a natural number of 2 or more.

[0078]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (95)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (96)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (97)$$

[0079]

<39> The buckling stress estimation program according to <38>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (102), using Formula (98) to Formula (101).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a

width of each of the first flange sheet element and the second flange sheet element.

[0080]

$$\begin{aligned}
 A &= \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (98) \\
 B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2v \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-v) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad \cdot \cdot (99) \\
 C &= \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (100) \\
 D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2v \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-v) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
 &\quad \cdot \cdot (101) \\
 \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (102)
 \end{aligned}$$

[0081]

<40> A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about the z-axis using the displacement estimation program according to <32>, in which, when the sheet element is the elastic element, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes asymmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (103) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the sheet

element based on an energy method using Formula (103).

Here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

[0082]

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w} + b_n \sin \frac{\pi y^n}{b_w} \right) \right] \quad \cdot \cdot (103)$$

[0083]

<41> The buckling stress estimation program according to <40>, in which the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (106), using Formula (104) and Formula (105).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0084]

$$\begin{aligned} A &= \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (104) \\ B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\ &\quad \cdot \cdot (105) \\ \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (106) \end{aligned}$$

[0085]

<42> A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a shear force acting as the external force using the displacement estimation program according to <32>, in which, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements, the first flange sheet element and the second

flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element, the shear force acts on the end surface of the H-section steel in the direction along the v-axis, a u-axis is defined as an axis in the direction along the x-axis of the web sheet element, a w-axis is defined as an axis in the direction along the z-axis of the web sheet element, the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element, a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis, an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis, a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a , with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (107) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from

each of Formula (108) and Formula (109) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (107) to Formula (109).

Here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

[0086]

$$W_w = \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (107)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (108)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (109)$$

[0087]

<43> The buckling stress estimation program according to <42>, in which the stress calculation portion obtains the buckling stress τ_{cr} based on the a_n , the b_n , the λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (113), using Formula (110) to Formula (112).

Here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

[0088]

$$\begin{aligned}
A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (1 \ 1 \ 0) \\
B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (1 \ 1 \ 1) \\
C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (1 \ 1 \ 2) \\
\tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2 t_f \sum_{i=1}^2 C_i}{b_f^2 t_w A} \quad \cdot \cdot (1 \ 1 \ 3)
\end{aligned}$$

[0089]

<44> A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation program according to <32>, in which, when the sheet element is the elastic element, an axis that extends in the sheet thickness direction of the sheet element is defined as a z-axis, and a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a, with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (114) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and as a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (114).

Here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

[0090]

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (114)$$

[0091]

<45> The buckling stress estimation program according to <44>, in which the stress calculation portion obtains the buckling stress τ_{cr} based on the undetermined coefficients a_n , b_n , and λ and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (117), using Formula (115) and Formula (116).

Here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

[0092]

$$\begin{aligned} A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (115) \\ B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\ &\quad \cdot \cdot (116) \\ \tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (117) \end{aligned}$$

[0093]

<46> The buckling stress estimation program according to any one of <34> to <45>, in which N is 2.

[Effects of the Invention]

[0094]

According to the displacement estimation device, the buckling stress estimation device, the displacement estimation method, the buckling stress estimation method, the

displacement estimation program, and the buckling stress estimation program of the present invention, it is possible to simplify calculation necessary for estimation compared with a case where the Fourier series is used and to formulate estimation results to be easily understood physically.

[Brief Description of the Drawings]

[0095]

FIG. 1 is a perspective view of a building including H-section steels to which a displacement estimation device of a first embodiment of the present invention is applied.

FIG. 2 is a view showing analysis results by an FEM when a bending moment has acted on the same H-section steel.

FIG. 3 is a view showing an outline of the same displacement estimation device.

FIG. 4 is a perspective view schematically showing a state in which, in a case where a web of the same H-section steel is sufficiently long in a direction along an x-axis, the web buckles so as to be symmetrical in a y-axis direction.

FIG. 5 is an enlarged perspective view of a half wavelength-long part in the direction along the x-axis in the web of FIG. 4.

FIG. 6 is a view showing an example of an estimation result of a first out-of-plane displacement of the web along y-axis coordinates in a case a compressive force acts on the web.

FIG. 7 is a view showing another example of the estimation result of the first out-of-plane displacement of the web along the y-axis coordinates in a case where the compressive force acts on the web.

FIG. 8 is a view showing ratios of standard deviations when the first out-of-

plane displacement of the web has been estimated from Formula (1) with respect to N.

FIG. 9 is a view showing ratios of squared sums of differences when the first out-of-plane displacement of the web has been estimated from Formula (1) with respect to N.

FIG. 10 is a perspective view of the web that has buckled so as to be asymmetrical in the y-axis direction.

FIG. 11 is a view showing an example of the estimation result of the out-of-plane displacement of the web along the y-axis coordinates in a case where the web has buckled so as to become asymmetrical in the y-axis direction.

FIG. 12 is a view showing another example of the estimation result of the first out-of-plane displacement of the web along the y-axis coordinates in a case where the web has buckled so as to become asymmetrical in the y-axis direction.

FIG. 13 is a view showing an outline of a displacement estimation device according to a second embodiment of the present invention.

FIG. 14 is a perspective view schematically showing a state in which, in a case where the same H-section steel is sufficiently long in a direction along an u-axis, the H-section steel buckles due to a compressive force acting thereon.

FIG. 15 is a cross-sectional view of the same H-section steel orthogonal to a longitudinal direction.

FIG. 16 is an enlarged perspective view of a half wavelength-long part in the direction along the u-axis in the H-section steel of FIG. 14.

FIG. 17 is a cross-sectional view along a cutting-plane line A5-A5 in FIG. 16.

FIG. 18 is a view showing comparison results between buckling stresses that are estimated by the same buckling stress estimation device and eigenvalue analyses that are estimated by the FEM.

FIG. 19 is a perspective view schematically showing a state in which a web that is a target of a displacement estimation device of a third embodiment of the present invention buckles.

FIG. 20 is an enlarged perspective view of a half wavelength-long part in the direction along the x-axis in the web of FIG. 19.

FIG. 21 is a view showing an example of an estimation result of an out-of-plane displacement of the web along y-axis coordinates in a case a compressive force acts on the web.

FIG. 22 is a view showing an example of a change in buckling coefficients with respect to N in a case where a compressive force acts on the web.

FIG. 23 is a perspective view schematically showing a state in which an H-section steel that is a target of a displacement estimation device of a fourth embodiment of the present invention buckles.

FIG. 24 is an enlarged perspective view of a half wavelength-long part in the direction along the u-axis in the H-section steel of FIG. 23.

FIG. 25 is a cross-sectional view along a cutting-plane line A9-A9 in FIG. 24.

FIG. 26 is a view showing comparison results between buckling stresses that are estimated by the same buckling stress estimation device and eigenvalue analyses that are estimated by the FEM.

FIG. 27 is a perspective view schematically showing a state in which a web that is a target of a displacement estimation device of a fifth embodiment of the present invention buckles.

FIG. 28 is an enlarged perspective view of a half wavelength-long part in the direction along the x-axis in the web of FIG. 27.

FIG. 29 is a view showing an example of an estimation result of an out-of-

plane displacement of the web along y-axis coordinates in a case a bending moment acts on the web.

FIG. 30 is a view showing an example of a change in buckling coefficients with respect to N in a case where a bending moment acts on the web.

FIG. 31 is a perspective view schematically showing a state in which an H-section steel that is a target of a displacement estimation device of a sixth embodiment of the present invention buckles.

FIG. 32 is a cross-sectional view of the same H-section steel orthogonal to a longitudinal direction.

FIG. 33 is an enlarged perspective view of a half wavelength-long part in the direction along the u-axis in the H-section steel of FIG. 31.

FIG. 34 is a cross-sectional view along a cutting-plane line A13-A13 in FIG. 33.

FIG. 35 is a view showing comparison results between buckling stresses that are estimated by the same buckling stress estimation device and eigenvalue analyses that are estimated by the FEM.

FIG. 36 is a perspective view schematically showing a state in which a web that is a target of a displacement estimation device of a seventh embodiment of the present invention buckles.

FIG. 37 is an enlarged perspective view of a wavelength-long part in the direction along the x-axis in the web of FIG. 36.

FIG. 38 is a view showing an example of an estimation result of an out-of-plane displacement of the web along y-axis coordinates in a case a shear force acts on the web.

FIG. 39 is a view showing an example of a change in buckling coefficients

with respect to N in a case where a shear force acts on the web.

FIG. 40 is a view showing an example of a change in buckling coefficients with respect to N in a case where a sheet element receives uniform bending.

FIG. 41 is a view showing comparison results between buckling stresses that are estimated by a conventional estimation method and eigenvalue analyses that are estimated by the FEM.

FIG. 42 is a view showing comparison results between buckling stresses that are estimated by the same buckling stress estimation device and eigenvalue analyses that are estimated by the FEM.

[Embodiments of the Invention]

[0096]

[First Embodiment]

Hereinafter, a first embodiment of a displacement estimation device according to the present invention will be described with reference to FIG. 1 to FIG. 12.

This displacement estimation device (estimation device, hereinafter also simply referred to as the estimation device) is used to estimate a displacement of, for example, an H-section steel 10 or the like that is used as a steel beam in a building 1 shown in FIG. 1. The H-section steel 10 includes a lower flange (first flange sheet element) 11, an upper flange (second flange sheet element) 12, and a web (web sheet element) 13 that couples the lower flange 11 and the upper flange 12 to each other. In FIG. 1, a floor slab 20 described below is indicated by a chain double-dashed line. In a second embodiment and onward, the lower flange 11 will also be referred to as the first flange sheet element 11. The upper flange 12 will also be referred to as the second flange sheet element 12, and the web 13 will also be referred to as the web sheet element 13.

The lower flange 11, the upper flange 12, and the web 13 that are included in

the H-section steel 10 are each an elastic element and are formed of a steel sheet. The elastic element is an element for which the non-linear shape of a material is not taken into account.

[0097]

The H-section steel 10 extends, for example, in a direction along the horizontal plane. The lower flange 11 is formed in a flat sheet shape and is disposed such that the thickness direction of the lower flange 11 is along the vertical direction. The upper flange 12 is formed in a flat sheet shape and is disposed above the lower flange 11. The upper flange 12 is disposed such that the thickness direction of the upper flange 12 is along the vertical direction.

The web 13 is formed in a flat sheet shape that shows a rectangular shape when viewed in the thickness direction of the web 13. The web 13 is disposed such that the thickness direction of the web 13 is along the horizontal plane. The Web 13 couples the center of the lower surface of the lower flange 11 in the width direction and the center of the upper surface of the upper flange 12 in the width direction.

[0098]

An end portion of the H-section steel 10 in the longitudinal direction is fixed to a column 15 or the like. The H-section steel 10 supports the floor slab 20 from below the floor slab 20. The upper flange 12 of the H-section steel 10 is provided with shear connectors 21 such as a headed stud. The shear connectors 21 are embedded in the floor slab 20.

The building 1 is used by installing a facility, not shown, on the floor slab 20.

[0099]

FIG. 2 shows an analysis result by a finite element method (FEM) of the H-section steel 10 in which a downward external force F1 acts on a middle portion of the

H-section steel 10 in the longitudinal direction. An end portion of the H-section steel 10 in the longitudinal direction is fixed to the column 15. The external force F1 acting downward makes a bending moment act on the H-section steel 10. In this analysis result, there is a region R1 where local buckling occurs at an end portion of the web 13.

The estimation device of the present embodiment estimates a first out-of-plane displacement (out-of-plane displacement) of the H-section steel 10 when an external force acts on the H-section steel 10 and the H-section steel 10 buckles (locally buckles) without performing analysis by the FEM. The first out-of-plane displacement mentioned herein means a displacement in a direction orthogonal to a plane.

Hereinafter, in order to simplify the description, a case where the elastic element, which is a target from which the estimation device estimates the first out-of-plane displacement, is the web 13 will be described. Incidentally, in a case where the thicknesses of the flanges 11 and 12 of the H-section steel 10 are thin enough to be ignored, the rigidity of the flanges 11 and 12 is low enough to be ignored, or the like, the first out-of-plane displacement of the web 13 in the H-section steel 10 becomes equal to the first out-of-plane displacement of the web 13 alone.

[0100]

FIG. 3 shows an estimation device 50 of the present embodiment. The estimation device 50 is a computer and includes a central processing unit (CPU) 51, a main storage device 55, an auxiliary storage device 60, an input and output interface (IO·I/F) 65, and a recording and reproduction device 70. The CPU 51, the main storage device 55, the auxiliary storage device 60, the input and output interface 65, and the recording and reproduction device 70 are connected to each other with a bus 75.

The main storage device 55 is a random access memory (RAM) or the like, which serves as a work area or the like of the CPU 51.

The input and output interface 65 is connected to an input device 66, such as a keyboard or a mouse, and a display device 67.

The recording and reproduction device 70 records or reproduces data on or from a recording medium 71 such as a universal serial bus (USB) memory.

[0101]

The auxiliary storage device 60 is a hard disk drive device or the like where a variety of data, programs, or the like are stored. In the auxiliary storage device 60, a variety of programs, such as a displacement estimation program for making the computer function as the estimation device 50 (hereinafter, also simply referred to estimation program) 61 or an operating system (OS) program, and the like are stored. The variety of programs including the estimation program 61 are fed into the auxiliary storage device 60 from the recording medium 71 via the recording and reproduction device 70. The estimation program 61 and the like are stored in the recording medium 71.

These programs may be fed into the auxiliary storage device 60 from an external device via a disc-type recording medium such as a CD or DVD or a communication device, not shown.

[0102]

The CPU 51 executes a variety of arithmetic processes. The CPU 51 includes a first displacement estimation portion 52 that, functionally, estimates the first out-of-plane displacement of the web 13. The first displacement estimation portion 52, which is a functional constituent element of the CPU 51, is made to function by making the CPU 51 execute the estimation program 61 or the like that is stored in the auxiliary storage device 60. The estimation program 61 or the like is a program for the estimation device 50. The estimation program 61 makes the estimation device 50

function as the first displacement estimation portion 52.

[0103]

In the first displacement estimation portion 52 of the estimation device 50 of the present embodiment, as shown in FIG. 4, the position coordinates of the web 13 are recognized based on the right-handed orthogonal coordinate system composed of the x-axis, the y-axis, and the z-axis (hereinafter, also referred to as the xyz coordinate system). The web 13 is assumed to extend (extend) along the x-axis and the y-axis, which are orthogonal to each other. For the web 13, between the x-axis and the y-axis, for example, the x-axis is assumed to extend along the horizontal plane. The x-axis is the material axis direction of the web 13. The y-axis is assumed to extend along the vertical direction. The z-axis is orthogonal to each of the x-axis and the y-axis and is assumed to be along the thickness direction (sheet thickness direction) of the web 13. When viewed in a direction along the z-axis (hereinafter, referred to as the z-axis direction. This is also true for the x-axis, the y-axis, a u-axis described below, and the like), the web 13 shows a rectangular shape having a side that extends in a direction along the x-axis and a side that extends in a direction along the y-axis. The web 13 is assumed to have a sufficiently long length in the x-axis direction compared with the length in the y-axis direction.

Here, a surface that is disposed at each end of the web 13 in the x-axis direction and extends in the y-axis direction will be, hereinafter, referred to as an end surface 13a in the x-axis direction. The expression “the web 13 has a sufficiently long length in the x-axis direction compared with the length in the y-axis direction” mentioned herein means that the web 13 has a length in the x-axis direction long enough to ignore the influence of the boundary condition of the end surface 13a in the x-axis direction on buckling distortion.

[0104]

As described below, when external forces F_2 act on the end surfaces 13a of the web 13 in the x-axis direction and the web 13 buckles in the z-axis direction, as the web 13 runs toward a first end in the x-axis direction (one of the end surfaces 13a in the x-axis direction), the web 13 is alternately displaced in a wavy shape in the positive orientation of the z-axis and in the negative orientation of the z-axis. Therefore, the web 13 is displaced in a wavy shape of a plurality-of-wavelength length (hereinafter, referred to as the wavy shape in the x-axis direction) as a whole. In the web 13, the middle portion between a second end and the first end in the x-axis direction is the origin of the x-axis. An orientation toward the first end in the x-axis direction from this middle portion is the positive orientation of the x-axis.

The origin of the y-axis is the lower end of the web 13. The positive orientation of the y-axis is the upward orientation (an orientation toward the upper flange 12 from the lower flange 11).

The origin of the z-axis is the center of the web 13 in the z-axis direction (the center in the thickness direction). The positive orientation of the z-axis is an orientation that constitutes the right-handed orthogonal coordinate system with respect to the positive orientation of the x-axis and the positive orientation of the y-axis.

[0105]

Here, in the first embodiment, the length (height) in the y-axis direction of the web 13 is indicated by b_w . As the unit of lengths and the like described below, the SI unit such as “m” is preferably used for lengths.

The estimation device 50 estimates the first out-of-plane displacement of the web 13 directed in the direction along the z-axis at predetermined x-axis and y-axis coordinates when, for example, a bending moment acts on the web 13.

[0106]

When the out-of-plane displacement of the web 13 is estimated in the first displacement estimation portion 52 of the estimation device 50 of the present embodiment, the following assumptions 1 to 6 are performed.

1. The thickness (length in the z-axis direction) of the web 13 is thin, and the thickness of the web 13 is short compared with the length in the x-axis direction and the length in the y-axis direction of the web 13.

2. The deflection (out-of-plane displacement caused by buckling) of the web 13 is small and smaller than the thickness of the web 13.

3. The central plane of the web 13 in the thickness direction does not expand or contract due to the bending of the web 13 and holds a neutral plane.

4. In the cross section of the web 13, an assumption of holding a flat plane against bending is established.

5. The material of the web 13 is homogeneous and isotropic.

6. The displacement of the web 13 under the action of an external force complies with the Hooke's law.

[0107]

(1. Estimation of first out-of-plane displacement in case where first out-of-plane displacement is estimated to be symmetrical with respect to reference line)

As shown in FIG. 4, when the external forces (for example, compressive forces) F_2 act on the end surfaces 13a of the web 13 in the x-axis direction, the web 13 is displaced in a wavy shape in the x-axis direction. The external forces (for example, compressive forces) F_2 are an external force that acts with an equal magnitude throughout the entire length in the y-axis direction.

When first out-of-plane displacements in the x-axis direction of the web 13

displaced in a wavy shape in the x-axis direction are assumed to be represented by a formula $\sin(\pi x/a)$, the wavelength of the web 13 displaced in a wavy shape in the x-axis direction of the web 13 becomes $2a$.

[0108]

In a case where the external forces (for example, compressive forces) F_2 are acting on the web 13, conventionally, a first out-of-plane displacement w_w of the web 13 directed in the z-axis direction was estimated using the Fourier series represented by Formula (1).

The value of Y for a portion of the web 13 present at y_0 in the y-axis coordinate becomes a value of (y_0/b_w) . Therefore, the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction is obtained as the value of the first out-of-plane displacement w_w when the value of (y_0/b_w) is assigned to Y in Formula (1).

The inventors studied a plurality of functions with which the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function. Here, a line that passes through the central position of the length b_w of the web 13 in the y-axis direction and is along the x-axis is defined as a reference line M1. The reference line M1 may pass through the center of the web 13 in the z-axis direction.

[0109]

As a result, it was found that, in a case where the external forces (for example, compressive forces) F_2 act on the web 13 and the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis is estimated to be symmetrical in the y-axis direction with respect to the reference line M1, the first out-of-plane displacement w_w at a certain coordinate of the web 13 in

the y-axis is estimated from Formula (121) with a smaller number of terms than in the Fourier series. Here, in Formula (121), the term including the coefficient b_n represents, among the components of the first out-of-plane displacement w_w , an out-of-plane displacement for which the boundary condition at both ends in the y-axis direction becomes simple support. The term including the coefficient a_n represents, among the components of the first out-of-plane displacement w_w , an out-of-plane displacement for which the boundary condition at both ends in the direction along the y-axis direction becomes are fixed support.

[0110]

Specifically, the term including the coefficient b_n in Formula (121) is “ $b_n \cos(\pi/2)Y^n$ ”. The fact that this term “represents, among the components of the first out-of-plane displacement w_w , the out-of-plane displacement for which the boundary condition at both ends in the y-axis direction becomes simple support (pin support)” means that this term represents an out-of-plane displacement for which both ends in the y-axis direction are freely rotatable.

Incidentally, the term including the coefficient a_n in Formula (121) is “ $a_n \cos \pi Y^n$ ”. The fact that this term “represents, among the components of the first out-of-plane displacement w_w , the out-of-plane displacement for which the boundary condition at both ends in the direction along the y-axis becomes fixed support” means that this term represents an out-of-plane displacement for which the rotation of both ends in the y-axis direction is restrained and no rotation angle is generated.

[0111]

In addition, the value of Y in Formula (121) is a value for which a y-axis coordinate is made dimensionless using the length b_w of the web 13 in the y-axis direction. N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined

coefficients (coefficients).

$\cos \pi Y^n$ and $\cos(\pi/2)Y^n$ serve as the bases. In Formula (121), the first out-of-plane displacement w_w is represented as a function of Y alone.

[0112]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot \cdot (1 \ 2 \ 1)$$

[0113]

The case where the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis is estimated to be symmetrical with respect to the reference line M1 is, for example, a case where the shape and the restraint conditions of the web 13 are symmetrical with respect to the reference line M1 or the like. When viewed in the z-axis direction, since the web 13 has a rectangular shape having a side along the x-axis direction and a side along the y-axis direction, a line that can become the reference line M1 is a line along the x-axis direction that passes through the center of the web 13 in the y-axis direction and the origin of the z-axis.

Here, a surface that is disposed at each end of the web 13 in the y-axis direction and extends in the x-axis direction will be referred to as an end surface 13b in the y-axis direction. In this example, the end surfaces 13b of the web 13 in the y-axis direction are each fixedly supported, and the external forces F2 are an equally distributed compressive force. Therefore, all of the shape and restraint conditions of the web 13 and the external forces acting on the web 13 in the y-axis direction be symmetrical with respect to the reference line M1. Therefore, the first displacement estimation portion 52 estimates (determines) that the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate of the web 13 in the

y-axis becomes symmetrical in the y-axis direction with respect to the reference line M1. In addition, the first displacement estimation portion 52 estimates the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis from Formula (121).

The expression “being symmetrical in the y-axis direction with respect to the reference line M1” means being symmetrical in the y-axis direction with respect to a reference plane that includes the reference line M1 and is orthogonal to the y-axis.

[0114]

In order to actually estimate the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis using Formula (121), the first out-of-plane displacement w_w is preferably estimated in an order as described below.

That is, as in Formula (122), values expressed using the value of Y and the length b_w of the web 13 in the y-axis direction are used to represent the y-axis coordinates. In other words, as in Formula (123), the value of Y is a value for which a y-axis coordinate is made dimensionless using the length b_w (a value obtained by subtracting one from a value obtained by dividing twice a y-axis coordinate by the length b_w).

In addition, the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis is estimated from Formula (124) that is obtained by assigning Formula (122) to Formula (121). Hereinafter, in a case where a compressive force acts on the web 13, such a conversion as Formula (121) into Formula (124) will be referred to correction of a first out-of-plane displacement w_w formula at the time of compression.

[0115]

$$y = b_w \cdot \frac{Y+1}{2} \quad \cdot \cdot (1 \ 2 \ 2)$$

$$Y = \frac{2y}{b_w} - 1 \quad \cdot \cdot (1 \ 2 \ 3)$$

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \quad \cdot \cdot (1 \ 2 \ 4)$$

[0116]

Incidentally, an operator who operates the estimation device 50 may perform the above-described estimation and input the estimated result into the estimation device 50.

In a case where N is 2, Formula (121) turns into Formula (125), and Formula (124) turns into Formula (126).

[0117]

$$w_w = a_0 + a_1 \cos \pi Y + b_1 \cos \frac{\pi}{2} Y + a_2 \cos \pi Y^2 + b_2 \cos \frac{\pi}{2} Y^2 \quad \cdot \cdot (1 \ 2 \ 5)$$

$$w_w = a_0 + a_1 \cos \frac{2\pi y}{b_w} + b_1 \sin \frac{\pi y}{b_w} + a_2 \cos \pi \left(\frac{2y}{b_w} - 1 \right)^2 + b_2 \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^2 \quad \cdot \cdot (1 \ 2 \ 6)$$

[0118]

A second out-of-plane displacement (out-of-plane displacement) W_w in the entire region of the web 13 in a portion where the length of the web 13 in the x-axis direction is half wavelength a , which is shown in FIG. 5, will be described. When represented by functions of the y-axis and the x-axis using the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate in the y-axis, this second out-of-plane displacement W_w turns into Formula (127).

When Formula (124) is assigned to Formula (127), Formula (128) is obtained.

[0119]

$$W_w = \sin \frac{\pi x}{a} \cdot w_w \quad \cdot \cdot (1 \ 2 \ 7)$$

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (1 \ 2 \ 8)$$

[0120]

The second out-of-plane displacement W_w in FIG. 4 is repetition of the second out-of-plane displacement W_w in FIG. 5 in the x-axis direction. Since the estimation of the second out-of-plane displacement W_w of the web 13 in FIG. 4 is the same as the estimation of the second out-of-plane displacement W_w of the web 13 in FIG. 5, Formula (127) above is a formula that has estimated the second out-of-plane displacement W_w in FIG. 5.

For example, before the external forces F2 act on the web 13 of FIG. 5, the z-axis coordinate of a portion having an x-axis coordinate of x_0 and a y-axis coordinate of y_0 in the web 13 (hereinafter, referred to as the estimation target portion) is 0. After the external forces F2 have acted on the web 13, the second out-of-plane displacement W_w in this estimation target portion is estimated from Formula (129), and the z-axis coordinate at this time is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (129) to 0. That is, after the external forces F2 have acted, the estimation target portion is estimated to be disposed at a position where the x-axis coordinate becomes x_0 , the y-axis coordinate becomes y_0 , and the z-axis coordinate becomes W_w .

[0121]

$$W_w = \sin \frac{\pi x_0}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y_0}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y_0}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (129)$$

[0122]

The values of undetermined coefficients a_1 , a_2 , b_1 , and b_2 in Formula (125) above are obtained as described below.

Here, the thickness of the web 13 is indicated by t_w , the Poisson's ratio of the web 13 is indicated by ν , the Young's modulus of the web 13 is indicated by E , the sheet rigidity of the web 13 is indicated by D_w , the buckling stress of the web 13 is indicated

by σ_{cr} , and be the displacement of the web 13 in the x-axis direction due to buckling is indicated by δ_w .

At this time, the sheet rigidity D_w is represented by Formula (132), and a strain energy U that is generated in the web 13 due to buckling distortion and an external force potential V that is imparted due to the external forces F_2 are each represented by Formula (133) and Formula (134). In addition, a total potential energy Π in the energy method is imparted from Formula (135), which is the sum of the strain energy U and the external force potential V .

[0123]

$$\begin{aligned}
 D_w &= \frac{Et_w}{12(1-\nu^2)} \quad \cdot \cdot (1 \ 3 \ 2) \\
 U &= \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
 &\quad + \int_0^a \int_0^{b_w} \sigma_{cr} t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial x} \right)^2 \right] dy dx \quad \cdot \cdot (1 \ 3 \ 3) \\
 V &= -\sigma_{cr} b_w t_w \delta_w \quad \cdot \cdot (1 \ 3 \ 4) \\
 \Pi &= U + V \quad \cdot \cdot (1 \ 3 \ 5)
 \end{aligned}$$

[0124]

A formula obtained by assigning 0 to the total potential energy Π in Formula (135) will be solved with respect to the buckling stress σ_{cr} . Then, the buckling stress σ_{cr} is represented by Formula (140) using Formula (138) and Formula (139).

Here, a_1 , a_2 , b_1 , b_2 , and the half wavelength a are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (140).

[0125]

Here, the reason for using the energy method is that the buckling stress σ_{cr} of the web 13 can be obtained such that the total potential energy Π that is obtained based on the first out-of-plane displacement w_w of the web 13 becomes 0.

A method of obtaining the buckling stress σ_{cr} of the web 13 is not limited to the

energy method.

[0126]

$$\begin{aligned}
 A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (138) \\
 B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
 &\quad \cdot \cdot (139) \\
 \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (140)
 \end{aligned}$$

[0127]

Specifically, the half wavelength a is treated as a constant. In this state, a simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_1 , a_2 , b_1 , and b_2 is equal to 0 is created, whereby a_1 , a_2 , b_1 , and b_2 , which are real numbers, can be obtained. In a case where there is a plurality of sets of a_1 , a_2 , b_1 , and b_2 that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on, among the plurality of sets of a_1 , a_2 , b_1 , and b_2 , the set of a_1 , a_2 , b_1 , and b_2 that imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (140) (by assigning the set of a_1 , a_2 , b_1 , and b_2 to Formula (140)). Next, the half wavelength a is treated as a variable. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_1 , a_2 , b_1 , and b_2 has been obtained, by the half wavelength a is equal to 0, the half wavelength a is obtained. The buckling stress σ_{cr} obtained based on the set of a_1 , a_2 , b_1 , and B_2 and the half wavelength a obtained as described above becomes a buckling stress σ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_1 , a_2 , b_1 , and b_2 that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on the set of a_1 , a_2 , b_1 , and b_2 in a case where the set of a_1 , a_2 , b_1 , and b_2 imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula

(140). Next, the half wavelength a is treated as a variable, and the buckling stress σ_{cr} is obtained as described above.

[0128]

Formula (126) and Formula (127) from which first out-of-plane displacements w_w of the web 13 in the y -axis direction have been estimated from the obtained values of the a_1 , a_2 , b_1 , and b_2 and the half wavelength a are specifically obtained.

Evaluation of accuracy of Formula (126)

FIG. 6 and FIG. 7 show the estimation results of the first out-of-plane displacement w_w of the web 13 along the y -axis coordinates in a case where the web 13 is estimated to buckle so as to be symmetrical in the y -axis direction. The first out-of-plane displacement w_w is the first out-of-plane displacement in a cross section along a cutting-plane line A1-A1 in FIG. 5.

In FIG. 6 and FIG. 7, the horizontal axis represents the y -axis coordinates with respect to the length b_w of the web 13 (the values of Y), and the vertical axis represents the estimated first out-of-plane displacements w_w of the web 13. 0 in the horizontal axis represents the lower end of the web 13, and 1 in the horizontal axis represents the upper end of the web 13. FIG. 6 and FIG. 7 show the y -axis coordinates 0 to 1 that are divided into several tens of sections. The coordinates of the boundaries between the sections are, for example, 0, 0.02, 0.04, ..., 1, and the like.

[0129]

In FIG. 6 and FIG. 7, a line L1 indicated by a solid line represents analysis results by the FEM. The first out-of-plane displacements w_w of the web 13 estimated by the FEM are symmetrical in the y -axis direction with respect to the reference line M1 (refer to FIG. 5).

In FIG. 6, a line L2 indicated by a dotted line represents results estimated using

Formula (126) of the present embodiment. Since the line L2 almost coincides with the line L1, the line L2 overlaps the line L1.

In FIG. 7, a line L3 indicated by a dotted line represents the estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), in a case where N is 1. Similarly, a line L4 indicated by an alternate long and short dash line and a line L5 indicated by a chain double-dashed line each represent the estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), in a case where N is 5 or 15. Since the line L5 almost coincides with the line L1, the line L5 overlaps the line L1. The estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), further coincide with that the first out-of-plane displacements w_w of the web 13 estimated by the FEM as N becomes larger.

[0130]

Here, the standard deviation of the ratio of the first out-of-plane displacement w_w of the web 13 estimated from Formula (126) (Formula (124) in a case where N is 2) to the first out-of-plane displacement w_w of the web 13 in the y-axis direction estimated by the FEM at a coordinate of a boundary between individual sections other than 0 and 1 in the y-axis coordinates will be referred to as a first standard deviation. The standard deviation of the ratio of the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) to the first out-of-plane displacement w_w of the web 13 estimated by the FEM at a coordinate of a boundary between individual sections other than 0 and 1 in the y-axis coordinates will be referred to as a second standard deviation. Table 1 represents the ratios of the second standard deviation to the first standard deviation (hereinafter, referred to as the standard deviation ratios).

In Formula (1), N was changed to 1, 3, 5, 7, 10, and 15. When this standard deviation ratio is 1, a condition where the ratio of the first out-of-plane displacement w_w of the web 13 estimated from Formula (126) to the first out-of-plane displacement w_w of the web 13 estimated by the FEM is scattered and a condition where the ratio of the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) to the first out-of-plane displacement w_w of the web 13 estimated by the FEM is scattered becomes the same as each other.

Table 1 also shows results in a case where the web 13 buckles so as to be asymmetrical in the y -axis direction, which will be described below.

[0131]

[Table 1]

※ Standard deviation ratio

N	Compressive force	Bending moment
1	107.6	156.8
3	56.0	23.6
5	35.0	15.2
7	24.2	8.0
10	17.7	6.8
15	12.6	5.6

[0132]

FIG. 8 shows Table 1 graphically. In FIG. 8, the horizontal axis represents N, and the vertical axis represents the standard deviation ratio. A line L8 indicated by a solid line represents the results in a case where the web 13 buckles so as to be symmetrical in the y-axis direction, and a line L9 indicated by a dotted line represents the results in a case where the web 13 buckles so as to be asymmetrical in the y-axis direction.

As indicated by the line L8, the standard deviation ratio becomes smaller as N becomes larger, but the standard deviation ratio is 10 or more even when N is set to 15.

[0133]

Here, the sum of squared differences between the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis estimated from Formula (126) at the coordinate of each boundary between individual sections other than 0 and 1 in the y-axis coordinate and the first out-of-plane displacement w_w of the web 13 estimated by the FEM will be referred to as a first squared sum. The sum of squared differences between the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) at the coordinate of each

boundary between individual sections other than 0 and 1 in the y-axis coordinate and the first out-of-plane displacement w_w of the web 13 estimated by the FEM will be referred to as a second squared sum. Table 2 shows the ratios of the second squared sum to the first squared sum (hereinafter, referred to as the squared sum ratio).

In Formula (1), N was changed to 1, 3, 5, 7, 10, and 15. When this squared sum ratio is 1, an error of the first out-of-plane displacement w_w of the web 13 estimated from Formula (126) with respect to the first out-of-plane displacement w_w of the web 13 estimated by the FEM and an error of the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) with respect to the first out-of-plane displacement w_w of the web 13 estimated by the FEM becomes equal to each other.

Table 2 also shows results in the case where the web 13 buckles so as to be asymmetrical in the y-axis direction, which will be described below.

[0134]

[Table 2]

※ Squared sum ratio

N	Compressive force	Bending moment
1	50108	1641.3
3	3552	60.4
5	603	22.7
7	159	15.7
10	55	14.0
15	38	0.4

[0135]

FIG. 9 shows Table 2 graphically. In FIG. 9, the horizontal axis represents N, and the vertical axis represents the squared sum ratio. A line L10 indicated by a solid line represents the results in a case where the web 13 buckles so as to be symmetrical in the y-axis direction, and a line L11 indicated by a dotted line represents the results in a

case where the web 13 buckles so as to be asymmetrical in the y-axis direction.

As indicated by the line L10, the squared sum ratio becomes smaller as N becomes larger, but the squared sum ratio is 10 or more even when N is set to 15. Even when N is set to 15, the error between the first out-of-plane displacement w_w of the web 13 estimated from Formula (126) and the first out-of-plane displacement w_w of the web 13 estimated by the FEM is smaller than the error between the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) and the first out-of-plane displacement w_w of the web 13 estimated by the FEM.

[0136]

(2. Estimation of first out-of-plane displacement in case where first out-of-plane displacement is estimated to be asymmetrical with respect to reference line)

Next, as shown in FIG. 10, a case where external forces (for example, bending moments) F3 act on the end surfaces 13c of the web 13 in the x-axis direction will be described. In this example, the end surfaces 13b of the web 13 in the y-axis direction are each fixedly supported throughout the entire length in the x-axis direction. The external forces (for example, bending moments) F3 act so as to compress the web 13 above the reference line M1 but acts so as to extend the web 13 below the reference line M1. Therefore, the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate in the y-axis is estimated to become asymmetrical in the y-axis direction with respect to the reference line M1.

The case where the first out-of-plane displacement w_w of the web 13 is estimated to be asymmetrical with respect to the reference line M1 is, for example, a case where a normal stress in the x-axis direction that is generated due to an external force is asymmetrical with respect to the reference line M1.

[0137]

Regarding this example as well, the inventors studied a plurality of functions with which the first out-of-plane displacement of the web 13 can be estimated by a smaller number of terms than in the Fourier series. As a result, it was found that the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis is estimated from Formula (143) with a smaller number of terms than in the Fourier series with respect to the y-axis having coordinates of 0 or more and 1 or less. $\cos 2\pi Y^n$ and $\sin \pi Y^n$ serve as the bases. In Formula (143), the first out-of-plane displacement w_w is represented as a function of Y alone.

In this case, as in Formula (144), values expressed using the value of Y and the length b_w of the web 13 in the y-axis direction (products of the value of Y and the length b_w) are used to represent the y-axis coordinates. In other words, as in Formula (145), the value of Y is a value for which a y-axis coordinate is made dimensionless using the length b_w (by dividing a y-axis coordinate by the length b_w).

[0138]

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (1 \ 4 \ 3)$$

$$y = b_w Y \quad \cdot \cdot (1 \ 4 \ 4)$$

$$Y = \frac{y}{b_w} \quad \cdot \cdot (1 \ 4 \ 5)$$

[0139]

In a case where the first displacement estimation portion 52 has estimated that the first out-of-plane displacement w_w directed in the z-axis direction at a coordinate in the y-axis of the web 13 becomes asymmetrical in the y-axis direction with respect to the reference line M1, the first displacement estimation portion 52 estimates the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis from Formula (143). A first out-of-plane displacement w_w directed in the z-axis direction of the web 13 present at y_0 in the y-axis coordinates is

obtained as a value of the first out-of-plane displacement w_w when the value (y_0/b_w) is assigned to Y in Formula (143).

In order to actually estimate the first out-of-plane displacement w_w directed in the z-axis direction at a certain value of Y of the web 13 using Formula (143), the first out-of-plane displacement w_w is preferably estimated in an order as described below. That is, the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis is estimated from Formula (146) that is obtained by assigning Formula (122) to Formula (143).

[0140]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w} + b_n \sin \frac{\pi y^n}{b_w} \right) \quad \cdot \cdot (146)$$

[0141]

Incidentally, an operator who operates the estimation device 50 may perform the above-described estimation and input the estimated result into the estimation device 50.

[0142]

At the time of applying Formula (146) to the estimation of the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis, N was assumed to be 2 in Formula (146). As shown in FIG. 10, when represented by functions of the y-axis and the x-axis using the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate in the y-axis, the second out-of-plane displacement W_w in the entire region of the web 13 in a portion where the length of the web 13 in the x-axis direction is half wavelength a turns into Formula (147). In this case, Formula (148) is used instead of Formula (133) above for the strain energy U , and Formula (149) is used instead of Formula (134) above for the

external force potential V.

[0143]

$$\begin{aligned}
 W_w &= \sin \frac{\pi x}{a} \cdot w_w \quad \cdot \cdot (147) \\
 U &= \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
 &\quad + \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \sigma_{cr} t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial x} \right)^2 \right] dy dx \quad \cdot \cdot (148) \\
 V &= - \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \sigma_{cr} b_w t_w \delta_w dy \quad \cdot \cdot (149)
 \end{aligned}$$

[0144]

The buckling stress σ_{cr} in this case is represented as Formula (140), and, as the constant A, a value obtained from Formula (150) is used.

[0145]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (150)$$

[0146]

The values of the undetermined coefficients a_1 , a_2 , b_1 , and b_2 and the half wavelength a are obtained as real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (140). Formula (146) and Formula (147) from which a first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis have been estimated from these values of the a_1 , a_2 , b_1 , and b_2 and the half wavelength a are specifically obtained.

Evaluation of accuracy of Formula (146)

FIG. 11 and FIG. 12 show the estimation results of the first out-of-plane displacement w_w of the web 13 along the y-axis coordinates in a case where the web 13 buckles so as to be asymmetrical in the y-axis direction. The first out-of-plane displacement w_w is an out-of-plane displacement in a cross section along a cutting-plane

line A2-A2 in FIG. 10.

In FIG. 11 and FIG. 12, the horizontal axis represents the y-axis coordinates with respect to the length b_w of the web 13, and the vertical axis represents the estimated first out-of-plane displacements w_w of the web 13.

In FIG. 11 and FIG. 12, a line L14 indicated by a solid line represents analysis results by the FEM. In FIG. 11, a line L15 indicated by a dotted line represents results estimated using Formula (147) of the present embodiment.

[0147]

In FIG. 12, a line L16 indicated by a dotted line represents the estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), in a case where N is 1. Similarly, a line L17 indicated by an alternate long and short dash line and a line L18 indicated by a chain double-dashed line each represent the estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), in a case where N is 5 or 15. Since the line L18 almost coincides with the line L14, the line L18 overlaps the line L14.

The estimation results of the first out-of-plane displacement w_w of the web 13 using the Fourier series, which is represented by Formula (1), further coincide with that the first out-of-plane displacements w_w of the web 13 estimated by the FEM as N becomes larger.

[0148]

Table 1 shows the standard deviation ratios of the ratios of the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) and Formula (146) to the first out-of-plane displacement w_w of the web 13 estimated by the FEM, and FIG. 8 shows Table 1 graphically. As indicated by the line L9, the standard deviation ratio

becomes smaller as N becomes larger, but the standard deviation ratio is approximately 6 even when N is set to 15. In a case where N is 3 or more, the standard deviation ratio in a case where the web 13 buckles so as to be asymmetrical in the y -axis direction is smaller than the standard deviation ratio in a case where the compressive forces F_2 act on the web 13.

[0149]

Table 2 shows the squared sum ratios of the first out-of-plane displacements w_w of the web 13 estimated from Formula (1) and Formula (146) to the first out-of-plane displacement w_w directed in the z -axis direction at a certain coordinate of the web 13 in the y -axis estimated by the FEM (here, $N = 2$ in Formula (146)). FIG. 9 shows Table 2 graphically. As indicated by the line L11, the squared sum ratio becomes smaller as N becomes larger, and the squared sum ratio becomes smaller than 1 when N is 15. That is, an error of the first out-of-plane displacement w_w directed in the z -axis direction at a certain coordinate of the web 13 in the y -axis estimated from Formula (1) becomes smaller than an error of the first out-of-plane displacement w_w directed in the z -axis direction at a certain coordinate of the web 13 in the y -axis estimated from Formula (146).

It is found that, in order to make the error of the first out-of-plane displacement w_w of the web 13 estimated from Formula (1) where N is 15 equal to the error of the first out-of-plane displacement w_w of the web 13 estimated by the FEM, N in Formula (146) needs to be smaller than 15.

[0150]

The estimation of the first out-of-plane displacement w_w of the web 13 alone can be used for the estimation of the first out-of-plane displacement w_w of the web 13 in the H-section steel 10 in a case where the thicknesses of the flanges 11 and 12 are thin

enough to be ignored and the rigidity of the flanges 11 and 12 is low enough to be ignored.

In a displacement estimation method of the present embodiment (hereinafter, simply referred to as the estimation method), a first displacement estimation step of estimating the first out-of-plane displacement w_w of the web 13 from Formula (124) or Formula (146) is performed. Formula (124) is used in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the y-axis direction with respect to the reference line M1. Formula (146) is used in a case where the first out-of-plane displacement w_w is estimated to be asymmetrical in the y-axis direction with respect to the reference line M1.

The estimation of the first out-of-plane displacement w_w of the web 13 using Formula (124) including y and the estimation of the first out-of-plane displacement w_w of the web 13 using Formula (11) including Y are the same as each other. Similarly, the estimation of the first out-of-plane displacement w_w of the web 13 using Formula (146) including y and the estimation of the first out-of-plane displacement w_w of the web 13 using Formula (143) including Y are the same as each other.

[0151]

As described above, in the estimation device 50, the estimation method, and the estimation program 61 of the present embodiment, the inventors studied the plurality of functions with which the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function. As a result, it was found that the first out-of-plane displacement w_w of the web 13 can be estimated accurately with a smaller number of terms than in the Fourier series using Formula (121) in a case where the first out-of-plane displacement w_w of the web 13 is

symmetrical with respect to the reference line M1 and using Formula (143) in a case where the first out-of-plane displacement w_w of the web 13 is asymmetrical with respect to the reference line M1.

Since the first out-of-plane displacement w_w directed in the z-axis direction at a certain coordinate of the web 13 in the y-axis can be estimated by a smaller number of terms than in the Fourier series, Formula (121) or Formula (143) makes it possible to simplify the calculation necessary for estimation compared with cases where the Fourier series is used. Furthermore, since the number of terms necessary to estimate the first out-of-plane displacement w_w with the same degree of accuracy is smaller in the case of estimation using Formula (121) or Formula (143) than in the case of estimation using the Fourier series of Formula (1), it is possible to formulate estimation results to be more easily understood physically than cases where the Fourier series is used.

[0152]

In addition, N is 2 in Formula (121) or Formula (143). Formula (121) or Formula (27) is a formula not including the half wavelength a , and constants necessary to obtain Formula (121) or Formula (143) are equal to or smaller than 4, that is, the undetermined coefficients a_1 , a_2 , b_1 , and b_2 . Therefore, it is possible to easily obtain the constants of the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

[0153]

The first out-of-plane displacement w_w of the lower flange 11, the upper flange 12, and the web 13 of the H-section steel 10 can be estimated using the estimation device 50 of the present embodiment. In this case, the thicknesses of the flanges 11 and 12 (the lengths in the y-axis direction) are preferably smaller than the lengths in the x-axis direction and the lengths in the z-axis direction of the flanges 11 and 12.

[0154]

In the above-described embodiment, N may be 3 or more in Formula (121), Formula (143), and the like.

The H-section steel 10, which is an elastic element, was described to be formed of steel, but the material that forms the elastic element is not limited to steel as long as the material shows an elastic property and may be wood, rubber, or the like.

[0155]

Hereinafter, individual embodiments of a buckling stress estimation device 50, a buckling stress estimation method, and a buckling stress estimation program, all of which the estimation device 50, the estimation method, and the estimation program 61 of the present embodiment are used, will be described.

[0156]

[Second Embodiment]

Next, a second embodiment of the present invention will be described with reference to FIG. 13 to FIG. 18, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) 80 shown in FIG. 13 is used to estimate the buckling stress of the H-section steel 10 that buckles due to a compressive force acting as an external force (refer to FIG. 14). The estimation device 80 estimates the buckling stress of the H-section steel 10 using the displacement estimation device 50 of the first embodiment.

[0157]

As shown in FIG. 14, the H-section steel 10 includes a web sheet element 13, a

first flange sheet element 11, and a second flange sheet element 12. The first flange sheet element 11, the second flange sheet element 12, and the web sheet element 13 are each an elastic element. FIG. 14 shows an xyz coordinate system S_{11} for the first flange sheet element 11 and an xyz coordinate system S_{13} for the web sheet element 13. The first flange sheet element 11 and the second flange sheet element 12 are disposed so as to sandwich the web sheet element 13 in a direction along the y-axis of the web sheet element 13.

In the present embodiment, the entire H-section steel 10 is an estimation target, and the entire H-section steel 10 is regarded as an elastic element. The reference line M1 is a reference line based on the web sheet element 13. That is, the reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the direction along the y-axis and is along the x-axis of the web sheet element 13.

[0158]

FIG. 13 shows the estimation device 80 of the present embodiment. The estimation device 80 is configured in the same manner as the estimation device 50. However, in the present embodiment, a buckling stress estimation program for making the computer function as the estimation device 80 (hereinafter, simply referred to as the estimation program) 81 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0159]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 82 that estimates a second out-of-plane displacement of the web sheet element 13 and a second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12 and a stress calculation portion

83 that obtains the buckling stress of the H-section steel 10 based on the energy method using the second out-of-plane displacement of the web sheet element 13 and the second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12. The second displacement estimation portion 82 and the stress calculation portion 83, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 81 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 82.

The estimation program 81 or the like is a program for the estimation device 80. The estimation program 81 makes the estimation device 80 function as the second displacement estimation portion 82 and the stress calculation portion 83. The estimation program 81 uses the estimation program 61.

[0160]

In the second displacement estimation portion 82 and the stress calculation portion 83 of the estimation device 80 of the present embodiment, as shown in FIG. 14, the position coordinates of the H-section steel 10 are recognized based on the right-handed orthogonal coordinate system composed of the u-axis, the v-axis, and the w-axis (hereinafter, also referred to as the uvw coordinate system). This is also true for the fourth embodiment and the sixth embodiment described below. The prescriptions for the uvw coordinate systems of the fourth embodiment and the sixth embodiment are the same as the prescriptions for the uvw coordinate system of the second embodiment except that, in the sixth embodiment, the origin of the v-axis is different from that of the second embodiment.

In FIG. 14 and FIG. 16 shown below, the second out-of-plane displacement of the web sheet element 13 or the like is shown to be larger than an estimated value.

FIG. 14 shows a state in which the H-section steel 10 buckles.

The v-axis is prescribed as an axis in a direction along the y-axis of the xyz coordinate system S_{13} for the web sheet element 13. The w-axis is prescribed as an axis in a direction along the z-axis of the xyz coordinate system S_{13} for the web sheet element 13. The u-axis is orthogonal to each of the v-axis and the w-axis. The u-axis is prescribed as an axis in a direction along the x-axis of the xyz coordinate system S_{13} for the web sheet element 13.

The second out-of-plane displacement of the web sheet element 13 is a displacement directed in the z-axis direction of the xyz coordinate system S_{13} for the web sheet element 13 (w-axis direction).

[0161]

The second out-of-plane displacements of the first flange sheet element 11 and the second flange sheet element 12 are each a displacement directed in the z-axis direction (v-axis direction) of the xyz coordinate system.

The H-section steel 10 is assumed to be sufficiently long in the u-axis direction. The expression “the H-section steel 10 is sufficiently long in the u-axis direction” mentioned herein means that the H-section steel 10 has a length long enough to ignore the influence of the boundary condition of a surface that is disposed at each end of the H-section steel 10 in the u-axis direction and extends in the v-axis direction (hereinafter, referred to as the end surface in the u-axis direction) 10a on buckling distortion.

[0162]

When a compressive force F_6 acts in the u-axis direction on each of the end surfaces 10a of the H-section steel 10 in the u-axis direction, there are cases where the H-section steel 10 buckles. The compressive forces F_6 are transmitted throughout the

entire length of the H-section steel 10 in the u-axis direction. In the present embodiment, for example, the compressive forces F6 are an equally distributed stress acting throughout the entire length of each end surface 10a in the v-axis direction.

The compressive forces F6 acting on the individual end surfaces 10a of the H-section steel 10 in the u-axis direction are external forces having an equal magnitude.

[0163]

In this case, as the web sheet element 13 runs toward a first end of the web sheet element 13 in the u-axis direction (one of the end surfaces 10a in the u-axis direction), the web sheet element 13 is alternately displaced in the positive orientation of the w-axis and in the negative orientation of the w-axis, and the web sheet element 13 is displaced in a wavy shape in the u-axis direction as a whole. The flange sheet elements 11 and 12 are also displaced in association with the web sheet element 13.

In one wavelength-long part of the web sheet element 13 displaced along the u-axis, a second end opposite to the first end in the u-axis direction is defined as the origin of the u-axis, and an orientation toward the first end in the u-axis direction from the second end is defined as the positive orientation of the u-axis.

[0164]

As shown in FIG. 14 and FIG. 15, the central position of the first flange sheet element 11 in a direction along the v-axis is defined as the origin of the v-axis. An orientation toward the second flange sheet element 12 from the first flange sheet element 11 is defined as the positive orientation of the v-axis.

The origin of the w-axis is defined as the center of the web sheet element 13 in the w-axis direction (the center in the thickness direction). The positive orientation of the w-axis is defined as an orientation that constitutes the right-handed orthogonal coordinate system with respect to the positive orientation of the u-axis and the positive

orientation of the v-axis.

The reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the v-axis direction and is along the u-axis.

[0165]

Here, the dimensions of the H-section steel 10 in a cross section orthogonal to the longitudinal direction are prescribed as shown in FIG. 15. As the unit of lengths and the like described below, the SI unit such as “m” is preferably used for lengths.

The thickness (the length in the w-axis direction) of the web sheet element 13 is indicated by t_w . The distance between the center of the first flange sheet element 11 and the center of the second flange sheet element 12 in the v-axis direction is indicated by b_w (this is also true for the fourth embodiment and the sixth embodiment in which the H-section steel 10 is regarded as an evaluation target).

The width of the first flange sheet element 11 (the length in the w-axis direction) and the width of the second flange sheet element 12 are equal to each other, and the value of half the width of each of the first flange sheet element 11 and the second flange sheet element 12 is indicated by b_f . The width of each of the first flange sheet element 11 and the second flange sheet element 12 is indicated by B_f .

The thickness of the first flange sheet element 11 and the thickness of the second flange sheet element 12 are equal to each other, and the thickness of each of the first flange sheet element 11 and the second flange sheet element 12 is indicated by t_f .

The Young's modulus of the H-section steel 10 (the web sheet element 13 and the first and second flange sheet elements 11 and 12) is indicated by E , and the Poisson's ratio of the H-section steel 10 is indicated by ν .

[0166]

The estimation device 80 of the present embodiment estimates the buckling

stress of the H-section steel 10 when the compressive forces F_6 act on the H-section steel 10 and the H-section steel 10 buckles. In the second displacement estimation portion 82 and the stress calculation portion 83 of the estimation device 80, at the time of estimating the buckling stress of the H-section steel 10, the above-described assumptions 1 to 3 and the following assumptions 4A to 6A are performed.

4A. In the cross section of the H-section steel 10, an assumption of holding a flat plane against bending is established.

5A. The material of the H-section steel 10 is homogeneous and isotropic.

6A. The displacement of the H-section steel 10 under the action of an external force complies with the Hooke's law.

[0167]

As shown in FIG. 14, when the compressive forces F_6 act on the H-section steel 10, there are cases where the web sheet element 13 and the like of the H-section steel 10 are displaced in a wavy shape in the u-axis direction. When the v-axis coordinate is a certain value in the web sheet element 13 displaced in a wavy shape in the u-axis direction, the second out-of-plane displacement of the web sheet element 13 directed in the w-axis direction at the certain coordinate in the u-axis is assumed to be represented by Formula $\sin(\pi u/a)$ (Assumption 1). At this time, the wavelength in the u-axis direction of the web sheet element 13 displaced in a wavy shape in the u-axis direction of the web sheet element 13 becomes $2a$. The half wavelength (the length of half the wavelength) in the u-axis direction of the web sheet element 13 becomes a .

FIG. 16 is a view showing second out-of-plane displacements W_w in the entire region of the H-section steel 10 in a portion where the length of the H-section steel 10 in the u-axis direction is the half wavelength a .

[0168]

FIG. 17 shows a state in which the compressive forces F6 act on the H-section steel 10 with a solid line. What is indicated with a dotted line in FIG. 17 shows a state in which the compressive forces F6 do not act on the H-section steel 10.

[0169]

Conventionally, in the width-thickness ratio classification of H-section steels against compressive forces, coupled buckling between sheet elements such as webs (web sheet elements) and flanges (flange sheet elements) is not taken into account, and the width-thickness ratio classification of H-section steels has been constructed based on the proof stress formula elucidated regarding sheet elements under a simple support condition.

However, in the local buckling of H-section steels, since the web and the flanges interact each other, it is not possible to accurately estimated the buckling stress of an H-section steel (local buckling stress) with the conventional width-thickness ratio classification. The shape of local buckling when a compressive force acts on an H-section steel shows complicated periodic behaviors in both the web and the flanges. Therefore, when the Fourier series represented by Formula (1) above is used in a changed expression such as Formula (159), it is possible to estimate the second out-of-plane displacement W_w of the web or the like, which is a sheet element of an H-section steel (for example, refer to Non-Patent Document 1).

Here, b_w represents the distance between the centers of both flanges of the H-section steel in the thickness direction.

[0170]

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w} + b_n \sin \frac{\pi v^n}{b_w} \right) \right] \quad \cdot \cdot (159)$$

[0171]

As described above, in a case where the compressive forces F6 act on the web sheet element 13, conventionally, the out-of-plane displacement of the web sheet element 13 has been estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which, when the u-axis coordinate is a certain value, the first out-of-plane displacement w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function. The first out-of-plane displacement w_w is a function of the v-axis coordinates, not a function of the u-axis coordinates (a function at a certain coordinate on the u-axis).

As a result, it was found that, in a case where the compressive forces F6 act on the H-section steel 10, when the u-axis coordinate is a certain value, the first out-of-plane displacement w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis is estimated from Formula (160) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (160) includes a trigonometric term for which the power function of the v-axis coordinates is used. $\cos(\pi(2v/b_w-1)^n)$ and $\cos(\pi/2 \times (2v/b_w-1)^n)$ serve as the bases. Formula (160) can be preferably used to estimate the first out-of-plane displacement of a sheet element such as the web sheet element 13.

[0172]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \quad \cdots (160)$$

[0173]

In the present embodiment, since the first out-of-plane displacement w_w of the

H-section steel 10 is estimated to be symmetrical in the v -axis direction with respect to the reference line M1 as described below, the first out-of-plane displacement w_w is estimated from Formula (121) above. Formula (160) is the same as Formula (124) in the first embodiment. Formula (121) is converted into Formula (160) through the correction of the first out-of-plane displacement w_w formula at the time of compression in the first embodiment and the replacement of the y -axis with the v -axis.

[0174]

On the other hand, when the u -axis coordinate is an arbitrary value, the second out-of-plane displacement W_w of the web sheet element 13 directed in the w -axis direction at a certain coordinate in the v -axis is estimated from Formula (161).

Formula (161) is based on the assumption 1, that is, as described above, when the v -axis coordinate is a certain value in the web sheet element 13, the out-of-plane displacement in the u -axis direction is represented by Formula $\sin(\pi u/a)$.

The second out-of-plane displacement W_w in FIG. 14 is repetition of the second out-of-plane displacement W_w in FIG. 16 in the u -axis direction. Since the estimation of the second out-of-plane displacement W_w of the web sheet element 13 in FIG. 14 is the same as the estimation of the second out-of-plane displacement W_w of the web sheet element 13 in FIG. 16, Formula (161) above is a formula that has estimated the second out-of-plane displacement W_w in FIG. 16. The second out-of-plane displacement W_w is each of a v -axis coordinate function and a u -axis coordinate function and is used to estimate the buckling stress of the web sheet element 13.

When Formula (160) is assigned to Formula (161), Formula (162) is obtained. In a case where N is 2, Formula (162) can be converted into Formula (163).

[0175]

$$\begin{aligned}
W_w &= \sin \frac{\pi u}{a} \cdot w_w \quad \cdot \cdot (161) \\
W_w &= \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (162) \\
W_w &= \sin \frac{\pi u}{a} \left(a_0 + a_1 \cos \pi \left(\frac{2v}{b_w} - 1 \right) + b_1 \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right) + a_2 \cos \pi \left(\frac{2v}{b_w} - 1 \right)^2 + b_2 \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^2 \right) \\
&\quad \cdot \cdot (163)
\end{aligned}$$

[0176]

In addition, the second out-of-plane displacement W_{f1} at a predetermined coordinate in the w-axis of the first flange sheet element 11 is estimated from Formula (164), and the second out-of-plane displacement W_{f2} at a predetermined coordinate in the w-axis of the second flange sheet element 12 is estimated from Formula (165).

Formula (164) and Formula (165) include a trigonometric term for which the power function of the v-axis coordinates is used.

[0177]

$$\begin{aligned}
W_{f1} &= w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (164) \\
W_{f2} &= w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (165)
\end{aligned}$$

[0178]

For example, before the compressive forces F6 act on the H-section steel 10 of FIG. 16, the w-axis coordinate of a portion having a u-axis coordinate of u_0 and a v-axis coordinate of v_0 in the web sheet element 13 (hereinafter, referred to as the first estimation target portion) is 0. The second out-of-plane displacement W_w in this first estimation target portion is estimated from Formula (162-1). After the compressive forces F6 have acted on the H-section steel 10 in FIG. 16, the w-axis coordinate of the first estimation target portion is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (162-1) to 0. That is, after the compressive forces F6 have acted, the first estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes v_0 , and

the w-axis coordinate becomes W_w .

For example, before the compressive forces F6 act on the H-section steel 10 of FIG. 16, the v-axis coordinate of a portion having a u-axis coordinate of u_0 and a w-axis coordinate of w_0 in the second flange sheet element 12 (hereinafter, referred to as the second estimation target portion) is b_w . The second out-of-plane displacement W_{f2} in this second estimation target portion is estimated from Formula (165-1). After the compressive forces F6 have acted on the H-section steel 10 in FIG. 16, the v-axis coordinate of the second estimation target portion is a value obtained by adding the second out-of-plane displacement W_{f2} estimated from Formula (165-1) to b_w . That is, after the compressive forces F6 have acted, the second estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes $(b_w + W_{f2})$, and the w-axis coordinate becomes W_0 .

[0179]

$$W_w = \sin \frac{\pi u_0}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v_0}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v_0}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (162-1)$$

$$W_{f2} = w_0 \frac{\partial W_w}{\partial v} \Big|_{v=b_w, u=u_0, w=w_0} \quad \cdot \cdot (165-1)$$

[0180]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 82 estimates that, when the compressive forces F6 act on the H-section steel 10, the first out-of-plane displacement w_w of the H-section steel 10 (entire H-section steel 10) becomes symmetrical in the v-axis direction with respect to the reference line M1. That is, in the estimation program 81, the first displacement estimation portion 52 is made to estimate that the first out-of-plane displacement w_w of the H-section steel 10 becomes symmetrical in the v-axis direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is

that the shape and the restraint conditions of the H-section steel 10 are symmetrical with respect to the reference line M1 and the normal stress in the u-axis direction, which is generated by the compressive forces F6 acting on the H-section steel 10, is uniform in any cross sections in the v-axis direction.

The second displacement estimation portion 82 estimates the second out-of-plane displacement W_w of the web sheet element 13 from Formula (162) using the first out-of-plane displacement w_w of the web sheet element 13 estimated by the first displacement estimation portion 52. The second displacement estimation portion 82 estimates the second out-of-plane displacement W_{f1} of the first flange sheet element 11 from Formula (164) and estimates the second out-of-plane displacement W_{f2} of the second flange sheet element 12 from Formula (165) using the first out-of-plane displacement w_w of each of the first flange sheet element 11 and the second flange sheet element 12 estimated by the first displacement estimation portion 52.

[0181]

Here, for example, estimation of the second out-of-plane displacement W_w of the web sheet element 13 from Formula (162) using the first out-of-plane displacement w_w of the web sheet element 13 estimated by the first displacement estimation portion 52 has the following meaning. That is, since the first out-of-plane displacement w_w of the H-section steel 10 becomes symmetrical with respect to the reference line M1, the first displacement estimation portion 52 estimates the first out-of-plane displacement w_w of the web sheet element 13 from Formula (121). The correction of the first out-of-plane displacement w_w formula at the time of compression and the assumption 1 are applied thereto, and the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (162).

[0182]

For example, in the present embodiment, estimation of the second out-of-plane displacement W_{f1} of the first flange sheet element 11 from Formula (164) using the first out-of-plane displacement w_w of the first flange sheet element 11 estimated by the first displacement estimation portion 52 has the following meaning. That is, a value obtained by multiplying the partial differential of the second out-of-plane displacement W_w of the web sheet element 13 estimated from Formula (162) at $v = 0$ by the w -axis coordinate is regarded as the second out-of-plane displacement W_{f1} of the first flange sheet element 11. That is, in the present embodiment, the first flange sheet element 11 at a predetermined u -axis value is a linear shape inclined in accordance with the value of the above-described partial differential.

Based on the energy method, the strain energy U_w that is generated in the web sheet element 13 due to buckling distortion is represented as Formula (167), and the strain energy U_f in the first and second flange sheet elements 11 and 12 is represented as Formula (168).

[0183]

$$\begin{aligned}
 U_w &= \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad + \int_0^a \int_0^{b_w} \sigma_{cr} t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial u} \right)^2 \right] dv du \quad \cdot \cdot (167) \\
 U_f &= \sum_{i=1}^2 \left\{ \frac{D_f}{2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \right. \\
 &\quad \left. + \int_0^a \int_{-b_f}^{b_f} \sigma_{cr} t_f \left[\frac{\delta_{fi}}{a} - \frac{1}{2} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 \right] dw du \right\} \quad \cdot \cdot (168)
 \end{aligned}$$

[0184]

However, the sheet rigidity D_w of the web sheet element 13 is expressed as Formula (169). The sheet rigidity D_f of the first and second flange sheet elements 11 and 12 is represented as Formula (170). The buckling stress of the H-section steel 10 is indicated by σ_{cr} .

The function δ_w is a displacement in the u-axis direction at a certain coordinate in the v-axis of the web sheet element 13 when buckling occurs and is represented as Formula (171) by indicating the u-axis displacement that is generated at the center of the second flange sheet element 12 as δ .

[0185]

$$\begin{aligned} D_w &= \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (1 \ 6 \ 9) \\ D_f &= \frac{Et_f^3}{12(1-\nu^2)} \quad \cdot \cdot (1 \ 7 \ 0) \\ \delta_w &= \delta \quad \cdot \cdot (1 \ 7 \ 1) \end{aligned}$$

[0186]

The functions δ_{f1} and δ_{f2} are functions that express the displacements of the first and second flange sheet elements 11 and 12 in the u-axis direction when buckling occurs. The function δ_{f1} and the function δ_{f2} are equal to δ .

[0187]

In addition, the external force potential energy V_w of the web sheet element 13 is represented as Formula (178), and the external force potential energy V_f of the first and second flange sheet elements 11 and 12 is represented as Formula (179).

[0188]

$$\begin{aligned} V_w &= -\sigma_{cr} b_w t_w \delta \quad \cdot \cdot (1 \ 7 \ 8) \\ V_f &= -2\sigma_{cr} b_f t_f \delta \quad \cdot \cdot (1 \ 7 \ 9) \end{aligned}$$

[0189]

The total potential energy Π of the H-section steel 10 is represented as Formula (180) as the sum of the strain energy and the external force potential energy.

[0190]

$$\Pi = U_w + U_f + V_w + V_f \quad \cdot \cdot (1 \ 8 \ 0)$$

[0191]

The stress calculation portion 83 obtains the buckling stress σ_{cr} of the H-section steel 10 based on the energy method using the second out-of-plane displacement W_w of the web sheet element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (162), Formula (164), and Formula (165). That is, the stress calculation portion 53 obtains the buckling stress σ_{cr} based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (185), using Formula (181) to Formula (184).

[0192]

$$\begin{aligned}
 A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (181) \\
 B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad \cdot \cdot (182) \\
 C &= \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (183) \\
 D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
 &\quad \cdot \cdot (184) \\
 \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (185)
 \end{aligned}$$

[0193]

Specifically, the half wavelength a is treated as a constant. In this state, a simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set of a_n and b_n that imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (185) (by assigning the set of a_n and b_n to Formula (185)).

Next, the half wavelength a is treated as a variable. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a is equal to 0, the half wavelength a is obtained. The buckling stress σ_{cr} obtained based on the set of a_n and b_n and the half wavelength a obtained as described above becomes a buckling stress σ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (185). Next, the half wavelength a is treated as a variable, and the buckling stress σ_{cr} is obtained as described above.

[0194]

A buckling coefficient k_w of the web sheet element 13 is represented by Formula (188), and a buckling coefficient k_f of each of the first and second flange sheet elements 11 and 12 is represented by Formula (189).

[0195]

$$k_w = \frac{B}{A + \frac{t_f}{t_w} C} \quad \cdot \cdot (188)$$

$$k_f = \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (189)$$

[0196]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress σ_{cr} of the H-section steel 10 which buckles due to the compressive forces F_6 acting in the direction along the u -axis is estimated using the displacement estimation method of the

first embodiment. In the estimation method, a second displacement estimation step and a stress calculation step are performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since the shape and the restraint conditions of the H-section steel 10 are symmetrical with respect to the reference line M1 and the normal stress in the u-axis direction, which is generated by the compressive forces F6 acting on the H-section steel 10, is uniform in any cross sections in the v-axis direction, in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel 10 is estimated to be symmetrical in the v-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (162) using the first out-of-plane displacement w_w of the web sheet element 13 estimated in the first displacement estimation step. In addition, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are each estimated from Formula (164) and Formula (165) using the first out-of-plane displacement w_w of each of the first and second flange sheet elements 11 and 12 estimated in the first displacement estimation step.

In the stress calculation step, the buckling stress σ_{cr} is obtained based on the energy method using the second out-of-plane displacement W_w of the web sheet element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (162), Formula (164), and Formula (165).

[0197]

The compressive force F6 acting on the H-section steel 10 when the buckling stress σ_{cr} is generated in the H-section steel 10 can be obtained from a known equation regarding beams. When the compressive forces F6 acting on the H-section steel 10 are

made smaller than this compressive force F_6 , it is possible to suppress buckling of the H-section steel 10.

In addition, the application range of the dimensions such as the thicknesses t_f of the first and second flange sheet elements 11 and 12 in the estimation device 80, the estimation method, and the estimation program 81 of the present embodiment is preferably an application range 1 below.

- Width-thickness ratios (b_f/t_f) of first and second flange sheet elements 11 and 12: 20 or less
- Width-thickness ratio (b_w/t_w) of web sheet element 13: 300 or less
- Aspect ratio (b_w/B_f): 0.5 or more and 10 or less
- Sheet thickness ratio (t_f/t_w): 0.5 or more and 5.0 or less

[0198]

(Evaluation of estimation accuracy of buckling stress)

FIG. 18 shows a comparison result of the buckling stress that is estimated by the estimation method (the estimation device 80, and the estimation program 81) of the present embodiment and the buckling stress that is estimated by the FEM. N_y represents the yield axial force of the H-section steel 10. The yield axial force N_y is equal to the product of the yield stress σ_y of the H-section steel 10 and a cross-sectional area A of the H-section steel 10. N_{cr_pre} represents the elastic buckling proof stress of the H-section steel 10 that is estimated by the estimation method of the present embodiment. The elastic property buckling proof stress N_{cr_pre} is equal to the product of the buckling stress σ_{cr} of the H-section steel 10 that is estimated by the estimation method of the present embodiment and the cross-sectional area A . N_{cr_FEM} represents the elastic property buckling proof stress of H-section steel 10 that is estimated by the FEM. The elastic property buckling proof stress N_{cr_FEM} is equal to the product of the buckling stress σ_{cr_FEM} of the H-section steel 10 that is estimated by the FEM and the

cross-sectional area A . In FIG. 18, the horizontal axis represents the value of $\sqrt{(N_y/N_{cr_pre})}$, and the vertical axis represents the value of (N_{cr_pre}/N_y) or (N_{cr_FEM}/N_y) . The buckling stress and the like of the H-section steels 10 of a variety of specifications were estimated by the FEM and the estimation method of the present embodiment.

[0199]

In FIG. 18, the $\circ$ marks represent the results estimated by the FEM, that is, the results with the values of (N_{cr_FEM}/N_y) along the vertical axis. Along the horizontal axis of the $\circ$ marks, the values of $\sqrt{(N_y/M_{cr_pre})}$ of the H-section steel 10 that has the same specification as the H-section steel 10 analyzed by the FEM and is estimated by the estimation method of the present embodiment are used. The curve represents the results estimated by the estimation method of the present embodiment, that is, the results with the values of (N_{cr_pre}/N_y) along the vertical axis.

[0200]

The yield axial force N_y becomes a constant value in accordance with the material strength regardless of the FEM and the estimation method of the present embodiment. The estimation accuracy of the present embodiment can be evaluated by comparing the elastic property buckling proof stress N_{cr_pre} that is obtained from the estimation method of the present embodiment and the buckling stress σ_{cr_FEM} that is estimated by the FEM. For the H-section steels 10 having the same specification, the results estimated by the FEM and the results estimated by the estimation method of the present embodiment show that, in FIG. 18, the values along the horizontal axis are equal to each other and the values along the vertical axis shift from each other according to errors.

[0201]

In FIG. 18, the elastic property buckling proof stress N_{cr_FEM} estimated by the

FEM and the elastic property buckling proof stress N_{cr_pre} estimated by the estimation method of the present embodiment favorably correspond to each other. Since there is a certain relationship between the elastic property buckling proof stress N_{cr_pre} that is estimated by the estimation method of the present embodiment and the buckling stress σ_{cr_FEM} that is estimated by the FEM, it is possible to estimate the buckling stress σ_{cr} with a practically sufficient accuracy even when the buckling stress σ_{cr} is estimated by the estimation method of the present embodiment.

[0202]

In the case of attempting to estimate the buckling stress or the like of an H-section steel on which a compressive force acts with the Fourier series of Formula (159), it is necessary to set N to 30 or more, and furthermore, the buckling stress cannot be indicated by a positive solution. On the other hand, in the estimation method of the present embodiment, in a case where the second out-of-plane displacement W_w of the web sheet element 13 is represented by Formula (162) and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are represented by Formula (164) and Formula (165), the buckling stress σ_{cr} can be calculated as a positive solution such as Formula (185).

[0203]

As described above, according to the estimation device 80, the estimation method, and the estimation program 81 of the present embodiment, for the H-section steel 10 on which the compressive forces $F6$ act, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (162). As shown in Formula (164), the second out-of-plane displacement W_{f1} of the first flange sheet element 11 is determined according to a function obtained by assigning 0 to the v -axis coordinate of a function of the first order partial differential equation with respect to v

of the second out-of-plane displacement W_w of the web sheet element 13. In addition, as shown in Formula (165), the second out-of-plane displacement W_{f2} of the second flange sheet element 12 is determined according to a function obtained by assigning b_w to the v -axis coordinate of a function of the first order partial differential equation with respect to v of the second out-of-plane displacement W_w of the web sheet element 13.

[0204]

Depending on a variety of amounts of the cross sections and the material properties of the web sheet element 13 and the first and second flange sheet elements 11 and 12, the degree of mutual influence between the web sheet element 13 and the first and second flange sheet elements 11 and 12 changes, and the second out-of-plane displacement W_w of the web sheet element 13 and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are determined. As described above, when the buckling stress σ_{cr} of the H-section steel 10 is obtained based on the energy method using the second out-of-plane displacement W_w and the second out-of-plane displacements W_{f1} and W_{f2} , it is possible to estimate the buckling stress σ_{cr} in consideration of the coupled buckling of the web sheet element 13 and the first and second flange sheet elements 11 and 12.

[0205]

It is possible to estimate the second out-of-plane displacement W_w or the like of the web sheet element 13 with a smaller number of terms than in the Fourier series while using a trigonometric function and to simplify calculation necessary for the estimation of the second out-of-plane displacement W_w or the like.

Since the number of terms necessary to estimate the second out-of-plane displacement W_w or the like with a certain accuracy is smaller in the case of estimation using Formula (162) than in the case of estimation using the Fourier series of Formula

(159), it is possible to formulate the estimation result of the second out-of-plane displacement W_w or the like to be easily understood physically.

[0206]

Furthermore, the estimation device 80, the estimation method, and the estimation program 81 of the present embodiment have the following features 1 to 8.

1. The resistance element of the web sheet element 13 to the first and second flange sheet elements 11 and 12 is taken into account, whereby the buckling stress that is estimated for the first and second flange sheet elements 11 and 12 increases, and it is possible to estimate the buckling stress of the first and second flange sheet elements 11 and 12 with a more favorable accuracy than in conventional estimation methods that have been evaluated as safe.

2. The resistance element of the first and second flange sheet elements 11 and 12 to the web sheet element 13 is taken into account, whereby the buckling stress that is estimated for the web sheet element 13 increases, and it is possible to estimate the buckling stress of the web sheet element 13 with a more favorable accuracy than in conventional estimation methods that have been evaluated as safe.

3. The resistance element to the local buckling of 1 and 2 is taken into account, whereby a buckling stress to be estimated increases compared with the buckling stress of the entire H-section steel 10 derived based on a simple support condition.

4. Because the behaviors of the local buckling of the H-section steel 10 are complex, no formula of the local buckling stress of the H-section steel 10 has thus far been derived. However, the use of the power function makes it possible to derive a formula of the local buckling stress of the H-section steel 10 as a simple formula having a relatively small number of terms.

[0207]

5. The power function-based formula of the local buckling stress of the H-section steel 10 is used, whereby it is possible to estimate the local buckling stress of the H-section steel 10 that receives the compressive forces F_6 without using a numerical simulation.

6. It is possible to set a sheet thickness ratio classification in consideration of the interaction among the sheet elements 11, 12, and 13 from the ratio relationship between the formula of the local buckling stress of the H-section steel 10 that receives the compressive forces F_6 and the buckling stress in a full plastic property state.

7. In a width-thickness ratio classification in consideration of the interaction among the sheet elements 11, 12, and 13, there is a possibility that the web sheet element 13 may be treated as an earthquake-resistant member even in a range where the width-thickness ratio of the web sheet element 13 is large (the width of the web sheet element 13 is wide with respect to the thickness of the web sheet element 13) compared with the conventional width-thickness ratio classification.

8. In the width-thickness ratio classification in consideration of the interaction among the sheet elements 11, 12, and 13, it becomes possible to replace the H-section steel 10 with a member in which the mass of the H-section steel 10 (steel weight) per unit length is small compared with conventional estimation methods, and a more inexpensive building can be designed.

[0208]

In addition, N is 2 in Formula (162). First, in Formula (162), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a is treated as a constant, the half wavelength a is then treated as a variable, and the half wavelength a in Formula (162) is obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (162), the number of undetermined

coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 83 obtains the buckling stress σ_{cr} based on a_n and b_n , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (185), using Formula (181) to Formula (184). Therefore, at the time of obtaining the buckling stress σ_{cr} based on the energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , Formula (162), Formula (164), and Formula (165), the buckling stress σ_{cr} can be accurately obtained using numerical formulae.

[0209]

For example, in the above-described embodiment, N may be 3 or more in Formula (162).

At the time of obtaining the buckling stress σ_{cr} based on the energy method, Formula (181) to Formula (185) may not be used.

[0210]

[Third Embodiment]

Next, a third embodiment of the present invention will be described with reference to FIG. 13 and FIG. 19 to FIG. 22, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) is used to estimate the buckling stress of the web (sheet element) 13 that buckles due to a compressive force

acting as an external force in the x-axis direction. The estimation device estimates the buckling stress of the web 13 using the displacement estimation device 50 of the first embodiment.

The lower flange 11 and the upper flange 12 of the H-section steel 10 are also sheet elements. The sheet elements are elastic elements. The elastic element is an element for which the non-linear shape of a material is not taken into account.

[0211]

FIG. 13 shows an estimation device 90 of the present embodiment. The estimation device 90 is configured in the same manner as the estimation device 50. However, in the present embodiment, a buckling stress estimation program for making the computer function as the estimation device 90 (hereinafter, simply referred to as the estimation program) 91 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0212]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 92 that estimates the second out-of-plane displacement of the web 13 and a stress calculation portion 93 that obtains the buckling stress of the web 13, which causes the second out-of-plane displacement, based on the energy method. The second displacement estimation portion 92 and the stress calculation portion 93, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 91 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 92.

The estimation program 91 or the like is a program for the estimation device 90. The estimation program 91 makes the estimation device 90 function as the second

displacement estimation portion 92 and the stress calculation portion 93. The estimation program 91 uses the estimation program 61.

[0213]

In the second displacement estimation portion 92 and the stress calculation portion 93 of the estimation device 90 of the present embodiment, as shown in FIG. 19, the position coordinates of the web 13 are recognized based on the right-handed orthogonal coordinate system composed of the x-axis, the y-axis, and the z-axis. In FIG. 19 and FIG. 21 shown below, the second out-of-plane displacement of the web 13 or the like is shown to be larger than an estimated value.

The web 13 is assumed to be sufficiently long in the x-axis direction. The expression “the web 13 is sufficiently long in the x-axis direction” mentioned herein means that the web 13 has a length long enough to ignore the influence of the boundary condition of the end surface 13a of the web 13 in the x-axis direction on buckling distortion.

The second out-of-plane displacement of the web 13 is a displacement of the web 13 directed in the z-axis direction.

[0214]

When a compressive force F_8 acts in the x-axis direction on each of the end surfaces 13a of the web 13 in the x-axis direction, there are cases where the web 13 buckles (local buckling). In this example, the compressive force F_8 acting on each of the end surfaces of the web 13 is an equally distributed load acting on the end surface of the web 13 in the x-axis direction throughout the entire length in the y-axis direction. The magnitudes of the compressive forces F_8 acting on the individual end surfaces of the web 13 are equal to each other.

[0215]

In this case, there are cases where, as the web 13 runs toward a first end in the x-axis direction (one of the end surfaces 13a in the x-axis direction), the web 13 is alternately displaced in a wavy shape in the positive orientation of the z-axis and in the negative orientation of the z-axis, and the web 13 is displaced in a wavy shape in the x-axis direction as a whole.

In one wavelength-long part of the web 13 displaced along the x-axis, a second end opposite to the first end in the x-axis direction is defined as the origin of the x-axis, and an orientation toward the first end in the x-axis direction from the second end is defined as the positive orientation of the x-axis.

The origin of the y-axis is defined as the lower end (first end) of the web 13 in the y-axis direction. The positive orientation of the y-axis is defined as the upward orientation (an orientation toward the second end from the first end).

The origin of the z-axis is defined as the center of the web 13 in the z-axis direction (the center in the thickness direction). The positive orientation of the z-axis is defined as an orientation that constitutes the right-handed orthogonal coordinate system with respect to the positive orientation of the x-axis and the positive orientation of the y-axis.

[0216]

The length (height) in the y-axis direction of the web 13 is indicated by b_w (which is also true for the fifth embodiment and the seventh embodiment in which the web 13 is regarded as an evaluation target), and the thickness (the length in the z-axis direction) of the web 13 is indicated by t_w . The Young's modulus of the web 13 is indicated by E , and the Poisson's ratio of the web 13 is indicated by ν .

The estimation device 90 estimates the buckling stress of the web 13 when the compressive forces F_8 act on the web 13 with which the flanges 11 and 12 are not

coupled and the web 13 buckles. Incidentally, in a case where the thicknesses of the flanges 11 and 12 of the H-section steel 10 are thin enough to be ignored, the rigidity of the flanges 11 and 12 is low enough to be ignored, or the like, the estimation device 90 may estimate the buckling stress of the H-section steel 10 as the buckling stress of the web 13.

[0217]

In the second displacement estimation portion 92 and the stress calculation portion 93 of the estimation device 90 of the present embodiment, at the time of estimating the buckling stress of the web 13, the above-described assumptions 1 to 6 are performed.

[0218]

As shown in FIG. 19, when the compressive forces F_8 act on the web 13, there are cases where the web 13 is displaced in a wavy shape in the x-axis direction. When out-of-plane displacements in the x-axis direction of the web 13 displaced in a wavy shape in the x-axis direction are assumed to be represented by a formula $\sin(\pi x/a)$, the wavelength in the x-axis direction of the web 13 displaced in a wavy shape in the x-axis direction becomes $2a$. The half wavelength (the length of half the wavelength) in the x-axis direction becomes a .

FIG. 20 is a view showing out-of-plane displacements in a portion where the length in the x-axis direction is the half wavelength a in the center portion of the web 13 in the x-axis direction.

[0219]

In a case where the compressive forces F_8 are acting on the web 13, conventionally, a first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis was

estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function. The first out-of-plane displacement w_w is a function of the y-axis coordinates, not a function of the x-axis coordinates (a function at a certain coordinate on the x-axis).

As a result, it was found that, in a case where the compressive forces F8 act on the web 13, the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (196) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (196) includes a trigonometric term for which the power function of the y-axis coordinates is used. $\cos(\pi(2y/b_w-1)^n)$ and $\cos(\pi/2 \times (2y/b_w-1)^n)$ serve as the bases. Formula (196) can be preferably used to estimate the out-of-plane distortion of a sheet element such as the web 13.

[0220]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \quad \cdot \cdot (196)$$

[0221]

On the other hand, the second out-of-plane displacement W_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (198). Formula (198) is based on an assumption, that is, as described above, the out-of-plane displacement directed in the

z-axis direction at a certain coordinate on the x-axis in the web 13 is represented by Formula $\sin(\pi x/a)$. The second out-of-plane displacement W_w is each of a y-axis coordinate function and an x-axis coordinate function and is used to estimate the buckling stress of the web 13. The second out-of-plane displacement W_w in FIG. 19 is repetition of the second out-of-plane displacement W_w in FIG. 20 in the x-axis direction. Since the estimation of the buckling stress of the web 13 in FIG. 19 is the same as the estimation of the buckling stress of the web 13 in FIG. 20, Formula (198) above is a formula that has estimated the second out-of-plane displacement W_w in FIG. 20.

When Formula (196) is assigned to Formula (198), Formula (199) is obtained.

In a case where N is 2, Formula (199) can be converted into Formula (200).

[0222]

$$\begin{aligned}
 W_w &= \sin \frac{\pi x}{a} \cdot w_w \quad \cdot \cdot (198) \\
 W_w &= \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (199) \\
 W_w &= \sin \frac{\pi x}{a} \left(a_0 + a_1 \cos \pi \left(\frac{2y}{b_w} - 1 \right) + b_1 \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right) + a_2 \cos \pi \left(\frac{2y}{b_w} - 1 \right)^2 + b_2 \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^2 \right) \\
 &\quad \cdot \cdot (200)
 \end{aligned}$$

[0223]

For example, before the compressive forces F8 act on the web 13 of FIG. 20, the z-axis coordinate of a portion having an x-axis coordinate of x_0 and a y-axis coordinate of y_0 in the web 13 (hereinafter, referred to as the estimation target portion) is 0. After the compressive forces F8 have acted on the web 13, the second out-of-plane displacement W_w in this estimation target portion is estimated from Formula (199-1), and the z-axis coordinate at this time is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (199-1) to 0. That is, after the compressive forces F8 have acted, the estimation target portion is estimated to be disposed at a position where the x-axis coordinate becomes x_0 , the y-axis coordinate

becomes y_0 , and the z-axis coordinate becomes W_w .

[0224]

$$W_w = \sin \frac{\pi x_0}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y_0}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y_0}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (199 - 1)$$

[0225]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 92 estimates that, when the compressive forces F8 act on the web 13, the first out-of-plane displacement w_w of the web 13 becomes symmetrical in the y-axis direction with respect to the reference line M1. That is, in the estimation program 91, the first displacement estimation portion 52 is made to estimate that the first out-of-plane displacement w_w of the web 13 becomes symmetrical in the y-axis direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is that the shape and the restraint conditions of the web 13 are symmetrical with respect to the reference line M1 and the normal stress in the x-axis direction, which is generated by the compressive forces F8 acting on the web 13, is uniform in any cross sections in the y-axis direction.

The second displacement estimation portion 92 estimates the second out-of-plane displacement W_w of the web 13 from Formula (199) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion 52.

Here, estimation of the second out-of-plane displacement W_w of the web 13 from Formula (199) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion 52 has the following meaning. That is, the first displacement estimation portion 52 estimates the first out-of-plane displacement w_w from Formula (121). The second displacement estimation portion 92 estimates the second out-of-plane displacement W_w from Formula (199) in which the reason 1 and the

assumption 1 are applied to the first out-of-plane displacement w_w .

[0226]

The web 13 is disposed in a closed section where the x-axis coordinates are 0 or more and a or less and is disposed in a closed section where the y-axis coordinates are 0 or more and b_w or less. At this time, the strain energy U that is generated in the web 13 due to buckling distortion is represented by Formula (201), and the external force potential V that is imparted due to the compressive forces F_8 is represented by Formula (202).

The total potential energy Π is represented by Formula (203) as the sum of the strain energy U and the external force potential V .

[0227]

$$U = \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$+ \int_0^a \int_0^{b_w} \sigma_w t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial x} \right)^2 \right] dy dx \quad \cdot \cdot (201)$$

$$V = -\sigma_w b_w t_w \delta_w \quad \cdot \cdot (202)$$

$$\Pi = U + V \quad \cdot \cdot (203)$$

[0228]

Here, D_w is the sheet rigidity of the web 13 and is represented by Formula (205). σ_w is the stress function of the web 13 on which the compressive forces F_8 act and is represented by Formula (206). Here, σ_{cr} is the buckling stress of the web 13 and becomes positive in the case of compression. The function δ_w is a function that expresses the distortion of the web 13 in the x-axis direction when buckling occurs and is represented by Formula (207). Here, δ is the displacement of the web 13 in the x-axis direction.

For example, $(\partial^2 W_w / \partial x^2)$ means a function of the second order partial differential equation with respect to x of W_w , and $(\partial^2 W_w / (\partial x \partial y))$ means a function of

the first order partial differential equation with respect to each of x and y of W_w .

[0229]

$$D_w = \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (205)$$

$$\sigma_w = \sigma_{cr} \quad \cdot \cdot (206)$$

$$\delta_w = \delta \quad \cdot \cdot (207)$$

[0230]

The stress calculation portion 93 obtains the buckling stress σ_{cr} of the web 13 based on the energy method using Formula (199). The stress calculation portion 93 obtains the buckling stress σ_{cr} of the web 13 based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (212), using Formula (210) and Formula (211).

Here, the buckling coefficient k is obtained from Formula (213).

[0231]

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (210)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\quad \cdot \cdot (211)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (212)$$

$$k = \frac{B}{A} \quad \cdot \cdot (213)$$

[0232]

Specifically, the half wavelength a is treated as a constant. In this state, a simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set

of a_n and b_n that imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (212) (by assigning the set of a_n and b_n to Formula (212)). Next, the half wavelength a is treated as a variable. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a is equal to 0, the half wavelength a is obtained. The buckling stress σ_{cr} obtained based on the set of a_n and B_n and the half wavelength a obtained as described above becomes a buckling stress σ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (212). Next, the half wavelength a is treated as a variable, and the buckling stress σ_{cr} is obtained as described above.

[0233]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress σ_{cr} of the web 13 which buckles due to the compressive forces F_8 acting in the direction along the x-axis is estimated using the displacement estimation method of the first embodiment. In the estimation method, a second displacement estimation step of estimating the second out-of-plane displacement W_w of the web 13 from Formula (199) and a stress calculation step of obtaining the buckling stress σ_{cr} of the web 13 based on the energy method are performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since all of the shape and

restraint conditions of the web 13 and the compressive forces F_8 acting on the web 13 are symmetrical with respect to the reference line M1, in the first displacement estimation step, the first out-of-plane displacement w_w of the web 13 is estimated to be symmetrical in the y-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web 13 is estimated from (199).

In the stress calculation step, the buckling stress σ_{cr} of the web 13 is obtained based on the energy method using Formula (199).

[0234]

The compressive forces F_8 acting on the web 13 when the buckling stress σ_{cr} of the web 13 is generated can be obtained from a well-known equation regarding the sheet elements. When the compressive forces F_8 acting on the web 13 are made smaller than this compressive force F_8 , it is possible to suppress buckling of the web 13.

[0235]

(Evaluation of estimation accuracy of out-of-plane displacement and buckling stress)

(Comparison by out-of-plane displacement)

FIG. 21 shows the estimation results of the second out-of-plane displacement W_w of the web 13 along the y-axis coordinates in a case where the compressive forces F_8 act on the web 13. The end surfaces 13b of the web 13 in the y-axis direction were assumed to be fixedly supported (supported so as to be incapable of rotating, rigidly connected). The second out-of-plane displacement W_w is an out-of-plane displacement in a cross section along a cutting-plane line A7-A7 in FIG. 20.

In FIG. 21, the horizontal axis represents the y-axis coordinates with respect to the length b_w of the web 13, and the vertical axis represents the estimated second out-of-

plane displacements W_w of the web 13. 0 in the horizontal axis represents the lower end of the web 13, and 1 in the horizontal axis represents the upper end of the web 13. In the vertical axis, the value of the second out-of-plane displacement W_w is made dimensionless with the maximum value of the second out-of-plane displacement W_w .

[0236]

In FIG. 21, a line L21 indicated by a solid line represents analysis results by the FEM. A line L22 indicated by a dotted line represents the estimation results using Formula (199) of the present embodiment (where N is 2), and a line L23 indicated by an alternate long and short dash line represents the estimation results using Formula (159) (where N is 15). Since the line L22 and the line L23 almost coincide with the line L21, the line L22 and the line L23 overlaps the line L21.

It was found that N in Formula (199) of the present embodiment that is necessary to approximate the analysis results by the FEM with almost the same accuracy as that in a case where N is 15 in the Fourier series of Formula (159) is 2.

[0237]

(Comparison by buckling stress)

Results obtained by obtaining the buckling stress σ_{cr} of the web 13 from Formula (159) and Formula (199) of the present embodiment and comparing buckling coefficients are shown in Table 3 and FIG. 22.

[0238]

[Table 3]

	N	Method for supporting end faces of web in y-axis direction	
		Simple support	Fixed support
Embodiment: Formula (199)	2	4.000	6.975
Fourier series: Formula (159)	4	8.410	30.451
	5	6.250	20.806
	7	4.530	12.488
	9	4.045	9.205
	11	4.000	7.754
	13	4.000	7.154
	15	4.000	7.012
	20	4.000	7.011
	25	4.000	7.010

[0239]

In the case of using Formula (199) of the present embodiment, N was set to 2. On the other hand, in the case of using the Fourier series of Formula (159), which is a comparative example, N was changed to 4, 5, 7, ..., 25.

In Table 3, the buckling coefficients in a case where the end surfaces 13b of the web 13 in the y-axis direction are simply supported converges to 4.0 as the estimation accuracy of the second out-of-plane displacement W_w and the buckling stress σ_{cr} increases (refer to a line L26 in FIG. 22). The buckling coefficients in a case where the end surfaces 13b of the web 13 in the y-axis direction are fixedly supported converges to 6.98 as the estimation accuracy of the second out-of-plane displacement W_w and the buckling stress σ_{cr} increases (refer to a line L27 in FIG. 22).

[0240]

In FIG. 22, the horizontal axis represents N, and the vertical axis represents the buckling coefficient k. The white round marks represent the estimation results in the

case of simple support for which Formula (199) of the present embodiment is used. The black round marks represent the estimation results in the case of simple support for which the Fourier series of Formula (159) is used. The white square marks represent the estimation results in the case of fixed support for which Formula (199) of the present embodiment is used. The black square marks represent the estimation results in the case of fixed support for which the Fourier series of Formula (159) is used.

It was found that the accuracy in the case of evaluating the buckling coefficient k using Formula (199) of the present embodiment is approximately the same as the accuracy in a case where N is 15 in the Fourier series of the Formula (159) in both the simple support and the fixed support.

[0241]

As described above, according to the estimation device 90, the estimation method, and the estimation program 91 of the present embodiment, the inventors studied the plurality of functions with which the out-of-plane displacements of the web 13 on which the compressive forces F_8 act can be estimated by a smaller number of terms than in the Fourier series of Formula (159) while using a trigonometric function. As a result, it was found that the second out-of-plane displacement W_w of the web 13 can be estimated by a smaller number of terms than in the Fourier series using Formula (199).

Formula (199) makes it possible to estimate the second out-of-plane displacement W_w of the web 13 with a smaller number of terms than in the Fourier series of Formula (159) and thus makes it possible to simplify the calculation necessary for estimation compared with cases where the Fourier series is used. Furthermore, since the number of terms necessary to estimate the second out-of-plane displacement W_w with a certain accuracy is smaller in the case of estimation using Formula (199)

than in the case of estimation using the Fourier series of Formula (159), it is possible to formulate estimation results to be more easily understood physically than cases where the Fourier series is used.

[0242]

The use of Formula (199) makes it possible to rapidly approximate the second out-of-plane displacement W_w of the web 13. That is, it is possible to rapidly approximate a buckling waveform when local buckling occurs in a member of a building that receives in-plane bending or a sheet element that constitutes the member.

[0243]

In addition, N is 2. First, in Formula (199), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a is treated as a constant, the half wavelength a is then treated as a variable, and the half wavelength a in Formula (199) is obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (199), the number of undetermined coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 93 obtains the buckling stress σ_{cr} based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (212), using Formula (210) and Formula (211). At the time of obtaining the buckling stress σ_{cr} based on the energy method, the buckling stress σ_{cr} can be accurately obtained using numerical formulae of Formula (210) to Formula (212).

[0244]

In the above-described embodiment, N may be 3 or more in Formula (199).

At the time of obtaining the buckling stress σ_{cr} based on the energy method, Formula (210) to Formula (212) may not be used.

In the above-described embodiment, the estimation device 90 estimates the buckling stress of the web 13, which is a sheet element, but the sheet element is not limited to the web 13 and may be the lower flange 11, the upper flange 12, or the like.

[0245]

[Fourth Embodiment]

Next, a fourth embodiment of the present invention will be described with reference to FIG. 13 and FIG. 23 to FIG. 26, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) 100 shown in FIG. 13 is used to estimate the buckling stress of the H-section steel 10 that buckles due to a bending moment acting as an external force (refer to FIG. 23). The estimation device 100 estimates the buckling stress of the H-section steel 10 using the displacement estimation device 50 of the first embodiment.

In the present embodiment, the entire H-section steel 10 shown in FIG. 23 is an estimation target. The reference line M1 is a reference line based on the web sheet element 13. That is, the reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the y-axis direction and is along the x-axis of the web sheet element 13. In other words, the reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the v-axis direction and is along the u-axis.

[0246]

FIG. 13 shows an estimation device 100 of the present embodiment. The estimation device 100 is configured in the same manner as the estimation device 80. However, in the present embodiment, a buckling stress estimation program for making the computer function as the estimation device 100 (hereinafter, simply referred to as the estimation program) 101 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0247]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 102 that estimates a second out-of-plane displacement of the web sheet element 13 and a second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12 and a stress calculation portion 103 that obtains the buckling stress of the H-section steel 10 based on the energy method using the second out-of-plane displacement of the web sheet element 13 and the second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12. The second displacement estimation portion 102 and the stress calculation portion 103, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 101 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 102.

The estimation program 101 or the like is a program for the estimation device 100. The estimation program 101 makes the estimation device 100 function as the second displacement estimation portion 102 and the stress calculation portion 103. The estimation program 101 uses the estimation program 61.

[0248]

In the second displacement estimation portion 102 and the stress calculation

portion 103 of the estimation device 100 of the present embodiment, as shown in FIG. 23, the position coordinates of the H-section steel 10 are recognized based on the uvw coordinate system. In FIG. 23 and FIG. 25 shown below, the second out-of-plane displacement of the web sheet element 13 or the like is shown to be larger than an estimated value. FIG. 23 shows a state in which the H-section steel 10 buckles.

[0249]

When a bending moment F11 about the w-axis acts on each of the end surfaces 10a of the H-section steel 10 in the u-axis direction, there are cases where the H-section steel 10 buckles. The bending moments F11 are transmitted throughout the entire length of the H-section steel 10 in the u-axis direction. The transmitted bending moments F11 act about an axial line that passes through the neutral axis of the H-section steel 10 and is parallel to the w-axis (hereinafter, referred to as the rotation axis of the bending moment F11).

The bending moments F11 acting on the individual end surfaces 10a of the H-section steel 10 in the u-axis direction are external forces having an equal magnitude. In this example, the bending moments F11 act on the H-section steel 10 such that the first flange sheet element 11 receives a tensile force due to the bending moments F11, the second flange sheet element 12 receives a compressive force due to the bending moments F11, and the H-section steel 10 bends so as to become wider downward.

[0250]

In this case, as the web sheet element 13 runs toward a first end of the web sheet element 13 in the u-axis direction (one of the end surfaces 10a in the u-axis direction), the web sheet element 13 is alternately displaced in the positive orientation of the w-axis and in the negative orientation of the w-axis, and the web sheet element 13 is displaced in a wavy shape in the u-axis direction as a whole. In association with the

web sheet element 13, the second flange sheet element 12 that receives a compressive force is displaced in a wavy shape, but the first flange sheet element 11 that receives a tensile force is rarely displaced.

In one wavelength-long part of the web sheet element 13 displaced along the u-axis, a second end opposite to the first end in the u-axis direction is defined as the origin of the u-axis, and an orientation toward the first end in the u-axis direction from the second end is defined as the positive orientation of the u-axis.

[0251]

The estimation device 100 of the present embodiment estimates the buckling stress of the H-section steel 10 when the bending moments F_{11} act on the H-section steel 10 and the H-section steel 10 buckles. In the second displacement estimation portion 102 and the stress calculation portion 103 of the estimation device 50, at the time of estimating the buckling stress of the H-section steel 10, the above-described assumptions 1 to 3 and the assumptions 4A to 6A are performed.

[0252]

As shown in FIG. 23, when the bending moments F_{11} act on the H-section steel 10, there are cases where the web sheet element 13 and the like of the H-section steel 10 are displaced in a wavy shape in the u-axis direction. At this time, the same assumption 1 as in the second embodiment is performed.

FIG. 24 is a view showing second out-of-plane displacements W_w in the entire region of the H-section steel 10 in a portion where the length of the H-section steel 10 in the u-axis direction is the half wavelength a .

[0253]

FIG. 25 shows a state in which the bending moments F_{11} act on the H-section steel 10 with a solid line. What is indicated with a dotted line in FIG. 25 shows a state

in which the bending moments F11 do not act on the H-section steel 10.

[0254]

In a case where the bending moments F11 act on the web sheet element 13, conventionally, the out-of-plane displacement of the web sheet element 13 has been estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which, when the u-axis coordinate is a certain value, the first out-of-plane displacement w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function.

As a result, it was found that, in a case where the bending moments F11 act on the H-section steel 10, when the u-axis coordinate is a certain value, the first out-of-plane displacement w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis is estimated from Formula (220) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (220) includes a trigonometric term for which the power function of the v-axis coordinates is used. $\cos(2\pi v^n/b_w^n)$ and $\sin(\pi v^n/b_w^n)$ serve as the bases. Formula (220) can be preferably used to estimate the first out-of-plane displacement of a sheet element such as the web sheet element 13.

[0255]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \quad \cdot \cdot \cdot (220)$$

[0256]

In the present embodiment, since the first out-of-plane displacement w_w of the

H-section steel 10 is estimated to be asymmetrical in the v-axis direction with respect to the reference line M1 as described below, the first out-of-plane displacement w_w is estimated from Formula (143) above. Formula (220) of the present embodiment is derived from Formula (143) as described below.

That is, as in Formula (144), values expressed using the value of Y and the length b_w of the web 13 in the y-axis direction are used to represent the y-axis coordinates. In other words, as in Formula (145), the value of Y is a value for which a y-axis coordinate is made dimensionless using the length b_w (a value obtained by dividing a y-axis coordinate by the length b_w).

In addition, the first out-of-plane displacement w_w directed in the w-axis direction at a certain coordinate of the web 13 in the v-axis is estimated from Formula (146) that is obtained by assigning Formula (145) to Formula (143) and, furthermore, Formula (220) in which the y-axis of Formula (146) is replaced with the v-axis.

[0257]

On the other hand, when the u-axis coordinate is an arbitrary value, the second out-of-plane displacement W_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis is estimated from Formula (221).

Formula (221) is based on the assumption 1.

When Formula (220) is assigned to Formula (221), Formula (222) is obtained.

In a case where N is 2, Formula (222) can be converted into Formula (223).

[0258]

$$\begin{aligned}
 W_w &= \sin \frac{\pi u}{a} \cdot w_w \quad \cdot \cdot (2 \ 2 \ 1) \\
 W_w &= \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (2 \ 2 \ 2) \\
 W_w &= \sin \frac{\pi u}{a} \left(a_0 + a_1 \cos \frac{2\pi v}{b_w} + b_1 \sin \frac{\pi v}{b_w} + a_2 \cos \frac{2\pi v^2}{b_w^2} + b_2 \sin \frac{\pi v^2}{b_w^2} \right) \quad \cdot \cdot (2 \ 2 \ 3)
 \end{aligned}$$

[0259]

In addition, the second out-of-plane displacement W_{f1} at a predetermined coordinate in the w-axis of the first flange sheet element 11 is estimated from Formula (224), and the second out-of-plane displacement W_{f2} at a predetermined coordinate in the w-axis of the second flange sheet element 12 is estimated from Formula (225).

Formula (224) and Formula (225) include a trigonometric term for which the power function of the v-axis coordinates is used.

[0260]

$$\begin{aligned} W_{f1} &= w \frac{\partial W_w}{\partial v} \Big|_{v=0} \cdot \cdot (2 \ 2 \ 4) \\ W_{f2} &= w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \cdot \cdot (2 \ 2 \ 5) \end{aligned}$$

[0261]

For example, before the bending moments F11 act on the H-section steel 10 of FIG. 24, the w-axis coordinate of a portion having a u-axis coordinate of u_0 and a v-axis coordinate of v_0 in the web sheet element 13 (hereinafter, referred to as the first estimation target portion) is 0. The second out-of-plane displacement W_w in this first estimation target portion is estimated from Formula (222-1). After the bending moments F11 have acted on the H-section steel 10 in FIG. 24, the w-axis coordinate of the first estimation target portion is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (222-1) to 0. That is, after the bending moments F11 have acted, the first estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes v_0 , and the w-axis coordinate becomes W_w .

For example, before the bending moments F11 act on the H-section steel 10 of FIG. 24, the v-axis coordinate of a portion having a u-axis coordinate of u_0 and a w-axis coordinate of w_0 in the second flange sheet element 12 (hereinafter, referred to as the

second estimation target portion) is b_w . The second out-of-plane displacement W_{f2} in this second estimation target portion is estimated from Formula (225-1). After the bending moments F11 have acted on the H-section steel 10 in FIG. 24, the v-axis coordinate of the second estimation target portion is a value obtained by adding the second out-of-plane displacement W_{f2} estimated from Formula (225-1) to b_w . That is, after the bending moments F11 have acted, the second estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes $(b_w + W_{f2})$, and the w-axis coordinate becomes W_0 .

[0262]

$$W_w = \sin \frac{\pi u_0}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v_0^n}{b_w^n} + b_n \sin \frac{\pi v_0^n}{b_w^n} \right) \right] \quad \cdot \cdot (225-1)$$

$$W_{f2} = w_0 \frac{\partial W_w}{\partial v} \Big|_{v=b_w, u=u_0, w=w_0} \quad \cdot \cdot (225-1)$$

[0263]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 102 estimates that, when the bending moments F11 act on the H-section steel 10, the first out-of-plane displacement w_w of the H-section steel 10 becomes asymmetrical in the v-axis direction with respect to the reference line M1. That is, in the estimation program 101, the first displacement estimation portion 52 is made to estimate that the first out-of-plane displacement w_w of the H-section steel 10 becomes asymmetrical in the v-axis direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is that the normal stress in the u-axis direction that is generated by the bending moments F11 acting on the H-section steel 10 is asymmetrical with respect to the reference line M1.

The second displacement estimation portion 102 estimates the second out-of-plane displacement W_w of the web sheet element 13 from Formula (222) using the first

out-of-plane displacement w_w of the web sheet element 13 estimated by the first displacement estimation portion 52. The second displacement estimation portion 102 estimates the second out-of-plane displacement W_{f1} of the first flange sheet element 11 from Formula (224) and estimates the second out-of-plane displacement W_{f2} of the second flange sheet element 12 from Formula (225) using the first out-of-plane displacement w_w of each of the first flange sheet element 11 and the second flange sheet element 12 estimated by the first displacement estimation portion 52.

Here, based on the energy method, the strain energy U_w that is generated in the web sheet element 13 due to buckling distortion is represented as Formula (227), and the strain energy U_f in the first and second flange sheet elements 11 and 12 is represented as Formula (228).

[0264]

$$\begin{aligned}
 U_w &= \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad + \int_0^a \int_0^{b_w} \sigma_w t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial u} \right)^2 \right] dv du \quad \cdots (227) \\
 U_f &= \sum_{i=1}^2 \left\{ \frac{D_f}{2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \right. \\
 &\quad \left. + \int_0^a \int_{-b_f}^{b_f} \sigma_{fi} t_f \left[\frac{\delta_{fi}}{a} - \frac{1}{2} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 \right] dw du \right\} \quad \cdots (228)
 \end{aligned}$$

[0265]

However, the sheet rigidity D_w of the web sheet element 13 is expressed as Formula (229). The sheet rigidity D_f of the first and second flange sheet elements 11 and 12 is represented as Formula (230). The stress function σ_w of the web sheet element 13 on which the bending moments F_{11} act is represented as Formula (231) by indicating the buckling stress of the H-section steel 10 as σ_{cr} . Here, the stress function σ_w becomes positive in the case of compression.

The function δ_w is a displacement in the u -axis direction at a certain coordinate

in the v -axis of the web sheet element 13 when buckling occurs and is represented as Formula (232) by indicating the u -axis displacement that is generated at the center of the second flange sheet element 12 as δ .

[0266]

$$\begin{aligned} D_w &= \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (2 \ 2 \ 9) \\ D_f &= \frac{Et_f^3}{12(1-\nu^2)} \quad \cdot \cdot (2 \ 3 \ 0) \\ \sigma_w &= \sigma_{cr} \left(\frac{2v}{b_w} - 1 \right) \quad \cdot \cdot (2 \ 3 \ 1) \\ \delta_w &= \delta \left(\frac{2v}{b_w} - 1 \right) \quad \cdot \cdot (2 \ 3 \ 2) \end{aligned}$$

[0267]

The stress functions σ_{f1} and σ_{f2} are the stress function of each of the first and second flange sheet elements 11 and 12 on which the bending moments F_{11} act. The stress function σ_{f1} is equal to $-\sigma_{cr}$, and the stress function σ_{f2} is equal to σ_{cr} . Here, the stress functions σ_{f1} and σ_{f2} becomes positive in the case of compression.

The functions δ_{f1} and δ_{f2} are functions that express the displacements of the first and second flange sheet elements 11 and 12 in the u -axis direction when buckling occurs. The function δ_{f1} is equal to $-\delta$, and the function δ_{f2} is equal to δ .

[0268]

In addition, the external force potential energy V_w of the web sheet element 13 is represented as Formula (238), and the external force potential energy V_f of the first and second flange sheet elements 11 and 12 is represented as Formula (239).

[0269]

$$\begin{aligned} V_w &= - \int_0^{b_w} \sigma_w t_w \delta_w dv \quad \cdot \cdot (2 \ 3 \ 8) \\ V_f &= - \sum_{i=1}^2 \int_{-b_f}^{b_f} \sigma_{fi} t_f \delta_{fi} dw \quad \cdot \cdot (2 \ 3 \ 9) \end{aligned}$$

[0270]

The total potential energy Π of the H-section steel 10 is represented as Formula (240) as the sum of the strain energy and the external force potential energy.

[0271]

$$\Pi = U_w + U_f + V_w + V_f \quad \cdot \cdot (240)$$

[0272]

The stress calculation portion 103 obtains the buckling stress σ_{cr} of the H-section steel 10 based on the energy method using the second out-of-plane displacement W_w of the web sheet element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (222), Formula (224), and Formula (225). That is, the stress calculation portion 103 obtains the buckling stress σ_{cr} based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (245), using Formula (241) to Formula (244).

[0273]

$$\begin{aligned} A &= \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (241) \\ B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2v \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-v) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\ &\quad \cdot \cdot (242) \\ C &= \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (243) \\ D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2v \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-v) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\ &\quad \cdot \cdot (244) \\ \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (245) \end{aligned}$$

[0274]

Specifically, the half wavelength a is treated as a constant. In this state, a simultaneous equation representing that a function obtained by partially differentiating

the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set of a_n and b_n that imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (245) (by assigning the set of a_n and b_n to Formula (245)). Next, the half wavelength a is treated as a variable. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a is equal to 0, the half wavelength a is obtained. The buckling stress σ_{cr} obtained based on the set of a_n and b_n and the half wavelength a obtained as described above becomes a buckling stress σ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (245). Next, the half wavelength a is treated as a variable, and the buckling stress σ_{cr} is obtained as described above.

[0275]

A buckling coefficient k_w of the web sheet element 13 is represented by Formula (248), and a buckling coefficient k_f of each of the first and second flange sheet elements 11 and 12 is represented by Formula (249).

[0276]

$$k_w = \frac{B}{A + \frac{t_f}{t_w} C} \quad \cdot \cdot (248)$$

$$k_f = \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (249)$$

[0277]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress σ_{cr} of the H-section steel 10 which buckles due to the bending moments F11 acting about the w-axis is estimated using the displacement estimation method of the first embodiment. In the estimation method, a second displacement estimation step and a stress calculation step are performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since the bending moments F11 acting on the H-section steel 10 are asymmetrical with respect to the reference line M1, in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel 10 is estimated to become asymmetrical in the v-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (222) using the first out-of-plane displacement w_w of the web sheet element 13 estimated in the first displacement estimation step. In addition, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are each estimated from Formula (224) and Formula (225) using the first out-of-plane displacements w_w of the first and second flange sheet elements 11 and 12 estimated in the first displacement estimation step.

In the stress calculation step, the buckling stress σ_{cr} is obtained based on the energy method using the second out-of-plane displacement W_w of the web sheet

element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (222), Formula (224), and Formula (225).

[0278]

The bending moment $F11$ acting on the H-section steel 10 when the buckling stress σ_{cr} is generated in the H-section steel 10 can be obtained from a known equation regarding beams. When the bending moments $F11$ acting on the H-section steel 10 are made smaller than this bending moment $F11$, it is possible to suppress buckling of the H-section steel 10.

In addition, the application range of the dimensions such as the thicknesses t_f of the first and second flange sheet elements 11 and 12 in the estimation device 100, the estimation method, and the estimation program 101 of the present embodiment is preferably the application range 1.

[0279]

(Evaluation of estimation accuracy of buckling stress)

FIG. 26 shows a comparison result of the buckling stress that is estimated by the estimation method (the estimation device 100, and the estimation program 101) of the present embodiment and the buckling stress that is estimated by the FEM. M_p represents the full plastic moment on the H-section steel 10 (the bending moment when the H-section steel 10 is completely plasticized). M_{cr_pre} represents the bending moment during the buckling of the H-section steel 10 that is estimated by the estimation method of the present embodiment. M_{cr_FEM} represents the bending moment during the buckling of the H-section steel 10 that is estimated by the FEM. In FIG. 26, the horizontal axis represents the value of $\sqrt{(M_p/M_{cr_pre})}$, and the vertical axis represents the value of (M_{cr_pre}/M_p) or (M_{cr_FEM}/M_p) . The buckling stress and the like of the H-section steels 10 of a variety of specifications were estimated by the FEM and the

estimation method of the present embodiment.

[0280]

In FIG. 26, the $\circ$ marks represent the results estimated by the FEM, that is, the results with the values of (M_{cr_FEM}/M_p) along the vertical axis. Along the horizontal axis of the $\circ$ marks, the values of $\sqrt{(M_p/M_{cr_pre})}$ of the H-section steel 10 that has the same specification as the H-section steel 10 analyzed by the FEM and is estimated by the estimation method of the present embodiment are used. The curve represents the results estimated by the estimation method of the present embodiment, that is, the results with the values of (M_{cr_pre}/M_p) along the vertical axis.

[0281]

Incidentally, when multiplied by a cross section coefficient Z of the H-section steel 10, the buckling stress σ_{cr} turns into a bending moment M_{cr} during buckling.

The full plastic moment M_p becomes a constant value in accordance with the material strength regardless of the FEM and the estimation method of the present embodiment. The estimation accuracy of the present embodiment can be evaluated by comparing the bending moment M_{cr_pre} during buckling that is obtained from the estimation method of the present embodiment and the buckling stress that is estimated by the FEM. For the H-section steels 10 having the same specification, the results estimated by the FEM and the results estimated by the estimation method of the present embodiment show that, in FIG. 26, the values along the horizontal axis are equal to each other and the values along the vertical axis shift from each other according to errors.

[0282]

In FIG. 26, the bending moment M_{cr_FEM} during buckling estimated by the FEM and the bending moment M_{cr_pre} during buckling estimated by the estimation method of the present embodiment favorable correspond to each other. Since there is a

certain relationship between the bending moment M_{cr_pre} during buckling that is estimated by the estimation method of the present embodiment and the buckling stress that is estimated by the FEM, it is possible to estimate the buckling stress σ_{cr} with a practically sufficient accuracy even when the buckling stress σ_{cr} is estimated by the estimation method of the present embodiment.

[0283]

In the case of attempting to estimate the buckling stress or the like of an H-section steel on which a bending moment acts with the Fourier series of Formula (159), it is necessary to set N to 30 or more, and furthermore, the buckling stress cannot be indicated by a positive solution. On the other hand, in the estimation method of the present embodiment, in a case where the second out-of-plane displacement W_w of the web sheet element 13 is represented by Formula (222) and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are represented by Formula (225) and Formula (225), the buckling stress σ_{cr} can be calculated as a positive solution such as Formula (245).

[0284]

As described above, according to the estimation device 100, the estimation method, and the estimation program 101 of the present embodiment, for the H-section steel 10 on which the bending moments $F11$ act, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (222). As shown in Formula (224), the second out-of-plane displacement W_{f1} of the first flange sheet element 11 is determined according to a function obtained by assigning 0 to the v -axis coordinate of a function of the first order partial differential equation with respect to v of the second out-of-plane displacement W_w of the web sheet element 13. In addition, as shown in Formula (225), the second out-of-plane displacement W_{f2} of the second

flange sheet element 12 is determined according to a function obtained by assigning b_w to the v -axis coordinate of a function of the first order partial differential equation with respect to v of the second out-of-plane displacement W_w of the web sheet element 13.

[0285]

Depending on a variety of amounts of the cross sections and the material properties of the web sheet element 13 and the first and second flange sheet elements 11 and 12, the degree of mutual influence between the web sheet element 13 and the first and second flange sheet elements 11 and 12 changes, and the second out-of-plane displacement W_w of the web sheet element 13 and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are determined. As described above, when the buckling stress σ_{cr} of the H-section steel 10 is obtained based on the energy method using the second out-of-plane displacement W_w and the second out-of-plane displacements W_{f1} and W_{f2} , it is possible to estimate the buckling stress σ_{cr} in consideration of the coupled buckling of the web sheet element 13 and the first and second flange sheet elements 11 and 12.

[0286]

It is possible to estimate the second out-of-plane displacement W_w or the like of the web sheet element 13 with a smaller number of terms than in the Fourier series while using a trigonometric function and to simplify calculation necessary for the estimation of the second out-of-plane displacement W_w or the like.

Since the number of terms necessary to estimate the second out-of-plane displacement W_w or the like with a certain accuracy is smaller in the case of estimation using Formula (222) than in the case of estimation using the Fourier series of Formula (159), it is possible to formulate the estimation result of the second out-of-plane displacement W_w or the like to be easily understood physically.

[0287]

Furthermore, the estimation device 100, the estimation method, and the estimation program 101 of the present embodiment have the following features 1 to 4, 7, and 8 and the following features 5A and 6A.

5A. The power function-based formula of the local buckling stress of the H-section steel 10 is used, whereby it is possible to estimate the local buckling stress of the H-section steel 10 that receives the bending moments F11 about the w-axis without using a numerical simulation.

6A. It is possible to set a sheet thickness ratio classification in consideration of the interaction among the sheet elements 11, 12, and 13 from the ratio relationship between the formula of the local buckling stress of the H-section steel 10 that receives the bending moments F11 and the buckling stress in a full plastic property state.

[0288]

In addition, N is 2 in Formula (222). First, in Formula (222), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a is treated as a constant, the half wavelength a is then treated as a variable, and the half wavelength a in Formula (222) is obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (222), the number of undetermined coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 103 obtains the buckling stress σ_{cr} based on a_n and b_n , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (245), using Formula (241) to Formula (244). Therefore, at the time of obtaining the buckling

stress σ_{cr} based on the energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , Formula (222), Formula (224), and Formula (225), the buckling stress σ_{cr} can be accurately obtained using numerical formulae.

[0289]

For example, in the above-described embodiment, N may be 3 or more in Formula (222).

At the time of obtaining the buckling stress σ_{cr} based on the energy method, Formula (241) to Formula (245) may not be used.

[0290]

[Fifth Embodiment]

Next, a fifth embodiment of the present invention will be described with reference to FIG. 13 and FIG. 27 to FIG. 30, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) is used to estimate the buckling stress of the web (sheet element) 13 that buckles due to a bending moment acting about the z-axis as an external force. The estimation device estimates the buckling stress of the web 13 using the displacement estimation device 50 of the first embodiment.

[0291]

FIG. 13 shows an estimation device 110 of the present embodiment. The estimation device 110 is configured in the same manner as the estimation device 50. However, in the present embodiment, a buckling stress estimation program for making

the computer function as the estimation device 110 (hereinafter, simply referred to as the estimation program) 111 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0292]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 112 that estimates the second out-of-plane displacement of the web 13 and the stress calculation portion 113 that obtains the buckling stress of the web 13, which causes the second out-of-plane displacement, based on the energy method. The second displacement estimation portion 112 and the stress calculation portion 113, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 111 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 112.

The estimation program 111 or the like is a program for the estimation device 110. The estimation program 111 makes the estimation device 110 function as the second displacement estimation portion 112 and the stress calculation portion 113. The estimation program 111 uses the estimation program 61.

[0293]

In the second displacement estimation portion 112 and the stress calculation portion 113 of the estimation device 110 of the present embodiment, as shown in FIG. 27, the position coordinates of the web 13 are recognized based on the right-handed orthogonal coordinate system composed of the x-axis, the y-axis, and the z-axis. In FIG. 27 and FIG. 29 shown below, the out-of-plane displacement of the web 13 or the like is shown to be larger than an estimated value.

The web 13 is assumed to be sufficiently long in the x-axis direction.

[0294]

When a bending moment F_{13} about the z-axis acts on each of the end surfaces 13a of the web 13 in the x-axis direction, there are cases where the web 13 buckles (local buckling). The bending moments F_{13} are transmitted throughout the entire length of the web 13 in the x-axis direction. The transmitted bending moments F_{13} act about an axial line that passes through the neutral axis of the web 13 and is parallel to the z-axis (hereinafter, referred to as the rotation axis of the bending moment F_{13}). The neutral axis is generated at a position of the web 13 in the y-axis direction in which a tensile force and a compressive force acting on the web 13 due to the bending moment F_{13} are balanced.

The bending moments F_{13} acting on the individual end surfaces 13a of the web 13 in the x-axis direction are external forces having an equal magnitude. In this example, the bending moments F_{13} act on the web 13 such that a tensile stress acts on the lower end of the web 13 and a compressive stress acts on the upper end of the web 13 to make the web 13 bend so as to become wider downward.

[0295]

In this case, there are cases where, as the web 13 runs toward a first end in the x-axis direction, the web 13 is alternately displaced in a wavy shape in the positive orientation of the z-axis and in the negative orientation of the z-axis, and the web 13 is displaced in a wavy shape in the x-axis direction as a whole.

The estimation device 110 estimates the buckling stress of the web 13 when the bending moments F_{13} act on the web 13 with which the flanges 11 and 12 are not coupled and the web 13 buckles. Incidentally, in a case where the thicknesses of the flanges 11 and 12 of the H-section steel 10 are thin enough to be ignored, the rigidity of the flanges 11 and 12 is low enough to be ignored, or the like, the estimation device 110

may estimate the buckling stress of the H-section steel 10 as the buckling stress of the web 13.

[0296]

In the second displacement estimation portion 112 and the stress calculation portion 113 of the estimation device 110 of the present embodiment, at the time of estimating the buckling stress of the web 13, the above-described assumptions 1 to 6 are performed.

[0297]

As shown in FIG. 27, when the bending moments F_{13} act on the web 13, there are cases where the web 13 is displaced in a wavy shape in the x-axis direction. When out-of-plane displacements in the x-axis direction of the web 13 displaced in a wavy shape in the x-axis direction are assumed to be represented by a formula $\sin(\pi x/a)$, the wavelength in the x-axis direction of the web 13 displaced in a wavy shape in the x-axis direction becomes $2a$. The half wavelength in the x-axis direction becomes a .

FIG. 28 is a view showing out-of-plane displacements in a portion where the length in the x-axis direction is the half wavelength a in the center portion of the web 13 in the x-axis direction.

[0298]

In a case where the bending moments F_{13} are acting on the web 13, conventionally, a first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis was estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis can be estimated by a smaller number

of terms than in the Fourier series while using a trigonometric function.

As a result, it was found that, in a case where the bending moments F_{13} act on the web 13, the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (256) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (256) includes a trigonometric term for which the power function of the y-axis coordinates is used. $\cos(2\pi y^n/b_w^n)$ and $\sin(\pi y^n/b_w^n)$ serve as the bases. Formula (256) can be preferably used to estimate the out-of-plane distortion of a sheet element such as the web 13.

[0299]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w^n} + b_n \sin \frac{\pi y^n}{b_w^n} \right) \quad \cdot \cdot (256)$$

[0300]

On the other hand, the second out-of-plane displacement W_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (258). Formula (258) is based on an assumption, that is, as described above, the out-of-plane displacement directed in the z-axis direction at a certain coordinate on the x-axis in the web 13 is represented by Formula $\sin(\pi x/a)$. The second out-of-plane displacement W_w is each of a y-axis coordinate function and an x-axis coordinate function and is used to estimate the buckling stress of the web 13.

When Formula (256) is assigned to Formula (258), Formula (259) is obtained. In a case where N is 2, Formula (259) can be converted into Formula (260).

[0301]

$$W_w = \sin \frac{\pi x}{a} \cdot w_w \quad \cdot \cdot (258)$$

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w^n} + b_n \sin \frac{\pi y^n}{b_w^n} \right) \right] \quad \cdot \cdot (259)$$

$$W_w = \sin \frac{\pi x}{a} \left(a_0 + a_1 \cos \frac{2\pi y}{b_w} + b_1 \sin \frac{\pi y}{b_w} + a_2 \cos \frac{2\pi y^2}{b_w^2} + b_2 \sin \frac{\pi y^2}{b_w^2} \right) \quad \cdot \cdot (260)$$

[0302]

For example, before the bending moments F13 act on the web 13 of FIG. 28, the z-axis coordinate of a portion having an x-axis coordinate of x_0 and a y-axis coordinate of y_0 in the web 13 (hereinafter, referred to as the estimation target portion) is 0. After the bending moments F13 have acted on the web 13, the second out-of-plane displacement W_w in this estimation target portion is estimated from Formula (259-1), and the z-axis coordinate at this time is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (259-1) to 0. That is, after the bending moments F13 have acted, the estimation target portion is estimated to be disposed at a position where the x-axis coordinate becomes x_0 , the y-axis coordinate becomes y_0 , and the z-axis coordinate becomes W_w .

[0303]

$$W_w = \sin \frac{\pi x_0}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y_0^n}{b_w^n} + b_n \sin \frac{\pi y_0^n}{b_w^n} \right) \right] \quad \cdot \cdot (259-1)$$

[0304]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 112 estimates that, when the bending moments F13 act on the web 13, the first out-of-plane displacement w_w of the web 13 becomes asymmetrical in the y-axis direction with respect to the reference line M1. That is, in the estimation program 111, the first displacement estimation portion 52 is made to

estimate that the first out-of-plane displacement w_w of the web 13 becomes asymmetrical in the y-axis direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is that the normal stress in the x-axis direction that is generated by the bending moments F13 acting on the web 13 is asymmetrical with respect to the reference line M1.

The second displacement estimation portion 112 estimates the second out-of-plane displacement W_w of the web 13 from Formula (259) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion 52.

[0305]

The web 13 is disposed in a closed section where the x-axis coordinates are 0 or more and a or less and is disposed in a closed section where the y-axis coordinates are 0 or more and b_w or less. At this time, the strain energy U that is generated in the web 13 due to buckling distortion is represented by Formula (261), and the external force potential V that is imparted due to the bending moments F13 is represented by Formula (262).

The total potential energy Π is represented by Formula (263) as the sum of the strain energy U and the external force potential V.

[0306]

$$U = \frac{D_w}{2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$+ \int_0^a \int_0^{b_w} \sigma_w t_w \left[\frac{\delta_w}{a} - \frac{1}{2} \left(\frac{\partial W_w}{\partial x} \right)^2 \right] dy dx \quad \cdot \cdot (261)$$

$$V = - \int_0^{b_w} \sigma_w t_w \delta_w dy \quad \cdot \cdot (262)$$

$$\Pi = U + V \quad \cdot \cdot (263)$$

[0307]

Here, D_w is the sheet rigidity of the web 13 and is represented by Formula (265). σ_w is the stress function of the web 13 on which the bending moments F13 act

and is represented by Formula (266). Here, σ_{cr} is the buckling stress of the web 13 and becomes positive in the case of compression. The function δ_w is a function that expresses the distortion of the web 13 in the x-axis direction when buckling occurs and is represented by Formula (267). Here, δ is a displacement in the x-axis direction at the second end (upper end) in the y-axis direction on the second end in the x-axis direction of the web 13.

[0308]

$$D_w = \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (265)$$

$$\sigma_w = \left(\frac{2y}{b_w} - 1\right) \sigma_{cr} \quad \cdot \cdot (266)$$

$$\delta_w = \left(\frac{2y}{b_w} - 1\right) \delta \quad \cdot \cdot (267)$$

[0309]

The stress calculation portion 113 obtains the buckling stress σ_{cr} of the web 13 based on the energy method using Formula (259). The stress calculation portion 113 obtains the buckling stress σ_{cr} of the web 13 based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (272), using Formula (270) and Formula (271).

Here, the buckling coefficient k is obtained from Formula (273).

[0310]

$$A = \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1\right) \left(\frac{\partial W_w}{\partial x}\right)^2 dy dx \quad \cdot \cdot (270)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2}\right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2}\right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2}\right) \left(\frac{\partial^2 W_w}{\partial y^2}\right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y}\right)^2 \right] dy dx$$

$$\quad \cdot \cdot (271)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (272)$$

$$k = \frac{B}{A} \quad \cdot \cdot (273)$$

[0311]

Specifically, the half wavelength a is treated as a constant. In this state, a

simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set of a_n and b_n that imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (272) (by assigning the set of a_n and b_n to Formula (272)). Next, the half wavelength a is treated as a variable. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a is equal to 0, the half wavelength a is obtained. The buckling stress σ_{cr} obtained based on the set of a_n and B_n and the half wavelength a obtained as described above becomes a buckling stress σ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress σ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress σ_{cr} represented by Formula (272). Next, the half wavelength a is treated as a variable, and the buckling stress σ_{cr} is obtained as described above.

[0312]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress σ_{cr} of the web 13 which buckles due to the bending moments $F13$ acting about the z -axis is estimated using the displacement estimation method of the first embodiment. In the estimation method, a second displacement estimation step of estimating the second out-

of-plane displacement W_w of the web 13 from Formula (259) and a stress calculation step of obtaining the buckling stress σ_{cr} of the web 13 based on the energy method are performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since the bending moments F13 acting on the web 13 are asymmetrical with respect to the reference line M1, in the first displacement estimation step, the first out-of-plane displacement w_w of the web 13 is estimated to become asymmetrical in the y-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web 13 is estimated from (259).

In the stress calculation step, the buckling stress σ_{cr} of the web 13 is obtained based on the energy method using Formula (259).

[0313]

The bending moments F13 acting on the web 13 when the buckling stress σ_{cr} of the web 13 is generated can be obtained from a well-known equation regarding the sheet elements. When the bending moments F13 acting on the web 13 are made smaller than this bending moment F13, it is possible to suppress buckling of the web 13.

[0314]

(Evaluation of estimation accuracy of out-of-plane displacement and buckling stress)

(Comparison by out-of-plane displacement)

FIG. 29 shows the estimation results of the second out-of-plane displacement W_w of the web 13 along the y-axis coordinates in a case where the bending moments F13 act on the web 13. The end surfaces 13b of the web 13 in the y-axis direction were assumed to be fixedly supported. The second out-of-plane displacement W_w is

an out-of-plane displacement in a cross section along a cutting-plane line A11-A11 in FIG. 28.

In FIG. 29, the horizontal axis represents the y-axis coordinates with respect to the length b_w of the web 13, and the vertical axis represents the estimated second out-of-plane displacements W_w of the web 13. 0 in the horizontal axis represents the lower end of the web 13, and 1 in the horizontal axis represents the upper end of the web 13. In the vertical axis, the value of the second out-of-plane displacement W_w is made dimensionless with the maximum value of the second out-of-plane displacement W_w .

[0315]

In FIG. 29, a line L31 indicated by a solid line represents analysis results by the FEM. A line L32 indicated by a dotted line represents the estimation results using Formula (259) of the present embodiment (where N is 2), and a line L33 indicated by an alternate long and short dash line represents the estimation results using Formula (159) (where N is 15). Since the line L32 and the line L33 almost coincide with the line L31, the line L32 and the line L33 overlaps the line L31.

It was found that N in Formula (259) of the present embodiment that is necessary to approximate the analysis results by the FEM with almost the same accuracy as that in a case where N is 15 in the Fourier series of Formula (159) is 2.

[0316]

(Comparison by buckling stress)

Results obtained by obtaining the buckling stress σ_{cr} of the web 13 from Formula (159) and Formula (259) of the present embodiment and comparing buckling coefficients are shown in Table 4 and FIG. 30.

[0317]

[Table 4]

	N	Method for supporting end faces of web in y-axis direction	
		Simple support	Fixed support
Embodiment: Formula (259)	2	24.0	40.3
Fourier series: Formula (159)	4	89.9	272.1
	5	58.3	182.6
	7	37.3	104.3
	9	29.2	72.3
	11	25.7	56.6
	13	24.2	48.3
	15	23.9	43.6
	20	23.9	39.7
	25	23.9	39.7

[0318]

In the case of using Formula (259) of the present embodiment, N was set to 2. On the other hand, in the case of using the Fourier series of Formula (159), which is a comparative example, N was changed to 4, 5, 7, ..., 25.

In Table 4, the buckling coefficients in a case where the end surfaces 13b of the web 13 in the y-axis direction are simply supported converges to 23.88 as the estimation accuracy of the second out-of-plane displacement W_w and the buckling stress σ_{cr} increases (refer to a line L36 in FIG. 30). The buckling coefficients in a case where the end surfaces 13b of the web 13 in the y-axis direction are fixedly supported converges to 39.6 as the estimation accuracy of the out-of-plane displacement W_w and the buckling stress σ_{cr} increases (refer to a line L37 in FIG. 30).

[0319]

In FIG. 30, the horizontal axis represents N, and the vertical axis represents the buckling coefficient k. The white round marks represent the estimation results in the case of simple support for which Formula (259) of the present embodiment is used.

The black round marks represent the estimation results in the case of simple support for which the Fourier series of Formula (159) is used. The white square marks represent the estimation results in the case of fixed support for which Formula (259) of the present embodiment is used. The black square marks represent the estimation results in the case of fixed support for which the Fourier series of Formula (159) is used.

It was found that the accuracy in the case of evaluating the buckling coefficient k using Formula (259) of the present embodiment is approximately the same as the accuracy in a case where N is 25 in the Fourier series of the Formula (159) in both the simple support and the fixed support.

[0320]

As described above, according to the estimation device 110, the estimation method, and the estimation program 111 of the present embodiment, the inventors studied the plurality of functions with which the out-of-plane displacements of the web 13 on which the bending moments F_{13} act can be estimated by a smaller number of terms than in the Fourier series of Formula (159) while using a trigonometric function. As a result, it was found that the second out-of-plane displacement W_w of the web 13 can be estimated by a smaller number of terms than in the Fourier series using Formula (259).

Formula (259) makes it possible to estimate the second out-of-plane displacement W_w of the web 13 with a smaller number of terms than in the Fourier series of Formula (159) and thus makes it possible to simplify the calculation necessary for estimation compared with cases where the Fourier series is used. Furthermore, since the number of terms necessary to estimate the second out-of-plane displacement W_w with a certain accuracy is smaller in the case of estimation using Formula (259) than in the case of estimation using the Fourier series of Formula (159), it is possible to

formulate estimation results to be more easily understood physically than cases where the Fourier series is used.

[0321]

The use of Formula (259) makes it possible to rapidly approximate the second out-of-plane displacement W_w of the web 13. That is, it is possible to rapidly approximate a buckling waveform when local buckling occurs in a member of a building that receives in-plane bending or a sheet element that constitutes the member.

[0322]

In addition, N is 2. First, in Formula (259), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a is treated as a constant, the half wavelength a is then treated as a variable, and the half wavelength a in Formula (259) is obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (259), the number of undetermined coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 113 obtains the buckling stress σ_{cr} based on a_n , b_n , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress σ_{cr} represented by Formula (272), using Formula (270) and Formula (271). At the time of obtaining the buckling stress σ_{cr} based on the energy method, the buckling stress σ_{cr} can be accurately obtained using numerical formulae of Formula (270) to Formula (272).

[0323]

In the above-described embodiment, N may be 3 or more in Formula (259).

At the time of obtaining the buckling stress σ_{cr} based on the energy method,

Formula (270) to Formula (272) may not be used.

In the above-described embodiment, the estimation device 110 estimates the buckling stress of the web 13, which is a sheet element, but the sheet element is not limited to the web 13 and may be the lower flange 11, the upper flange 12, or the like.

[0324]

[Sixth Embodiment]

Next, a sixth embodiment of the present invention will be described with reference to FIG. 13 and FIG. 31 to FIG. 35, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) 120 shown in FIG. 13 is used to estimate the buckling stress of the H-section steel 10 that buckles due to a shear force acting as an external force (refer to FIG. 31). The estimation device 120 estimates the buckling stress of the H-section steel 10 using the displacement estimation device 50 of the first embodiment.

In the present embodiment, the entire H-section steel 10 shown in FIG. 31 is an estimation target. The reference line M1 is a reference line based on the web sheet element 13. That is, the reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the y-axis direction and is along the x-axis of the web sheet element 13. In other words, the reference line M1 becomes a line that passes through the central position of the length of the web sheet element 13 in the v-axis direction and is along the u-axis.

[0325]

FIG. 13 shows an estimation device 120 of the present embodiment. The

estimation device 120 is configured in the same manner as the estimation device 80. However, in the present embodiment, a buckling stress estimation program for making the computer function as the estimation device 120 (hereinafter, simply referred to as the estimation program) 121 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0326]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 122 that estimates a second out-of-plane displacement of the web sheet element 13 and a second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12 and a stress calculation portion 123 that obtains the buckling stress of the H-section steel 10 based on the energy method using the second out-of-plane displacement of the web sheet element 13 and the second out-of-plane displacement of each of the first flange sheet element 11 and the second flange sheet element 12. The second displacement estimation portion 122 and the stress calculation portion 123, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 121 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 122.

The estimation program 121 or the like is a program for the estimation device 120. The estimation program 121 makes the estimation device 120 function as the second displacement estimation portion 122 and the stress calculation portion 123. The estimation program 121 uses the estimation program 61.

[0327]

In the second displacement estimation portion 122 and the stress calculation portion 123 of the estimation device 120 of the present embodiment, as shown in FIG.

31, the position coordinates of the H-section steel 10 are recognized based on the uvw coordinate system. In FIG. 31 and FIG. 33 shown below, the out-of-plane displacement of the web sheet element 13 or the like is shown to be larger than an estimated value. FIG. 31 shows a state in which the H-section steel 10 buckles.

[0328]

When a shear force F_{16} acts in the v-axis direction on each of the end surfaces 10a of the H-section steel 10 in the u-axis direction, there are cases where the H-section steel 10 buckles. The shear forces F_{16} are transmitted throughout the entire length of the H-section steel 10 in the u-axis direction.

The shear forces F_{16} acting on the individual end surfaces 10a of the H-section steel 10 in the u-axis direction are external forces having an equal magnitude, but acting in opposite orientations. For example, a shear force F_{16} in the positive orientation in the v-axis direction acts on the end surface 10a on the negative orientation side in the u-axis direction, and a shear force F_{16} in the negative orientation in the v-axis direction acts on the end surface 10a on the positive orientation side in the u-axis direction.

Incidentally, a shear force F_{16} in the negative orientation in the v-axis direction may act on the end surface 10a on the negative orientation side in the u-axis direction, and a shear force F_{16} in the positive orientation in the v-axis direction may act on the end surface 10a on the positive orientation side in the u-axis direction.

[0329]

In this case, as the web sheet element 13 runs toward a first end of the web sheet element 13 in the u-axis direction (one of the end surfaces 10a in the u-axis direction), the web sheet element 13 is alternately displaced in the positive orientation of the w-axis and in the negative orientation of the w-axis, and the web sheet element 13 is displaced in a wavy shape in the u-axis direction as a whole. In association with the

web sheet element 13, the first flange sheet element 11 and the second flange sheet element 12 are displaced in a wavy shape.

In one wavelength-long part of the web sheet element 13 displaced along the u-axis, a second end opposite to the first end in the u-axis direction is defined as the origin of the u-axis, and an orientation toward the first end in the u-axis direction from the second end is defined as the positive orientation of the u-axis.

[0330]

As shown in FIG. 31 and FIG. 32, the central position of the web sheet element 13 in the v-axis direction is defined as the origin of the v-axis. An orientation toward the second flange sheet element 12 from the first flange sheet element 11 is defined as the positive orientation of the v-axis.

The origin of the z-axis is defined as the center of the web sheet element 13 in the w-axis direction (the center in the thickness direction). The positive orientation of the w-axis is defined as an orientation that constitutes the right-handed orthogonal coordinate system with respect to the positive orientation of the u-axis and the positive orientation of the v-axis.

[0331]

The estimation device 120 of the present embodiment estimates the buckling stress of the H-section steel 10 when the shear forces F16 act on the H-section steel 10 and the H-section steel 10 buckles. In the second displacement estimation portion 122 and the stress calculation portion 123 of the estimation device 120, at the time of estimating the buckling stress of the H-section steel 10, the above-described assumptions 1 to 3 and the assumptions 4A to 6A are performed.

[0332]

As shown in FIG. 31, when the shear forces F16 act on the H-section steel 10,

there are cases where the web sheet element 13 and the like of the H-section steel 10 are displaced in a wavy shape in the u-axis direction. When the v-axis coordinate is a certain value in the web sheet element 13 displaced in a wavy shape in the u-axis direction, the second out-of-plane displacement of the web sheet element 13 directed in the w-axis direction at the certain coordinate in the u-axis is assumed to be represented by Formula $\sin(\pi(u+\lambda\sin(\pi v/b_w))/a)$ (Assumption 2). At this time, the wavelength in the u-axis direction of the web sheet element 13 displaced in a wavy shape in the u-axis direction of the web sheet element 13 becomes $2a$. The half wavelength (the length of half the wavelength) in the u-axis direction of the web sheet element 13 becomes a .

FIG. 33 is a view showing second out-of-plane displacements W_w in the entire region of the H-section steel 10 in a portion where the length of the H-section steel 10 in the u-axis direction is the half wavelength a .

[0333]

FIG. 34 shows a state in which the shear forces F_{16} act on the H-section steel 10 with a solid line. What is indicated with a dotted line in FIG. 34 shows a state in which the shear forces F_{16} do not act on the H-section steel 10.

[0334]

In a case where the shear forces F_{16} act on the web sheet element 13, conventionally, the out-of-plane displacement of the web sheet element 13 has been estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which, when the u-axis coordinate is a certain value, the out-of-plane displacement (first out-of-plane displacement) w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function.

As a result, it was found that, in a case where the shear forces F16 act on the H-section steel 10, when the u-axis coordinate is a certain value, the first out-of-plane displacement w_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis is estimated from Formula (280) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (280) includes a trigonometric term for which the power function of the v-axis coordinates is used. $\cos\pi(2v/b_w)^n$ and $\cos(\pi/2)(2v/b_w)^n$ serve as the bases. Formula (280) can be preferably used to estimate the out-of-plane displacement of a sheet element such as the web sheet element 13.

[0335]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \quad \cdot \cdot (280)$$

[0336]

In the present embodiment, since the first out-of-plane displacement w_w of the H-section steel 10 is estimated to be symmetrical in the v-axis direction with respect to the reference line M1 as described below, the first out-of-plane displacement w_w is estimated from Formula (121) above. Formula (280) of the present embodiment is derived from Formula (121) as described below.

That is, as in Formula (122-2), values expressed using the value of Y and the length b_w of the web 13 in the y-axis direction are used to represent the y-axis coordinates. In other words, as in Formula (123-2), the value of Y is a value for which a y-axis coordinate is made dimensionless using the length b_w (a value obtained by dividing twice a y-axis coordinate by the length b_w).

In addition, the first out-of-plane displacement w_w directed in the w-axis

direction at a certain coordinate of the web 13 in the v-axis is estimated from Formula (124-2) that is obtained by assigning Formula (122-2) to Formula (121) and, furthermore, Formula (280) in which the y-axis of Formula (124-2) is replaced with the v-axis.

[0337]

$$y = b_w \cdot \frac{Y}{2} \quad \cdot \cdot (122-2)$$

$$Y = \frac{2y}{b_w} \quad \cdot \cdot (123-2)$$

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \quad \cdot \cdot (124-2)$$

[0338]

On the other hand, when the u-axis coordinate is an arbitrary value, the second out-of-plane displacement W_w of the web sheet element 13 directed in the w-axis direction at a certain coordinate in the v-axis is estimated from Formula (281).

Formula (281) is based on the assumption 2. Here, the undetermined coefficient λ in the Formula (281) is a real number that represents a phase shift in the v-axis direction.

When Formula (280) is assigned to Formula (281), Formula (282) is obtained.

In a case where N is 2, Formula (282) can be converted into Formula (283).

[0339]

$$W_w = \sin \frac{\pi}{\alpha} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \cdot w_w \quad \cdot \cdot (281)$$

$$W_w = \sin \frac{\pi}{\alpha} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (282)$$

$$W_w = \sin \frac{\pi}{\alpha} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left(a_0 + a_1 \cos \pi \left(\frac{2v}{b_w} \right) + b_1 \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right) + a_2 \cos \pi \left(\frac{2v}{b_w} \right)^2 + b_2 \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^2 \right) \quad \cdot \cdot (283)$$

[0340]

In addition, the second out-of-plane displacement W_{f1} at a predetermined coordinate in the w-axis of the first flange sheet element 11 is estimated from Formula

(284), and the second out-of-plane displacement W_{f2} at a predetermined coordinate in the w-axis of the second flange sheet element 12 is estimated from Formula (285).

Formula (284) and Formula (285) include a trigonometric term for which the power function of the v-axis coordinates is used.

[0341]

$$\begin{aligned} W_{f1} &= w \frac{\partial W_w}{\partial v} \bigg|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (284) \\ W_{f2} &= w \frac{\partial W_w}{\partial v} \bigg|_{v=\frac{b_w}{2}} \quad \cdot \cdot (285) \end{aligned}$$

[0342]

For example, before the shear forces F16 act on the H-section steel 10 of FIG. 33, the w-axis coordinate of a portion having a u-axis coordinate of u_0 and a v-axis coordinate of v_0 in the web sheet element 13 (hereinafter, referred to as the first estimation target portion) is 0. The second out-of-plane displacement W_w in this first estimation target portion is estimated from Formula (282-1). After the shear forces F16 have acted on the H-section steel 10 in FIG. 33, the w-axis coordinate of the first estimation target portion is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (282-1) to 0. That is, after the shear forces F16 have acted, the first estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes v_0 , and the w-axis coordinate becomes W_w .

For example, before the shear forces F16 act on the H-section steel 10 of FIG. 33, the v-axis coordinate of a portion having a u-axis coordinate of u_0 and a w-axis coordinate of w_0 in the second flange sheet element 12 (hereinafter, referred to as the second estimation target portion) is $b_w/2$. The second out-of-plane displacement W_{f2} in this second estimation target portion is estimated from Formula (285-1). After the

shear forces F16 have acted on the H-section steel 10 in FIG. 33, the v-axis coordinate of the second estimation target portion is a value obtained by adding the second out-of-plane displacement W_{f2} estimated from Formula (285-1) to $b_w/2$. That is, after the shear forces F16 have acted, the second estimation target portion is estimated to be disposed at a position where the u-axis coordinate becomes u_0 , the v-axis coordinate becomes $(b_w/2 + W_{f2})$, and the w-axis coordinate becomes W_0 .

[0343]

$$W_w = \sin \frac{\pi}{a} \left(u_0 + \lambda \sin \frac{\pi v_0}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v_0}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v_0}{b_w} \right)^n \right) \right] \cdot \cdot (282-1)$$

$$W_{f2} = w_0 \frac{\partial W_w}{\partial y} \Big|_{v=\frac{b_w}{2}, u=u_0, w=w_0} \cdot \cdot (285-1)$$

[0344]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 122 estimates that, when the shear forces F16 act on the H-section steel 10, the first out-of-plane displacement w_w of the H-section steel 10 becomes symmetrical in the v-axis direction with respect to the reference line M1. That is, in the estimation program 121, the first displacement estimation portion 52 is made to estimate that the first out-of-plane displacement w_w of the H-section steel 10 becomes symmetrical in the v-axis direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is that the shape and the restraint conditions of the H-section steel 10 are symmetrical with respect to the reference line M1 and the shear forces F16 acting on the H-section steel 10 are uniform in any v-axis direction cross sections in the u-axis direction.

The second displacement estimation portion 122 estimates the second out-of-plane displacement W_w of the web sheet element 13 from Formula (282) using the first out-of-plane displacement w_w of the web sheet element 13 estimated by the first

displacement estimation portion 52. The second displacement estimation portion 122 estimates the second out-of-plane displacement W_{f1} of the first flange sheet element 11 from Formula (284) and estimates the second out-of-plane displacement W_{f2} of the second flange sheet element 12 from Formula (285) using the first out-of-plane displacement w_w of each of the first flange sheet element 11 and the second flange sheet element 12 estimated by the first displacement estimation portion 52.

Here, based on the energy method, the strain energy U_w that is generated in the web sheet element 13 due to buckling distortion is represented as Formula (287), and the strain energy U_f in the first and second flange sheet elements 11 and 12 is represented as Formula (288).

[0345]

$$U_w = \frac{D_w}{2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du$$

$$+ \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \tau_{cr} t_w \left[\frac{\delta_w}{b_w} - \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) \right] dv du \quad \cdot \cdot (287)$$

$$U_f = \sum_{i=1}^2 \left\{ \frac{D_f}{2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \right\}$$

$$\cdot \cdot (288)$$

[0346]

However, the sheet rigidity D_w of the web sheet element 13 is expressed as Formula (289). The sheet rigidity D_f of the first and second flange sheet elements 11 and 12 is represented as Formula (290). The buckling stress of the H-section steel 10 is indicated by τ_{cr} .

The function δ_w is a function that expresses the distortion of the web sheet element 13 in the u-axis direction when buckling occurs and is represented as Formula (291) by indicating the u-axis displacement that is generated at the center of the first flange sheet element 11 with respect to the center of the second flange sheet element 12

as δ .

[0347]

$$\begin{aligned} D_w &= \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (289) \\ D_f &= \frac{Et_f^3}{12(1-\nu^2)} \quad \cdot \cdot (290) \\ \delta_w &= \delta \quad \cdot \cdot (291) \end{aligned}$$

[0348]

In addition, the external force potential energy V_w of the web sheet element 13 is represented as Formula (298), and the external force potential energy V_f of the first and second flange sheet elements 11 and 12 is represented as Formula (299).

[0349]

$$\begin{aligned} V_w &= -\tau_{cr} a t_w \delta_w \quad \cdot \cdot (298) \\ V_f &= 0 \quad \cdot \cdot (299) \end{aligned}$$

[0350]

The total potential energy Π of the H-section steel 10 is represented as Formula (300) as the sum of the strain energy and the external force potential energy.

[0351]

$$\Pi = U_w + U_f + V_w + V_f \quad \cdot \cdot (300)$$

[0352]

The stress calculation portion 123 obtains the buckling stress τ_{cr} of the H-section steel 10 based on the energy method using the second out-of-plane displacement W_w of the web sheet element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (282), Formula (284), and Formula (285). That is, the stress calculation portion 123 obtains the buckling stress τ_{cr} based on a_n , b_n , λ , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress τ_{cr} represented by Formula (304), using

Formula (301) to Formula (303).

[0353]

$$\begin{aligned}
 A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (301) \\
 B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2v \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-v) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
 &\quad \cdot \cdot (302) \\
 C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2v \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-v) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
 &\quad \cdot \cdot (303) \\
 \tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2 t_f \sum_{i=1}^2 C_i}{b_f^2 t_w A} \quad \cdot \cdot (304)
 \end{aligned}$$

[0354]

Specifically, the half wavelength a and the undetermined coefficient λ are treated as constants. In this state, a simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress τ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set of a_n and b_n that imparts the minimum positive value to the buckling stress τ_{cr} represented by Formula (304) (by assigning the set of a_n and b_n to Formula (304)). Next, the half wavelength a and the undetermined coefficient λ are treated as variables. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a and the undetermined coefficient λ is equal to 0, the half wavelength a and the undetermined coefficient λ are obtained. The buckling stress τ_{cr} obtained based on the set of a_n and B_n , the half wavelength a , and the undetermined coefficient λ obtained as described above becomes a buckling stress τ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress τ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress τ_{cr} represented by Formula (304). Next, the half wavelength a and the undetermined coefficient λ are treated as variables, and the buckling stress τ_{cr} is obtained as described above.

[0355]

A buckling coefficient k_w of the web sheet element 13 is represented by Formula (308), and a buckling coefficient k_f of each of the first and second flange sheet elements 11 and 12 is represented by Formula (309).

[0356]

$$k_w = \frac{B}{A} \quad \cdot \cdot (308)$$

$$k_f = \frac{t_f \sum_{i=1}^2 C_i}{t_w A} \quad \cdot \cdot (309)$$

[0357]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress τ_{cr} of the H-section steel 10 which buckles due to the shear forces F16 acting thereon is estimated using the displacement estimation method of the first embodiment. In the estimation method, a second displacement estimation step and a stress calculation step are performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since all of the shape and restraint conditions of the H-section steel 10 and the compressive forces F6 acting on the H-section steel 10 are symmetrical with respect to the reference line M1, in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section

steel 10 is estimated to be symmetrical in the v-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (282) using the first out-of-plane displacement w_w of the web sheet element 13 estimated in the first displacement estimation step. In addition, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are each estimated from Formula (284) and Formula (285) using the first out-of-plane displacements w_w of the first and second flange sheet elements 11 and 12 estimated in the first displacement estimation step.

In the stress calculation step, the buckling stress τ_{cr} is obtained based on the energy method using the second out-of-plane displacement W_w of the web sheet element 13, the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12, Formula (282), Formula (284), and Formula (285).

[0358]

The shear force F16 acting on the H-section steel 10 when the buckling stress τ_{cr} is generated in the H-section steel 10 can be obtained from a known equation regarding beams. When the shear forces F16 acting on the H-section steel 10 are made smaller than this shear force F16, it is possible to suppress buckling of the H-section steel 10.

In addition, the application range of the dimensions such as the thicknesses t_f of the first and second flange sheet elements 11 and 12 in the estimation device 120, the estimation method, and the estimation program 121 of the present embodiment is preferably the application range 1.

[0359]

(Evaluation of estimation accuracy of buckling stress)

FIG. 35 shows a comparison result of the buckling stress that is estimated by the estimation method (the estimation device 50, and the estimation program 61) of the present embodiment and the buckling stress that is estimated by the FEM. Q_y represents a yield shear force on the web sheet element 13. The yield shear force Q_y is equal to the product of a yield stress of the web sheet element 13 and a cross-sectional area A_w of the web sheet element 13.

Q_{cr_pre} represents a shear buckling proof stress of the web sheet element 13 that is estimated by the estimation method of the present embodiment. The shear buckling proof stress Q_{cr_pre} is equal to the product of the buckling stress of the web sheet element 13 when buckling occurs and the cross-sectional area A_w of the web sheet element 13. Since the first and second flange sheet elements 11 and 12 are assumed not to contribute to resistance to the shear forces $F16$, the buckling stress of the web sheet element 13 becomes equal to the buckling stress τ_{cr} of the H-section steel 10.

[0360]

Q_{cr_FEM} represents a shear buckling proof stress of the web sheet element 13 that is estimated by the FEM. The shear buckling proof stress Q_{cr_FEM} is equal to the product of the buckling stress of the web sheet element 13 when buckling occurs that is estimated by the FEM and the cross-sectional area A_w of the web sheet element 13. In FIG. 35, the horizontal axis represents the value of $\sqrt{(Q_y/Q_{cr_pre})}$, and the vertical axis represents the value of (Q_{cr_pre}/Q_y) or (Q_{cr_FEM}/Q_y) . The buckling stress and the like of the H-section steels 10 of a variety of specifications were estimated by the FEM and the estimation method of the present embodiment.

In FIG. 35, the $\circ$ marks represent the results estimated by the FEM, that is, the results with the values of (Q_{cr_FEM}/Q_y) along the vertical axis. Along the horizontal axis of the $\circ$ marks, the values of $\sqrt{(Q_y/Q_{cr_pre})}$ of the H-section steel 10 that has the

same specification as the H-section steel 10 analyzed by the FEM and is estimated by the estimation method of the present embodiment are used. The curve represents the results estimated by the estimation method of the present embodiment, that is, the results with the values of (Q_{cr_pre}/Q_y) along the vertical axis.

[0361]

The yield shear force Q_y becomes a constant value in accordance with the material strength regardless of the FEM and the estimation method of the present embodiment. The estimation accuracy of the present embodiment can be evaluated by comparing the shear buckling proof stress Q_{cr_pre} during buckling that is obtained from the estimation method of the present embodiment and the buckling stress that is estimated by the FEM. For the H-section steels 10 having the same specification, the results estimated by the FEM and the results estimated by the estimation method of the present embodiment show that, in FIG. 35, the values along the horizontal axis are equal to each other and the values along the vertical axis shift from each other according to errors.

[0362]

In FIG. 35, the shear buckling proof stress Q_{cr_FEM} during buckling estimated by the FEM and the shear buckling proof stress Q_{cr_pre} during buckling estimated by the estimation method of the present embodiment favorably correspond to each other. Since there is a certain relationship between the shear buckling proof stress Q_{cr_pre} during buckling that is estimated by the estimation method of the present embodiment and the buckling stress that is estimated by the FEM, it is possible to estimate the buckling stress τ_{cr} with a practically sufficient accuracy even when the buckling stress τ_{cr} is estimated by the estimation method of the present embodiment.

[0363]

In the case of attempting to estimate the buckling stress or the like of an H-section steel on which a shear force acts with the Fourier series of Formula (159), it is necessary to set N to 30 or more, and furthermore, the buckling stress cannot be indicated by a positive solution. On the other hand, in the estimation method of the present embodiment, in a case where the second out-of-plane displacement W_w of the web sheet element 13 is represented by Formula (282) and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are represented by Formula (284) and Formula (285), the buckling stress τ_{cr} can be calculated as a positive solution such as Formula (304).

[0364]

As described above, according to the estimation device 120, the estimation method, and the estimation program 121 of the present embodiment, for the H-section steel 10 on which the shear forces $F16$ act, the second out-of-plane displacement W_w of the web sheet element 13 is estimated from Formula (282). As shown in Formula (284), the second out-of-plane displacement W_{f1} of the first flange sheet element 11 is determined according to a function obtained by assigning $-b_w/2$ to the v -axis coordinate of a function of the first order partial differential equation with respect to v of the second out-of-plane displacement W_w of the web sheet element 13. In addition, as shown in Formula (285), the second out-of-plane displacement W_{f2} of the second flange sheet element 12 is determined according to a function obtained by assigning $b_w/2$ to the y -axis coordinate of a function of the first order partial differential equation with respect to y of the second out-of-plane displacement W_w of the web sheet element 13.

[0365]

Depending on a variety of amounts of the cross sections and the material properties of the web sheet element 13 and the first and second flange sheet elements 11

and 12, the degree of mutual influence between the web sheet element 13 and the first and second flange sheet elements 11 and 12 changes, and the second out-of-plane displacement W_w of the web sheet element 13 and the second out-of-plane displacements W_{f1} and W_{f2} of the first and second flange sheet elements 11 and 12 are determined. As described above, when the buckling stress τ_{cr} of the H-section steel 10 is obtained based on the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and the energy method, it is possible to estimate the buckling stress τ_{cr} in consideration of the coupled buckling of the web sheet element 13 and the first and second flange sheet elements 11 and 12.

[0366]

It is possible to estimate the second out-of-plane displacement W_w or the like of the web sheet element 13 with a smaller number of terms than in the Fourier series while using a trigonometric function and to simplify calculation necessary for the estimation of the second out-of-plane displacement W_w or the like.

Since the number of terms necessary to estimate the second out-of-plane displacement W_w or the like with a certain accuracy is smaller in the case of estimation using Formula (282) than in the case of estimation using the Fourier series of Formula (159), it is possible to formulate the estimation result of the second out-of-plane displacement W_w or the like to be easily understood physically.

[0367]

Furthermore, the estimation device 120, the estimation method, and the estimation program 121 of the present embodiment have the characteristics of 1 to 4, 7, and 8 described above, and the following characteristics of 5B and 6B.

5B. The power function-based formula of the local buckling stress of the H-section steel 10 is used, whereby it is possible to estimate the local buckling stress of the H-section

steel 10 that receives the shear forces F16 without using a numerical simulation.

6B. It is possible to set a sheet thickness ratio classification in consideration of the interaction among the sheet elements 11, 12, and 13 from the ratio relationship between the formula of the local buckling stress of the H-section steel 10 that receives the shear forces F16 and the buckling stress in a full plastic property state.

[0368]

In addition, N is 2 in Formula (282). First, in Formula (282), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a and the undetermined coefficient λ are treated as constants, the half wavelength a and the undetermined coefficient λ are then treated as variables, and the half wavelength a and the undetermined coefficient λ in Formula (282) are obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (282), the number of undetermined coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 53 obtains the buckling stress τ_{cr} based on a_n , b_n , λ , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress τ_{cr} represented by Formula (304), using Formula (301) to Formula (303). Therefore, at the time of obtaining the buckling stress τ_{cr} based on the energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , Formula (282), Formula (284), and Formula (285), the buckling stress τ_{cr} can be accurately obtained using numerical formulae.

[0369]

For example, in the above-described embodiment, N may be 3 or more in

Formula (282).

At the time of obtaining the buckling stress τ_{cr} based on the energy method, Formula (301) to Formula (304) may not be used.

[0370]

[Seventh Embodiment]

Next, a seventh embodiment of the present invention will be described with reference to FIG. 13 and FIG. 36 to FIG. 39, but the same portions as those in the above-described embodiment will be given the same reference numerals and will not be described again, and only differences will be described.

A buckling stress estimation device of the present embodiment (estimation device, hereinafter, also simply referred to the estimation device) is used to estimate the buckling stress of the web (sheet element) 13 that buckles due to a shear force acting as an external force. The estimation device estimates the buckling stress of the web 13 using the displacement estimation device 50 of the first embodiment.

[0371]

FIG. 13 shows an estimation device 130 of the present embodiment. The estimation device 130 is configured in the same manner as the estimation device 50. However, in the present embodiment, a buckling stress estimation program for making the computer function as the estimation device 130 (hereinafter, simply referred to as the estimation program) 131 or a variety of programs such as an OS program are stored in the auxiliary storage device 60.

[0372]

In addition, the CPU 51, functionally, includes a second displacement estimation portion 132 that estimates the second out-of-plane displacement of the web 13 and the stress calculation portion 133 that obtains the buckling stress of the web 13,

which causes the second out-of-plane displacement, based on the energy method. The second displacement estimation portion 132 and the stress calculation portion 133, which are the functional constituent elements of the CPU 51, are made to function by making the CPU 51 execute the estimation program 131 or the like that is stored in the auxiliary storage device 60. The first displacement estimation portion 52 is included in the second displacement estimation portion 132.

The estimation program 131 or the like is a program for the estimation device 130. The estimation program 131 makes the estimation device 130 function as the second displacement estimation portion 132 and the stress calculation portion 133. The estimation program 131 uses the estimation program 61.

[0373]

In the second displacement estimation portion 132 and the stress calculation portion 133 of the estimation device 50 of the present embodiment, as shown in FIG. 36, the position coordinates of the web 13 are recognized based on the right-handed orthogonal coordinate system composed of the x-axis, the y-axis, and the z-axis. In FIG. 36 and FIG. 37 shown below, the out-of-plane displacement of the web 13 or the like is shown to be larger than an estimated value.

The web 13 is assumed to be sufficiently long in the x-axis direction.

[0374]

When a shear force F_{18} acts as an external force in the y-axis direction on each of the end surfaces 13a of the web 13 in the x-axis direction, there are cases where the web 13 buckles (local buckling). The shear forces F_{18} are transmitted throughout the entire length of the web 13 in the x-axis direction.

The shear forces F_{18} acting on the individual end surfaces 13a of the web 13 in the x-axis direction are external forces having an equal magnitude.

[0375]

In this case, there are cases where, as the web 13 runs toward a first end in the x-axis direction, the web 13 is alternately displaced in a wavy shape in the positive orientation of the z-axis and in the negative orientation of the z-axis, and the web 13 is displaced in a wavy shape in the x-axis direction as a whole.

The origin of the y-axis is defined as the center of the web 13 in the y-axis direction. The positive orientation of the y-axis is defined as the upward orientation.

[0376]

In this example, the shear force F18 acts in the positive orientation of the y-axis on the end surface 13a in the x-axis direction, where the x-axis coordinate is small, and the shear force F18 acts in the negative orientation of the y-axis on the end surface 13a in the x-axis direction, where the x-axis coordinate is large.

A shear force F19 is generated as an internal force at each end surface 13b of the web 13 in the y-axis direction so as to balance the shear force F18, which is an external force acting on each end surface 13a in the x-axis direction.

[0377]

The estimation device 130 estimates the buckling stress of the web 13 when the shear forces F18 act on the web 13 with which the flanges 11 and 12 are not coupled and the web 13 buckles. Incidentally, in a case where the thicknesses of the flanges 11 and 12 of the H-section steel 10 are thin enough to be ignored, the rigidity of the flanges 11 and 12 is low enough to be ignored, or the like, the estimation device 130 may estimate the buckling stress of the H-section steel 10 as the buckling stress of the web 13.

[0378]

In the second displacement estimation portion 132 and the stress calculation

portion 133 of the estimation device 130 of the present embodiment, at the time of estimating the buckling stress of the web 13, the above-described assumptions 1 to 6 are performed.

[0379]

As shown in FIG. 36, when the shear forces F18 act on the web 13, there are cases where the web 13 is displaced in a wavy shape in the x-axis direction. When out-of-plane displacements directed in the z-axis direction at a certain coordinate on the y-axis and a certain coordinate on the x-axis in the web 13 displaced in a wavy shape in the x-axis direction are assumed to be represented by a formula $\sin(\pi(x+\lambda\sin(\pi y/b_w))/a)$, the wavelength in the x-axis direction of the web 13 displaced in a wavy shape in the x-axis direction becomes $2a$. The half wavelength in the x-axis direction becomes a .

FIG. 37 is a view showing out-of-plane displacements in a portion where the length in the x-axis direction is the wavelength $2a$ in the center portion of the web 13 in the x-axis direction.

[0380]

In a case where the shear forces F18 are acting on the web 13, conventionally, a first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis was estimated using the Fourier series represented by Formula (159).

The inventors studied a plurality of functions with which the first out-of-plane displacement w_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis can be estimated by a smaller number of terms than in the Fourier series while using a trigonometric function.

As a result, it was found that, in a case where the shear forces F18 act on the web 13, the first out-of-plane displacement w_w of the web 13 directed in the z-axis

direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (316) with a smaller number of terms than in the Fourier series. Here, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

Formula (316) includes a trigonometric term for which the power function of the y-axis coordinates is used. $\cos\pi(2y/b_w)^n$ and $\cos(\pi/2)(2y/b_w)^n$ serve as the bases. Formula (316) can be preferably used to estimate the out-of-plane distortion of a sheet element such as the web 13.

[0381]

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos\pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \quad \cdot \cdot (316)$$

[0382]

On the other hand, the second out-of-plane displacement W_w of the web 13 directed in the z-axis direction at a certain coordinate on the x-axis and a certain coordinate on the y-axis is estimated from Formula (318). Formula (318) is based on an assumption, that is, as described above, the out-of-plane displacement directed in the z-axis direction at a certain coordinate on the x-axis in the web 13 is represented by Formula $\sin(\pi(x+\lambda\sin(\pi y/b_w))/a)$. Here, the undetermined coefficient λ in the Formula (318) is a real number that represents a phase shift in the y-axis direction.

When Formula (316) is assigned to Formula (318), Formula (319) is obtained. In a case where N is 2, Formula (319) can be converted into Formula (320).

[0383]

$$\begin{aligned}
W_w &= \sin \frac{\pi}{\alpha} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \cdot w_w \quad \cdot \cdot (318) \\
W_w &= \sin \frac{\pi}{\alpha} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (319) \\
W_w &= \sin \frac{\pi}{\alpha} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left(a_0 + a_1 \cos \pi \left(\frac{2y}{b_w} \right) + b_1 \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right) + a_2 \cos \pi \left(\frac{2y}{b_w} \right)^2 + b_2 \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^2 \right) \\
&\quad \cdot \cdot (320)
\end{aligned}$$

[0384]

For example, before the shear forces F18 act on the web 13 of FIG. 37, the z-axis coordinate of a portion having an x-axis coordinate of x_0 and a y-axis coordinate of y_0 in the web 13 (hereinafter, referred to as the estimation target portion) is 0. After the shear forces F18 have acted on the web 13, the second out-of-plane displacement W_w in this estimation target portion is estimated from Formula (319-1), and the z-axis coordinate at this time is a value obtained by adding the second out-of-plane displacement W_w estimated from Formula (319-1) to 0. That is, after the shear forces F18 have acted, the estimation target portion is estimated to be disposed at a position where the x-axis coordinate becomes x_0 , the y-axis coordinate becomes y_0 , and the z-axis coordinate becomes W_w .

[0385]

$$W_w = \sin \frac{\pi}{\alpha} \left(x_0 + \lambda \sin \frac{\pi y_0}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y_0}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y_0}{b_w} \right)^n \right) \right] \quad \cdot \cdot (319-1)$$

[0386]

The first displacement estimation portion 52 that is included in the second displacement estimation portion 132 estimates that, when the shear forces F18 act on the web 13, the first out-of-plane displacement w_w of the web 13 becomes symmetrical in the y-axis direction with respect to the reference line M1. That is, in the estimation program 91, the first displacement estimation portion 52 is made to estimate that the first out-of-plane displacement w_w of the web 13 becomes symmetrical in the y-axis

direction with respect to the reference line M1 with the displacement estimation program 61. The reason for this is that the shape and the restraint conditions of the web 13 are symmetrical with respect to the reference line M1 and the shear forces F18 acting on the web 13 are uniform in any y-axis direction cross sections in the x-axis direction.

The second displacement estimation portion 132 estimates the second out-of-plane displacement W_w of the web 13 from Formula (319) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion 52.

[0387]

The web 13 is disposed in a closed section where the x-axis coordinates are 0 or more and a or less and is disposed in a closed section where the y-axis coordinates are $-(b_w/2)$ or more $(b_w/2)$ or less. At this time, the strain energy U that is generated in the web 13 due to buckling distortion is represented by Formula (321), and the external force potential V that is imparted due to the shear forces F18 is represented by Formula (322).

The total potential energy Π is represented by Formula (323) as the sum of the strain energy U and the external force potential V.

[0388]

$$U = \frac{D_w}{2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dx dy$$

$$+ \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \tau_{cr} t_w \left[\frac{\delta_w}{a} - \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) \right] dx dy \quad \cdot \cdot (321)$$

$$V = -\tau_{cr} b_w t_w \delta_w \quad \cdot \cdot (322)$$

$$\Pi = U + V \quad \cdot \cdot (323)$$

[0389]

Here, D_w is the sheet rigidity of the web 13 and is represented by Formula (325). τ_{cr} is the buckling stress of the web 13. The function δ_w is a function that

expresses the distortion of the web 13 in the x-axis direction when buckling occurs and is represented by Formula (326). Here, δ is a displacement in the y-axis direction at the second end (upper end) in the y-axis direction on the second end in the x-axis direction of the web 13.

[0390]

$$D_w = \frac{Et_w^3}{12(1-\nu^2)} \quad \cdot \cdot (325)$$

$$\delta_w = \delta \quad \cdot \cdot (326)$$

[0391]

The stress calculation portion 133 obtains the buckling stress τ_{cr} of the web 13 based on the energy method using Formula (319). The stress calculation portion 133 obtains the buckling stress τ_{cr} of the web 13 based on a_n , b_n , λ , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress τ_{cr} represented by Formula (332), using Formula (330) and Formula (331).

Here, the buckling coefficient k is obtained from Formula (333).

[0392]

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (330)$$

$$B = \frac{h_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\quad \cdot \cdot (331)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{h_w^2 A} \quad \cdot \cdot (332)$$

$$k = \frac{B}{A} \quad \cdot \cdot (333)$$

[0393]

Specifically, the half wavelength a and the undetermined coefficient λ are treated as constants. In this state, a simultaneous equation representing that a function obtained by partially differentiating the total potential energy Π by the undetermined coefficients a_n and b_n is equal to 0 is created, thereby obtaining a_n and b_n , which are real

numbers. In a case where there is a plurality of sets of a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress τ_{cr} is obtained based on, among the plurality of sets of a_n and b_n , the set of a_n and b_n that imparts the minimum positive value to the buckling stress τ_{cr} represented by Formula (332) (by assigning the set of a_n and b_n to Formula (332)). Next, the half wavelength a and the undetermined coefficient λ are treated as variables. From an equation representing that a function obtained by partially differentiating the total potential energy Π , for which the set of a_n and b_n has been obtained, by the half wavelength a and the undetermined coefficient λ is equal to 0, the half wavelength a and the undetermined coefficient λ are obtained. The buckling stress τ_{cr} obtained based on the set of a_n and B_n , the half wavelength a , and the constant λ obtained as described above becomes a buckling stress τ_{cr} in demand.

In a case where there is only one set of the undetermined coefficients a_n and b_n that serves as the solution to the simultaneous equation, the buckling stress τ_{cr} is obtained based on the set of a_n and b_n in a case where the set of a_n and b_n imparts the minimum positive value to the buckling stress τ_{cr} represented by Formula (332). Next, the half wavelength a and the undetermined coefficient λ are treated as variables, and the buckling stress τ_{cr} is obtained as described above.

[0394]

In the buckling stress estimation method of the present embodiment (hereinafter, also simply referred to as the estimation method), the buckling stress τ_{cr} of the web 13 which buckles due to the shear forces $F18$ acting thereon is estimated using the displacement estimation method of the first embodiment. In the estimation method, a second displacement estimation step of estimating the second out-of-plane displacement W_w of the web 13 from Formula (319) and a stress calculation step of obtaining the buckling stress τ_{cr} of the web 13 based on the energy method are

performed.

In the second displacement estimation step, the first displacement estimation step of the displacement estimation method is performed. Since all of the shape and restraint conditions of the web 13 and the shear forces F_{18} acting on the web 13 are symmetrical with respect to the reference line M1, in the first displacement estimation step, the first out-of-plane displacement w_w of the web 13 is estimated to be symmetrical in the y-axis direction with respect to the reference line M1. In the second displacement estimation step, the second out-of-plane displacement W_w of the web 13 is estimated from (319).

In the stress calculation step, the buckling stress τ_{cr} of the web 13 is obtained based on the energy method using Formula (319).

[0395]

The shear forces F_{18} acting on the web 13 when the buckling stress τ_{cr} of the web 13 is generated can be obtained from a well-known equation regarding the sheet elements. When the shear forces F_{18} acting on the web 13 are made smaller than this shear force F_{18} , it is possible to suppress buckling of the web 13.

[0396]

(Evaluation of estimation accuracy of out-of-plane displacement and buckling stress)

(Comparison by out-of-plane displacement)

FIG. 38 shows the estimation results of the second out-of-plane displacement W_w of the web 13 along the y-axis coordinates in a case where the shear forces F_{18} act on the web 13. The end surfaces 13b of the web 13 in the y-axis direction were assumed to be fixedly supported. The second out-of-plane displacement W_w is an out-of-plane displacement in a cross section along a cutting-plane line A15-A15 in FIG. 37.

In FIG. 38, the horizontal axis represents the y-axis coordinates with respect to values $(b_w/2)$ of half the length b_w of the web 13, and the vertical axis represents the estimated second out-of-plane displacements w_w of the web 13. -1 in the horizontal axis represents the lower end of the web 13, and 1 in the horizontal axis represents the upper end of the web 13. In the vertical axis, the value of the second out-of-plane displacement W_w is made dimensionless with the maximum value of the second out-of-plane displacement W_w in the range of FIG. 37. That is, in FIG. 37, in cross sections along lines other than the cutting-plane line A15-A15, there are portions that are displaced as approximately twice much as the second out-of-plane displacement W_w in the cross section along the cutting-plane line A15-A15. Therefore, the dimensionless second out-of-plane displacement W_w in the cross section along the cutting-plane line A15-A15 becomes a value of approximately -0.5 to 0.5.

[0397]

In FIG. 38, a line L41 indicated by a solid line represents analysis results by the FEM. A line L42 indicated by a dotted line represents the estimation results using Formula (319) of the present embodiment (where N is 2), and a line L43 indicated by an alternate long and short dash line represents the estimation results using Formula (159) (where N is 25). Since the line L42 and the line L43 almost coincide with the line L41, the line L42 and the line L43 overlaps the line L41.

It was found that N in Formula (319) of the present embodiment that is necessary to approximate the analysis results by the FEM with almost the same accuracy as that in a case where N is 25 in the Fourier series of Formula (159) is 2.

[0398]

(Comparison by buckling stress)

Results obtained by obtaining the buckling stress τ_{cr} of the web 13 from

Formula (159) and Formula (319) of the present embodiment and comparing buckling coefficients are shown in Table 5 and FIG. 39.

[0399]

[Table 5]

	N	Method for supporting end faces of web in y-axis direction	
		Simple support	Fixed support
Embodiment: Formula (319)	2	5.37	9.05
Fourier series: Formula (159)	4	9.62	21.24
	5	7.65	16.59
	7	5.97	12.10
	9	5.46	10.18
	11	5.59	9.33
	13	5.39	9.06
	15	5.39	9.04
	20	5.39	9.03
	25	5.39	9.03

[0400]

In the case of using Formula (319) of the present embodiment, N was set to 2. On the other hand, in the case of using the Fourier series of Formula (159), which is a

comparative example, N was changed to 4, 5, 7, ..., 25.

In Table 5, the buckling coefficients in a case where the end surfaces 13b of the web 13 in the y -axis direction are simply supported converges to 5.34 as the estimation accuracy of the second out-of-plane displacement W_w and the buckling stress τ_{cr} increases (refer to a line L46 in FIG. 39). The buckling coefficients in a case where the end surfaces 13b of the web 13 in the y -axis direction are fixedly supported converges to 8.98 as the estimation accuracy of the out-of-plane displacement W_w and the buckling stress τ_{cr} increases (refer to a line L12 in FIG. 39).

[0401]

In FIG. 39, the horizontal axis represents N , and the vertical axis represents the buckling coefficient k . The white round marks represent the estimation results in the case of simple support for which Formula (319) of the present embodiment is used. The black round marks represent the estimation results in the case of simple support for which the Fourier series of Formula (159) is used. The white square marks represent the estimation results in the case of fixed support for which Formula (319) of the present embodiment is used. The black square marks represent the estimation results in the case of fixed support for which the Fourier series of Formula (159) is used.

It was found that the accuracy in the case of evaluating the buckling coefficient k using Formula (319) of the present embodiment is approximately the same as the accuracy in a case where N is 25 in the Fourier series of the Formula (159) in both the simple support and the fixed support.

[0402]

As described above, according to the estimation device 50, the estimation method, and the estimation program 131 of the present embodiment, the inventors studied the plurality of functions with which the out-of-plane displacements of the web

13 on which the shear forces F_{18} act can be estimated by a smaller number of terms than in the Fourier series of Formula (159) while using a trigonometric function. As a result, it was found that the second out-of-plane displacement W_w of the web 13 can be estimated by a smaller number of terms than in the Fourier series using Formula (319).

Formula (319) makes it possible to estimate the second out-of-plane displacement W_w of the web 13 with a smaller number of terms than in the Fourier series of Formula (159) and thus makes it possible to simplify the calculation necessary for estimation compared with cases where the Fourier series is used. Furthermore, since the number of terms necessary to estimate the second out-of-plane displacement W_w with a certain accuracy is smaller in the case of estimation using Formula (319) than in the case of estimation using the Fourier series of Formula (159), it is possible to formulate estimation results to be more easily understood physically than cases where the Fourier series is used.

[0403]

The use of Formula (319) makes it possible to rapidly approximate the second out-of-plane displacement W_w of the web 13. That is, it is possible to rapidly approximate a buckling waveform when local buckling occurs in a member of a building that receives in-plane bending or a sheet element that constitutes the member.

[0404]

In addition, N is 2. First, in Formula (319), the undetermined coefficients a_1 , a_2 , b_1 , and b_2 are obtained in a state in which the half wavelength a and the undetermined coefficient λ are treated as constants, the half wavelength a and the undetermined coefficient λ are then treated as variables, and the half wavelength a and the undetermined coefficient λ in Formula (319) are obtained. At the time of obtaining the undetermined coefficients a_1 and the like in Formula (319), the number of

undetermined coefficients that are obtained at one time is 4 or less. Therefore, it is possible to easily obtain the undetermined coefficients a_1 , a_2 , b_1 , and b_2 using a fourth or lower-degree equation for which the solution formula is known.

In addition, (in the stress calculation step,) the stress calculation portion 133 obtains the buckling stress τ_{cr} based on a_n , b_n , λ , and the half wavelength a , which are real numbers that impart the minimum positive value to the buckling stress τ_{cr} represented by Formula (332), using Formula (330) and Formula (331). At the time of obtaining the buckling stress τ_{cr} based on the energy method, the buckling stress τ_{cr} can be accurately obtained using numerical formulae of Formula (330) to Formula (332).

[0405]

In the above-described embodiment, a shear force, which is an external force, may act in the x-axis direction on each end surface 13b of the web 13 in the y-axis direction. A shear force is generated as an internal force at each end surface 13a of the web 13 in the x-axis direction so as to balance the shear force acting on each end surface 13b in the y-axis direction. In addition, Formula (321) is applied by reading δ_w/a in the parentheses of the second term in the right-hand side expression as δ_w/b_w , and Formula (322) is applied by reading b_w in the right-hand side expression as a . In this case, δ is a displacement in the x-axis direction at the second end (upper end) in the y-axis direction on the second end in the x-axis direction of the web 13.

[0406]

In Formula (319), N may be 3 or more.

At the time of obtaining the buckling stress τ_{cr} based on the energy method, Formula (330) to Formula (332) may not be used.

In the above-described embodiment, the estimation device 130 estimates the buckling stress of the web 13, which is a sheet element, but the sheet element is not

limited to the web 13 and may be the lower flange 11, the upper flange 12, or the like.

[0407]

A sheet-shaped body design method of the present embodiment is a sheet-shaped body design method in which a sheet-shaped body that is at least one of the H-section steel 10 and the web (sheet element) 13 is designed using the displacement estimation methods of the second embodiment to the seventh embodiment. The sheet element may be the lower flange 11 or the upper flange 12.

[0408]

Hitherto, the first embodiment and the seventh embodiment of the present invention have been described in detail with reference to the drawings, but the specific constitution is not limited to these embodiments and also includes the modification, combination, deletion, or the like of constitutions within the scope not departing from the gist of the present invention. Furthermore, it is needless to say that it is possible to use the individual constitutions described in the individual embodiments in appropriate combination.

[0409]

(Evaluation of estimation accuracy of buckling stress)

(1. Case where sheet element receives uniform bending)

The evaluation results of the estimation accuracy of the buckling stress with the estimation device of the present embodiment in a case where, for example, a bending moment acts on a sheet element will be described.

As an accuracy comparison target, “Recommendations for Stability Design of Steel Structures” (edited by Architectural Institute of Japan, hereinafter, referred to as Document 1) was used. In Document 1, the buckling coefficient k of a sheet element that buckles due to a bending moment acting thereon is described.

The specification and boundary condition of the sheet element at this time are as described below. Both ends of the sheet element are simply supported or fixedly supported. Since bending moments having an equal magnitude act on both ends of the sheet element, a state in which the bending moments acting on the sheet element are balanced (uniform bending) is formed.

The buckling stress σ_c and the buckling coefficient k have a relationship of Formula (336).

[0410]

$$\sigma_{cr} = k \frac{\pi^2 E}{12(1 - \nu^2)} \quad \cdot \cdot (336)$$

[0411]

Document 1 describes that, in a case where both ends of the sheet element are simply supported, the buckling coefficient k becomes 23.9. On the other hand, Document 1 describes that, in a case where both ends of the sheet element are fixedly supported, the buckling coefficient k becomes 39.6. These results are shown in Table 6 and are shown by lines L51 and L52 in FIG. 40.

[0412]

[Table 6]

	N	Method for supporting end faces of web in y-axis direction	
		Simple support	Fixed support
Embodiment	1	24.01	40.27
Fourier series: Formula (195)	4	82.92	272.14
	5	58.35	182.62
	7	37.35	104.27
	9	29.24	72.29
	11	25.70	56.65
	13	24.23	48.27
	15	23.88	43.64
	20	23.88	39.75

	25	23.88	39.66
Recommendations for Stability Design of Steel Structures		23.9	39.6

[0413]

In FIG. 40, the horizontal axis represents the N , and the vertical axis represents the buckling coefficient k . The line L51 indicated by a solid line represents the case of simple support in Document 1. The line L52 indicated by a dotted line represents the case of fixed support in Document 1.

[0414]

On the other hand, the buckling stress of the sheet element that buckled due to the bending moment acting thereon was estimated by the buckling stress of the fifth embodiment. Here, the aspect ratio of the sheet element was set to 10. That is, the ratio of the length of the sheet element in the x -axis direction to the length of the sheet element in the y -axis direction is 10.

In the case of simple support, in the Fourier series of Formula (159), the solution converges with the 15th partial sum ($N = 15$). On the other hand, in the estimation method of the fifth embodiment, an analytical solution having almost the same accuracy can be obtained with the first partial sum.

In addition, in the case of fixation, in the Fourier series of Formula (159), the solution converges with the 25th partial sum ($N = 25$). On the other hand, in the estimation method of the fifth embodiment, an analytical solution having almost the same accuracy can be obtained with the first partial sum.

That is, in the Fourier series of Formula (159), a long time is required for the convergence calculation. On the other hand, it was found that, in the estimation method of the fifth embodiment, the analytical solution can be immediately calculated by calculation for which convergence calculation is not used (manual calculation).

[0415]

(2. Case where H-section steel receives uniform bending)

On H-section steels having a variety of specifications, the buckling eigenvalue analysis by the FEM and the estimation method of the present embodiment were performed. The specification and boundary condition of the H-section steel are as described below.

- Targets are approximately 600-series H-section steels having a beam height of 400 mm to 1000 mm.

- Both ends of the H-section steel are simply supported.

FIG. 41 shows results by a conventional estimation method. The horizontal axis and the vertical axis in FIG. 41 are the same as those in FIG. 26.

FIG. 42 shows results by the estimation method of the present embodiment. The horizontal axis and the vertical axis in FIG. 42 are the same as those in FIG. 26.

A line L56 in FIG. 41 and a line L57 in FIG. 41 are lines drawn by each estimation method. The ○ marks represent the results of the buckling eigenvalue analysis by the FEM.

[0416]

It was found that the conventional estimation method shown in FIG. 41 significantly varies with respect to the results of the buckling eigenvalue analysis by the FEM. On the other hand, in the estimation method of the present embodiment shown in FIG. 42, the plots of the results of the buckling eigenvalue analysis by the FEM are disposed on the line L57 by the present estimation method. Therefore, it was found that the accuracy significantly improves in the estimation method of the present embodiment compared with the conventional estimation method.

Incidentally, the ratio of the buckling stress obtained by each estimation

method to the buckling stress obtained by the FEM was calculated. In the conventional estimation method, the average of these ratios was 1.207, and the standard deviation was 0.312. On the other hand, in the estimation method of the present embodiment, the average of these ratios was 0.992, and the standard deviation was 0.007.

[Industrial Applicability]

[0417]

According to the present invention, it is possible to provide a displacement estimation device, a buckling stress estimation device, a displacement estimation method, a buckling stress estimation method, a displacement estimation program, and a buckling stress estimation program which make it possible to simplify calculation necessary for estimation compared with a case where the Fourier series is used and to formulate estimation results to be easily understood physically. Therefore, the present invention is significantly industrially applicable.

[Brief Description of the Reference Symbols]

[0418]

10 H-section steel

11 Lower flange (elastic element, first flange sheet element)

12 Upper flange (elastic element, second flange sheet element)

13 Web (elastic element, web sheet element)

13a, 13c End surface

50 Estimation device (buckling stress estimation device)

52 First displacement estimation portion

53, 83 Stress calculation portion

61 Estimation program (buckling stress estimation program)

80, 90, 100, 110, 120, 130 Estimation device (buckling stress estimation device)

81, 91, 101, 111, 121, 131 estimation program (buckling stress estimation program)

82, 92, 102, 112, 122, 132 Second displacement estimation portion

F6, F8 Compressive force

F11, F13 Bending moment

F16, F18 Shear force

M1 Reference line

[Document Type][CLAIMS]

1. A displacement estimation device that estimates a first out-of-plane displacement w_w of an elastic element directed in a direction along a z-axis, which is a sheet thickness direction of the elastic element being formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis, the displacement estimation device comprising:

a first displacement estimation portion that,

when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and

a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line,

estimates the first out-of-plane displacement w_w from Formula (1) in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the direction along the y-axis with respect to the reference line and estimates the first out-of-plane displacement w_w from Formula (2) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line,

wherein, in Formula (1) and Formula (2), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed

support,

here, a value of Y in Formula (1) and Formula (2) is a value for which a coordinate of the y -axis is made dimensionless using the length of the elastic element in the direction along the y -axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot (1)$$

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (2)$$

2. The displacement estimation device according to claim 1,

wherein N is 2.

3. A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation device according to claim 1,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v -axis that is the y -axis of the web sheet element,

the compressive force acts on the end surface of the H-section steel in a direction along a u -axis that is the x -axis of the web sheet element,

a w -axis is defined as an axis in the direction along the z -axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y -axis and is along the x -axis of the web sheet element,

a central position of the first flange sheet element in the direction along the v -axis is defined as an origin of the v -axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v -axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v -axis is indicated by b_w , and

a half wavelength in the direction along the u -axis of the web sheet element that is displaced in a positive orientation of the w -axis and a negative orientation of the w -axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u -axis is indicated by a ,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v -axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w -axis in the web sheet element from Formula (3) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v -axis in the first flange sheet element and the second flange sheet element from each of Formula (4) and Formula (5) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (3) to Formula (5),

here, N is a natural number of 2 or more.

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (3)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (4)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (5)$$

4. The buckling stress estimation device according to claim 3,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (10), using Formula (6) to Formula (9),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (6)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \quad \cdot \cdot (7)$$

$$C = \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (8)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \quad \cdot \cdot (9)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (10)$$

5. A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation device according to claim 1,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (11) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (11),

here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (11)$$

6. The buckling stress estimation device according to claim 5,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (14), using Formula (12) and Formula (13),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the

sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (12)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\cdot \cdot (13)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (14)$$

7. A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation device according to claim 1,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the bending moment acts on the end surface of the H-section steel about a w-axis that is the z-axis of the web sheet element,

a u-axis is defined as an axis in the direction along the x-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

the first flange sheet element is assumed to receive a tensile force due to the bending moment,

a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange

sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the H-section steel becomes asymmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (15) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (16) and Formula (17) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (15) to Formula (17),

here, N is a natural number of 2 or more.

$$\begin{aligned}
W_w &= \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (15) \\
W_{f1} &= w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (16) \\
W_{f2} &= w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (17)
\end{aligned}$$

8. The buckling stress estimation device according to claim 7,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (22), using Formula (18) to Formula (21),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (18) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (19) \\
C &= \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (20) \\
D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (21) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (22)
\end{aligned}$$

9. A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about the z-axis using the displacement estimation device according to claim 1,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is

displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes asymmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (23) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (23),

here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w} + b_n \sin \frac{\pi y^n}{b_w} \right) \right] \quad \cdot \cdot (23)$$

10. The buckling stress estimation device according to claim 9,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (26), using Formula (24) and Formula (25),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (24) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
&\quad \cdot \cdot (25) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (26)
\end{aligned}$$

11. A buckling stress estimation device that estimates a buckling stress of an H-section steel that buckles due to a shear force acting as the external force using the displacement estimation device according to claim 1,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the shear force acts on the end surface of the H-section steel in the direction along the v-axis,

a u-axis is defined as an axis in the direction along the x-axis of the web sheet element,

a w-axis is defined as an axis in the direction along the z-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (27) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (28) and Formula (29) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (27) to Formula (29),

here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

$$W_w = \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (27)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (28)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (29)$$

12. The buckling stress estimation device according to claim 11,

wherein the stress calculation portion obtains the buckling stress τ_{cr} based on the a_n , the b_n , the λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (33), using Formula (30) to Formula (32),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (30)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \quad \cdot \cdot (31)$$

$$C_i = \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \quad \cdot \cdot (32)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2 t_f \sum_{i=1}^2 C_i}{b_f^2 t_w A} \quad \cdot \cdot (33)$$

13. A buckling stress estimation device that estimates a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation device according to claim 1,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

the first displacement estimation portion estimates that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation device comprises

a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (34) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion; and

a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (34),

here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (34)$$

14. The buckling stress estimation device according to claim 13,

wherein the stress calculation portion obtains the buckling stress τ_{cr} based on the undetermined coefficients a_n , b_n , and λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (37), using Formula (35) and Formula (36),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (35)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

· · (36)

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (37)$$

15. The buckling stress estimation device according to any one of claims 3 to 14,

wherein N is 2.

16. A displacement estimation method of estimating a first out-of-plane displacement w_w of an elastic element directed in a direction along a z-axis, which is a sheet thickness direction of the elastic element being formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis, the displacement estimation method comprising:

a first displacement estimation step of,

when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and

a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line,

estimating the first out-of-plane displacement w_w from Formula (41) in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the direction along the y-axis with respect to the reference line and estimating the first out-of-plane displacement w_w from Formula (42) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis

with respect to the reference line,

wherein, in Formula (41) and Formula (42), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed support,

here, a value of Y in Formula (41) and Formula (42) is a value for which a coordinate of the y-axis is made dimensionless using the length of the elastic element in the direction along the y-axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot \cdot (4 \ 1)$$

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos 2\pi Y^n + b_n \sin \pi Y^n \right) \quad \cdot \cdot \cdot (4 \ 2)$$

17. The displacement estimation method according to claim 16,

wherein N is 2.

18. A buckling stress estimation method of estimating a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation method according to claim 16,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the compressive force acts on the end surface of the H-section steel in a direction along a u-axis that is the x-axis of the web sheet element,

a w-axis is defined as an axis in the direction along the z-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to be symmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (43) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements

W_{f1} and W_{f2} directed in the direction along the v -axis in the first flange sheet element and the second flange sheet element from each of Formula (44) and Formula (45) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and

a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (43) to Formula (45),

here, N is a natural number of 2 or more.

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (43)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \bigg|_{v=0} \quad \cdot \cdot (44)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \bigg|_{v=b_w} \quad \cdot \cdot (45)$$

19. The buckling stress estimation method according to claim 18,

wherein, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (50), using Formula (46) to Formula (49),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (46) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (47) \\
C &= \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (48) \\
D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (49) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (50)
\end{aligned}$$

20. A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation method according to claim 16,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to be symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (51); and

a stress calculation step of obtaining the buckling stress of the sheet element based on an energy method using Formula (51),

here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (51)$$

21. The buckling stress estimation method according to claim 20,

wherein, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (54), using Formula (52) and Formula (53),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (52)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (53)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (54)$$

22. A buckling stress estimation method of estimating a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation method according to claim 16,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the bending moment acts on the end surface of the H-section steel about a w-axis that is the z-axis of the web sheet element,

a u-axis is defined as an axis in the direction along the x-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

the first flange sheet element is assumed to receive a tensile force due to the bending moment,

a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to become asymmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (55) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements

W_{f1} and W_{f2} directed in the direction along the v -axis in the first flange sheet element and the second flange sheet element from each of Formula (56) and Formula (57) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and

a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (55) to Formula (57),

here, N is a natural number of 2 or more.

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (55)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (56)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (57)$$

23. The buckling stress estimation method according to claim 22,

wherein, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (62), using Formula (58) to Formula (61),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (58) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2v \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-v) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (59) \\
C &= \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (60) \\
D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2v \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-v) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (61) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (62)
\end{aligned}$$

24. A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about the z-axis using the displacement estimation method according to claim 16,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (63); and

a stress calculation step of obtaining the buckling stress of the sheet element based on an energy method using Formula (63),

here, N is a natural number of 2 or more, and b_w is a length of the sheet

element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w} + b_n \sin \frac{\pi y^n}{b_w} \right) \right] \quad \cdot \cdot (63)$$

25. The buckling stress estimation method according to claim 24,

wherein, in the stress calculation step, the buckling stress σ_{cr} is obtained based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (66), using Formula (64) and Formula (65),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$\begin{aligned} A &= \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (64) \\ B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\ &\quad \cdot \cdot (65) \\ \sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (66) \end{aligned}$$

26. A buckling stress estimation method of estimating a buckling stress of an

H-section steel that buckles due to a shear force acting as the external force using the displacement estimation method according to claim 16,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the shear force acts on the end surface of the H-section steel in the direction along the v-axis,

a u-axis is defined as an axis in the direction along the x-axis of the web sheet

element,

a w-axis is defined as an axis in the direction along the z-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

in the first displacement estimation step, the first out-of-plane displacement w_w of the H-section steel is estimated to be symmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (67) using the first out-of-plane displacement w_w estimated in the first displacement estimation step and estimating each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element

and the second flange sheet element from each of Formula (68) and Formula (69) using the first out-of-plane displacement w_w estimated in the first displacement estimation step; and

a stress calculation step of obtaining the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (67) to Formula (69),

here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

$$W_w = \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (67)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (68)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (69)$$

27. The buckling stress estimation method according to claim 26,

wherein, in the stress calculation step, the buckling stress τ_{cr} is obtained based on the a_n , the b_n , the λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (73), using Formula (70) to Formula (72),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (70) \\
B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (71) \\
C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (72) \\
\tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2 t_f \sum_{i=1}^2 C_i}{b_f^2 t_w A} \quad \cdot \cdot (73)
\end{aligned}$$

28. A buckling stress estimation method of estimating a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation method according to claim 16,

wherein, when the sheet element is the elastic element,

an axis that extends in the sheet thickness direction of the sheet element is defined as the z-axis, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

in the first displacement estimation step, the first out-of-plane displacement w_w of the sheet element is estimated to be symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation method comprises

a second displacement estimation step of estimating a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (74); and

a stress calculation step of obtaining the buckling stress of the sheet element

based on an energy method using Formula (74),

here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (74)$$

29. The buckling stress estimation method according to claim 28,

wherein, in the stress calculation step, the buckling stress τ_{cr} is obtained based on the undetermined coefficients a_n , b_n , and λ , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (77), using Formula (75) and Formula (76),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (75)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \quad \cdot \cdot (76)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (77)$$

30. The buckling stress estimation method according to any one of claims 18 to 29,

wherein N is 2.

31. A sheet-shaped body design method of designing a sheet-shaped body that is at least one of an H-section steel and a sheet element using the displacement estimation method according to claim 16 or 17.

32. A displacement estimation program for an estimation device that estimates a first out-of-plane displacement w_w of an elastic element directed in a direction along a z-axis, which is a sheet thickness direction of the elastic element being

formed in a flat sheet shape that extends along an x-axis and a y-axis that are orthogonal to each other, when an external force acts on an end surface of the elastic element and the elastic element buckles in the direction along the z-axis,

wherein, when the elastic element shows a rectangular shape having a length in a direction along the x-axis longer than a length in a direction along the y-axis when viewed along the z-axis, and

a line that passes through a central position of a length of the elastic element in the direction along the y-axis and is along the x-axis is defined as a reference line,

the displacement estimation program causes the displacement estimation device to function as a first displacement estimation portion that estimates the first out-of-plane displacement w_w from Formula (81) in a case where the first out-of-plane displacement w_w is estimated to be symmetrical in the direction along the y-axis with respect to the reference line and estimates the first out-of-plane displacement w_w from Formula (82) in a case where the first out-of-plane displacement w_w is estimated to become asymmetrical in the direction along the y-axis with respect to the reference line, and

in Formula (81) and Formula (82), a term including a coefficient b_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a simple support, and a term including a coefficient a_n represents, among components of the first out-of-plane displacement w_w , an out-of-plane displacement for which a boundary condition of both ends in the direction along the y-axis is a fixed support,

here, a value of Y in Formula (81) and Formula (82) is a value for which a coordinate of the y-axis is made dimensionless using the length of the elastic element in

the direction along the y-axis, N is a natural number of 2 or more, and a_0 , a_n , and b_n are undetermined coefficients.

$$w_w = a_0 + \sum_{n=1}^N \left(a_n \cos \pi Y^n + b_n \cos \frac{\pi}{2} Y^n \right) \quad \cdot \cdot (8\ 1)$$

$$w_w = a_0 + \sum_{n=1}^N (a_n \cos 2\pi Y^n + b_n \sin \pi Y^n) \quad \cdot \cdot (8\ 2)$$

33. The displacement estimation program according to claim 32,
wherein N is 2.

34. A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a compressive force acting as the external force using the displacement estimation program according to claim 32,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the compressive force acts on the end surface of the H-section steel in a direction along a u-axis that is the x-axis of the web sheet element,

a w-axis is defined as an axis in the direction along the z-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange

sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (83) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (84) and Formula (85) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (83) to Formula (85),

here, N is a natural number of 2 or more.

$$\begin{aligned}
W_w &= \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (83) \\
W_{f1} &= w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (84) \\
W_{f2} &= w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (85)
\end{aligned}$$

35. The buckling stress estimation program according to claim 34,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (90), using Formula (86) to Formula (89),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (86) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (87) \\
C &= \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (88) \\
D &= \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (89) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (90)
\end{aligned}$$

36. A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a compressive force acting as the external force in the direction along the x-axis using the displacement estimation program according to claim 32,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (91) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (91),

here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} - 1 \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} - 1 \right)^n \right) \right] \quad \cdot \cdot (91)$$

37. The buckling stress estimation program according to claim 36,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (94), using Formula (92) and Formula (93),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the

sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_0^{b_w} \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (9 \ 2)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\cdot \cdot (9 \ 3)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (9 \ 4)$$

38. A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a bending moment acting as the external force using the displacement estimation program according to claim 32,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the bending moment acts on the end surface of the H-section steel about a w-axis that is the z-axis of the web sheet element,

a u-axis is defined as the direction along the x-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

the first flange sheet element is assumed to receive a tensile force due to the bending moment,

a central position of the first flange sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes asymmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (95) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (96) and Formula (97) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (95) to Formula (97),

here, N is a natural number of 2 or more.

$$W_w = \sin \frac{\pi u}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi v^n}{b_w^n} + b_n \sin \frac{\pi v^n}{b_w^n} \right) \right] \quad \cdot \cdot (95)$$

$$W_{f1} = w \frac{\partial W_w}{\partial v} \Big|_{v=0} \quad \cdot \cdot (96)$$

$$W_{f2} = w \frac{\partial W_w}{\partial v} \Big|_{v=b_w} \quad \cdot \cdot (97)$$

39. The buckling stress estimation program according to claim 38,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (102), using Formula (98) to Formula (101),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$A = \int_0^a \int_0^{b_w} \left(\frac{2v}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial u} \right)^2 dv du \quad \cdot \cdot (98)$$

$$B = \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \quad \cdot \cdot (99)$$

$$C = \sum_{i=1}^2 (-1)^{(i+1)} \int_0^a \int_{-b_f}^{b_f} \left(\frac{\partial W_{fi}}{\partial u} \right)^2 dw du \quad \cdot \cdot (100)$$

$$D = \frac{b_f^2}{\pi^2} \sum_{i=1}^2 \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \quad \cdot \cdot (101)$$

$$\sigma_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A + \frac{t_f}{t_w} C} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{D}{\frac{t_w}{t_f} A + C} \quad \cdot \cdot (102)$$

40. A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a bending moment acting as the external force about the z-axis using the displacement estimation program according to claim 32,

wherein, when the sheet element is the elastic element, and

a half wavelength in the direction along the x-axis of the sheet element that is

displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes asymmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (103) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (103),

here, N is a natural number of 2 or more, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi x}{a} \left[a_0 + \sum_{n=1}^N \left(a_n \cos \frac{2\pi y^n}{b_w^n} + b_n \sin \frac{\pi y^n}{b_w^n} \right) \right] \quad \cdot \cdot (103)$$

41. The buckling stress estimation program according to claim 40,

wherein the stress calculation portion obtains the buckling stress σ_{cr} based on the a_n , the b_n , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress σ_{cr} represented by Formula (106), using Formula (104) and Formula (105),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$\begin{aligned}
A &= \int_0^a \int_0^{b_w} \left(\frac{2y}{b_w} - 1 \right) \left(\frac{\partial W_w}{\partial x} \right)^2 dy dx \quad \cdot \cdot (104) \\
B &= \frac{b_w^2}{\pi^2} \int_0^a \int_0^{b_w} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx \\
&\quad \cdot \cdot (105) \\
\sigma_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (106)
\end{aligned}$$

42. A buckling stress estimation program that estimates a buckling stress of an H-section steel that buckles due to a shear force acting as the external force using the displacement estimation program according to claim 32,

wherein, when the H-section steel includes a web sheet element, a first flange sheet element, and a second flange sheet element that are the elastic elements,

the first flange sheet element and the second flange sheet element are disposed so as to sandwich the web sheet element in a direction along a v-axis that is the y-axis of the web sheet element,

the shear force acts on the end surface of the H-section steel in the direction along the v-axis,

a u-axis is defined as an axis in the direction along the x-axis of the web sheet element,

a w-axis is defined as an axis in the direction along the z-axis of the web sheet element,

the reference line is defined as a line that passes through a central position of a length of the web sheet element in the direction along the y-axis and is along the x-axis of the web sheet element,

a central position of the web sheet element in the direction along the v-axis is defined as an origin of the v-axis,

an orientation toward the second flange sheet element from the first flange sheet element is defined as a positive orientation of the v-axis,

a distance between a center of the first flange sheet element and a center of the second flange sheet element in the direction along the v-axis is indicated by b_w , and

a half wavelength in the direction along the u-axis of the web sheet element that is displaced in a positive orientation of the w-axis and a negative orientation of the w-axis alternately in a wavy shape toward a first end of the web sheet element in the direction along the u-axis is indicated by a ,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the H-section steel becomes symmetrical in the direction along the v-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w directed in a direction along the w-axis in the web sheet element from Formula (107) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion and estimates each of second out-of-plane displacements W_{f1} and W_{f2} directed in the direction along the v-axis in the first flange sheet element and the second flange sheet element from each of Formula (108) and Formula (109) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the H-section sheet based on an energy method using the second out-of-plane displacement W_w , the second out-of-plane displacements W_{f1} and W_{f2} , and Formula (107) to Formula (109),

here, N is a natural number of 2 or more, and λ is an undetermined coefficient.

$$\begin{aligned}
W_w &= \sin \frac{\pi}{a} \left(u + \lambda \sin \frac{\pi v}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2v}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2v}{b_w} \right)^n \right) \right] \quad \cdot \cdot (107) \\
W_{f1} &= w \frac{\partial W_w}{\partial v} \Big|_{v=-\frac{b_w}{2}} \quad \cdot \cdot (108) \\
W_{f2} &= w \frac{\partial W_w}{\partial v} \Big|_{v=\frac{b_w}{2}} \quad \cdot \cdot (109)
\end{aligned}$$

43. The buckling stress estimation program according to claim 42,

wherein the stress calculation portion obtains the buckling stress τ_{cr} based on the a_n , the b_n , the λ , and the half wavelength a , which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by Formula (113), using Formula (110) to Formula (112),

here, E is a Young's modulus of the H-section steel, ν is a Poisson's ratio of the H-section steel, t_w is a thickness of the web sheet element, t_f is a thickness of each of the first flange sheet element and the second flange sheet element, and b_f is a value of half a width of each of the first flange sheet element and the second flange sheet element.

$$\begin{aligned}
A &= \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial u} \right) \left(\frac{\partial W_w}{\partial v} \right) dv du \quad \cdot \cdot (110) \\
B &= \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial v^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial u^2} \right) \left(\frac{\partial^2 W_w}{\partial v^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial u \partial v} \right)^2 \right] dv du \\
&\quad \cdot \cdot (111) \\
C_i &= \frac{b_f^2}{2\pi^2} \int_0^a \int_{-b_f}^{b_f} \left[\left(\frac{\partial^2 W_{fi}}{\partial u^2} \right)^2 + \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_{fi}}{\partial u^2} \right) \left(\frac{\partial^2 W_{fi}}{\partial w^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_{fi}}{\partial u \partial w} \right)^2 \right] dw du \\
&\quad \cdot \cdot (112) \\
\tau_{cr} &= \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2}{b_w^2} \frac{B}{A} + \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_f^2}{b_f^2} \frac{\sum_{i=1}^2 C_i}{t_w A} \quad \cdot \cdot (113)
\end{aligned}$$

44. A buckling stress estimation program that estimates a buckling stress of a sheet element that buckles due to a shear force acting as the external force in the direction along the x-axis or the direction along the y-axis using the displacement estimation program according to claim 32,

wherein, when the sheet element is the elastic element,

an axis that extends in the sheet thickness direction of the sheet element is defined as a z-axis, and

a half wavelength in the direction along the x-axis of the sheet element that is displaced in a positive orientation of the z-axis and a negative orientation of the z-axis alternately in a wavy shape toward a first end of the sheet element in the direction along the x-axis is indicated by a,

with the displacement estimation program, the first displacement estimation portion is made to estimate that the first out-of-plane displacement w_w of the sheet element becomes symmetrical in the direction along the y-axis with respect to the reference line, and

the buckling stress estimation program causes the estimation device to function as a second displacement estimation portion that estimates a second out-of-plane displacement W_w of the sheet element directed in the direction along the z-axis from Formula (114) using the first out-of-plane displacement w_w estimated by the first displacement estimation portion, and

as a stress calculation portion that obtains the buckling stress of the sheet element based on an energy method using Formula (114),

here, N is a natural number of 2 or more, λ is an undetermined coefficient, and b_w is a length of the sheet element in the direction along the y-axis.

$$W_w = \sin \frac{\pi}{a} \left(x + \lambda \sin \frac{\pi y}{b_w} \right) \left[a_0 + \sum_{n=1}^N \left(a_n \cos \pi \left(\frac{2y}{b_w} \right)^n + b_n \cos \frac{\pi}{2} \left(\frac{2y}{b_w} \right)^n \right) \right] \quad \cdot \cdot (114)$$

45. The buckling stress estimation program according to claim 44,

wherein the stress calculation portion obtains the buckling stress τ_{cr} based on the undetermined coefficients a_n , b_n , and λ , and the half wavelength a, which are real numbers that impart a minimum positive value to the buckling stress τ_{cr} represented by

Formula (117), using Formula (115) and Formula (116),

here, E is a Young's modulus of the sheet element, ν is a Poisson's ratio of the sheet element, and t_w is a thickness of the sheet element.

$$A = \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left(\frac{\partial W_w}{\partial x} \right) \left(\frac{\partial W_w}{\partial y} \right) dy dx \quad \cdot \cdot (115)$$

$$B = \frac{b_w^2}{2\pi^2} \int_0^a \int_{-\frac{b_w}{2}}^{\frac{b_w}{2}} \left[\left(\frac{\partial^2 W_w}{\partial x^2} \right)^2 + \left(\frac{\partial^2 W_w}{\partial y^2} \right)^2 + 2\nu \left(\frac{\partial^2 W_w}{\partial x^2} \right) \left(\frac{\partial^2 W_w}{\partial y^2} \right) + 2(1-\nu) \left(\frac{\partial^2 W_w}{\partial x \partial y} \right)^2 \right] dy dx$$

$$\cdot \cdot (116)$$

$$\tau_{cr} = \frac{\pi^2 E}{12(1-\nu^2)} \frac{t_w^2 B}{b_w^2 A} \quad \cdot \cdot (117)$$

46. The buckling stress estimation program according to any one of claims 34 to 45,

wherein N is 2.