

[Document Type] Specification

[Title of the Invention] ANALYSIS METHOD, DESIGN METHOD,
MANUFACTURING METHOD, AND PROGRAM

[Technical Field of the Invention]

[0001]

The present invention relates to an analysis method for evaluating lateral torsional buckling proof stress of a steel girder, a design method for a steel girder, a manufacturing method for a steel girder, and a program.

Priority is claimed on the basis of Japanese Patent Application No. 2017-028462 filed February 17, 2017, the content of which is incorporated herein by reference.

[Related Art]

[0002]

As an evaluation equation of the lateral torsional buckling proof stress of steel girders for buildings in the related art, the following equation (91) has been proposed. In addition, a design method for a steel girder disclosed in Patent Document 1 has been proposed for the purpose of increasing the accuracy of the design of steel girders using an evaluation equation of lateral torsional buckling proof stress in which two moment correction coefficients are used depending on the torsion conditions of steel girders.

[0003]

For a number of fundamental equations of buckling (differential equations of girder deflection) of the related art, correct solutions are not known, but the equations are too complicated, and thus, generally, energy methods are used for the calculation of buckling loads. In these energy methods, a strain energy ΔU that is accumulated in a

member due to the distortion of the member and a work ΔT done by an external force are obtained with an assumption of the distortion of the member, and a buckling load is obtained on the basis of a fact that the strain energy and the work are in a neutral equilibrium state ($\Delta U = \Delta T$) under the buckling load. However, in the related art, there have been no known correct energy equations of lateral torsional buckling under the action of intermediate loads, and torsional buckling loads have been calculated using approximate energy equations, and thus lateral torsional buckling loads obtained using energy methods could not have been put into practical use.

[0004]

By the way, in the fundamental equations of buckling of the related art, the distortion of lateral torsional buckling of girders having an upper flange of which the lateral movement is restrained in a case where an antisymmetric moment acts during earthquakes is complicated, and thus it has been difficult to express the lateral torsional buckling of girders with a numerical equation and, furthermore, to obtain a closed-form solution of lateral torsional buckling proof stress M_e . At this time, the calculation of lateral torsional buckling proof stress M_0 in a case where a uniform bending moment acts is simple, and thus an approximate equation of the following (91) equation obtained by multiplying this lateral torsional buckling proof stress M_0 by a moment correction coefficient C_b is being employed as an evaluation equation of the lateral torsional buckling proof stress M_e of girders under the action of the antisymmetric moment.

[0005]

$$M_e = C_b M_0 \quad \cdot \cdot \cdot \quad (91)$$

[0006]

The correct solution of lateral torsional buckling proof stress M_0 in a case where a uniform bending moment acts on a both-end-fixed girder having an upper flange of which the lateral movement is restrained is given in the following equation (92) as a sum of a resistance force by Wagner torsion (warping torsion) and a resistance force by St. Venant torsion (pure torsion). In the following equation (92), E represents Young's modulus, I_f represents the cross-sectional second-order moment of a lower flange, G represents the shear elastic modulus, J represents the St. Venant torsion constant, l represents the length of a girder, and d_b represents the distance between the sheet thickness centers of an upper flange and the lower flange.

[0007]

$$M_o = \frac{4\pi^2 EI_f}{l^2} d_b + \frac{GJ}{d_b} \cdot \cdot \cdot \quad (92)$$

[0008]

In addition, the design method disclosed in Patent Document 1 is a design method for a steel girder for preventing the lateral torsional buckling of steel girders having an upper flange of which the lateral movement is restrained. In the design method disclosed in Patent Document 1, the following equation (93) and the following equation (94) are used as evaluation equations of the elastic lateral torsional buckling proof stress M_e of girders, and the resistance force by Wagner torsion and the resistance force by St. Venant torsion are respectively multiplied by different moment correction coefficients C_1 and C_2 , thereby computing the elastic lateral torsional buckling proof stress M_e . In the following equation (93) as well, E represents Young's modulus, I_f represents the cross-sectional second-order moment of a lower flange, G represents the shear elastic modulus, J represents the St. Venant torsion

constant, l represents the length of a girder, and d_b represents the distance between the sheet thickness centers of an upper flange and the lower flange.

[0009]

$$M_e = C_1 \frac{4\pi^2 EI_f}{l^2} d_b + C_2 \frac{GJ}{d_b} \quad \cdot \cdot \cdot \quad (93)$$

$$C_1 \neq C_2 \quad \cdot \cdot \cdot \quad (94)$$

[0010]

However, the evaluation equations of the lateral torsional buckling proof stress M_e of girders using the equation (91) and the equation (92) had the following problems. That is, the equation (91) is an approximate solver based on experiments and analyses since the buckling load M_0 in a case where a uniform bending moment acts is multiplied by a moment correction coefficient C_b that adds the influence of a moment gradient, but the approximation accuracy is low, and thus a large safety rate is required in a case in which the equation is used as a design method, which creates room for improvement.

[0011]

In addition, the equation (91) is an evaluation equation in which a single moment correction coefficient C_b is used. That is, the equation is an attempt to express load conditions as a linear influence coefficient, has a low evaluation accuracy, and acts as a cause for inhibiting economic structural designs. In contrast, the evaluation equation of the lateral torsional buckling proof stress M_e of girders using the equation (93) and the equation (94) is an evaluation equation in which two moment correction coefficients C_1 and C_2 are used and enables the design of steel girders with high accuracy. However, this evaluation equation is an equation that deals with only

an antisymmetric moment and is thus incapable of dealing with the loads of steel girders in actual buildings in which vertical loads and lateral loads act in combination in diverse manners.

[Prior Art Document]

[Patent Document]

[0012]

[Patent Document 1] Japanese Unexamined Patent Application, First Publication No. 2016-23446

[Disclosure of the Invention]

[Problems to be Solved by the Invention]

[0013]

Therefore, the present invention has been proposed in consideration of the above-described problems, and an object of the present invention is to provide an analysis method, a design method, a manufacturing method, and a program which are capable of evaluating the lateral torsional buckling proof stress of steel girders with high accuracy.

[Means for Solving the Problem]

[0014]

(1) An analysis method according to an aspect of the present invention is an analysis method for evaluating lateral torsional buckling proof stress of a steel girder, in which a subject is a girder for which shaped steel having an upper flange and a lower flange coupled through a web is used, both end portions of the girder in a

material axis direction are fixed, and, in a middle portion of the girder in the material axis direction, under conditions in which lateral movement of the upper flange in a width direction is restrained, an intermediate load acts on the upper flange from above, and end loads act on both end portions of the girder in the material axis direction, lateral torsional buckling proof stress M_{cr} of the girder is computed from an equation (12) to an equation (16) below.

[0015]

$$M_{cr} = \frac{1}{(1-\beta-\gamma)A + (\beta+\gamma)C + \gamma D} \left(B \frac{2\pi^2 E I d_b}{L^2} + A \frac{GJ}{d_b} \right) \cdot \cdot \cdot \quad (12)$$

$$A = L \int_0^L \phi'^2 dz \cdot \cdot \cdot \quad (13)$$

$$B = \frac{L^3}{2\pi^2} \int_0^L \phi''^2 dz \cdot \cdot \cdot \quad (14)$$

$$C = \int_0^L z \phi'^2 dz \cdot \cdot \cdot \quad (15)$$

$$D = \frac{2}{L} \int_0^L \int_0^z (z-t) \phi'^2 dt dz \cdot \cdot \cdot \quad (16)$$

Here, β and γ are coefficients determined by load conditions V and w that serve as presumptions from an equation (1) and an equation (2) below. V represents a shear force acting on an end portion of the girder in the material axis direction, and w represents an intermediate load acting on the middle portion of the girder in the material axis direction.

In addition, L represents a length of the girder in the material axis direction, E represents Young's modulus, I represents a cross-sectional second-order moment around a weak axis of the lower flange, G represents a shear elastic modulus, J represents St. Venant's torsional constant, d_b represents a distance between sheet

thickness centers of the upper flange and the lower flange, and z represents a length from one end portion of the girder in the material axis direction which serves as a criterion to an arbitrary point of the girder in the material axis direction. ϕ represents a torsion angle generated in the girder by lateral torsional buckling. ϕ' represents a first-order differentiation of ϕ , and ϕ'' represents a second-order differentiation of ϕ . t represents a parameter for integration.

[0016]

$$V = -(\beta + \gamma) \frac{M_{cr}}{L} \cdot \cdot \cdot \quad (1)$$

$$\int_0^L w z \, dz = \gamma M_{cr} \cdot \cdot \cdot \quad (2)$$

[0017]

(2) In the analysis method according to another aspect of the present invention, β and γ are determined as real numbers in ranges by an equation (3a) and an equation (3b) below in the analysis method according to (1).

[0018]

$$0 \leq \beta \leq 3 \cdot \cdot \cdot \quad (3a)$$

$$-3 \leq \gamma \leq 6 - 2\beta \cdot \cdot \cdot \quad (3b)$$

[0019]

(3) In the analysis method according to still another aspect of the present invention, in (1) or (2), in a case where both end portions of the girder are fixed by rigid connection, ϕ is computed using an equation (10a) or an equation (10b) below.

[0020]

$$\text{Antisymmetric torsional buckling : } \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ 2\pi \left(\frac{z}{L} \right)^n \right\} \cdot \cdot \cdot \quad (10a)$$

$$\text{Symmetric torsional buckling : } \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ \pi \left(\frac{2z}{L} - 1 \right)^n \right\} \cdot \cdot \cdot \quad (10b)$$

Here, a_n is an undetermined coefficient of an n^{th} term and, when ϕ is expressed by the equation (10a) or the equation (10b), represents weight of each term configuring a series in the series.

[0021]

(4) A design method for a steel girder according to an aspect of the present invention includes a step of computing M_{cr} on the basis of the analysis method according to any one of (1) to (3) and a step of determining cross-sectional dimensions of a steel girder on the basis of M_{cr} .

[0022]

(5) A manufacturing method for a steel girder according to an aspect of the present invention includes a step of computing M_{cr} on the basis of the analysis method according to any one of (1) to (3), a step of determining cross-sectional dimensions of a steel girder on the basis of M_{cr} , and a step of manufacturing the steel girder on the basis of the determined cross-sectional dimensions of the steel girder.

[0023]

(6) When a program according to an aspect of the present invention is executed using a CPU, it is possible to realize the analysis method according to any one of (1) to (3).

[0024]

(7) When a program according to an aspect of the present invention is

executed using a CPU, it is possible to realize the design method according to (4).

[Effects of the Invention]

[0025]

In the analysis method for evaluating the lateral torsional buckling proof stress of a steel girder, the design method for a steel girder, the manufacturing method for a steel girder, and the program, it is possible to evaluate the lateral torsional buckling proof stress of steel girders with high accuracy and to carry out the design of steel girders and the manufacturing of steel girders based on the evaluation.

[Brief Description of the Drawings]

[0026]

FIG. 1 is a perspective view showing a steel girder that is a subject of an analysis method according to the present embodiment.

FIG. 2(a) is a front view showing a free body of the steel girder that is the subject of the analysis method according to the present embodiment, and FIG. 2(b) is a side view thereof.

FIG. 3A is a front view showing a state in which both end portions of the steel girder that is the subject of the analysis method according to the present embodiment are fixed and lateral movement of an upper flange is restrained.

FIG. 3B is a side view of the steel girder shown in FIG. 3A.

FIG. 3C is a front view showing an example in which an opening is provided in a portion of a floor slab in an upper portion of the steel girder that is the subject of the analysis method according to the present embodiment.

FIG. 4(a) is a perspective view showing a linear buckling analysis result

example by FEM of a steel girder having an upper flange of which the lateral movement is restrained, and FIG. 4(b) is a perspective view showing a linear buckling analysis result example by FEM of a steel girder having an upper flange of which the lateral movement is not restrained.

FIG. 5(a) is a side view showing an example of the imaginary dislocation of the steel girder that is the subject of the analysis method according to the present embodiment, FIG. 5(b) is a bottom view thereof, and FIG. 5(c) is a cross-sectional view along an A-A' line in FIG. 5(a).

FIG. 6(a) is a schematic side view showing a bending moment distribution in a material axis direction in a case where both end portions of the steel girder that is the subject of the analysis method according to the present embodiment uniformly bends, and FIG. 6(b) to FIG. 6(d) are schematic side views showing antisymmetric moments and the like in a case where both end portions does not uniformly bend.

FIG. 7(a) is a graph showing a calculation result for which ϕ that is approximated using a predetermined series in the analysis method according to the present embodiment is used, and FIG. 7(b) is a graph showing a calculation result for which ϕ that is approximated by the approximation of a fourth term of the Fourier cosine series is used.

FIG. 8 is a flowchart for describing a flow of an analysis method according to the present embodiment.

FIG. 9 is a flowchart for describing a flow of a design method according to an embodiment of the present invention.

[Embodiments of the Invention]

[0027]

Hereinafter, a form for carrying out an analysis method to which the present invention is applied will be described in detail with reference to drawings. In an analysis method according to the present embodiment, a subject is a steel girder that is used as a structural material of a floor structure such as a building or the like, an earth floor structure, a framed structure, or the like as shown in FIG. 1 as an example.

[0028]

The analysis method according to the present embodiment is a method that is used to evaluate the lateral torsional buckling proof stress of steel girders, analyzes a girder 2 for which a steel H-shape 20 having an upper flange 21 and a lower flange 22 coupled through a web 23 is used as a subject, and is intended to estimate the lateral torsional buckling proof stress of the girder 2 with high accuracy.

[0029]

As shown in FIG. 2(a), the girder 2 is provided with a vertical pair of the upper flange 21 and the lower flange 22 that extend in a width direction X, and the vertical pair of the upper flange 21 and the lower flange 22 are coupled together through a web 23. In the girder 2, for example, upper and lower end portions of the web 23 are connected to substantial centers of the upper flange 21 and the lower flange 22 in the width direction X, thereby forming a steel girder having a substantial H shape in a cross section.

[0030]

As shown in FIG. 2(b), the girder 2 extends in a material axis direction Z as a whole and has a predetermined length L. In addition, in the girder 2, the distance from the center of the sheet thickness of the upper flange 21 to the center of the sheet thickness of the lower flange 22 in a height direction Y reaches a distance d_b between the sheet thickness centers of the upper flange 21 and the lower flange 22.

[0031]

The distance d_b between the sheet thickness centers can also be treated as substantially the same distance as a distance from an upper surface of the upper flange 21 to an upper surface of the lower flange 22 in the height direction Y or a distance from a lower surface of the upper flange 21 to a lower surface of the lower flange 22 in the height direction Y. Furthermore, the distance d_b between the sheet thickness centers can also be treated as substantially the same distance as a distance from the lower surface of the upper flange 21 to the upper surface of the lower flange 22 in the height direction Y or a distance from the lower surface of the upper flange 21 to the upper surface of the lower flange 22 in the height direction Y of the girder 2.

[0032]

As shown in FIG. 2, the girder 2 is formed of the upper flange 21 and the lower flange 22 extending in the width direction X and the web 23 extending in the height direction Y, whereby the width direction X becomes a strong axis (therefore, a rotation direction around the width direction X as an axis is around the strong axis), and the height direction Y becomes a weak axis (therefore, a rotation direction around the height direction Y as an axis is around the weak axis). In addition, in the girder 2, the lower flange 22 deflects in the width direction X with respect to a flat frame in the material axis direction Z and the height direction Y, whereby lateral torsional buckling occurs.

[0033]

As shown in FIG. 3B, the girder 2 that is the subject of the analysis method according to the present embodiment is fixed to columns 3 or the like at both end portions 2a and 2a of the girder 2 in the material axis direction Z by rigid connection. At this time, in a case where, for example, rectangular steel tubes are used as the

columns 3, both end portions 2a and 2a of the girder 2 are connected by welding to diaphragms 30 provided on side surfaces of the rectangular steel tubes, whereby the girder is fixed to and supported by the columns 3 by rigid connection.

[0034]

In addition, in a case where reinforced concrete columns or unreinforced concrete columns are used as the columns 3, both end portions 2a and 2a of the girder 2 may be connected by welding to steel girders that are substantially orthogonal to each other in the columns 3. Furthermore, in a case where steel-framed reinforced concrete columns are used as the columns 3, both end portions 2a and 2a of the girder 2 may be connected by welding to steel columns that extend in the height direction Y in the columns 3.

[0035]

Both end portions 2a and 2a of the girder 2 become fixed ends with respect to lateral torsional buckling distortion. That is, the girder 2 is connected to the columns at the end portions so as to prevent the rotation of the girder around an Y axis, and the upper flange 21 of the girder 2 is connected to the columns 3 so as to prevent the rotation of the upper flange around a Z axis. This condition can be realized by connecting the upper flange 21 to steel columns by welding or the like at the end portions of the girder 2 or implanting some of the end portions 2a of the girder 2 into concrete columns.

[0036]

The girder 2 that is the subject of the analysis method according to the present embodiment may be fixed to the columns 3 or the like at both end portions 2a and 2a of the girder 2 in the material axis direction Z by semirigid connection or pin connection. The semirigid connection refers to a connection type in which the rotary

movement of the girder 2 relative to the columns 3 is restrained to a certain extent and a connection type in which bending stress that can be transferred between the columns 3 and the girder 2 is smaller compared with that in complete rigid connection. In addition, the pin connection refers to a connection type in which the rotary movement of the girder 2 relative to the columns 3 is not restrained and a connection type in which bending stress that can be transferred between the columns 3 and the girder 2 is not present or extremely small. In addition, the definitions of the semirigid connection, the pin connection, and the rigid connection are based on Eurocode 3 Part 1-8. However, as described above, torsion at both end portions 2a and 2a of the girder 2 in the material axis direction Z and warping of the upper flange 21 and the lower flange 22 need to be in a fixed state.

[0037]

In addition, the girder 2 that is the subject of the analysis method according to the present embodiment is provided with a floor slab 4 made of concrete or the like on the upper flange 21 in a middle portion 2b of the girder 2 in the material axis direction Z. As the floor slab 4, not only is a concrete slab including concrete as the principal structure used, but a deck-synthesized slab including concrete and a deck plate made of steel or the like as the principal structure is also used.

[0038]

Hereinafter, the floor slab 4 will be exemplified, but a part of a member configuring a roof may be provided on the upper flange 21, an intermediate load caused by the weight of the roof, a movable load, and the like may act thereon, and the lateral movement of the upper flange 21 in the width direction X may be restrained. In the analysis method according to the present embodiment, portions except for end surfaces at both end portions 2a and 2a are defined as the middle portion of the girder 2.

[0039]

In addition, the girder 2 that is the subject of the analysis method according to the present embodiment is provided with one or a plurality of shear connectors 25 such as headed studs on an upper surface of the upper flange 21 at predetermined intervals in the middle portion 2b of the girder 2 in the material axis direction Z. The shear connectors 25 are provided so as to protrude upwards from the upper surface of the upper flange 21 of the girder 2 and are buried or the like in concrete or the like of the floor slab 4 on the upper flange 21 of the girder 2. At this time, the shear connectors 25 are buried or the like in the floor slab 4, whereby, in the middle portion 2b in the material axis direction Z of the girder 2 that is the subject of the analysis method according to the present embodiment, the lateral movement of the upper flange 21 in the width direction X is restrained as shown in FIG. 3A.

[0040]

In addition to headed studs that are broadly and generally used, it is possible to use, as the shear connector 25, any members that fix the upper flange 21 of the girder 2 to the floor slab tightly enough to restrain the lateral movement of the upper flange 21 of the girder 2 in the width direction X such as a parker tack, puddle welding in a case where a deck-synthesized slab is used as the floor slab 4, or the like.

[0041]

In addition, even in a case where there is an opening 40 in the floor slab 4 in a length l_b that is approximately a third of a length L of the girder 2 in the material axis direction Z as shown in FIG. 3C, it is possible to apply the analysis method according to the present embodiment. When the upper flange 21 of the girder 2 is appropriately restrained on both sides of the opening 40 using an opening reinforcement material 41 or a straight girder so as to prevent the lateral movement of the upper flange 21 of the

girder 2 around this section, it is possible to preferably use the analysis method according to the present embodiment.

[0042]

In addition, in the girder 2 that is the subject of the analysis method according to the present embodiment, an intermediate load caused by the weight of the floor slab 4, a movable load, and the like acts on the middle portion 2b of the girder 2 in the material axis direction Z as shown in FIG. 3B. At this time, in the girder 2 that is the subject of the analysis method according to the present embodiment, the intermediate load acts on the upper flange 21 from above as a uniformly distributed load in the middle portion 2b of the girder 2 in the material axis direction Z.

In addition, in a case where the respective columns 3 are inclined by earthquake or the like, end loads act on both end portions 2a and 2a of the girder 2 in the material axis direction Z from the columns 3. In the girder 2 that is the subject of the analysis method according to the present embodiment, an internal force is generated along the material axis direction Z of the girder 2 in each of both end portions 2a and 2a of the girder 2 in the material axis direction Z due to the action of a bending moment around an axis in the width direction X, a shear force along the height direction Y, or a load generated by the combination of the above-described moment and force. It is needless to say that the intensity of one or a plurality of these forces may be zero.

In addition, the girder 2 that is the subject of the analysis method according to the present embodiment is about girders that are not reinforced using a reinforcement member such as a subsidiary girder or the like, but the analysis method according to the present embodiment is a method that evaluates the buckling proof stress of girders that are reinforced using a reinforcement member so as to guarantee safety, and thus

reinforced girders can also be the subject. Reinforcing bars are not included in the scope of the reinforcement member.

[0043]

In the analysis method according to the present embodiment, particularly, the lateral movement of the upper flange 21 in the width direction X is restrained by the floor slab 4 as shown in FIG. 4(a), and thus the girder 2 does not reach the buckling proof stress in an early stage. The analysis method according to the present embodiment is a method for evaluating an effect for suppressing the lateral torsional buckling of the girder 2 for which the above-described restraint of lateral movement is used.

In contrast, in a case where the lateral movement of the girder 2 in the width direction X is not restrained, as shown in FIG. 4(b), the lateral torsional buckling of the girder 2 occurs, and the girder 2 reaches the proof stress and deteriorates in an early stage.

[0044]

The analysis method according to the present embodiment is a method for computing the lateral torsional buckling proof stress M_{cr} of the girder 2 under conditions in which, as shown in FIG. 5, the subject is the girder 2 for which shaped steel such as the steel H-shape 20 or the like is used, both end portions 2a and 2a of the girder 2 in the material axis direction Z are fixed, the lateral movement of the upper flange 21 in the width direction X is restrained in the middle portion 2b of the girder 2 in the material axis direction Z, the intermediate load acts on the upper flange 21 from above, and end loads act on both end portions 2a and 2a of the girder 2 in the material axis direction Z.

[0045]

In FIG. 5, a local coordinate system X-Y-Z fixed to the left-side end portion 2a of the girder 2 is used, and the rotation of the girder 2 is considered to be positive in a direction in which the right-handed screw advances. In addition, in FIG. 5, a solid line indicates a free body of the girder 2, and a broken line indicates an example of virtual displacement that is generated in the free body of the girder 2 by lateral torsional buckling.

[0046]

<Geometric boundary conditions>

For the upper flange 21 of the girder 2, the displacement in the X direction (lateral movement) on a central line 0-0' thereof is restrained. Geometric boundary conditions of the end portion 2a of the girder 2 are determined depending on the end conditions of a series that approximates lateral torsional buckling distortion. In the girder 2, lateral torsional buckling generates bending torsion around 0-0' that is a predetermined rotary axis and generates deflection as secondary small distortion. In this analysis, the upper flange 21, the lower flange 22, and the web 23 are treated as flat sheets, and the strength of the girder 2 against lateral torsional buckling is dominated by the in-plane bending stiffness of the upper flange 21 and the lower flange 22 and the torsion stiffness of the upper flange 21, the lower flange 22, and the web 23.

[0047]

<Dynamic boundary conditions>

In the middle portion 2b of the girder 2, a vertical uniformly distributed load w is caused to act on 0-0' as an intermediate load. In addition, a bending moment M_{cr} and a shear force V are caused to act on the right-side end portion 2a of the girder 2, and a bending moment M_1 and a shear force V_1 that offset the above-described bending

moment and the shear force are caused to act on the left-side end portion 2a of the girder 2. At this time, a relationship between M_{cr} and V and a relationship between M_{cr} and w can be expressed by an equation (1) and an equation (2) below respectively depending on the offset conditions of the forces.

[0048]

$$V = -(\beta + \gamma) \frac{M_{cr}}{L} \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

$$\int_0^L wz \, dz = \gamma M_{cr} \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

$$0 \leq \beta \leq 3 \quad \cdot \quad \cdot \quad \cdot \quad (3a)$$

$$-3 \leq \gamma \leq 6 - 2\beta \quad \cdot \quad \cdot \quad \cdot \quad (3b)$$

Here, L represents the length of the girder 2 in the material axis direction Z , and z represents a length from one end portion (the left-side end portion 2a in the case of the girder shown in FIG. 5) of the girder 2 in the material axis direction Z which serves as a criterion to an arbitrary point of the girder 2 in the material axis direction Z . β and γ represent coefficients that are determined by the load conditions of a material end load and the intermediate load and coefficients that represent the bending moment distribution of the girder 2. The use of β and γ enables the obtainment of the lateral torsional buckling load M_{cr} in consideration of the load conditions of the girder.

[0049]

The bending moment distributions of the girder 2 and the relationships between β and γ are shown as exemplary examples in FIG. 6. A bending moment distribution that is generated in actual girders can be expressed by, in a case where the right and left member ends of the girder 2 uniformly bend (symmetric torsional

buckling) as shown in FIG. 6(a), setting β to zero and adjusting the value of γ .

In addition, the bending moment distribution can be expressed by, in a case where the right and left member ends of the girder 2 do not uniformly bend (antisymmetric torsional buckling) as shown in FIGS. 6(b) to 6(d), setting β to a real number in a range of 1 to 3 (FIGS. 6(b) to 6(d) show cases where β is 1, 2, and 3 respectively as exemplary examples) and adjusting the value of γ . In the analysis method according to the present embodiment, β and γ that are determined as described above are used, that is, β and γ are determined so as to correspond the bending moment distribution that is generated in actual girders, whereby the analytic solutions of lateral torsional buckling proof stress that correspond the bending moment distribution that is generated in actual girders are obtained.

[0050]

<Generalized displacement>

In order to treat lateral torsional buckling as a linear torsional buckling issue, the distortion of the respective portions of the girder 2 by lateral torsional buckling is expressed as a continuous function of a coordinate value (that is, the length from the left-side end portion 2a of the girder 2 to an arbitrary point of the girder 2 in the material axis direction Z) in the material axis direction Z. At this time, a torsion angle ϕ in a lateral cross section that is generated in the girder 2 by lateral torsional buckling is supposed to smoothly continue in the material axis direction Z as shown in FIG. 5.

[0051]

In the analysis method of the present embodiment, analytic solutions of lateral torsional buckling proof stress are derived by the series approximation of the distortion of the respective portions of the girder 2 caused by lateral torsional buckling. Lateral

torsional buckling does not accompany the distortion of the lateral cross section of the girder 2, and thus other distortions necessary for the derivation of the analytic solutions, that is, a deflection v (the left-handed terms of an equation (3) below) of the girder 2, a rotary angle Φ of the right end of the girder 2, and a deflection Δ of the right end of the girder 2 shown in FIG. 5 can be expressed by the equation (3) to an equation (5) below. As such, the distortion of the respective portions of the girder 2 by lateral torsional buckling can be uniquely represented by ϕ .

[0052]

$$\bar{v} = \frac{d_b}{2} \int_0^z (z-t) \phi'^2 dt \quad \cdot \cdot \cdot \quad (3)$$

$$\Phi = -\frac{d_b}{2} \int_0^L \phi'^2 dz \quad \cdot \cdot \cdot \quad (4)$$

$$\Delta = \frac{d_b}{2} \int_0^L (L-z) \phi'^2 dz \quad \cdot \cdot \cdot \quad (5)$$

Here, d_b represents the distance between the sheet thickness centers of the upper flange 21 and the lower flange 22. ϕ' represents a first-order differentiation of ϕ . t represents a parameter for integration.

[0053]

<Potential energy>

When lateral torsional buckling occurs in the girder 2, a total potential energy Π of this system is given by an equation (6) below.

[0054]

$$\Pi = \Delta U - \Delta T \quad \cdot \cdot \cdot \quad (6)$$

Here, ΔU represents a strain energy of the girder 2, and ΔT represents a potential energy of an external force.

[0055]

Next, ΔU is given by an equation (7) below as the sum of a strain energy by bending torsion and a strain energy by pure torsion.

[0056]

$$\Delta U = \frac{1}{2} \int_0^L EI \phi''^2 dz + \frac{1}{2} \int_0^L GJ \phi'^2 dz \quad \cdot \quad \cdot \quad \cdot \quad (7)$$

Here, E represents Young's modulus, I represents a cross-sectional second-order moment around a weak axis of the lower flange 22, G represents a shear elastic modulus, and J represents the St. Venant torsion constant. ϕ'' represents a second-order differentiation of ϕ .

[0057]

Next, ΔT is given by an equation (8) below as the sum of the potential energies of M_{cr} , V , and w .

[0058]

$$\Delta T = -M_{cr} \Phi + V \Delta + \int_0^L w v dz \quad \cdot \quad \cdot \quad \cdot \quad (8)$$

[0059]

<Approximation of lateral torsional buckling distortion>

An arbitrary ϕ that is permitted to the girder 2 having both end portions 2a and 2a in the material axis direction Z that are fixed and supported can be approximated by a finite series with an arbitrary accuracy.

[0060]

That is, the Fourier series expansion given by an equation (9) below can be applied to a number of continuous functions, and a series calculation thereof is also simple, and thus, in all of the retrospective torsional buckling studies by the energy method, torsional buckling distortion is approximated using the Fourier series.

[0061]

$$\phi = \frac{a_0}{2} + \sum_{n=1}^N a_n \cos \frac{n\pi z}{L} \quad \cdot \cdot \cdot \quad (9)$$

[0062]

Furthermore, in the analysis method according to the present embodiment, in a case where both end portions 2a and 2a of the girder 2 are fixed by rigid connection, as the lateral torsional buckling distortion of the girder 2 having both end portions 2a and 2a in the material axis direction Z that are fixed and supported, ϕ can be approximated using a series given by, particularly, an equation (10a) or an equation (10b) below.

[0063]

$$\text{Antisymmetric torsional buckling} : \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ 2\pi \left(\frac{z}{L} \right)^n \right\} \quad \cdot \cdot \cdot \quad (10a)$$

$$\text{Symmetric torsional buckling} : \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ \pi \left(\frac{2z}{L} - 1 \right)^n \right\} \quad \cdot \cdot \cdot \quad (10b)$$

Here, a_n is an undetermined coefficient of the n^{th} term and, when ϕ is expressed by the equation (10a) or the equation (10b), represents the weight of each term configuring a series in the series.

[0064]

In the analysis method according to the present embodiment, the subject is the girder 2 having both end portions 2a and 2a as fixation ends with respect to lateral torsional buckling, and, in order to express the above description, a cosine function is used in each term of a series. Therefore, it becomes possible to express the conditions of the fixation ends with respect to lateral torsional buckling regardless of the value of a_n .

[0065]

<Derivation of lateral torsional buckling proof stress>

According to the principle of minimum potential energy, an equation (12) below is obtained as a fundamental equation of lateral torsional buckling proof stress by substituting the equation (7) and the equation (8) into an equation (11) below and, furthermore, substituting the equation (1) to the equation (5) thereinto.

[0066]

$$\Pi = \Delta U - \Delta T = 0 \quad \cdot \quad \cdot \quad \cdot \quad (11)$$

[0067]

$$M_{cr} = \frac{1}{(1 - \beta - \gamma)A + (\beta + \gamma)C + \gamma D} \left(B \frac{2\pi^2 E I d_b}{L^2} + A \frac{GJ}{d_b} \right) \quad \cdot \quad \cdot \quad \cdot \quad (12)$$

Here, A, B, C, and D represent functionals of ϕ represented by an equation (13) to an equation (16) below.

[0068]

$$A = L \int_0^L \phi'^2 dz \quad \cdot \quad \cdot \quad \cdot \quad (13)$$

$$B = \frac{L^3}{2\pi^2} \int_0^L \phi''^2 dz \quad \cdot \quad \cdot \quad \cdot \quad (14)$$

$$C = \int_0^L z \phi'^2 dz \quad \cdot \quad \cdot \quad \cdot \quad (15)$$

$$D = \frac{2}{L} \int_0^L \int_0^z (z-t) \phi'^2 dt dz \quad \cdot \quad \cdot \quad \cdot \quad (16)$$

Here, β and γ are coefficients determined by load conditions V and w that serve as presumptions from an equation (1) and an equation (2) below. V represents a shear force acting on the end portion 2a of the girder 2 in the material axis direction Z , and w represents an intermediate load acting on the middle portion 2b of the girder 2 in the material axis direction Z .

In addition, L represents the length of the girder 2 in the material axis direction Z , E represents Young's modulus, I represents a cross-sectional second-order moment around a weak axis of the lower flange 22, G represents a shear elastic modulus, J represents St. Venant's torsional constant, d_b represents the distance between sheet thickness centers of the upper flange 21 and the lower flange 22, and z represents the length from one end portion of the girder in the material axis direction which serves as a criterion to an arbitrary point of the girder in the material axis direction. ϕ represents a torsion angle generated in the girder 2 by lateral torsional buckling. ϕ' represents a first-order differentiation of ϕ , and ϕ'' represents a second-order differentiation of ϕ . t represents a parameter for integration.

[0069]

The equation (12) is a linear sum of a proof stress with respect to bending

torsion and a proof stress with respect to pure torsion, and, generally, B is not equal to A. In the design method disclosed in Patent Document 1, regarding a case where an antisymmetric bending moment acts on the girder 2 having the upper flange 21 of which the lateral movement is restrained, different correction coefficients are given respectively to these two proof stresses, thereby finding highly accurate approximation solutions of lateral torsional buckling proof stress.

[0070]

<Minimum conditions>

Regarding a case where ϕ is approximated using the series of the equation (9) or the equation (10a) and the equation (10b), analytic solutions of lateral torsional buckling proof stress are obtained. Specifically, in a case where ϕ is approximated using the series of the equation (9) or the equation (10a) and the equation (10b), the minimum analytic solution corresponding to the first-order mode of lateral torsional buckling, that is, the analytic solution of lateral torsional buckling proof stress is obtained by obtaining a undetermined coefficient sequence (a_n) that minimizes the equation (12) on the basis of the extremes principle.

A condition necessary for minimizing the equation (12) is an equation (17) below, and an equation (18) below is obtained as the analytic solution of lateral torsional buckling proof stress by performing this differentiation.

[0071]

$$\frac{\partial}{\partial a_n} M_{cr} = 0 \quad n = 1, 2, \dots, N \quad \cdot \cdot \cdot \quad (17)$$

$$[f_{nm}](a_n) = 0 \quad n = 1, 2, \dots, N \quad m = 1, 2, \dots, N \quad \cdot \cdot \cdot \quad (18)$$

f_{nm} in the equation (18) represents an equation (19) below. n and m in the

equation (17) to an equation (23) represent tensor notation numbers for calculation.

[0072]

$$f_{nm} = \{(1-\beta)L_{nm} + \beta N_{nm} + \gamma O_{nm}\}M_{cr} - M_{nm}M_b - L_{nm}M_t \quad \cdot \quad \cdot \quad \cdot \quad (19)$$

Here, L_{nm} , M_{nm} , N_{nm} , and O_{nm} in the equation (19) represent an equation (20) to an equation (23) below. L_{nm} , M_{nm} , N_{nm} , and O_{nm} are determined by putting ϕ into the equation (20) to the equation (23) and performing integration.

[0073]

$$L_{nm} = L \int_0^L \phi'_n \phi'_m dz \quad \cdot \quad \cdot \quad \cdot \quad (20)$$

$$M_{nm} = \frac{L^3}{2\pi^2} \int_0^L \phi''_n \phi''_m dz \quad \cdot \quad \cdot \quad \cdot \quad (21)$$

$$N_{nm} = \int_0^L z \phi'_n \phi'_m dz \quad \cdot \quad \cdot \quad \cdot \quad (22)$$

$$O_{nm} = \frac{2}{L} \int_0^L \int_0^z (z-t) \phi'_m \phi'_n dt dz \quad \cdot \quad \cdot \quad \cdot \quad (23)$$

[0074]

Here, ϕ_n represents an n^{th} basis function of a series that approximates ϕ . For example, ϕ_n becomes an equation (24) below with respect to the equation (10a).

[0075]

$$\phi_n = \cos \frac{2\pi z^n}{L^n} \quad \cdot \quad \cdot \quad \cdot \quad (24)$$

Here, ϕ_n' and ϕ_n'' respectively represent the first-order differentiation and the second-order differentiation of ϕ_n . n and m respectively correspond to the n^{th} term and the m^{th} term of the series by the equation (10a) or the equation (10b).

[0076]

<Analytic solution>

The equation (17) represents an N-order simultaneous equation. When the equation (17) gives a value other than zero with respect to at least one of undetermined coefficients $a_1, a_2, \dots, a_n$, there is a possibility of lateral torsional buckling distortion. That is, in order for the equation (12) to be a load when lateral torsional buckling occurs in the girder 2 (lateral torsional buckling proof stress), the equation (17) needs to give a value other than zero with respect to at least one of the undetermined coefficients $a_1, a_2, \dots, a_n$, and, in order for that, the determinant of the coefficient matrix of the equation (17) is supposed to be zero.

That is, the analytic solution of lateral torsional buckling proof stress can be obtained by solving the n-order equation of an equation (25) below.

[0077]

$$|f_{nm}| = 0 \quad \cdot \quad \cdot \quad \cdot \quad (25)$$

[0078]

In addition, the analytic solution of lateral torsional buckling proof stress in a case where ϕ is approximated by the third term partial sum of the series of the equation (9), the equation (10a), or the equation (10b) is given by an equation (26) to an equation (33) below.

[0079]

$$M_{cr} = \omega^k \sqrt{-\frac{q}{2} + \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} + \omega^{3-k} \sqrt{-\frac{q}{2} - \sqrt{\left(\frac{q}{2}\right)^2 + \left(\frac{p}{3}\right)^3}} - \frac{A_2}{3} \quad (k=0,1,2) \quad \cdot \cdot \cdot \quad (26)$$

$$\omega^0 = \omega^3 = 1 \quad \cdot \cdot \cdot \quad (27a)$$

$$\omega^1 = \frac{-1 + \sqrt{3}i}{2} \quad \cdot \cdot \cdot \quad (27b)$$

$$\omega^2 = \frac{-1 - \sqrt{3}i}{2} \quad \cdot \cdot \cdot \quad (27c)$$

$$p = A_1 - \frac{1}{3}A_2^2, \quad q = A_0 - \frac{1}{3}A_1A_2 + \frac{2}{27}A_2^3, \quad A_j = \frac{\alpha_j}{\alpha_3} \quad (j=1,2,3) \quad \cdot \cdot \cdot \quad (28)$$

$$\alpha_3 = \begin{vmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{vmatrix}, \quad \alpha_0 = \begin{vmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{vmatrix} \quad \cdot \cdot \cdot \quad (29)$$

$$\alpha_2 = \begin{vmatrix} h_{11} & h_{12} & h_{13} \\ g_{21} & g_{22} & g_{23} \\ g_{31} & g_{32} & g_{33} \end{vmatrix} + \begin{vmatrix} g_{11} & g_{12} & g_{13} \\ h_{21} & h_{22} & h_{23} \\ g_{31} & g_{32} & g_{33} \end{vmatrix} + \begin{vmatrix} g_{11} & g_{12} & g_{13} \\ g_{21} & g_{22} & g_{23} \\ h_{31} & h_{32} & h_{33} \end{vmatrix} \quad \cdot \cdot \cdot \quad (30)$$

$$\alpha_1 = \begin{vmatrix} g_{11} & g_{12} & g_{13} \\ h_{21} & h_{22} & h_{23} \\ h_{31} & h_{32} & h_{33} \end{vmatrix} + \begin{vmatrix} h_{11} & h_{12} & h_{13} \\ g_{21} & g_{22} & g_{23} \\ h_{31} & h_{32} & h_{33} \end{vmatrix} + \begin{vmatrix} h_{11} & h_{12} & h_{13} \\ h_{21} & h_{22} & h_{23} \\ g_{31} & g_{32} & g_{33} \end{vmatrix} \quad \cdot \cdot \cdot \quad (31)$$

$$g_{nm} = (1 - \beta)L_{nm} + \beta N_{nm} + \gamma O_{nm} \quad \cdot \cdot \cdot \quad (32)$$

$$h_{nm} = -M_{nm} \frac{2\pi^2 EI}{L^2} d_b - L_{nm} \frac{GJ}{d_b} \quad \cdot \cdot \cdot \quad (33)$$

[0080]

The analytic solution of lateral torsional buckling proof stress can be computed by substituting β and γ that are load conditions during designing into the equation (32) and substituting E (Young's modulus), I (the cross-sectional second-order moment of the lower flange 22 around a weak axis), L (the length of the girder 2 in the material axis direction Z), d_b (the distance between the sheet thickness centers of the upper flange 21 and the lower flange 22), G (the shear elastic modulus), and J (the St. Venant torsion constant) that are a variety of conditions of the girder 2 into the

equation (33).

n and m in the equation (26) to an equation (33) represent tensor notation numbers for calculation.

[0081]

At this time, the minimum positive value of the actual solutions of the equation (26) becomes the first-order lateral torsional buckling proof stress of the girder 2. In the analysis method according to the present embodiment, the subject is the girder 2 for which shaped steel having the upper flange 21 and the lower flange 22 coupled through the web 23 is used, both end portions 2a and 2a of the girder 2 in the material axis direction Z are fixed, and, in the middle portion 2b of the girder 2 in the material axis direction Z, under the conditions in which the lateral movement of the upper flange 21 in the width direction X is restrained, the intermediate load acts on the upper flange 21 from above, and end loads act on both end portions 2a and 2a of the girder 2 in the material axis direction Z, the lateral torsional buckling proof stress M_{cr} of the girder 2 is computed from an equation (12) to an equation (16) below.

[0082]

$$M_{cr} = \frac{1}{(1 - \beta - \gamma)A + (\beta + \gamma)C + \gamma D} \left(B \frac{2\pi^2 E I d_b}{L^2} + A \frac{GJ}{d_b} \right) \cdot \cdot \cdot \quad (12)$$

$$A = L \int_0^L \phi'^2 dz \quad \cdot \cdot \cdot \quad (13)$$

$$B = \frac{L^3}{2\pi^2} \int_0^L \phi''^2 dz \quad \cdot \cdot \cdot \quad (14)$$

$$C = \int_0^L z \phi'^2 dz \quad \cdot \cdot \cdot \quad (15)$$

$$D = \frac{2}{L} \int_0^L \int_0^z (z - t) \phi'^2 dt dz \quad \cdot \cdot \cdot \quad (16)$$

Here, β and γ are coefficients determined by load conditions V and w that serve as presumptions from an equation (1) and an equation (2) below. V represents a shear force acting on the end portion 2a of the girder 2 in the material axis direction Z , and w represents an intermediate load acting on the middle portion 2b of the girder 2 in the material axis direction Z .

In addition, L represents the length of the girder 2 in the material axis direction Z , E represents Young's modulus, I represents a cross-sectional secondary moment around the weak axis of the lower flange 22, G represents a shear elastic modulus, J represents St. Venant's torsional constant, d_b represents the distance between the sheet thickness centers of the upper flange 21 and the lower flange 22, and z represents the length from one end portion of the girder in the material axis direction which serves as the criterion to an arbitrary point of the girder in the material axis direction. ϕ represents a torsion angle generated in the girder 2 by lateral torsional buckling. ϕ' represents a first-order differentiation of ϕ , and ϕ'' represents a second-order differentiation of ϕ . t represents a parameter for integration.

[0083]

In the analysis method according to the present embodiment, the lateral torsional buckling proof stress M_{cr} of the girder 2 is computed from the equation (12) to the equation (16) under conditions in which, in spite of the fact that the lateral torsional buckling distortion of the girder 2 of which the lateral movement is restrained becomes complicated, the lateral movement of the girder 2 is restrained, an intermediate load acts on the upper flange 21 from above, and end loads act on both end portions 2a and 2a of the girder 2 in the material axis direction Z , whereby it becomes possible to evaluate the lateral torsional buckling proof stress of the above-described steel girder with high accuracy.

[0084]

In the analysis method according to the present embodiment, β and γ are determined as real numbers by the equation (3a) and the equation (3b).

In the analysis method according to the present embodiment, β is set to zero in a case where the intermediate load causes uniform bending in the material axis direction Z of the girder 2 (symmetric torsional buckling), and β is set to a real number in a range of 1 to 3 in a case where the intermediate load does not cause uniform bending in the material axis direction Z of the girder 2 (antisymmetric torsional buckling), whereby it becomes possible to deal with any of the case of the uniform bending moment in which the intermediate load causes uniform bending and the case of the antisymmetric moment in which the intermediate load does not cause uniform bending using the equation (12) to the equation (16) and to evaluate the lateral torsional buckling proof stress of steel girders in consideration of a variety of load conditions that are predictable for actual steel girders.

[0085]

In the analysis method according to the present embodiment, in a case where both end portions of a girder is fixed by rigid connection, in the case of being approximated, ϕ is more preferably approximated using the series of the equation (10a) or the equation (10b).

In the analysis method according to the present embodiment, in a case where ϕ is approximated using the third term partial sum the series of of the equation (9), the equation (10a), or the equation (10b), an example of the analytic solution of lateral torsional buckling proof stress is shown in FIG. 7(a) or FIG. 7(b) with dimensionless lateral torsional buckling proof stress ($=M_{cr}/M_p$) obtained by dividing the lateral torsional buckling proof stress by the total plastic bending moment plotted along the

vertical axis and a slenderness ratio $\lambda_b (=M_{cr}/M_p)^{0.5}$ plotted along the horizontal axis. FIG. 7(a) and FIG. 7(b) show the analysis results plotted with different cross sections, lengths, and load conditions.

[0086]

It is found that, when the series of the equation (10a) or the equation (10b) is used at this time, as shown in FIG. 7(a), the analytic solutions of lateral torsional buckling proof stress with respect to a variety of conditions are arrayed in approximately a single line and it is possible to evaluate the lateral torsional buckling proof stress of steel girders with a higher accuracy.

[0087]

In addition, when the fourth term partial sum of the Fourier cosine series of the equation (9) is used, the analytic solutions of lateral torsional buckling proof stress are scattered as shown in FIG. 7(b).

When the bending moment of the end portion 2a of the girder 2 is larger than a bending moment that a building receives, the girder does not torsionally buckle. Therefore, when M_{cr} that is sufficiently higher than a load that a building receives is set as a realistic design, it is possible to build a safe design. In order to evaluate lateral torsional buckling proof stress with high accuracy using the Fourier series of the equation (9), ϕ is approximated using, for example, the tenth term partial sum.

[0088]

As such, in the analysis method according to the present embodiment, it becomes possible to evaluate the lateral torsional buckling proof stress of steel girders with a higher accuracy while avoiding the analytic calculation of the lateral torsional buckling proof stress from becoming more complicated than necessary by approximating ϕ using the series of the equation (10a) or the equation (10b). For

example, when ϕ is approximated using the series of the equation (10a) or the equation (10b), it becomes possible to evaluate the lateral torsional buckling proof stress of steel girders with a higher accuracy without carrying out complicated calculations.

[0089]

According to the analysis method according to the present embodiment, the lateral torsional buckling proof stress M_{cr} of the girder is computed from the equation (12) to the equation (16) under conditions in which, in spite of the fact that the lateral torsional buckling distortion of the girder of which the lateral movement is restrained becomes complicated, both end portions of the girder are fixed, the lateral movement of the girder is restrained, an intermediate load acts on the upper flange from above, and end loads act on both end portions of the girder in the material axis direction, whereby it becomes possible to evaluate the lateral torsional buckling proof stress of the above-described steel girder with high accuracy.

[0090]

(Other embodiments)

According to the present invention, a design method for a steel girder including a step of computing M_{cr} on the basis of the analysis method according to the above-described embodiment and further including a step of designing a steel girder on the basis of M_{cr} obtained using the analysis method is provided.

According to the design method for a steel girder, the lateral torsional buckling proof stress M_{cr} of the girder is computed from the equation (12) to the equation (16) under conditions in which, in spite of the fact that the lateral torsional buckling distortion of the girder of which the lateral movement is restrained becomes complicated, both end portions of the girder are fixed, the lateral movement of the girder is restrained, an intermediate load acts on the upper flange from above, and end

loads act on both end portions of the girder in the material axis direction, whereby it becomes possible to evaluate the lateral torsional buckling proof stress of the above-described steel girder with high accuracy.

[0091]

Therefore, in the step of designing a steel girder, it is possible to select the optimal cross section for preventing the occurrence of lateral torsional buckling under load conditions given in a fundamental design by determining E (Young's modulus), I (the cross-sectional second-order moment of the lower flange around a weak axis), L (the length of the girder in the material axis direction Z), d_b (the distance between the sheet thickness centers of the upper flange and the lower flange), and the like, which are a variety of conditions of the girder, on the basis of the lateral torsional buckling proof stress M_{cr} . Therefore, it is possible to prevent the weight or cross section of the girder from becoming greater than necessary and to design steel girders without impairing the habitability or economic efficiency of buildings.

[0092]

In addition, according to the present invention, a manufacturing method for a steel girder including a step of computing M_{cr} on the basis of the analysis method according to the above-described embodiment and a step of determining the cross-sectional dimensions of a steel girder on the basis of M_{cr} and including a step of manufacturing the steel girder on the basis of the determined cross-sectional dimensions of the steel girder determined in the above-described steps is provided.

[0093]

A steel girder is manufactured on the basis of the determination relating to a variety of conditions described above in the step of designing the steel girder, whereby it is possible to design an appropriate steel girder.

[0094]

FIG. 8 shows a flowchart for describing the flow of the analysis method according to the above-described embodiment. In addition, FIG. 9 shows a flowchart for describing the flow of a design method according to an embodiment of the present invention.

[0095]

A series of the flow of an analysis method according to an embodiment of the present invention will be described along the flowchart of FIG. 8. First, in the analysis method according to the above-described embodiment, the structure of a building that is a subject is planned. That is, the disposition of columns, girders, walls, floors, and the like and connection methods thereof are determined (S801). In addition, a movable load and predictable external forces such as a wind load, an earthquake load, a snow load, and the like are set (S802). In addition, the cross sections of the columns, the girders, the walls, the floors, and the like are presumed (S803).

Next, a frame analysis is carried out on the basis of the information of S801 to S803, and a fundamental design that computes an end load that acts on the girder which is the subject is carried out (S804). The order of S801 to S803 is variable.

[0096]

In addition, I (the cross-sectional second-order moment of the lower flange around a weak axis), L (the length of the girder in the material axis direction Z), and d_b (the distance between the sheet thickness centers of the upper flange and the lower flange) are obtained on the basis of the cross-sectional shape of the girder which is presumed in S803 by carrying out the analysis method according to the above-described embodiment, and M_{cr} is computed using these numerical values (S805).

[0097]

A series of the flow of the design method according to the above-described embodiment will be described along the flowchart of FIG. 9. First, similar to the analysis method, the structure of a building that is a subject is planned. That is, the disposition of columns, girders, walls, floors, and the like and connection methods thereof are determined (S901). In addition, a movable load and predictable external forces such as a wind load, an earthquake load, a snow load, and the like are set (S902). In addition, the cross sections of the columns, the girders, the walls, the floors, and the like are presumed (S903).

Next, a frame analysis is carried out on the basis of the information of S901 to S903, and a fundamental design that computes an end load that acts on the girder which is the subject is carried out (S904). The order of S901 to S903 is variable.

[0098]

In addition, M_{cr} of the cross section of the girder presumed in S903 is computed by carrying out the analysis method according to the above-described embodiment (S905).

[0099]

Next, a bending moment M obtained as the end load in S904 and M_{cr} obtained in S905 are compared to each other, and a determination is made (S906). In this determination, M and M_{cr} are compared to each other, and, in a case where the determination is “YES (M_{cr} is slightly above M)”, the cross-sectional dimensions of the girder are determined as set values (S907).

[0100]

In a case where the determination is “NO (M_{cr} is smaller than M)” or a case where the determination is “excess (M_{cr} is too greater than M)”, the process returns to

S903, and the cross section of the girder is presumed again.

In S906, the determination may be made by comparing a value obtained by multiplying M_{cr} by a safety rate (or by adding the safety rate) and M to each other in consideration of the safety rate.

[0101]

The above-described analysis method or design method is preferably realized using a computer device (not shown) in which a program recorded in a non-temporary tangible recording medium (not shown) is executed using CPU (not shown). In this case, the computer device preferably executes the above-described analysis method according to a command from an input device that is operated by an operator and outputs M_{cr} computed in S805 in FIG. 8 as an analysis result.

[0102]

Alternatively, the computer device preferably executes the above-described design method according to a command from the input device that is operated by the operator and outputs the comparison result of the determination of S906 in FIG. 9 as a design result. Alternatively, the cross-sectional dimensions of the girder of S907 in FIG. 9 are preferably output as a design result.

The analysis result or the output design result is preferably output to be visible through an output device (not shown).

[0103]

A steel girder is preferably manufactured using the existing techniques according to the design result (the cross-sectional dimensions of the girder) set by executing the above-described design method. In such a case, it is possible to obtain a steel H-shape having a structure (disposition and dimensions) in accordance with the design result set by the above-described design method.

[0104]

The analysis method, the design method, the manufacturing method, and the program according to the above-described embodiment can be applied to, as subjects, steel girders that serves as structural materials of floor structures such as buildings and the like, earth floor structures, framed structures, and the like, in buildings such as houses, schools, offices, hospital facilities, and the like, buildings such as low-story buildings, high-story buildings, ultrahigh-story buildings, and the like.

[0105]

Hitherto, examples of the embodiments of the present invention have been described in detail, but all of the above-described embodiments are simply specific examples for carrying out the present invention, and the technical scope of the present invention should not be interpreted in a limited manner by the embodiments.

[0106]

For example, the analysis method according to the present embodiment is preferably applicable not only to steel girders for which a steel H-shape having an upper flange and a lower flange coupled through a web in substantially the centers in the width direction X is used but also to I-section steels.

[Industrial Applicability]

[0107]

According to the present invention, it is possible to provide an analysis method, a design method for a steel girder, a manufacturing method for a steel girder, and a program which are capable of evaluating the lateral torsional buckling proof stress of a steel girder with high accuracy in consideration of a variety of load conditions that are predictable for actual steel girders.

[Brief Description of the Reference Symbols]

[0108]

2	: GIRDER
2a	: END PORTION
2b	: MIDDLE PORTION
20	: STEEL H-SHAPE
21	: UPPER FLANGE
22	: LOWER FLANGE
23	: WEB
25	: SHEAR CONNECTOR
3	: COLUMN
30	: DIAPHRAGM
4	: FLOOR SLAB
40	: OPENING
41	: OPENING REINFORCEMENT MATERIAL
X	: WIDTH DIRECTION
Y	: HEIGHT DIRECTION
Z	: MATERIAL AXIS DIRECTION

1. An analysis method for evaluating lateral torsional buckling proof stress of a steel girder,

wherein a subject is a girder for which shaped steel having an upper flange and a lower flange coupled through a web is used, both end portions of the girder in a material axis direction are fixed, and, in a middle portion of the girder in the material axis direction, under conditions in which lateral movement of the upper flange in a width direction is restrained, an intermediate load acts on the upper flange from above, and end loads act on both end portions of the girder in the material axis direction, lateral torsional buckling proof stress M_{cr} of the girder is computed from an equation (12) to an equation (16) below,

$$M_{cr} = \frac{1}{(1-\beta-\gamma)A + (\beta+\gamma)C + \gamma D} \left(B \frac{2\pi^2 E I d_b}{L^2} + A \frac{GJ}{d_b} \right) \cdot \cdot \cdot \quad (12)$$

$$A = L \int_0^L \phi'^2 dz \cdot \cdot \cdot \quad (13)$$

$$B = \frac{L^3}{2\pi^2} \int_0^L \phi''^2 dz \cdot \cdot \cdot \quad (14)$$

$$C = \int_0^L z \phi'^2 dz \cdot \cdot \cdot \quad (15)$$

$$D = \frac{2}{L} \int_0^L \int_0^z (z-t) \phi'^2 dt dz \cdot \cdot \cdot \quad (16)$$

where β and γ are coefficients determined by load conditions V and w that serve as presumptions from an equation (1) and an equation (2) below, V represents a shear force acting on an end portion of the girder in the material axis direction, w represents an intermediate load acting on the middle portion of the girder in the

material axis direction,

additionally, L represents a length of the girder in the material axis direction, E represents Young's modulus, I represents a cross-sectional second-order moment around a weak axis of the lower flange, G represents a shear elastic modulus, J represents St. Venant's torsional constant, d_b represents a distance between sheet thickness centers of the upper flange and the lower flange, z represents a length from one end portion of the girder in the material axis direction which serves as a criterion to an arbitrary point of the girder in the material axis direction, ϕ represents a torsion angle generated in the girder by lateral torsional buckling, ϕ' represents a first-order differentiation of ϕ , ϕ'' represents a second-order differentiation of ϕ , and t represents a parameter for integration,

$$V = -(\beta + \gamma) \frac{M_{cr}}{L} \quad \cdot \quad \cdot \quad \cdot \quad (1)$$

$$\int_0^L w z dz = \gamma M_{cr} \quad \cdot \quad \cdot \quad \cdot \quad (2)$$

2. The analysis method according to claim 1,

wherein β and γ are determined as real numbers in ranges by an equation (3a)

and an equation (3b) below,

$$0 \leq \beta \leq 3 \quad \cdot \quad \cdot \quad \cdot \quad (3a)$$

$$-3 \leq \gamma \leq 6 - 2\beta \quad \cdot \quad \cdot \quad \cdot \quad (3b)$$

3. The analysis method according to claim 1 or 2,

wherein, in a case where both end portions of the girder are fixed by rigid

connection, ϕ is computed using an equation (10a) or an equation (10b) below,

$$\text{Antisymmetric torsional buckling : } \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ 2\pi \left(\frac{z}{L} \right)^n \right\} \cdot \cdot \cdot \quad (10a)$$

$$\text{Symmetric torsional buckling : } \phi = a_0 + \sum_{n=1}^N a_n \cos \left\{ \pi \left(\frac{2z}{L} - 1 \right)^n \right\} \cdot \cdot \cdot \quad (10b)$$

where a_n is an undetermined coefficient of an n^{th} term.

4. A design method for a steel girder comprising:

computing M_{cr} on the basis of the analysis method according to any one of

claims 1 to 3; and

determining cross-sectional dimensions of a steel girder on the basis of M_{cr} .

5. A manufacturing method for a steel girder comprising:

computing M_{cr} on the basis of the analysis method according to any one of

claims 1 to 3;

determining cross-sectional dimensions of a steel girder on the basis of M_{cr} ;

and

manufacturing the steel girder on the basis of the determined cross-sectional

dimensions of the steel girder.

6. A program for causing a computer device to execute the analysis method

according to any one of claims 1 to 3.

7. A program for causing a computer device to execute the design method

according to claim 4.