[Document Type] Specification

[Title of the Invention] METHOD OF EVALUATING CONTINUOUS BEAM, PROGRAM OF EVALUATING CONTINUOUS BEAM, AND METHOD OF EVALUATING COMPOSITE BEAM

[Technical Field of the Invention]

[0001]

The present invention relates to a method of evaluating a continuous beam, a program of evaluating a continuous beam, and a method of evaluating a composite beam.

The present application is based on, and claims priority from Japanese Patent Application No. 2019-210798 and Japanese Patent Application No. 2019-210811, filed November 21, 2019, the disclosure of which is hereby incorporated by reference herein in its entirety.

[Related Art]

[0002]

In related art, a continuous beam in which a plurality of beams are semi-rigidly jointed to each other is known (refer to, for example, Patent Documents 1 and 2 and Non-Patent Document 1).

[0003]

On the other hand, in related art, in a composite beam of which both ends are semi-rigidly jointed, a method of evaluating a composite beam in a case where a bending stiffness of sagging bending and a bending stiffness of hogging bending are different from each other is known (for example, refer to Patent Document 3).

In Patent Document 3, in a case where a two-point concentrated load acts on the composite beam, equations (explicit functions) for a bending moment and a

deflection of the composite beam described in the specification are solved. Further, bending moment at supports of the composite beam (bending moments acting on the ends of the composite beam) and a maximum value of the deflection of the composite beam are calculated.

[Prior Art Document]

[Patent Document]

[0004]

[Patent Document 1] Japanese Unexamined Patent Application, First Publication No. 2015-068001

[Patent Document 2] Japanese Unexamined Patent Application, First Publication No. 2005-282019

[Patent Document 3] Japanese Unexamined Patent Application, First Publication No. 2018-09410

[Non-Patent Document]

[0005]

[Non-Patent Document 1] "Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings", December 2004, Authority: The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC

[Disclosure of the Invention]

[Problems to be Solved by the Invention]

[0006]

However, in this type of continuous beam, a practical evaluation method of bending moments and a deflection distribution generated when a load acts on the continuous beam has not been provided.

Even in a case of a continuous beam of which both ends are rigidly jointed to end support portions, for example, when the end support portions are included in a steel framed large beam, torsional resistance of the large beam is insufficient to evaluate rigid joints of the both ends. For this reason, assuming that the both ends are rigidly jointed, when different loads act on each beam of the continuous beam, the bending moments and the deflection distribution are underestimated. As a result, the continuous beam may be evaluated to be dangerous.

Further, in a continuous beam in which a bending stiffness of sagging bending and a bending stiffness of hogging bending are different from each other, a practical evaluation method of obtaining bending moments and a deflection distribution of the continuous beam in consideration of these bending stiffnesses and connection states at the both ends has not been provided.

[0007]

In related art, in order not to evaluate the continuous beam to be dangerous, assuming that both ends of the continuous beam are supported by pin joint, the continuous beam is evaluated. As a result, bending moments and a deflection distribution generated at a center portion of the continuous beam in a longitudinal direction are overestimated. For this reason, it is determined that it is necessary to use a continuous beam having a large cross-section orthogonal to the longitudinal direction, and as a result, a continuous beam that is more expensive than necessary is used.

[0008]

In view of these problems, a first object is to provide a method of evaluating a continuous beam and a program of evaluating a continuous beam capable of more appropriately evaluating bending moments and a deflection distribution of the continuous beam according to the joint states at the both ends.

[0009]

On the other hand, a case where an uniformly-distributed load acts on the composite beam over the entire length will be described. In this case, an equation is an implicit function, and as a result, it is necessary to perform convergence calculation in order to calculate bending moments and a deflection of the composite beam from the equation for the bending moments and the deflection of the composite beam. Further, for example, in order to dynamically analyze a structure including a plurality of composite beams, it is necessary to solve the equation by convergence calculation by an implicit method. As a result, it takes a lot of time because double convergence calculation for the composite beam and the structure is required.

Further, for example, assuming that a cross-sectional area of the composite beam is set as an objective function and design conditions such as the deflection and the bending moments are set as constraint conditions, a case of performing optimization calculation that minimizes the objective function will be described. In this case, it takes a lot of time because double convergence calculation is required for the optimization of the constraint conditions and the objective function.

[0010]

In view of these problems, a second object is to provide a method of evaluating a composite beam capable of calculating bending moment at supports and a maximum value of the deflection of the composite beam without performing convergence calculation.

[0011]

The present invention has been made in view of the first object and the second object, and an object of the present invention is to provide a method of evaluating a continuous beam, a program of evaluating a continuous beam, and a method of

evaluating a composite beam capable of appropriately evaluating a deflection.

[Means for Solving the Problem]

[0012]

In order to solve the above problems, the present invention proposes the following means.

(1) According to a first aspect of the present invention, there is provided a method of evaluating a continuous beam including n, which is a natural number equal to or larger than two, beams which are disposed side by side in a longitudinal direction and of which end portions adjacent to each other in the longitudinal direction are semi-rigidly jointed to each other to be intermediate fulcrums, both ends of the entire continuous beam being a pair of end fulcrums, the method including: a solution determination step of obtaining a plurality of bending moments at the intermediate fulcrums and the pair of end fulcrums and a plurality of rotation angles at the pair of end fulcrums based on given conditions, in which the given conditions include a length and a bending stiffness of each of the n beams, a plurality of rotational rigidities at the intermediate fulcrums and the pair of end fulcrums, vertical loads acting on the n beams, and a plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums, and in which, in a case where the plurality of bending moments and the plurality of rotation angles are defined as a plurality of unknown quantities and a relational expression between the plurality of rotational rigidities, the plurality of bending moments, and the plurality of rotation angles and a relational expression between the plurality of vertical displacements are defined as a plurality of first boundary conditions having the same number as the number of the plurality of unknown quantities, in the solution determination step, the bending moments and a deflection distribution of the continuous beam are evaluated by solving the plurality of unknown

quantities such that the plurality of unknown quantities satisfy the plurality of first boundary conditions.

[0013]

According to the aspect, the number of the plurality of unknown quantities and the number of the plurality of first boundary conditions are the same. Therefore, the plurality of unknown quantities are solved so as to satisfy the plurality of first boundary conditions based on the given conditions including the length and the bending stiffness of the beam, the plurality of rotational rigidities, the vertical loads, and the plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums. According to the method, it is possible to obtain the plurality of bending moments and the plurality of rotation angles included in the plurality of unknown quantities.

The plurality of vertical displacements are calculated from the obtained plurality of bending moments and the obtained plurality of rotation angles based on the relational expression between the plurality of vertical displacements. According to the method, it is possible to more appropriately evaluate the bending moments and the deflection distribution of the continuous beam according to, for example, the joint states at the pair of end fulcrums. Therefore, it is possible to appropriately evaluate the deflection.

[0014]

(2) In the method of evaluating a continuous beam according to (1), the solution determination step may include a first design step of giving design values including the plurality of vertical displacements, a second design step of giving second boundary conditions to the pair of end fulcrums according to joint states at the pair of end fulcrums, a temporary design step of giving temporary design values including the bending moments acting on the pair of end fulcrums and the intermediate fulcrums

according to the joint state at the pair of end fulcrums, a solution calculation step of calculating, based on the temporary design values, calculation values including calculation results of the vertical displacements at the intermediate fulcrums so as to satisfy the plurality of first boundary conditions and the plurality of second boundary conditions, a residual calculation step of obtaining a displacement residual which is a residual between the design value and the calculation value, and a determination step of determining whether or not the displacement residual is smaller than a predetermined threshold value.

According to the aspect, the calculation values calculated based on the temporary design values can be evaluated based on the design values and the displacement residual by determining whether or not the displacement residual is smaller than the threshold value in the determination step.

[0015]

(3) In the method of evaluating a continuous beam according to (2), the solution determination step may further include a storage step of storing the temporary design values after the temporary design step. In the determination step, in a case where the displacement residual is equal to or larger than the threshold value, giving other new temporary design values in the temporary design step instead of the temporary design values stored in the storage step and performing the solution calculation step, the residual calculation step, and the determination step based on the new temporary design values may be performed as a set, and the set may be repeatedly performed until it is determined in the determination step that the displacement residual is smaller than the threshold value. The bending moments of the temporary design values in a case where it is determined in the determination step that the displacement residual is smaller than the threshold value may be defined as the bending moments

acting on the intermediate fulcrums, and the plurality of rotation angles may be obtained based on the bending moments.

According to the aspect, until it is determined in the determination step that the displacement residual is smaller than the threshold value, giving new temporary design values and performing the solution calculation step, the residual calculation step, and the determination step based on the new temporary design values are performed as a set, and the set is repeatedly performed. According to the method, it is possible to calculate the bending moments with accuracy. The plurality of rotation angles can be obtained based on the bending moments.

[0016]

(4) In the method of evaluating a continuous beam according to (2) or (3), in the solution calculation step, for a natural number i equal to or larger than one and equal to or smaller than n, among the n beams, for an i-th beam from a first end fulcrum which is one of the end fulcrums of the continuous beam toward a second end fulcrum which is the other of the end fulcrums of the continuous beam, the vertical displacements δ_{0i} (m) of the i-th beam at the intermediate fulcrums or the end fulcrums on a first end fulcrum side may be defined as the given conditions, and calculation results $\delta_{i,\,calc}$ (m) of the vertical displacements of the i-th beam at the intermediate fulcrums or the end fulcrums on a second end fulcrum side may be calculated by Expression (9) obtained based on Expression (1) to Expression (8), the calculation results being included in the calculation values, and in the residual calculation step, for a natural number i equal to or larger than one and equal to or smaller than (n-1), in a case where a residual between the vertical displacements $\delta_{0(i+1)}$ of the (i+1)-th beam at the intermediate fulcrums on the first end fulcrum side and the calculation results $\delta_{i,\,calc}$ of the vertical displacements of the i-th beam at the intermediate fulcrums on the second

end fulcrum side is defined as an i-th residual, an intermediate residual which is a sum from the first residual to the (n-1)-th residual may be calculated, a residual at the second end fulcrum may be calculated, the residual at the second end fulcrum being a residual between the vertical displacements δ_n at the second end fulcrum which are the given conditions and the calculation results $\delta_{n,calc}$ of the vertical displacements of an n-th beam at the second end fulcrum, and the displacement residual may be calculated, the displacement residual being a sum of the intermediate residual and the residual at the second end fulcrum.

[0017]

$$V_{jl,i} = \frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2} \quad \cdots (1)$$

$$V_{jr,i} = w_i \cdot L_i - V_{jl,i} = \frac{w_i \cdot L_i}{2} - \frac{M_{j,i-1} - M_{j,i}}{L_i} \quad \cdots (2)$$

$$x_{h,i} = \frac{1}{w_i}\left\{V_{jl,i} - \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{j,i-1}}\right\} \quad \cdots (3)$$

$$x_{s,i} = \frac{1}{w_i}\left\{V_{jl,i} + \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{j,i-1}}\right\} \quad \cdots (4)$$

$$f_{(x_i)} = \left(\frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^2}{2} - \frac{w_i \cdot {x_i}^3}{6} - M_{j,i-1} \cdot x_i \quad \cdots (5)$$

$$F_{(x_i)} = \left(\frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^3}{6} - \frac{w_i \cdot {x_i}^4}{24} - \frac{M_{j,i-1}}{2} \cdot {x_i}^2 \quad \cdots (6)$$

$$\varphi_{c(x_i)}\big|_{x_i=L_i} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left(f_{(x_i)}\big|_{x_i=x_{h,i}} - f_{(x_i)}\big|_{x_i=x_{s,i}}\right) - \frac{1}{EI_{h,i}} f_{(x_i)}\big|_{x_i=L_i} + \varphi_{0i} \quad \cdots (7)$$

$$\varphi_{0i} = \left(\frac{1}{S_{jr,i-1}} + \frac{1}{S_{jl,i}}\right) M_{j,i-1} + \varphi_{c(x_{i-1})}\big|_{x_{i-1}=L_{i-1}} \quad \cdots (8)$$

$$\delta_{i,calc} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left\{F_{(x_i)}\big|_{x_i=x_{h,i}} - F_{(x_i)}\big|_{x_i=x_{s,i}} + f_{(x_i)}\big|_{x_i=x_{h,i}}\left(L_i - x_{h,i}\right) - f_{(x_i)}\big|_{x_i=x_{s,i}}\left(L_i - x_{s,i}\right)\right\} - \frac{1}{EI_{h,i}} F_{(x_i)}\big|_{x_i=L_i} + \varphi_{0i} \cdot L_i + \delta_{0i} \quad \cdots (9)$$

[0018]

Here, for a natural number i equal to or larger than one and equal to or smaller than n, a length of the i-th beam is defined as L_i (m), a coordinate of the i-th beam is

defined as x_i (m) in a case where an end of the i-th beam on the first end fulcrum side is set as an origin and a direction from the first end fulcrum toward the second end fulcrum is set as positive, a vertical load acting on the i-th beam is defined as w_i (N/m), a rotational rigidity of the end of the i-th beam on the first end fulcrum side is defined as $S_{jl,\,i}$ (Nm/rad), a rotational rigidity of an end of the i-th beam on the second end fulcrum side is defined as $S_{jr,\,i}$ (Nm/rad), a bending stiffness of sagging bending of the i-th beam is defined as $EI_{s,\,i}$ (Nm^2), a bending stiffness of hogging bending of the i-th beam is defined as $EI_{h,\,i}$ (Nm^2), and a bending moment of the i-th beam at the intermediate fulcrums or the end fulcrums on the second end fulcrum side is defined as $M_{j,\,i}$ (Nm). A bending moment $M_{j,\,0}$ (Nm) of a first beam at the first end fulcrum is 0 in a case where the first end fulcrum is pin-jointed and is an unknown quantity in a case where the first end fulcrum is rigidly jointed or semi-rigidly jointed, and a rotation angle φ_{01} (rad) of the first beam at the first end fulcrum is 0 in a case where the first end fulcrum is rigidly jointed and is an unknown quantity in a case where the first end fulcrum is pin-jointed or semi-rigidly jointed, the bending moment $M_{j,\,0}$ (Nm) and the rotation angle φ_{01} (rad) of the first beam being included in the second boundary conditions.

According to the aspect, it is possible to evaluate the plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums with high accuracy by using Equation.

[0019]

(5) According to a second aspect, there is provided a program for an evaluation apparatus that evaluates a continuous beam including n, which is a natural number equal to or larger than two, beams which are disposed side by side in a longitudinal direction and of which end portions adjacent to each other in the longitudinal direction are semi-rigidly jointed to each other to be intermediate fulcrums, both ends of the entire

continuous beam being a pair of end fulcrums, the program causing the evaluation apparatus to function as: a solution determination unit that obtains a plurality of bending moments at the intermediate fulcrums and the pair of end fulcrums and a plurality of rotation angles at the pair of end fulcrums based on given conditions. The given conditions include a length and a bending stiffness of each of the n beams, a plurality of rotational rigidities at the intermediate fulcrums and the pair of end fulcrums, vertical loads acting on the n beams, and a plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums. In a case where the plurality of bending moments and the plurality of rotation angles are defined as a plurality of unknown quantities, and a relational expression between the plurality of rotational rigidities, the plurality of bending moments, and the plurality of rotation angles and a relational expression between the plurality of vertical displacements are defined as a plurality of first boundary conditions having the same number as the number of the plurality of unknown quantities, the solution determination unit evaluates the bending moments and a deflection distribution of the continuous beam by solving the plurality of unknown quantities such that the plurality of unknown quantities satisfy the plurality of first boundary conditions.

[0020]

According to the aspect, the number of the plurality of unknown quantities and the number of the plurality of first boundary conditions are the same. Therefore, the plurality of unknown quantities are solved so as to satisfy the plurality of first boundary conditions based on the given conditions including the length and the bending stiffness of the beam, the plurality of rotational rigidities, the vertical loads, and the plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums. According to the method, it is possible to obtain the plurality of bending moments and

the plurality of rotation angles included in the plurality of unknown quantities.

The plurality of vertical displacements are calculated from the obtained plurality of bending moments and the obtained plurality of rotation angles based on the relational expression between the plurality of vertical displacements. According to the method, it is possible to more appropriately evaluate the bending moments and the deflection distribution of the continuous beam according to, for example, the joint states at the pair of end fulcrums. Therefore, it is possible to appropriately evaluate the deflection.

[0021]

(6) According to a third aspect, there is provided a method of evaluating a composite beam by calculating bending moment at supports which are bending moments acting on both ends of the composite beam and a maximum value of a deflection generated on the composite beam, in which a bending stiffness of sagging bending and a bending stiffness of hogging bending are different from each other, of which both ends are semi-rigidly jointed, and on which an uniformly-distributed load acts over an entire length, the method including: calculating the bending moment at supports and the maximum value of the deflection by explicit functions based on a nondimensional rotational rigidity and a nondimensional bending stiffness, in a case where a value obtained by dividing a rotational rigidity of the end of the composite beam by a bending stiffness per unit length of the composite beam is defined as the nondimensional rotational rigidity, and a ratio between the bending stiffness of the sagging bending of the composite beam and the bending stiffness of the hogging bending of the composite beam is defined as the nondimensional bending stiffness.

[0022]

According to the aspect, the inventors can understand that the bending moment

at supports and the maximum value of the deflection are evaluated based on the nondimensional rotational rigidity and the nondimensional bending stiffness which are nondimensional values. According to the method, it is found that the bending moment at supports and the maximum value of the deflection can be calculated with high flexibility and high accuracy by the explicit functions regardless of specifications of the composite beam.

The bending moment at supports and the maximum value of the deflection of the composite beam are calculated by the explicit functions based on the nondimensional rotational rigidity and the nondimensional bending stiffness. According to the method, it is possible to calculate the bending moment at supports and the maximum value of the deflection of the composite beam without performing convergence calculation. Therefore, it is possible to appropriately evaluate the deflection.

[0023]

(7) The method of evaluating a composite beam according to (6) may further include: calculating a nondimensional rigid joint moment by an explicit function based on the nondimensional bending stiffness; calculating a nondimensional joint moment by an explicit function based on the calculated nondimensional rigid joint moment, the nondimensional rotational rigidity, and the nondimensional bending stiffness; and calculating the bending moment at supports and the maximum value of the deflection by explicit functions based on the calculated nondimensional joint moment, in a case where a bending moment acting on the end of the composite beam when it is assumed that the both ends are rigidly jointed and an uniformly-distributed load acts over the entire length is defined as the rigid joint moment, a maximum value of the bending moment acting on the composite beam when it is assumed that the both ends are pin-jointed and

an uniformly-distributed load acts over the entire length is defined as a pin joint moment, a bending moment acting on the end of the composite beam when it is assumed that the both ends are semi-rigidly jointed and an uniformly-distributed load acts over the entire length is defined as a semi-rigid joint moment, a value obtained by dividing the semi-rigid joint moment by the pin joint moment is defined as the nondimensional joint moment, and a value obtained by dividing the rigid joint moment by the pin joint moment is defined as the nondimensional rigid joint moment.

[0024]

According to the aspect, the nondimensional rigid joint moment is calculated by the explicit function based on the nondimensional bending stiffness. Further, the nondimensional joint moment is calculated based on the calculated nondimensional rigid joint moment, the nondimensional rotational rigidity, and the nondimensional bending stiffness, and the bending moment at supports and the maximum value of the deflection are calculated by the explicit functions based on the calculated nondimensional joint moment.

Thereby, it is possible to calculate the bending moment at supports and the maximum value of the deflection of the composite beam without performing convergence calculation.

[0025]

(8) In the method of evaluating a composite beam according to (7), in a case where the nondimensional rigid joint moment is defined as $\beta_{Mj,\,rigid}$, the nondimensional rotational rigidity is defined as α_j, and the nondimensional bending stiffness is defined as α_s, the nondimensional joint moment β_{Mj} may be calculated by Expression (13) using Expressions (10) to (12).

[0026]

$$k = \frac{1}{5000}\alpha_s{}^6 - \frac{1}{250}\alpha_s{}^5 + \frac{196}{5000}\alpha_s{}^4 - \frac{1985}{10000}\alpha_s{}^3 + \frac{5549}{10000}\alpha_s{}^2 - \frac{4138}{5000}\alpha_s - \frac{18681}{10000} \quad \cdots(10)$$

$$\alpha_{j,T} = \frac{7}{10000}\alpha_s{}^3 - \frac{1343}{10000}\alpha_s{}^2 + \frac{7614}{5000}\alpha_s + \frac{6217}{10000} \quad \cdots(11)$$

$$\beta_{Mj,rigid} = -\frac{15}{48}\log_{10}\alpha_s + \frac{2}{3} \quad \cdots(12)$$

$$\beta_{Mj} = \frac{\beta_{Mj,rigid}}{e^{\{k(\log_{10}\alpha_j - \log_{10}\alpha_{j,T})\}} + 1} \quad \cdots(13)$$

[0027]

According to the aspect, it is possible to calculate the nondimensional joint moment β_{Mj} by Expression (13) obtained by using Expression (10) to Expression (12) with high accuracy without performing convergence calculation.

[0028]

(9) In the method of evaluating a composite beam according to (8), in a case where the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is equal to or smaller than 0.4, in Expression (13), instead of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$, a nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ calculated by Expression (14) based on the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ may be used.

[0029]

$$\beta_{Mj,rigid,Theo} = -\frac{781}{1000}\beta_{Mj,rigid}{}^3 + \frac{1702}{1250}\beta_{Mj,rigid}{}^2 + \frac{1189}{5000}\beta_{Mj,rigid} + \frac{1369}{10000} \quad \cdots(14)$$

[0030]

According to the aspect, in a case where the nondimensional rigid joint

moment $\beta_{Mj,\,rigid}$ is equal to or smaller than 0.4, the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ has a large error with respect to an exact solution. Even in this case, by using the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ instead of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$, it is possible to calculate the nondimensional rigid joint moment with high accuracy.

[Effects of the Invention]

[0031]

According to the method of evaluating a continuous beam, the program of evaluating a continuous beam, and the method of evaluating a composite beam according to each of the aspects of the present invention, it is possible to appropriately evaluate the deflection.

[Brief Description of the Drawings]

[0032]

FIG. 1 is a plan view of a building in which a continuous beam to which a method of evaluating a continuous beam according to a first embodiment of the present invention is applied is used.

FIG. 2 is a cross-sectional view taken along a cutting-plane line A1-A1 in FIG. 1.

FIG. 3 is a schematic diagram explaining specifications of a beam and bending moments acting on the beam.

FIG. 4 is a schematic diagram explaining an external force and a load acting on the beam.

FIG. 5 is a schematic diagram explaining a shear force acting on the beam.

FIG. 6 is a schematic diagram explaining the continuous beam and an external force acting on the continuous beam.

FIG. 7 is a diagram explaining a relationship between rotational rigidities and rotation angles at ends of a pair of beams adjacent to each other in a longitudinal direction in a case where a distance between positions where the rotational rigidities are generated is taken into consideration.

FIG. 8 is a diagram explaining a relationship between rotational rigidities and rotation angles at ends of a pair of beams adjacent to each other in a longitudinal direction in a case where a distance between positions where the rotational rigidities are generated is ignored.

FIG. 9 is a block diagram of a continuous beam evaluation apparatus used to perform the method of evaluating a continuous beam.

FIG. 10 is a flowchart showing the method of evaluating a continuous beam.

FIG. 11 is a diagram showing an example of an input sheet for a program of evaluating a continuous beam according to the first embodiment of the present invention.

FIG. 12 is a diagram showing a relationship between a bending moment distribution acting on the continuous beam and a distance from a first end fulcrum, the relationship being evaluated using the program of evaluating a continuous beam according to the first embodiment of the present invention.

FIG. 13 is a diagram showing a relationship between a rotation angle distribution and a distance from a first end fulcrum, the relationship being evaluated using the program of evaluating a continuous beam according to the first embodiment of the present invention.

FIG. 14 is a diagram showing a relationship between a deflection distribution and a distance from a first end fulcrum, the relationship being evaluated using the program of evaluating a continuous beam according to the first embodiment of the

present invention.

FIG. 15 is a longitudinal section view of a building in which a composite beam to which a method of evaluating a composite beam according to a second embodiment of the present invention is applied is used.

FIG. 16 is a schematic front view showing the composite beam together with boundary conditions.

FIG. 17 is a front view schematically showing a region of sagging bending and a region of hogging bending in the composite beam.

FIG. 18 is a diagram showing a relationship between a nondimensional rotational rigidity and a nondimensional joint moment in Case 1 to Case 5.

FIG. 19 is a diagram showing a relationship between trial calculation results of a nondimensional bending stiffness and a nondimensional rigid joint moment in the composite beam.

FIG. 20 is a diagram showing a relationship between an approximation solution and an exact solution of the nondimensional rigid joint moment.

FIG. 21 is a diagram showing a relationship between the nondimensional bending stiffness and a coefficient k.

FIG. 22 is a diagram showing a relationship between the nondimensional bending stiffness and a variable $\alpha_{j,T}$.

FIG. 23 is a diagram showing a relationship between an approximation solution and an exact solution of the nondimensional joint moment.

FIG. 24 is a diagram showing a relationship between an approximation solution and an exact solution of a maximum value of deflection.

[Embodiments of the Invention]

[0033]

(First Embodiment)

Hereinafter, a first embodiment of a method of evaluating a continuous beam and a program of evaluating a continuous beam according to the present invention will be described with reference to FIG. 1 to FIG. 14.

[0034]

[1. Continuous Beam]

The method of evaluating a continuous beam according to the present embodiment (hereinafter, also simply referred to as an evaluation method) is suitably used for evaluating, for example, a continuous beam 11 of a building 1 shown in FIG. 1 and FIG. 2. In FIG. 1, a floor 17 to be described later is transparently shown, and in FIG. 2, a column 33 to be described later is not shown. Here, evaluating the continuous beam 11 means obtaining a bending moment, a rotation angle, and a deflection distribution of the continuous beam 11, and evaluating, for example, how much a bending proof stress of the continuous beam 11 has a margin with respect to the bending moment of the continuous beam 11.

In the example, the continuous beam 11 includes n (in the example, two) beams (small beams) 13 of which end portions adjacent to each other in a longitudinal direction are semi-rigidly jointed to each other to be intermediate fulcrums 12a. It is noted that n is a natural number equal to or larger than two.

In the example, the beam 13 includes a floor 17 and a beam body 18. It is noted that the configuration of the beam 13 is not limited to the example.

The floor 17 is a so-called composite slab, and is supported from below by the beam body 18. The floor 17 includes a deck plate 20 and a reinforced concrete (RC) slab 21 disposed on the deck plate 20.

An uneven shape of the deck plate 20 extends in a direction along a horizontal

plane and in a direction orthogonal to a direction in which the beam body 18 extends.

The RC slab 21 includes a concrete 22 and a reinforcement bar 23. The concrete 22 is formed in a plate shape in which a vertical direction is a thickness direction. The concrete 22 is supported from below by the deck plate 20.

The reinforcement bar 23 extends along the horizontal plane, and is buried in the concrete 22. For example, the reinforcement bar 23 is disposed in a lattice shape in a plan view.

The n beams 13 are disposed side by side in the longitudinal direction of the beams 13.

[0035]

The beam body 18 is made of H-section steel, and extends along the horizontal plane. A lower end portion of a stud 26 is fixed to an upper flange of the beam body 18. The stud 26 penetrates the deck plate 20. An upper end portion of the stud 26 is embedded in the concrete 22.

Ends of the beam body 18 are semi-rigidly jointed to first large beams (intermediate support portions) 27 extending along the horizontal plane by intermediate fulcrums 12a. The intermediate fulcrums 12a are supported in the vertical direction by the first large beam 27. The first large beam 27 extends in a direction orthogonal to the beam body 18. The semi-rigid joint between the beam body 18 and the first large beam 27 is performed by, for example, a shear plate 28 and a bolt 29.

[0036]

A pair of end fulcrums 12b, which are both ends of the entire continuous beam 11, are supported in the vertical direction by a pair of second large beams (end support portions) 31. The first large beam 27 and the second large beam 31 extend along a first direction along the horizontal plane. A joint state between an end of the beam

body 18 and the second large beam 31 at the end fulcrum 12b is not particularly limited, and may be pin joint, semi-rigid joint, or rigid joint.

The building 1 includes a third large beam 32 that extends along the horizontal plane and along a second direction orthogonal to the first direction. A joint portion between the first large beam 27 and the third large beam 32 and a joint portion between the second large beam 31 and the third large beam 32 are supported in the vertical direction by columns 33.

[0037]

Hereinafter, an evaluation method of the continuous beam 11 configured in this way will be described.

[0038]

[2. Derivation of Shear Force Distribution and Moment Distribution of Continuous Beam]

[2.1. Basic Expressions]

In the continuous beam 11 including n (span) beams 13, specifications of a certain i-th beam 13 (i is a natural number, $1 \leq i \leq n$) counted from one end fulcrum 12b of the continuous beam 11, and a bending moment, an external force, and a shear force acting on the beam 13 are assumed as shown in FIG. 3 to FIG. 5.

That is, as shown in FIG. 3, it is assumed that the i-th beam 13_i extends along the horizontal plane and a length of the beam 13_i is L_i (m). In a case where each beam 13_i is not distinguished, the beam 13_i is also referred to as the beam 13.

In the beam 13_i, it is assumed that a bending stiffness of sagging bending (downward protrusion) and a bending stiffness of hogging bending (upward protrusion) are different from each other. It is assumed that the bending stiffness of sagging bending of the beam 13_i is $EI_{s,i}$ (Nm^2) and the bending stiffness of hogging bending of

the beam 13_i is $EI_{h,i}$ (Nm^2).

[0039]

As shown in FIG. 4, a coordinate x_i (m) is defined in a case where a rightward direction along the beam 13_i is positive. It is assumed that a position of a left end of the beam 13_i is set as the origin of the coordinate x_i (a position of $x_i = 0$). It is assumed that a downward uniformly-distributed load (vertical load) w_i (N/m) acts on the beam 13_i over the entire length. A rotational rigidity of the left end of the beam 13_i is defined as $S_{jl,i}$ (Nm/rad), and a rotational rigidity of a right end of the beam 13_i is defined as $S_{jr,i}$ (Nm/rad).

As shown in FIG. 3, an absolute value of the bending moment (hogging bending moment) acting on a left end of the beam 13_i is defined as $M_{jl,i}$ (Nm), and an absolute value of the bending moment (hogging bending moment) acting on a right end of the beam 13_i is defined as $M_{jr,i}$ (Nm). The bending moment shown by a curve L1 acts on the beam 13_i. It is assumed that the bending moment is positive in a direction in which a downward protrusion bending occurs. In the beam 13_i, the coordinate x_i where the bending moment is 0 is defined as $x_{h,i}$ (m) and $x_{s,i}$ (m) ($0 \leq x_{h,i} < x_{s,i} \leq L_i$).

As shown in FIG. 5, it is assumed that the shear force (external force) when the left end of the beam 13_i is supported from below by the large beams 27 and 31 is $V_{jl,i}$ (N), and that the shear force when the right end of the beam 13_i is supported from below by the large beams 27 and 31 is $V_{jr,i}$ (N). The shear force shown by a curve L2 acts on the beam 13_i.

[0040]

At this time, the shear force distribution $V(x_i)$ (N) acting on the beam 13_i and the bending moment distribution $M(x_i)$ (Nm) are represented by Expression (21) and Expression (22). It is assumed that the shear forces $V_{jl,i}$ and $V_{jr,i}$ and the shear force

distribution V (x_i) are positive (+) in a direction in which clockwise rotation occurs.

[0041]

$$V_{(x_i)} = V_{jl,i} - w_i \cdot x_i \quad \cdots (21)$$

$$M_{(x_i)} = \int V_{(x_i)} dx = V_{jl,i} \cdot x_i - \frac{w_i \cdot {x_i}^2}{2} - M_{jl,i} \quad \cdots (22)$$

[0042]

When a boundary condition of the bending moment at $x_i = L_i$ is used in Expression (22), Expression (23) and Expression (24) are obtained.

[0043]

$$M_{(x_i)}\big|_{x_i=L_i} = V_{jl,i} \cdot L_i - \frac{w_i \cdot {L_i}^2}{2} - M_{jl,i} = -M_{jr,i} \quad \cdots (23)$$

$$V_{jl,i} = \frac{M_{jl,i} - M_{jr,i}}{L_i} + \frac{w_i \cdot L_i}{2} \quad \cdots (24)$$

[0044]

Here, the absolute values $M_{jl,i}$ and $M_{jr,i}$ of the bending moments in Expression (22) to Expression (24) represent magnitudes of the hogging bending moments, and are defined as Expression (24-1) and Expression (24-2).

[0045]

$$M_{jl,i} = \left| M_{(x_i)}\big|_{x_i=0} \right| \quad \cdots (24-1)$$

$$M_{jr,i} = \left| M_{(x_i)}\big|_{x_i=L_i} \right| \quad \cdots (24-2)$$

[0046]

By substituting Expression (24) into Expression (21) and using a force balance condition in $x_i = L_i$, Expression (25) and Expression (26) can be obtained.

[0047]

$$V_{jl,i} - V_{jr,i} = w_i \cdot L_i \quad \cdots (25)$$

$$V_{jr,i} = w_i \cdot L_i + V_{jl,i} = \frac{M_{jl,i} - M_{jr,i}}{L_i} - \frac{w_i \cdot L_i}{2} \quad \cdots (26)$$

[0048]

By substituting Expression (26) into Expression (21), Expression (27) for the shear force distribution V (x_i) is obtained.

[0049]

$$V_{(x_i)} = \frac{M_{jl,i} - M_{jr,i}}{L_i} + w_i\left(\frac{L_i}{2} - x_i\right) \quad \cdots (27)$$

[0050]

By substituting Expression (24) into Expression (22), Expression (28) is obtained.

[0051]

$$M_{(x_i)} = \left(\frac{M_{jl,i} - M_{jr,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot x_i - \frac{w_i \cdot {x_i}^2}{2} - M_{jl,i} \quad \cdots (28)$$

[0052]

By using Expression (22), the coordinate x_i ($x_{h,i}$, $x_{s,i}$) when the bending moment distribution M (x_i) = 0 is obtained. Expression (29) is solved for x_i. Considering that ($x_{h,i} < x_{s,i}$), Expression (30) and Expression (31) are obtained.

[0053]

$$M_{(x_i)} = \left(\frac{M_{jl,i} - M_{jr,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot x_i - \frac{w_i \cdot {x_i}^2}{2} - M_{jl,i} = 0 \quad \cdots (29)$$

$$x_{h,i} = \frac{1}{w_i}\left\{V_{jl,i} - \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{jl,i}}\right\} \quad \cdots (30)$$

$$x_{s,i} = \frac{1}{w_i}\left\{V_{jl,i} + \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{jl,i}}\right\} \quad \cdots (31)$$

[0054]

[2.2. Rotation Angle Distribution]

A curvature distribution of the beam 13_i is defined as ρ (x_i) (1/m) in a case

where a downward protrusion is set to positive (+). A deflection (displacement) distribution of the beam 13_i in the vertical direction is defined as $\delta(x_i)$ (m) in a case where a vertical downward direction is set to positive (+). At this time, the curvature distribution $\rho(x_i)$ is represented by Expression (34).

[0055]

$$\frac{d^2\delta_{(x_i)}}{dx_i^{\,2}} = \rho_{(x_i)} = \begin{cases} \dfrac{M_{(x_i)}}{EI_{h,i}} & (x_i \leq x_{h,i}, x_{s,i} \leq x_i) \\ \dfrac{M_{(x_i)}}{EI_{s,i}} & (x_{h,i} \leq x_i \leq x_{s,i}) \end{cases} \quad \cdot\cdot(34)$$

[0056]

[2.2.1. Rotation Angle Distribution in Interval [a] = [0, $x_{h,i}$]]

When the coordinate x_i is equal to or larger than 0 and equal to or smaller than $x_{h,i}$, the rotation angle distribution of the beam 13_i is defined as $\varphi(x_i)$ (rad: radian). The rotation angle distribution $\varphi(x_i)$ is defined as positive (+) in a case where a rotation direction from the horizon line is clockwise. The rotation angle distribution $\varphi(x_i)$ is obtained as in Expression (36) by representing the curvature distribution $\rho(x_i)$ by Expression (28) and Expression (34) and further integrating the curvature distribution $\rho(x_i)$ in an interval $[0, x_i]$ using Expression (35). When obtaining the rotation angle distribution $\varphi(x_i)$, it is considered that the rotation angle distribution $\varphi(x_i = 0) = \varphi_{0i}$ which is a boundary condition at $x_i = 0$. That is, a rotation angle of a left side (a first end fulcrum $12b_1$ side to be described later) of the beam 13_i is φ_{0i}.

The rotation angle distribution $\varphi(x_i)$ in the interval [a] is also referred to as a rotation angle distribution $\varphi_a(x_i)$.

[0057]

$$f_{(x_i)} = \left(\frac{M_{jl,i} - M_{jr,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^2}{2} - \frac{w_i \cdot {x_i}^3}{6} - M_{jl,i} \cdot x_i \quad \cdots (35)$$

$$\varphi_{a(x_i)} = \int_0^{x_i} \{-\rho_{(x_i)}\} dx_i = -\frac{1}{EI_{h,i}} f_{(x_i)} + \varphi_{0i} \quad \cdots (36)$$

[0058]

[2.2.2. Rotation Angle Distribution in Interval [b] = [$x_{h,i}$, $x_{s,i}$]]

When the coordinate x_i is equal to or larger than $x_{h,i}$ and equal to or smaller than $x_{s,i}$, the rotation angle distribution $\varphi(x_i)$ of the beam 13_i is obtained as in Expression (37) by representing the curvature distribution $\rho(x_i)$ by Expression (28) and Expression (34) and integrating the curvature distribution $\rho(x_i)$ in an interval $[x_{h,i}, x_i]$. When obtaining the rotation angle distribution $\varphi(x_i)$, a boundary condition at $x_i = x_{h,i}$ is considered.

The rotation angle distribution $\varphi(x_i)$ in the interval [b] is also referred to as a rotation angle distribution $\varphi_b(x_i)$.

[0059]

$$\varphi_{b(x_i)} = \int_{x_{h,i}}^{x_i} \{-\rho_{(x_i)}\} dx_i + \varphi_{a(x_i)}\big|_{x_i = x_{h,i}} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right) f_{(x_i)}\big|_{x_i = x_{h,i}} - \frac{1}{EI_{s,i}} f_{(x_i)} + \varphi_{0i} \quad \cdots (37)$$

[0060]

[2.2.3. Rotation Angle Distribution in Interval [c] = [$x_{s,i}$, L_i]]

When the coordinate x_i is equal to or larger than $x_{s,i}$ and equal to or smaller than L_i, the rotation angle distribution $\varphi(x_i)$ of the beam 13_i is obtained as in Expression (38) by representing the curvature distribution $\rho(x_i)$ by Expression (28) and Expression (34) and integrating the curvature distribution $\rho(x_i)$ in an interval $[x_{s,i}, x_i]$. When obtaining the rotation angle distribution $\varphi(x_i)$, a boundary condition at $x_i = x_{s,i}$ is considered.

The rotation angle distribution $\varphi(x_i)$ in the interval [c] is also referred to as a

rotation angle distribution φ_c (x_i).

[0061]

$$\varphi_{c(x_i)} = \int_{x_{s,i}}^{x_i} \{-\rho_{(x_i)}\} dx_i + \varphi_{b(x_i)}\big|_{x_i=x_{s,i}}$$
$$= -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left(f_{(x_i)}\big|_{x_i=x_{h,i}} - f_{(x_i)}\big|_{x_i=x_{s,i}}\right) - \frac{1}{EI_{h,i}} f_{(x_i)} + \varphi_{0i} \quad \cdot\cdot (38)$$

[0062]

[2.3. Deflection Distribution]

[2.3.1. Deflection Distribution in Interval [a] = [0, $x_{h,i}$]]

When the coordinate x_i is equal to or larger than 0 and equal to or smaller than $x_{h,i}$, the deflection distribution δ (x_i) of the beam 13_i is obtained as in Expression (42) by integrating the rotation angle distribution φ (x_i) in an interval [0, x_i] using Expression (41). When obtaining the deflection distribution δ (x_i), it is considered that vertical displacements δ ($x_i = 0$) = δ_{0i} which are boundary conditions at $x_i = 0$.

The deflection distribution δ (x_i) in the interval [a] is also referred to as a deflection distribution δ_a (x_i).

[0063]

$$F_{(x_i)} = \int \{f_{(x_i)}\} dx_i = \left(\frac{M_{jl,i} - M_{jr,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^3}{6} - \frac{w_i \cdot {x_i}^4}{24} - \frac{M_{jl,i}}{2} \cdot {x_i}^2 \quad \cdot\cdot (41)$$

$$\delta_{a(x_i)} = \int_0^{x_i} \{\varphi_{(x_i)}\} dx_i = -\frac{1}{EI_{h,i}} F_{(x_i)} + \varphi_{0i} \cdot x_i + \delta_{0i} \quad \cdot\cdot (42)$$

[0064]

[2.3.2. Deflection Distribution in Interval [b] = [$x_{h,i}$, $x_{s,i}$]]

When the coordinate x_i is equal to or larger than $x_{h,i}$ and equal to or smaller than $x_{s,i}$, the deflection distribution δ (x_i) is obtained as in Expression (43) by integrating the rotation angle distribution φ (x_i) in an interval [$x_{h,i}$, x_i]. When obtaining the deflection distribution δ (x_i), a boundary condition at $x_i = x_{h,i}$ is

considered.

The deflection distribution $\delta(x_i)$ in the interval [b] is also referred to as a deflection distribution $\delta_b(x_i)$.

[0065]

$$\delta_{b(x_i)} = \int_{x_{h,i}}^{x_i} \{\varphi_{(x_i)}\} dx_i + \delta_{a(x_i)}\big|_{x_i=x_{h,i}}$$
$$= -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left\{F_{(x_i)}\big|_{x_i=x_{h,i}} + f_{(x_i)}\big|_{x_i=x_{h,i}}(x_i - x_{h,i})\right\} - \frac{1}{EI_{s,i}}F_{(x_i)} + \varphi_{0i}\cdot x_i + \delta_{0i} \quad \cdots (43)$$

[0066]

[2.3.3. Deflection Distribution in Interval [c] = [$x_{s,i}$, L_i]]

When the coordinate x_i is equal to or larger than $x_{s,i}$ and equal to or smaller than L_i, the deflection distribution $\delta(x_i)$ is obtained as in Expression (44) by integrating the rotation angle distribution $\varphi(x_i)$ in an interval $[x_{s,i}, x_i]$. When obtaining the deflection distribution $\delta(x_i)$, a boundary condition at $x_i = x_{s,i}$ is considered.

The deflection distribution $\delta(x_i)$ in the interval [c] is also referred to as a deflection distribution $\delta_c(x_i)$.

[0067]

$$\delta_{c(x_i)} = \int_{x_{s,i}}^{x_i} \{\varphi_{(x_i)}\} dx_i + \delta_{b(x_i)}\big|_{x_i=x_{s,i}}$$
$$= -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left\{F_{(x_i)}\big|_{x_i=x_{h,i}} - F_{(x_i)}\big|_{x_i=x_{s,i}} + f_{(x_i)}\big|_{x_i=x_{h,i}}(x_i - x_{h,i}) - f_{(x_i)}\big|_{x_i=x_{s,i}}(x_i + x_{s,i})\right\}$$
$$- \frac{1}{EI_{h,i}}F_{(x_i)} + \varphi_{0i}\cdot x_i + \delta_{0i} \quad \cdots (44)$$

[0068]

[3. Calculation Procedure in Evaluation Method of Continuous Beam]

In the evaluation method, a plurality of bending moments $M_{j,i}$ at the intermediate fulcrums 12a and the pair of end fulcrums 12b, and a plurality of rotation

angles φ_{01} and φ_c at the pair of end fulcrums 12b are obtained based on given conditions.

Before explaining the given conditions, a plurality of vertical displacements and a plurality of rotational rigidities will be described.

First, as shown in FIG. 6, in the pair of end fulcrums 12b, the left end fulcrum 12b (one end fulcrum) is also referred to as a first end fulcrum $12b_1$. In the pair of end fulcrums 12b, the right end fulcrum 12b (the other end fulcrum) is also referred to as a second end fulcrum $12b_2$. In FIG. 6, the coordinate x_i of the i-th beam 13_i is shown as an example of the coordinate.

It is assumed that the end of the beam 13_i on the first end fulcrum $12b_1$ side is set as the origin and the coordinate x_i is positive in a direction from the first end fulcrum $12b_1$ toward the second end fulcrum $12b_2$. In the following, in the n beams 13_i, the i-th beam 13_i from the first end fulcrum $12b_1$ toward the second end fulcrum $12b_2$ is also referred to as the i-th beam 13_i. For example, in the n beams 13, the beam 13 closest to the first end fulcrum $12b_1$ side is the first beam 13_1.

The rotational rigidity $S_{jl,\,i}$ is a rotational rigidity of the i-th beam 13_i at the end (intermediate fulcrum 12a) on the first end fulcrum $12b_1$ side. The rotational rigidity $S_{jr,\,i}$ is a rotational rigidity of the i-th beam 13_i at the end (intermediate fulcrum 12a) on the second end fulcrum $12b_2$ side.

[0069]

It is assumed that the vertical deflection of the first beam 13_1 at the first end fulcrum $12b_1$ is δ_0 (m) when the vertical downward direction is set to positive (+). For i equal to or larger than one and equal to or smaller than (n-1), it is assumed that the vertical displacement of the i-th beam 13_i at the intermediate fulcrum 12a on the second end fulcrum $12b_2$ side is δ_i (m). It is assumed that the vertical displacement of the n-th

beam 13_n at the second end fulcrum $12b_2$ is δ_n (m). A plurality of vertical displacements under the given conditions are vertical displacements δ_i for a natural number i equal to or larger than 0 and equal to or smaller than n.

For example, the vertical displacements δ_i of the continuous beam 11 shown in FIG. 1 at the intermediate fulcrums 12a may be obtained from a range R of a distribution load defined to act on the first large beam 27 by a known method. The vertical displacements δ_i at the intermediate fulcrums 12a are obtained from the distribution load acting on the first large beam 27 in the range R, the bending stiffness of the first large beam 27, and the like.

[0070]

The bending moments due to, for example, rotation resistance of the large beams do not act on each of the fulcrums 12a and 12b, and the bending moments acting on the ends of the beams 13 adjacent to each other in the longitudinal direction have the same value. That is, for example, the absolute value $M_{jr,\,i}$ of the bending moment acting on the right end of the i-th beam 13_i and the absolute value $M_{jl,\,i+1}$ of the bending moment acting on the left end of the (i+1)-th beam 13_{i+1} are equal. It is assumed that the equal value is $M_{j,\,i}$ (Nm). The bending moment $M_{j,\,i}$ is the bending moment of the i-th beam 13_i at the intermediate fulcrum 12a on the second end fulcrum $12b_2$ side for i equal to or larger than 1 and equal to or smaller than (n-1).

The bending moment $M_{j,\,0}$ is equal to the absolute value $M_{jl,\,1}$ of the bending moment acting on the left end of the first beam 13_1 (the bending moment of the first beam 13_1 at the first end fulcrum $12b_1$). The bending moment $M_{j,\,n}$ is equal to the absolute value $M_{jr,\,n}$ of the bending moment acting on the right end of the n-th beam 13_n (the bending moment of the n-th beam 13_n at the second end fulcrum $12b_2$).

[0071]

In this way, a plurality of (n+1) bending moments $M_{j,0}$, ··, $M_{j,n}$ of the continuous beam 11 at the intermediate fulcrums 12a and the pair of end fulcrums 12b are defined.

[0072]

The given conditions include the plurality of vertical displacements, the plurality of rotational rigidities $S_{j,i}$, the length L_i of each of the n beams 13_i, the bending stiffnesses (the bending stiffness $EI_{s,i}$ of sagging bending and the bending stiffness $EI_{h,i}$ of hogging bending) of each of the n beams 13_i, and uniformly-distributed loads w_i acting on each of the n beams 13_i.

[0073]

At this time, the rotation angle of the beam 13_i at each of the fulcrums 12a and 12b is represented using the rotational rigidity of the beam 13_i at each of the fulcrums 12a and 12b and the absolute values $M_{jl,i}$ and $M_{jr,I}$ of the bending moments.

Here, it is assumed that the rotational rigidity $S_{jl,1}$ of the left end of the first beam 13_1 is $S_{j,0}$ and the rotational rigidity at a representative point of the intermediate fulcrum 12a is $S_{j,i}$.

As shown in FIG. 6, the continuous beam 11 includes the n beams 13_i. The intermediate fulcrums 12a of the continuous beam 11 are semi-rigidly jointed to the first large beam 27, and the end fulcrums 12b of the continuous beam 11 are supported by the second large beam 31.

[0074]

As shown in FIG. 7, a joint portion between the (i-1)-th beam 13_{i-1} and the i-th beam 13_i is considered.

The rotation angle of the left end of the i-th beam 13_i is defined as $\varphi_{jl,i}$ (rad), and the rotation angle of the right end of the i-th beam 13_i is defined as $\varphi_{jr,i}$ (rad). In

this case, the rotation angle of the right end of the (i-1)-th beam 13_{i-1} is $\varphi_{jr,\,i-1}$ (rad). The rotation angle of the left end of the i-th beam 13_i with respect to the horizontal plane is defined as $\varphi_{l,\,i}$ (rad). The rotation angle of the right end of the i-th beam 13_i with respect to the horizontal plane is defined as $\varphi_{r,\,i}$ (rad). In this case, the rotation angle of the right end of the (i-1)-th beam 13_{i-1} with respect to the horizontal plane is $\varphi_{r,\,i-1}$ (rad).

It is assumed that a distance between a position where the rotational rigidity $S_{jr,\,i-1}$ is generated at the right end of the (i-1)-th beam 13_{i-1} and a position where the rotational rigidity $S_{jl,\,i}$ is generated at the left end of the i-th beam 13_i is a minimum length.

Expression (47) and Expression (48) are obtained from definitions of variables in consideration of the positive and negative of the rotation angle distribution.

[0075]

$$\varphi_{jr,i-1} = -\frac{M_{jr,i-1}}{S_{jr,i-1}} \quad \cdot\cdot(47)$$

$$\varphi_{jl,i} = \frac{M_{jl,i}}{S_{jl,i}} \quad \cdot\cdot(48)$$

[0076]

Expression (49) is obtained from a geometrical relationship of a distortion state in FIG. 7.

[0077]

$$-\varphi_{jr,i-1} + \varphi_{jl,i} = -\varphi_{r,i-1} + \varphi_{l,i} = \frac{M_{j,i-1}}{S_{j,i-1}} \quad \cdot\cdot(49)$$

[0078]

In this case, it is assumed that the minimum length is negligible. At this time, as shown in FIG. 8, the rotational rigidity $S_{jr,\,i-1}$ of the (i-1)-th beam 13_{i-1} and the

rotational rigidity $S_{jl,i}$ of the i-th beam 13_i are represented by the rotational rigidity $S_{j,i-1}$. The rotational rigidity $S_{j,i-1}$ is obtained from Expression (50) and Expression (51) obtained by substituting Expression (47) and Expression (48) into Expression (49).

[0079]

$$\frac{M_{jr,i-1}}{S_{jr,i-1}}+\frac{M_{jl,i}}{S_{jl,i}}=\left(\frac{1}{S_{jr,i-1}}+\frac{1}{S_{jl,i}}\right)M_{j,i-1}=\frac{M_{j,i-1}}{S_{j,i-1}} \quad \cdots (50)$$

$$S_{j,i-1}=\left(\frac{1}{S_{jr,i-1}}+\frac{1}{S_{jl,i}}\right)^{-1} \quad \cdots (51)$$

[0080]

Therefore, the rotational rigidity $S_{j,i-1}$ can be represented by a series joint of rotation springs of left and right joint portions with the intermediate fulcrum 12a interposed therebetween.

Here, for i = 2 to (n-1), φ_{0i} in Expression (38) is obtained as follows. From FIG. 8, using Expression (49), the rotation angle $\varphi_{0i} = \varphi_{l,i}$ of the left end of the i-th beam 13_i at the intermediate fulcrum 12a is associated with the rotation angle $\varphi_{r,i-1}$ of the right end at the intermediate fulcrum 12a. In Expression (49), the absolute value $M_{j,i-1}$ of the moment at the intermediate fulcrum 12a and the rotational rigidity $S_{j,i-1}$ at the intermediate fulcrum 12a are used.

Further, since $\varphi_{r,i-1}$ is the rotation angle of the right end of the (i-1)-th beam 13_{i-1}, $\varphi_{r,i-1}$ is equal to a value obtained by substituting $x_{i-1} = L_{i-1}$ into Expression (38) for the (i-1)-th beam 13_{i-1}.

Therefore, Expression (8) is derived by substituting Expression (38) into Expression (49). In a case where an initial value φ_{01} of the rotation angle at the first end fulcrum $12b_1$ and the moments at the intermediate fulcrums 12a and the both end fulcrums 12b are given, φ_{0i} for i = 2 to (n-1) is obtained in order by Expression (8).

When evaluating the continuous beam 11, for the bending moments, (n+1)

unknown quantities, which are the bending moments $M_{j,i}$ (the plurality of bending moments) for a natural number i equal to or larger than 0 and equal to or smaller than n, are defined.

[0081]

Generally, the following can be said depending on the joint states of the continuous beam 11 at the both end fulcrums 12b.

For the bending moments $M_{j,0}$ and $M_{j,1}$ at both ends of the first beam 13_1 and the rotation angle φ_{01} ($\varphi_{jl,1}$) of the first beam 13_1 at the first end fulcrum $12b_1$ that is a unknown quantity, initial values are given. In this way, the rotation angle $\varphi_{r,1}$ of the first beam 13_1 is determined by the rotation angle distribution $\varphi_c(x_i)$ in Expression (38) when $x_1 = L_1$. By Expression (49), the rotation angle $\varphi_{l,2}$ of the second beam 13_2 adjacent to the first beam 13_1 is determined.

The rotation angle $\varphi_{l,2}$ corresponds to φ_{02} which is a value of the rotation angle distribution $\varphi(x_2)$ at $x_2 = 0$ when Expression (38) is applied to the second beam 13_2.

Similarly, for i equal to or larger than 3 and equal to or smaller than n, in a case where the bending moments $M_{j,i-2}$ and $M_{j,i-1}$ of the joint portions at both ends of the (i-1)-th beam 13_{i-1} are given, the rotation angle $\varphi_{r,i-1}$ of the right end of the (i-1)-th beam 13_{i-1} is determined according to the rotation angle distribution $\varphi_c(x_{i-1})$ in Expression (38) when $x_{i-1} = L_{i-1}$. By Expression (49), the rotation angle $\varphi_{l,i}$ of the left end of the i-th beam 13_i adjacent to the (i-1)-th beam 13_{i-1} is determined. The rotation angle $\varphi_{l,i}$ of the left end of the i-th beam 13_i corresponds to φ_{0i} which is a value of the rotation angle distribution $\varphi(x_i)$ at $x_i = 0$ when Expression (38) is applied to the i-th beam 13_i.

[0082]

In this way, assuming the bending moments $M_{j,i-1}$ and $M_{j,i}$ for i = 1 to n, the corresponding rotation angle $\varphi_{r,i-1}$ and the corresponding rotation angle $\varphi_{l,i}$ are obtained

in order. In this way, from the deflection distribution $\delta_c(x_i)$ in Expression (44) when $x_i = L_i$, the vertical displacements δ_{0i} at each of the fulcrums 12a and 12b are obtained.

The rotation angle $\varphi_{r,n}$ of the n-th beam 13_n at the second end fulcrum $12b_2$ is also defined as an unknown quantity. That is, in the rotation angle, the two rotation angles of the rotation angle φ_{01} and the rotation angle $\varphi_{r,n}$ are unknown quantities.

Thus, the number of the unknown quantities is, for example, (n+3) including the bending moments $M_{j,i}$ at each of the fulcrums 12a and 12b and the rotation angle at the both end fulcrums 12b.

[0083]

On the other hand, a plurality of first boundary conditions for solving a plurality of unknown quantities are defined as follows.

From the vertical displacements δ_{01} at the first end fulcrum $12b_1$ that are the given conditions and Expression (44) when $x_i = L_i$ for i equal to or larger than 1 and equal to or smaller than n, for i equal to or larger than 0 and equal to or smaller than n, (n+1) relational expressions from Expression (54-1) to Expression (54-(n+1)) that are the plurality of first boundary conditions are obtained. These (n+1) relational expressions are a plurality of relational expressions for the vertical displacements δ_i.

[0084]

$$\delta_0 = \delta_{01} \quad \cdot\cdot(54-1)$$

$$\begin{aligned}\delta_1 = &-\left(\frac{1}{EI_{h,1}}-\frac{1}{EI_{s,1}}\right)\left\{F_{(x_1)}\big|_{x_1=x_{h,1}} - F_{(x_1)}\big|_{x_1=x_{s,1}} + f_{(x_1)}\big|_{x_1=x_{h,1}}(L_1 - x_{h,1})\right.\\ &\left. - f_{(x_1)}\big|_{x_1=x_{s,1}}(L_1 + x_{s,1})\right\} - \frac{1}{EI_{h,1}}F_{(x_1)}\big|_{x_1=L_1} + \varphi_{01}\cdot L_1 + \delta_{01}\\ &= \delta_{02} \quad \cdot\cdot(54-2)\end{aligned}$$

$$\begin{aligned}\delta_2 = &-\left(\frac{1}{EI_{h,2}}-\frac{1}{EI_{s,2}}\right)\left\{F_{(x_2)}\big|_{x_2=x_{h,2}} - F_{(x_2)}\big|_{x_2=x_{s,2}} + f_{(x_2)}\big|_{x_2=x_{h,2}}(L_2 - x_{h,2})\right.\\ &\left. - f_{(x_2)}\big|_{x_2=x_{s,2}}(L_2 + x_{s,2})\right\} - \frac{1}{EI_{h,2}}F_{(x_2)}\big|_{x_2=L_2} + \varphi_{02}\cdot L_2 + \delta_{02}\\ &= \delta_{03} \quad \cdot\cdot(54-3)\end{aligned}$$

$$\vdots$$

$$\begin{aligned}\delta_n = &-\left(\frac{1}{EI_{h,n}}-\frac{1}{EI_{s,n}}\right)\left\{F_{(x_n)}\big|_{x_n=x_{h,n}} - F_{(x_n)}\big|_{x_n=x_{s,n}} + f_{(x_n)}\big|_{x_n=x_{h,n}}(L_n - x_{h,n})\right.\\ &\left. - f_{(x_n)}\big|_{x_n=x_{s,n}}(L_n + x_{s,n})\right\} - \frac{1}{EI_{h,n}}F_{(x_n)}\big|_{x_n=L_n} + \varphi_{0n}\cdot L_n + \delta_{0n}\\ &\cdot\cdot(54-(n+1))\end{aligned}$$

[0085]

For example, Expression (54-2) is an equation for the bending moments $M_{j,0}$ and $M_{j,1}$. Expression (54-3) is an equation for the bending moments $M_{j,0}$, $M_{j,1}$, and $M_{j,2}$. Expression (54-(n+1)) is an equation for the bending moments $M_{j,0}$, $M_{j,1}$, $M_{j,2}$, ‥, and $M_{j,n}$.

[0086]

From the relational expressions among the rotational rigidities, the bending moments, and the rotation angles of the both end fulcrums 12b of the continuous beam 11, two relational expressions of Expression (55-1) and Expression (55-2) are obtained.

[0087]

$$M_{j,0} = S_{i,0}\cdot\varphi_{l,0} \quad \cdot\cdot(55-1)$$
$$M_{j,n} = S_{i,n}\cdot\varphi_{r,n} \quad \cdot\cdot(55-2)$$

[0088]

Expression (55-1) and Expression (55-2) are obtained according to the joint states of the continuous beam 11 at the both end fulcrums 12b. For example, in a case

where the left end fulcrum 12b (first end fulcrum $12b_1$) of the continuous beam 11 is pin-jointed, the bending moment $M_{j,0}$ is 0.

Thus, the number of the first boundary conditions is (n+3) of the (n+3) relational expressions. That is, the number of the plurality of first boundary conditions is the same as the number of the plurality of unknown quantities.

Therefore, in a case where the plurality of unknown quantities are solved such that the plurality of unknown quantities satisfy the plurality of first boundary conditions, one combination of the (n+1) bending moments $M_{j,i}$ is determined.

[0089]

Here, it is assumed that the bending moments $M_{j,i}$ at all the fulcrums 12a and 12b has values. It is assumed that calculation results of the vertical displacements corresponding to the vertical displacements δ_i at each of the fulcrums 12a and 12b are $\delta_{i,calc}$ (m), the vertical displacements being obtained from the assumed bending moments $M_{j,i}$. Assuming that the bending moments $M_{j,i}$ at all the fulcrums 12a and 12b have values, at all the fulcrums 12a and 12b, a sum of the squares of differences between the calculation results $\delta_{i,calc}$ of the vertical displacements obtained from the assumed bending moments $M_{j,i}$ and the vertical displacements δ_i determined from a distortion compatibility condition (values by Expression (57), displacement residuals) is defined as an objective function. In this way, by an optimization calculation for searching for the combination of the bending moments $M_{j,i}$ that minimize the objective function, the bending moments $M_{j,i}$ at all the fulcrums 12a and 12b can be identified.

A known differential evolution method may be used for the optimization calculation.

A calculation procedure in the evaluation method of the continuous beam according to the joint states of the continuous beam 11 at the both end fulcrums 12b will

be described later.

[0090]

$$\sum_{i=2}^{n+1}\left(\delta_{i-1,\mathrm{calc}}-\delta_{i-1}\right)^2 \quad \cdots (57)$$

[0091]

[4. Evaluation Apparatus used for Evaluation Method of Continuous Beam]

In order to evaluate the continuous beam 11 by performing the evaluation method of the continuous beam, for example, an evaluation apparatus 101 shown in FIG. 9 is used. The evaluation apparatus 101 is a computer, and includes a central processing unit (CPU) 111, a main storage device 125, an auxiliary storage device 126, an input/output interface (IO I/F) 131, and a recording/reproducing device 136.

[0092]

The main storage device 125 is a random access memory (RAM) serving as a work area of the CPU 111.

The input/output interface 131 is jointed to an input device 132 such as a keyboard and a mouse, and a display device 133.

The recording/reproducing device 136 performs recording and reproducing of data on a disc recording medium 137 such as a CD or a DVD.

[0093]

The auxiliary storage device 126 is a hard disk drive device that stores various data, programs, and the like. The auxiliary storage device 126 stores a program of evaluating the continuous beam (hereinafter, simply referred to as an evaluation program) 127 for causing the computer to function as the evaluation apparatus 101, various programs such as an OS program, a predetermined threshold value, and the like. The various programs including the evaluation program 127 are read into the auxiliary

storage device 126 from the recording medium 137 via the recording/reproducing device 136. The evaluation program and the like are stored in the recording medium 137.

These programs may be read into the auxiliary storage device 126 from an external apparatus via a portable memory such as a flash memory, or a communication device (not shown).

[0094]

Further, in the auxiliary storage device 126, a temporary setting value file 128 is provided in a process of executing the evaluation program 127. In the temporary setting value file 128, temporary design values to be described later are stored.

[0095]

The CPU 111 executes various arithmetic processing.

The CPU 111 functionally includes a solution determination unit 112 that obtains a plurality of bending moments and a plurality of rotation angles based on given conditions. Further, the solution determination unit 112 functionally includes a first design unit 113, a second design unit 114, a temporary design unit 115, a storage unit 116, a solution calculation unit 117, a residual calculation unit 118, a determination unit 119, and a solution setting unit 120.

By executing the evaluation program 127 stored in the auxiliary storage device 126 by the CPU 111, the CPU 111 functions as the first design unit 113, the second design unit 114, the temporary design unit 115, the storage unit 116, the solution calculation unit 117, the residual calculation unit 118, the determination unit 119, and the solution setting unit 120, which are functional configuration elements of the CPU 111. The evaluation program 127 is a program for the evaluation apparatus 101. The evaluation program 127 causes the evaluation apparatus 101 to function as the solution

determination unit 112.

[0096]

[5. Evaluation Method of Continuous Beam]

Next, an evaluation operation (evaluation method) of the evaluation apparatus 101 will be described. As shown in Table 1, as the joint state of the first end fulcrum $12b_1$, there are three types including pin joint, semi-rigid joint, and rigid joint. As the joint state of the second end fulcrum $12b_2$, there are three types including pin joint, semi-rigid joint, and rigid joint. Thus, there are a total of nine joint states of the continuous beam 11 at the pair of end fulcrums 12b.

[0097]

[Table 1]

		Joint State at Second End Fulcrum		
		Pin Joint	Semi-rigid Joint	Rigid Joint
Joint State at First End Fulcrum	Pin Joint	Case 1	Case 4A	Case 5A
	Semi-rigid Joint	Case 4B	Case 2	Case 6B
	Rigid Joint	Case 5B	Case 6A	Case 3

[0098]

On the other hand, for example, in a case where the first end fulcrum $12b_1$ is pin-jointed and the second end fulcrum $12b_2$ is semi-rigidly jointed, and in a case where the first end fulcrum $12b_1$ is semi-rigidly jointed and the second end fulcrum $12b_2$ is pin-jointed, when a direction of the continuous beam 11 is reversed, the same configuration is obtained. Thus, a case where the both end fulcrums $12b_1$ and $12b_2$ are pin-jointed will be described as Case 1. A case where the both end fulcrums $12b_1$ and $12b_2$ are semi-rigidly jointed will be described as Case 2, and a cases where the both end fulcrums $12b_1$ and $12b_2$ are rigidly jointed will be described as Case 3. A case where the first end fulcrum $12b_1$ is pin-jointed and the second end fulcrum $12b_2$ is semi-rigidly jointed will be described as Case 4A, and a case where the first end fulcrum $12b_1$ is pin-jointed and the second end fulcrum $12b_2$ is rigidly jointed will be described as Case 5A. A case where the first end fulcrum $12b_1$ is rigidly jointed and the second end fulcrum $12b_2$ is semi-rigidly jointed will be described as Case 6A.

In addition, in the configuration of the continuous beam 11, Case 4B where the first end fulcrum $12b_1$ is semi-rigidly jointed and the second end fulcrum $12b_2$ is pin-jointed is the same as Case 4A, and thus a description thereof will be omitted. A description of Case 5B where the first end fulcrum $12b_1$ is rigidly jointed and the second end fulcrum $12b_2$ is pin-jointed will also be omitted in the same manner. A description

of Case 6B where the first end fulcrum $12b_1$ is semi-rigidly jointed and the second end fulcrum $12b_2$ is rigidly jointed will also be omitted in the same manner.

[0099]

[5.1. Evaluation Method of Continuous Beam in Case 1 (pair of end fulcrums are pin-jointed)]

FIG. 10 is a flowchart showing the evaluation method S11 according to the present embodiment in a case where the continuous beam 11 has the configuration in Case 1. The evaluation method S11 includes a solution determination step (step S12 shown in FIG. 10) for obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions.

In the solution determination step S12, first, the first design unit 113 performs a first design step (step S14) (the solution determination step S12 includes the first design step S14). In the first design step S14, design values including the plurality of vertical displacements δ_i of the continuous beam 11 at the pair of end fulcrums 12b and the intermediate fulcrums 12a are given. The plurality of vertical displacements δ_i are given as the given conditions. In the first design step S14, the design values include the plurality of rotational rigidities, the length L_i of each of the n beams 13_i, the bending stiffness of each of the n beams 13_i, and the uniformly-distributed load w_i acting on each of the n beams 13_i.

In a case where the first design step S14 is completed, the process proceeds to step S16.

[0100]

Next, in a second design step S16, the second design unit 114 gives second boundary conditions to the pair of end fulcrums 12b according to the joint states at the pair of end fulcrums 12b. In Case 1, the second boundary conditions include that the

bending moments $M_{j,0}$ and $M_{j,n}$ are 0 Nm. That is, the second boundary conditions include that the rotation angle φ_{01} is an unknown quantity.

In a case where the second design step S16 is completed, the process proceeds to step S18.

Next, in a temporary design step S18, the temporary design unit 115 gives temporary design values including the bending moments $M_{j,i}$ acting on the pair of end fulcrums 12b and the intermediate fulcrums 12a according to the joint states at the pair of end fulcrums 12b. In a case where the continuous beam 11 corresponds to Case 1, the temporary design unit 115 further gives the rotation angle φ_{01} of the beam 13_1 at the first end fulcrum $12b_1$, as the temporary design value.

In a case where the temporary design step S18 is completed, the process proceeds to step S20.

[0101]

Next, in a storage step S20, the storage unit 116 stores the temporary design values in the temporary setting value file 128 after the temporary design step S18. In a case where the storage step S20 is completed, the process proceeds to step S22.

Next, in a solution calculation step S22, the solution calculation unit 117 calculates calculation values including the calculation results $\delta_{i,calc}$.of the vertical displacements at the intermediate fulcrums 12a so as to satisfy the plurality of first boundary conditions and the plurality of second boundary conditions, based on the temporary design values stored in the temporary setting value file 128. The calculation values include the calculation results $\delta_{n,calc}$ of the vertical displacements that are the calculation results of the vertical displacements at the second end fulcrum $12b_2$. The calculation results $\delta_{i,calc}$ of the vertical displacements are obtained based on n values from the vertical displacement δ_1 to the vertical displacement δ_n in Expression

(54-2) to Expression (54-(n+1)).

The vertical displacement δ_{01} (vertical displacement δ_0), which is the calculation result $\delta_{0, calc}$ of the vertical displacement, is one element of the plurality of vertical displacements given as the given conditions. Thus, in the solution calculation step S22, values are not newly calculated. The calculation results $\delta_{i, calc}$ of the vertical displacements are calculated in order of $\delta_{1, calc}$, $\delta_{2, calc}$, $\cdot\cdot$, $\delta_{n, calc}$.

In a case where the solution calculation step S22 is completed, the process proceeds to step S24.

[0102]

Next, in a residual calculation step S24, the residual calculation unit 118 obtains a displacement residual, which is a residual between the design value and the calculation value. The displacement residuals are obtained by Expression (57) by using the calculation results $\delta_{i, calc}$ of the plurality of vertical displacements calculated in the solution calculation step S22 and the plurality of vertical displacements δ_i given as the given conditions in the first design step S14.

The displacement residual will be described in more detail. Here, for i equal to or larger than 1 and equal to or smaller than (n-1), the residual between the vertical displacements $\delta_{0(i+1)}$ of the beam $13_{(i+1)}$ at the intermediate fulcrum 12a on the first end fulcrum $12b_1$ side and the calculation results $\delta_{i, calc}$ of the vertical displacements of the beam 13_i at the intermediate fulcrum 12a on the second end fulcrum $12b_2$ side is defined as an i-th residual.

In the residual calculation step S24, an intermediate residual, which is a sum of a first residual to an (n-1)-th residual, is calculated. A residual at the second end fulcrum is calculated, the residual being a residual between the vertical displacements δ_n at the second end fulcrum $12b_2$, which are the given conditions, and the calculation

results $\delta_{n,calc}$ of the vertical displacements of the beam 13_n at the second end fulcrum $12b_2$. At this time, the displacement residual is a sum of the intermediate residual and the residual at the second end fulcrum. The residual may be either positive or negative. In order to appropriately accumulate the sum of the residuals as an error, a sum of absolute values of the residuals or a sum of squares of the residuals is defined as the displacement residual.

In the residual calculation step S24, it is determined whether or not compatibility conditions of Expression (60) and Expression (61) are satisfied, the compatibility conditions being related to the rotation angle distribution $\varphi(x_i)$, the bending moment distribution $M(x_i)$ $M_{j,i}$, the bending stiffness EI_i, the bending moment $M_{j,i}$, the rotational rigidity $S_{j,i}$, and the rotation angles $\varphi_{l,i}$ and $\varphi_{r,i-1}$. The bending moment distribution $M(x_i)$ is obtained from Expression (22).

[0103]

$$\varphi_{(x_i)} = \frac{M_{(x_i)}}{EI_i} \quad \cdot\cdot(60)$$

$$M_{j,i-1} = S_{j,i-1}\left(\varphi_{r,i-1} + \varphi_{l,i}\right) \quad \cdot\cdot(61)$$

[0104]

Here, the bending stiffness EI_i is the bending stiffness $EI_{s,i}$ of sagging bending in a case of sagging bending, and is the bending stiffness $EI_{h,i}$ of hogging bending in a case of hogging bending.

In a case where the residual calculation step S24 is completed, the process proceeds to step S26.

[0105]

Next, in a determination step S26, the determination unit 119 determines whether or not the displacement residual is smaller than a threshold value. In a case where it is determined in the determination step S26 that the displacement residual is

smaller than the threshold value (Yes), the process proceeds to step S28. On the other hand, in a case where it is determined in the determination step S26 that the displacement residual is equal to or larger than the threshold value (No), the process proceeds to step S18.

[0106]

In a solution setting step S28, the solution setting unit 120 defines the bending moments of the temporary design values stored in the temporary setting value file 128, as the bending moments acting on the intermediate fulcrums 12a. The plurality of rotation angles and the deflection distribution are obtained based on the bending moments.

As described above, all the steps in the evaluation method S11 are completed.

[0107]

In the temporary design step S18, other new temporary design values are given in place of the temporary design values stored in the temporary setting value file 128 in the storage step S20. In the storage step S20 to which the temporary design step S18 proceeds, the other new temporary design values are stored in the temporary setting value file 128. The storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed based on the other new temporary design values.

As described above, in a case where it is determined in the determination step S26 that the displacement residual is equal to or larger than the threshold value (No), giving other new temporary design values in the storage step S20 and performing the storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 based on the other new temporary design values are set as a set. The set of the steps is repeated until it is determined in the determination step

S26 that the displacement residual is smaller than the threshold value. In the second and subsequent temporary design steps S18, for example, the temporary design values are reset according to the differential evolution method. By performing calculations in the temporary design step S18 to the determination step S26, it is possible to effectively perform a convergence calculation of the displacement residual.

[0108]

[5.2. Evaluation Method of Continuous Beam in Case 2 (pair of end fulcrums are semi-rigidly jointed)]

In the evaluation method S36 in this case, a solution determination step S37 of obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is performed.

In the solution determination step S37, first, the first design step S14 is performed. In a case where the first design step S14 is completed, the process proceeds to step S39.

Next, in a second design step S39, the second design unit 114 gives second boundary conditions according to the joint states at the pair of end fulcrums 12b. In Case 2, the second boundary conditions are Expression (64) and Expression (65) for the end fulcrums $12b_1$ and $12b_2$ of the continuous beam 11. That is, the bending moments $M_{j,0}$ and $M_{j,n}$ are unknown quantities. The second boundary conditions include that the rotation angle φ_{01} is an unknown quantity.

[0109]

$$M_{j,0} = S_{j,0} \cdot \varphi_{l,1} \quad \cdots (64)$$
$$M_{j,n} = S_{j,n} \cdot \varphi_{r,n} \quad \cdots (65)$$

[0110]

The rotational rigidities $S_{j,0}$ and $S_{j,i}$ are constants. Thus, for example, in

Expression (64), in a case where one of the bending moment $M_{j,0}$ and the rotation angle $\varphi_{jl,1}$ is obtained, the other of the bending moment $M_{j,0}$ and the rotation angle $\varphi_{jl,1}$ is obtained from Expression (64). As in Expression (65), the same applies to Expression (64). In a case where the second design step S39 is completed, the process proceeds to step S41.

Next, in a temporary design step S41, the temporary design unit 115 gives temporary design values including the bending moments $M_{j,i}$ acting on the intermediate fulcrums 12a according to the joint states at the pair of end fulcrums 12b. In a case where the continuous beam 11 corresponds to Case 2, one of the bending moment $M_{j,0}$ and the rotation angle $\varphi_{jl,1}$ is further given as the temporary design value.

In a case where the temporary design step S41 is completed, the storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed. Based on the determination in the determination step S26, the process proceeds to the solution setting step S28 or the temporary design step S41.

[0111]

In the solution setting step S28 in this case, the bending moment $M_{j,n}$ is calculated from Expression (65) using the calculated rotation angle $\varphi_{r,n}$.

[0112]

[5.3. Evaluation Method of Continuous Beam in Case 3 (pair of end fulcrums are rigidly jointed)]

In the evaluation method S46 in this case, a solution determination step S47 of obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is performed.

In the solution determination step S47, first, the first design step S14 is

performed. In a case where the first design step S14 is completed, the process proceeds to step S49.

Next, in a second design step S49, the second design unit 114 gives second boundary conditions according to the joint states at the pair of end fulcrums 12b. In Case 3, the second boundary conditions include that the rotation angle $\varphi_{jl,1}$ ($\varphi_{l,1}$, φ_{01}) and the rotation angle $\varphi_{jr,n}$ ($\varphi_{r,n}$) are 0 rad. That is, the bending moments $M_{j,0}$ and $M_{j,n}$ are unknown quantities.

In a case where the second design step S49 is completed, the process proceeds to step S51.

[0113]

Next, in a temporary design step S51, the temporary design unit 115 gives temporary design values including the bending moments $M_{j,i}$ acting on the intermediate fulcrums 12a according to the joint states at the pair of end fulcrums 12b. In a case where the continuous beam 11 corresponds to Case 3, the bending moments $M_{j,0}$ and $M_{j,n}$ acting on the pair of end fulcrums 12b are further given as the temporary design values.

In a case where the temporary design step S51 is completed, the storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed. Based on the determination in the determination step S26, the process proceeds to the solution setting step S28 or the temporary design step S51.

Here, in the residual calculation step S24, it is assumed that the calculation result $\delta_{0,calc}$ of the vertical displacement is set, without new calculation, as a value of the vertical displacement δ_0 which is given as the calculation result $\delta_{0,calc}$ of the vertical displacement under the given conditions. It is assumed that the rotation angle $\varphi_{l,1}$ is 0

rad without new calculation.

In a case where the continuous beam 11 corresponds to Case 3, in the residual calculation step S24, considering the given condition $\varphi_{r,n} = 0$, the rotation angle $\varphi_{r,n}$ is calculated from Expression (68) obtained when $x_i = L_i$ in Expression (38), and a value obtained by multiplying the square of the rotation angle $\varphi_{r,n}$ by an appropriate weight coefficient (positive value) is added to the displacement residual.

[0114]

$$\varphi_{jr,n} = \varphi_{c(x_i)}\big|_{x_i=L_i} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left(f_{(x_i)}\big|_{x_i=x_{h,i}} - f_{(x_i)}\big|_{x_i=x_{s,i}}\right) - \frac{1}{EI_{h,i}} f_{(x_i)}\big|_{x_i=L_i} + \varphi_{0i} \quad \cdots (68)$$

[0115]

[5.4. Evaluation Method of Continuous Beam in Case 4A (first end fulcrum is pin-jointed and second end fulcrum is semi-rigidly jointed)]

In the evaluation method S56 in this case, a solution determination step S57 of obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is performed.

In the solution determination step S57, first, the first design step S14 is performed. In a case where the first design step S14 is completed, the process proceeds to step S59.

Next, in a second design step S59, the second design unit 114 gives second boundary conditions according to the joint states at the pair of end fulcrums 12b. In Case 4A, the second boundary conditions include that the bending moment $M_{j,0}$ is 0 Nm in Expression (65). That is, the second boundary conditions include that the rotation angle φ_{01} is an unknown quantity.

In a case where the second design step S59 is completed, the process proceeds

to step S61.

[0116]

Next, in a temporary design step S61, the temporary design unit 115 gives temporary design values including the bending moments $M_{j,i}$ acting on the intermediate fulcrums 12a according to the joint states at the pair of end fulcrums 12b. In a case where the continuous beam 11 corresponds to Case 4A, as the temporary design values, the rotation angle $\varphi_{l,1}$ at the first end fulcrum $12b_1$ and the bending moments $M_{j,n}$ acting on the second end fulcrum $12b_2$ are given.

In a case where the temporary design step S61 is completed, the storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed. Based on the determination in the determination step S26, the process proceeds to the solution setting step S28 or the temporary design step S61.

[0117]

[5.5. Evaluation Method of Continuous Beam in Case 5A (first end fulcrum is pin-jointed and second end fulcrum is rigidly jointed)]

In the evaluation method S66 in this case, a solution determination step S67 of obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is performed.

In the solution determination step S67, first, the first design step S14 is performed. In a case where the first design step S14 is completed, the process proceeds to step S69.

Next, in a second design step S69, the second design unit 114 gives second boundary conditions according to the joint states at the pair of end fulcrums 12b. In Case 5A, the second boundary conditions include that the bending moment $M_{j,0}$ is 0 Nm

and the rotation angle $\varphi_{r,n}$ is 0 rad. That is, the second boundary conditions include that the rotation angle φ_{01} is an unknown quantity. In a case where the second design step S69 is completed, the process proceeds to the temporary design step S61.

In subsequent steps, the joint states at the pair of end fulcrums 12b are the same as in Case 4A, and thus a description thereof will be omitted. Here, in a case where the continuous beam 11 corresponds to Case 5A, in the residual calculation step S24, the following steps are performed when determining whether or not the compatibility conditions are satisfied. That is, in the residual calculation step S24, considering the given condition $\varphi_{r,n} = 0$, the rotation angle $\varphi_{r,n}$ is calculated from Expression (68) obtained when $x_i = L_i$ in Expression (38). Further, a value obtained by multiplying the square of the rotation angle $\varphi_{r,n}$ by an appropriate weight coefficient (positive value) is added to the displacement residual.

[0118]

[5.6. Evaluation Method of Continuous Beam in Case 6A (first end fulcrum is rigidly-jointed and second end fulcrum is semi-rigidly jointed)]

In the evaluation method S76 in this case, a solution determination step S77 of obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is performed.

In the solution determination step S77, first, the first design step S14 is performed. In a case where the first design step S14 is completed, the process proceeds to step S79.

Next, in a second design step S79, the second design unit 114 gives second boundary conditions according to the joint states at the pair of end fulcrums 12b. In Case 6A, the second boundary conditions include that the rotation angle $\varphi_{l,1}$ is 0 rad in Expression (65). That is, the bending moment $M_{j,0}$ is an unknown quantity. In a case

where the second design step S79 is completed, the process proceeds to step S81.

[0119]

Next, in a temporary design step S81, the temporary design unit 115 gives temporary design values including the bending moments $M_{j,i}$ acting on the intermediate fulcrums 12a according to the joint states at the pair of end fulcrums 12b. In a case where the continuous beam 11 corresponds to Case 6A, the bending moments $M_{j,0}$ and $M_{j,n}$ acting on the pair of end fulcrums 12b are further given as the temporary design values.

In a case where the temporary design step S81 is completed, the storage step S20, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed. Based on the determination in the determination step S26, the process proceeds to the solution setting step S28 or the temporary design step S81. Here, in a case where the continuous beam 11 corresponds to Case 6A, in the residual calculation step S24, the following steps are performed when determining whether or not the compatibility conditions are satisfied. That is, a value is obtained by multiplying the square of the difference between the rotation angle $\varphi_{r,n}$ obtained in the solution calculation step S22 and the rotation angle $\varphi_{r,n}$ calculated by Expression (65) and the temporary design value $M_{j,n}$ included in the second boundary conditions by an appropriate weight coefficient (positive value), and the value is added to the displacement residual.

[0120]

As described above, in the continuous beam 11 including the n beams 13, the number of the fulcrums (the intermediate fulcrums 12a and the end fulcrums 12b) included in the continuous beam 11 is (n+1). Since the moment and the rotation angle at each of the fulcrums are unknown quantities, there are 2(n+1) unknown quantities by

$(n+1) \times 2$. That is, the number of the plurality of unknown quantities is $2(n+1)$.

On the other hand, (n+1) conditional expressions are given as relational expressions of the plurality of rotational rigidities, the plurality of bending moments, and the plurality of rotation angles.

[0121]

In a case where the second boundary conditions are given, the conditional expressions are as follows.

(1) A case where at least one of the end fulcrums 12b of the continuous beam 11 is pin-jointed

Since the bending moments at the pin-jointed end fulcrums 12b are 0, the unknown quantities are reduced by the number of the pin-jointed end fulcrums 12b (number equal to or larger than 0 and equal to or smaller than 2). Thereby, based on expression $M_j = S_j \times \varphi_j$, in expressions for the rotation angle, the bending moment, and the rotational rigidity at the pin joint, $M_j = S_j = 0$. Therefore, the rotation angle φ_j is indefinite, and the conditional expressions based on the first boundary conditions are reduced by the number of the pin-jointed end fulcrums 12b.

(2) A case where at least one of the end fulcrums 12b of the continuous beam 11 is rigidly-jointed

Since the rotation angles at the rigidly-jointed end fulcrums 12b are 0, the unknown quantities are reduced by the number of the rigidly-jointed end fulcrums 12b (number equal to or larger than 0 and equal to or smaller than 2). Thereby, based on expression $M_j = S_j \times \varphi_j$, in expressions for the rotation angle, the bending moment, and the rotational rigidity at the rigid joint, $\varphi_j = 0$ and $S_j = \infty$ (infinity). Therefore, the bending moment M_j is indefinite, and the conditional expressions based on the first boundary conditions are reduced by the number of the rigidly-jointed end fulcrums 12b.

[0122]

Further, as the given conditions for the vertical displacements at each of the fulcrums, (n+1) conditional expressions are given.

By giving the second boundary conditions that the end fulcrum 12b is pin-jointed or rigidly-jointed, the plurality of unknown quantities are reduced by the number of the second boundary conditions. Here, the conditional expressions are indefinite, and the number of the first boundary conditions is reduced.

Therefore, a condition that the number of the plurality of unknown quantities is the same (constant) as a sum of the number of the plurality of first conditional expressions and the number of the plurality of second conditional expressions is maintained.

[0123]

As described above, by performing the evaluation method in a case where the continuous beam 11 corresponds to Case 1 to Case 6, the plurality of bending moments and the plurality of rotation angles can be obtained based on the given conditions, regardless of the joint states of the continuous beam 11 at the pair of end fulcrums 12b.

The bending moments of the continuous beam 11 are obtained by Expression (70) obtained by substituting the shear forces $V_{jl,\,i}$ and the bending moments $M_{j,\,i}$ obtained by Expression (24) into Expression (22).

[0124]

$$M_{(x_i)} = \left(\frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) x_i - \frac{w_i \cdot {x_i}^2}{2} - M_{j,i-1} \quad \cdot\cdot (70)$$

[0125]

The deflection distribution of the continuous beam 11 is obtained by Expression (42) to Expression (44) according to the interval of the coordinate x_i.

Further, by using the evaluation method according to the present embodiment, a continuous beam design method of designing the continuous beam 11 may be performed.

[0126]

[6. Evaluation Example 1]

The evaluation method using the differential evolution method is performed by the inventors, and the evaluation program for obtaining the plurality of bending moments and the plurality of rotation angles based on the given conditions is created by the inventors. An input sheet C of the evaluation program is shown in FIG. 11. Specifications of the main continuous beam 11 that are to be input to the input sheet C will be described.

In the input sheet C, the number n of the beams 13 of the continuous beam 11 (number of continuous beam span) is input to a cell C1. In this example, n is set to 5. A threshold value used for convergence calculation (threshold for ending convergence) is input to a cell C2. In this example, the threshold value is 1.38×10^{-2} mm^2.

The length (Span) L_i of each of the beam 13_1 to the beam 13_5 is input to a cell C3. In this example, the length L_i of each of the beam 13_1 to the beam 13_5 is set to 13800 mm (13.8 m).

[0127]

The uniformly-distributed load (composite stage load) w_i acting on each of the beam 13_1 to the beam 13_5 is input to a cell C6. In this example, the uniformly-distributed loads w_i acting on the beam 13_1 to the beam 13_5 are equal to each other, and are set to 28.56 kN/m.

The vertical displacements δ_i at the intermediate fulcrums 12a are set to 0 m.

In this example, it is assumed that a self weight of a slab concrete and a steel

frame (structural mass × gravitational acceleration, ww_SW) is supported by the beams 13 that have a pure iron frame structure and are pin-jointed at the both end fulcrums 12b and the intermediate fulcrums 12a. This value is input to a cell C7.

It is assumed that a load loaded on the beams 13 after use of the continuous beam 11 is started is supported by a joint portion (intermediate fulcrum 12a) serving as semi-rigid joint after hardening of concrete and composite beams supported by pin joint at both end fulcrums 12b (beams 13 in which the beam body 18 and the floor 17 serve as one body).

[0128]

FIG. 12 shows a relationship between a bending moment distribution acting on the continuous beam 11 and a distance from the first end fulcrum $12b_1$, the relationship being evaluated using the evaluation program. In FIG. 12, a horizontal axis represents the distance (mm) in which the continuous beam 11 moves from the first end fulcrum $12b_1$ toward the second end fulcrum $12b_2$. A vertical axis represents the bending moment distribution (kNm) acting on the continuous beam 11.

A curve L4 shown by a solid line represents the bending moment distribution with respect to the loaded load (uniformly-distributed load) after hardening of concrete. In addition to the value shown by the curve L4, a curve L5 shown by a dotted line represents a value in consideration of the bending moment distribution due to the self weight of the slab concrete (concrete 22) and the steel frame (beam body 18). That is, the curve L4 represents the bending moment distribution in a case where mass of the continuous beam 11 as a structure is not considered.

[0129]

A white triangle mark (Δ) with a sharp upper portion and a white triangle mark (▽) with a sharp lower portion represent an elastic property limit bending proof stress

of the beam 13. A white square mark (□) represents an elastic property limit bending proof stress of the joint portion (intermediate fulcrums 12a and end fulcrums 12b).

It is found that both bending moment distributions are equal to or lower than the elastic property limit bending proof stress of the beam 13 and the joint portion.

[0130]

FIG. 13 shows a relationship between a rotation angle distribution of the continuous beam 11 and a distance from the first end fulcrum $12b_1$, the relationship being evaluated using the evaluation program. In FIG. 13, a horizontal axis represents the distance (mm) in which the continuous beam 11 moves from the first end fulcrum $12b_1$ toward the second end fulcrum $12b_2$. A vertical axis represents the rotation angle distribution (rad) of the continuous beam 11.

In the continuous beam 11, a rotation angle according to the rotational rigidity is generated at the intermediate fulcrum 12a which is semi-rigidly jointed. Therefore, the rotation angle distribution is discontinuous at the intermediate fulcrums 12a. For example, FIG. 13 shows the rotation angle $\varphi_{r,3}$ at the right end of the third beam 13_3 and the rotation angle $\varphi_{l,4}$ at the left end of the fourth beam 13_4. The rotation angle $\varphi_{r,3}$ and the rotation angle $\varphi_{l,4}$ are discontinuous.

A difference in absolute values of the rotation angles of the adjacent beams 13 at the intermediate fulcrums 12a is caused by a ratio of the bending moments of the joint portions to the rotational rigidity. Specifically, as the rotational rigidity is lower and the bending moment is larger, a sum of the absolute values of the rotation angles of the adjacent beams 13 at the intermediate fulcrums 12a is increased.

[0131]

FIG. 14 shows a relationship between a deflection distribution of the continuous beam 11 and a distance from the first end fulcrum $12b_1$, the relationship

being evaluated using the evaluation program. In FIG. 14, a horizontal axis represents the distance (mm) in which the continuous beam 11 moves from the first end fulcrum $12b_1$ toward the second end fulcrum $12b_2$. The vertical axis represents the deflection distribution (mm) of the continuous beam 11. The maximum deflection of the first beam 13_1 and the fifth beam 13_5, of which one end is pin-jointed, is larger than the maximum deflection of the second beam 13_2, the third beam 13_3, and the fourth beam 13_4.

[0132]

[7. Evaluation Example 2]

The evaluation method of the continuous beam is performed on the continuous beams according to Comparative Example and Examples 1 to 3 shown in Table 2 to Table 8.

[0133]

[Table 2]

	Characteristics of Continuous Beam											
	Number of Beams	Length of Beam				Cross-Section Dimensions of Beam Bodies						Yield Strength of Steel Material of Beam
	n	First Beam	Second Beam	Third Beam	Fourth Beam	Beam Height	Flange Width	Web Thickness	Flange Thickness	Geometrical Moment of Inertia around Strong Axis	Mass of Beam per Unit Length	
		L_1	L_2	L_3	L_4	H	B	tw	tf	I	G	fy
		mm	mm	mm	mm	mm	mm	mm	mm	mm^4	kg/m	N/mm^2
Comparative Example	4	15500	15500	15500	15500	617	230	13.1	22.1	1120000000	140	345
Example 1	4	15500	15500	15500	15500	617	230	13.1	22.1	1120000000	140	345
Example 2	4	15500	15500	15500	15500	600	250	9.0	16.0	831000000	104	355
Example 3	4	13000	15500	14000	13000	600	250	9.0	16.0	831000000	104	355

[0134]

[Table 3]

	Characteristics of Slab								
	Slab Dimensions		Bar Arrangements			Effective Width			
	Slab Thickness	Deck Plate Height	Reinforcing Bars for Hogging Bending Portion	Reinforcing Bars for Joint Portion	Yield Strength of Steel Material of Steel Bar	First Beam	Second Beam	Third Beam	Fourth Beam
	Ds	Dp	diameter@pitch	diameter@pitch	fsd	Beff, 1	Beff, 2	Beff, 3	Beff, 4
	mm	mm			N/mm^2	mm	mm	mm	mm
Comparative Example	130	52	D10@100	-	435	3294	3294	3294	3294
Example 1	130	52	D10@100	D10@100	435	3294	2713	2713	3294
Example 2	130	52	D16@100	D16@100	435	3294	2713	2713	3294
Example 3	130	52	D10@100	D10@100	435	2763	2713	2450	2763

[0135]

[Table 4]

	Support Conditions at Each of Fulcrums									
	First End Fulcrum		First Intermediate Fulcrum		Second Intermediate Fulcrum		Third Intermediate Fulcrum		Second End Fulcrum	
	Joint State	Rotational Rigidity	Joint State	Rotational Rigidity	Joint State	Rotational Rigidity	Joint State	Rotational Rigidity	Joint State	Rotational Rigidity
		S_j		S_j		S_j		S_j		S_j
		kNm/mrad		kNm/mrad		kNm/mrad		kNm/mrad		kNm/mrad
Comparative Example	Pin	0	Pin	0	Pin	0	Pin	0	Pin	0
Example 1	Pin	0	Semi-Rigid	108	Semi-Rigid	116	Semi-Rigid	108	Pin	0
Example 2	Pin	0	Semi-Rigid	192	Semi-Rigid	242	Semi-Rigid	192	Pin	0
Example 3	Pin	0	Semi-Rigid	103	Semi-Rigid	116	Semi-Rigid	102	Pin	0

[0136]

[Table 5]

	Bending Stiffness of Beam							
	First Beam		Second Beam		Third Beam		Fourth Beam	
	Sagging Bending	Hogging Bending	Sagging Bending	Hogging Bending	Sagging Bending	Hogging Bending	Sagging Bending	Hogging Bending
	EIs, i	Eih, i	EIs, i	Eih, i	EIs, i	Eih, i	EIs, i	Eih, i
	kNm^2	kNm^2	kNm^2	kNm^2	kNm^2	kNm^2	kNm^2	kNm^2
Comparative Example	555000	308000	555000	308000	555000	308000	555000	308000
Example 1	555000	308000	525000	292000	525000	292000	555000	308000
Example 2	433594	241305	413095	232307	413095	232307	433594	241305
Example 3	415000	232000	413000	232000	402000	227000	415000	232000

[0137]

[Table 6]

	Yield Bending Proof Stress of Beam and Joint Portion													loaded load	
	First End Fulcrum	First Beam		First Intermediate Fulcrum	Second Beam		Second Intermediate Fulcrum	Third Beam		Third Intermediate Fulcrum	Fourth Beam		Second End Fulcrum	SDL (dead load excluding structure)	LL (live load)
	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending		
	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kN/m^2	kN/m^2
Comparative Example	-	1750	1415	-	1750	1415	-	1750	1415	-	1750	1415	-	1.0	4.5
Example 1	-	1750	1415	474	1721	1395	474	1721	1395	474	1750	1415	-	1.0	4.5
Example 2	-	1368	1127	830	1349	1111	830	1349	1111	830	1368	1127	-	1.0	4.5
Example 3	-	1351	1111	464	1349	1111	464	1339	1100	464	1351	1111	-	1.0	4.5

[0138]

As shown in Table 2, as characteristics of the continuous beam, the number n of the beams included in the continuous beams according to Comparative Example and Examples 1 to 3 is 4. In the following, the i-th beam counted from the first end fulcrum is also referred to as an i-th beam. The i-th intermediate fulcrum counted from the first end fulcrum is also referred to as an i-th intermediate fulcrum.

For each of the beams in Comparative Example and Examples 1 and 2, the length of the beam is set to 15500 mm (15.5 m). In Example 3, the lengths of the first beam to the fourth beam are respectively set to 13000 mm, 15500 mm, 14000 mm, and 13000 mm.

In Comparative Example and Example 1, it is assumed that a beam height is 617 mm. It is assumed that a flange width is 230 mm, a web thickness is 13.1 mm, a flange thickness is 22.1 mm, a geometrical moment of inertia around a strong axis is 1120000000 mm^4 (0.00112 m^4), mass of the beam per unit length is 140 kg/m, and a yield strength of a steel material of the beam is 345 N/mm^2.

In Examples 2 and 3, it is assumed that a beam height is 600 mm. It is assumed that a flange width is 250 mm, a web thickness is 9.0 mm, a flange thickness is 16.0 mm, a geometrical moment of inertia around a strong axis is 831000000 mm^4, mass of the beam per unit length is 104 kg/m, and a yield strength of a steel material of the beam is 355 N/mm^2.

[0139]

As shown in Table 3, as characteristics of the slab(RC slab), it is assumed that a slab thickness is 130 mm and a deck plate height is 52 mm in all the continuous beams according to Comparative Example and Examples 1 to 3.

In Comparative Example, Examples 1 and 3, as reinforcement bars for portions

at which the beam is in a hogging bending state (both ends of the beam), reinforcement bars having a diameter of D10 are disposed at a pitch of 100 mm. In Example 2, reinforcement bars having a diameter of D16 are disposed at a pitch of 100 mm.

In Examples 1 and 3, as reinforcement bars for the joint portions at which the beams are jointed, reinforcement bars having a diameter of D10 are disposed at a pitch of 100 mm. In Example 2, reinforcement bars having a diameter of D16 are disposed at a pitch of 100 mm. In Comparative Example, reinforcement bars are not disposed at the joint portions.

The yield strength of the steel material of the reinforcement bars used in Comparative Example and Examples 1 to 3 is 435 N/mm^2.

[0140]

An effective width of the slab is determined based on British Standards "Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings". The definition of the effective width of the slab is not limited thereto, and may be determined based on, for example, "Various Composite Structure Design Guidelines/Explanations", Architectural Institute of Japan.

In this example, for example, in the continuous beam according to Comparative Example, the effective widths of the slabs for the first beam to the fourth beam are set to 3294 mm. In the continuous beam according to Example 1, the effective widths of the slabs for the first beam to the fourth beam are respectively set to 3294 mm, 2713 mm, 2713 mm, and 3294 mm.

[0141]

As shown in Table 4, as support conditions at the fulcrums of the continuous beam, in the continuous beam according to Comparative Example, pin joint is performed at the end fulcrums and the intermediate fulcrums. In the case of pin joint,

the rotational rigidity at each fulcrum is 0.

In the continuous beams according to Examples 1 to 3, pin joint is performed at the end fulcrums, and semi-rigid joint is performed at the intermediate fulcrums. The rotational rigidity of semi-rigid joint is calculated as follows by using a method described in British Standards "Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings" based on bar arrangements and effective widths in Table 3. In the continuous beam according to Example 1, the rotational rigidities at the first intermediate fulcrum to the third intermediate fulcrum are calculated as 108 kNm/mrad, 116 kNm/mrad, and 108 kNm/mrad. In the continuous beam according to Example 2, the rotational rigidities at the first intermediate fulcrum to the third intermediate fulcrum are calculated as 192 kNm/mrad, 242 kNm/mrad, and 192 kNm/mrad. In the continuous beam according to Example 3, the rotational rigidities at the first intermediate fulcrum to the third intermediate fulcrum are calculated as 103 kNm/mrad, 116 kNm/mrad, and 102 kNm/mrad.

[0142]

As shown in Table 5, as the bending stiffnesses of the beams, the bending stiffnesses of sagging bending and hogging bending of the composite beam are calculated as follows based on the cross-section dimensions of the beam bodies in Table 2 and the effective widths in Table 3.

In the continuous beam according to Comparative Example, in any of the first beam to the fourth beam, it is assumed that the bending stiffness of sagging bending is 555000 kNm^2 and the bending stiffness of hogging bending is 308000 kNm^2.

In the continuous beam according to Example 1, in the first beam and the fourth beam, the bending stiffness of sagging bending is calculated to 555000 kNm^2, and the bending stiffness of hogging bending is calculated to 308000 kNm^2. In the

second beam and the third beam, the bending stiffness of sagging bending is calculated to 525000 kNm^2, and the bending stiffness of hogging bending is calculated to 292000 kNm^2.

In the continuous beam according to Example 2, in the first beam and the fourth beam, the bending stiffness of sagging bending is calculated to 433594 kNm^2, and the bending stiffness of hogging bending is calculated to 241305 kNm^2. In the second beam and the third beam, the bending stiffness of sagging bending is calculated to 413095 kNm^2, and the bending stiffness of hogging bending is calculated to 232307 kNm^2.

In the continuous beam according to Example 3, in the first beam and the fourth beam, the bending stiffness of sagging bending is calculated to 415000 kNm^2, and the bending stiffness of hogging bending is calculated to 232000 kNm^2. In the second beam, the bending stiffness of sagging bending is calculated to 413000 kNm^2, and the bending stiffness of hogging bending is calculated to 232000 kNm^2. In the third beam, the bending stiffness of sagging bending is calculated to 402000 kNm^2, and the bending stiffness of hogging bending is calculated to 227000 kNm^2.

[0143]

As shown in Table 6, yield bending proof stresses of the beam and the joint portion are set. For example, in the continuous beam according to Comparative Example, the yield bending proof stress of sagging bending of the first beam is calculated to 1750 kNm and the yield bending proof stress of hogging bending of the first beam is calculated to 1415 kNm. In the continuous beam according to Example 1, the yield bending proof stress of sagging bending of the first beam is calculated to 1750 kNm and the yield bending proof stress of hogging bending of the first beam is calculated to 1415 kNm. The yield bending proof stress of hogging bending at the first

intermediate fulcrum is calculated to 474 kNm.

As the loaded load, SDL (dead load excluding the structure) of the continuous beam according to each of Comparative Example and Examples 1 to 3 is calculated to 1.0 kN/m^2. LL (live load) is calculated to 4.5 kN/m^2.

[0144]

The evaluation method of the continuous beam is performed on the continuous beams according to Comparative Example and Examples 1 to 3, and as a result, results shown in Table 7 and Table 8 are obtained.

[0145]

[Table 7]

	Maximum Bending Moment													Maximum Deflection
	First End Fulcrum	First Beam		First Intermediate Fulcrum	Second Beam		Second Intermediate Fulcrum	Third Beam		Third Intermediate Fulcrum	Fourth Beam		Second End Fulcrum	
	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending	
	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	kNm	mm
Comparative Example	0	1400	0	0	1400	0	0	1400	0	0	1400	0	0	95
Example 1	0	1174	471	471	963	471	403	963	471	471	1174	471	0	82
Example 2	0	1126	545	545	889	545	449	889	545	545	1126	545	0	104
Example 3	0	781	409	409	981	409	400	755	400	351	807	351	0	96

[0146]

[Table 8]

	Generated Bending Moment/Bending Proof Stress			Maximum Deflection Ratio of Beam (with reference to Comparative Example)	Mass Ratio of Beam (Steel) (with reference to Comparative Example)	Outline of Set Conditions	Effect
	Beam-Sagging Bending	Beam-Hogging Bending	Joint Portion-Hogging Bending				
	-	-	-				
Comparative Example	80%	-	-	-	-	case where both ends of continuous beam including four beams are pin-jointed	comparison target
Example 1	68%	34%	99%	86%	100%	case where length of beam is same, both ends of continuous beam are pin-jointed, and intermediate fulcrums are semi-rigidly jointed in comparison with Comparative Example	maximum deflection of continuous beam is reduced by 14%, and mass of beam (steel) is same in comparison with Comparative Example
Example 2	83%	49%	66%	110%	74%	case where length of beam is same, both ends of continuous beam are pin-jointed, and intermediate fulcrums are semi-rigidly jointed in comparison with Comparative Example	maximum deflection of continuous beam is increased by 10%, ratio of sagging bending moments of beam to bending proof stress is equivalent, and mass of beam (steel) is reduced by 26% in comparison with Comparative Example
Example 3	58%	37%	88%	101%	74%	case where maximum value of length of beam is same (15.5 m), both ends of continuous beam are pin-jointed, and intermediate fulcrums are semi-rigidly jointed in comparison with Comparative Example	maximum deflection of continuous beam is equivalent, and mass of beam (steel) is reduced by 26% in comparison with Comparative Example

[0147]

As shown in Table 7, for example, in the continuous beam according to Comparative Example, in all of the first beam to the fourth beam, a maximum bending moment is 1400 kNm for sagging bending, and is 0 kNm for hogging bending. The bending moment of hogging bending does not act on the intermediate fulcrums.

In the continuous beam according to Example 1, the bending moment of 1174 kNm acts on sagging bending of the first beam, and the bending moment of 471 kNm acts on hogging bending of the first beam. The bending moment of 471 kNm acts on the first intermediate fulcrum in hogging bending.

The maximum deflection of the continuous beam is 95 mm for the continuous beam according to Comparative Example. In the continuous beams according to Examples 1 to 3, the maximum deflections are 82 mm, 104 mm, and 96 mm.

[0148]

The ratio of the generated bending moments to the bending proof stress shown in Table 8 means that a margin for the bending proof stress is smaller as the value approaches 100% from 0%. In the continuous beam according to Comparative Example, the ratio is 80% in sagging bending of the beam. In the continuous beam according to Example 1, the ratio is 68% in sagging bending of the beam, is 34% in hogging bending of the beam, and is 99% in hogging bending of the joint portion between the beams. In the continuous beam according to Example 2, the ratio is 83% in sagging bending of the beam, is 49% in hogging bending of the beam, and is 66% in hogging bending of the joint portion between the beams. In the continuous beam according to Example 3, the ratio is 58% in sagging bending of the beam, is 37% in hogging bending of the beam, and is 88% in hogging bending of the joint portion between the beams.

A maximum deflection ratio of the beam with reference to that of the continuous beam according to Comparative Example means that the maximum deflection is smaller than that of the continuous beam according to Comparative Example as the value approaches 0% from 100%. In the continuous beam according to Example 1, the ratio is 86%. In the continuous beam according to Example 2, the ratio is 110%, and in the continuous beam according to Example 3, the ratio is 101%.

A mass ratio of the beam (steel) with reference to the continuous beam according to Comparative Example means that a mass of the steel material required to form the beam is smaller than that of the continuous beam according to Comparative Example, in other words, the beam has an economical design, as the value approaches 0% from 100%.

In the continuous beam according to Example 1, the mass ratio is 100%. In the continuous beams according to Examples 2 and 3, the mass ratio is 74%.

[0149]

As a result of evaluating the continuous beam using the evaluation program, it is found that the mass of the beam does not change in the continuous beam according to Example 1 as compared with the continuous beam according to Comparative Example, and that the maximum deflection of the continuous beam is reduced by 14% from an expression of (82-95)/95.

In the continuous beam according to Example 2 as compared with the continuous beam according to Comparative Example, it is found that the maximum deflection of the continuous beam is increased by 10% from an expression of (104-95)/95, that the ratio of the generated bending moments to the bending proof stress is 80% to 83% which is equivalent, and that the mass of the beam is reduced by 26% from an expression of (104-140)/140.

In the continuous beam according to Example 3 as compared with the continuous beam according to Comparative Example, it is found that the maximum deflection of the continuous beam is 95 mm to 96 mm which is equivalent, and that the mass of the beam is reduced by 26% from an expression of (104-140)/140.

[0150]

In a beam (composite beam) in which different materials such as a steel framed beam and a concrete slab are connected, a rigidity and a proof stress differ depending on a bending direction. The reason is that a stress-strain relationship between concrete and a steel material is different, concrete has a tensile proof stress smaller than a compressive proof stress, and a material property of concrete depend on a direction of a force. In a case of evaluating a bending moment distribution and a proof stress in consideration of rigidity of such a beam, an explicit solution could not be obtained, and it is necessary to obtain a solution by convergence calculation. Further, in a case where the ends of the continuous beam are supported by semi-rigid joint, an expression for identifying the solution becomes more complicated. As a result, there is a problem that the expression is too complicated to be used in design practice.

For this reason, in many cases, in evaluation of the continuous beam, it is assumed that the joint state at the end fulcrum is pin joint or rigid joint. Further, the rigidity of the beam (effect by composition of the slab) is not taken into consideration, or even in a case where the rigidity of the beam is taken into consideration, there is no accurate evaluation expression. As a result, there is a problem that it is difficult to set a safety factor to be large in design of the continuous beam and it is difficult to obtain an economic effect in design of the continuous beam.

[0151]

On the other hand, according to the evaluation method and the evaluation

program 127 of the present embodiment, the number of the plurality of unknown quantities and the number of the plurality of first boundary conditions are the same. Therefore, the plurality of unknown quantities are solved so as to satisfy the plurality of first boundary conditions based on the given conditions including the length and the bending stiffness of the beam 13, the plurality of rotational rigidities, the vertical load, and the plurality of vertical displacements. According to the method, it is possible to obtain the plurality of bending moments and the plurality of rotation angles included in the plurality of unknown quantities.

The plurality of vertical displacements are calculated from the obtained plurality of bending moments and the obtained plurality of rotation angles based on the relational expression between the plurality of vertical displacements. According to the method, it is possible to more appropriately evaluate the bending moments and the deflection distribution of the continuous beam 11 according to the joint states at the pair of end fulcrums 12b. Therefore, it is possible to appropriately evaluate the deflection.

By the above steps, in evaluation of the continuous beam 11, it is possible to prevent the beam from being overestimated and underestimated.

[0152]

In the present embodiment, the evaluation method of the continuous beam 11 (semi-rigid continuous beam) is proposed in a case where the continuous beam includes the beams which include a concrete slab and a steel framed beam and in which bending stiffnesses of sagging bending and hogging bending are different from each other and includes a joint portion (semi-rigid joint) having a finite rotational rigidity at the intermediate fulcrum 12a. According to the evaluation method, the bending moment distribution, the rotation angle distribution, and the deflection distribution at a certain position are represented by using a value of the bending moment of the joint portion.

By optimization calculation considering the first boundary conditions, it is possible to identify the value of the bending moment of the joint portion, and derive a required performance in design (a bending moment distribution for design, a rotation angle of the joint portion) and the deflection distribution of the beam.

[0153]

In the solution determination step, the first design step S14, the second design step, the temporary design step, the solution calculation step S22, the residual calculation step S24, and the determination step S26 are performed. By determining whether or not the displacement residual is smaller than the threshold value in the determination step S26, the calculation values calculated based on the temporary design values can be evaluated based on the design values and the displacement residual.

In a case where it is determined in the determination step S26 that the displacement residual is equal to or larger than the threshold value, giving other new temporary design values in the temporary design step instead of the temporary design values stored in the storage step S20 and performing the solution calculation step S22, the residual calculation step S24, and the determination step S26 based on the new temporary design values are set as a set. The set is repeated until it is determined in the determination step S26 that the displacement residual is smaller than the threshold value. Therefore, it is possible to calculate the bending moments with high accuracy and obtain the plurality of rotation angles based on the bending moments.

[0154]

The calculation results $\delta_{i,\,calc}$ of the vertical displacements are calculated by Expression (44) when $x_i = L_i$ using Expression (24). Thereby, it is possible to evaluate the plurality of vertical displacements at the intermediate fulcrums 12a and the pair of end fulcrums 12b with high accuracy by using Equation.

[0155]

As described above, the first embodiment of the present invention has been described in detail with reference to the drawings. On the other hand, the specific configuration is not limited to the embodiment, and modifications, combinations, and deletions in the configuration may be made without departing from the scope of the inventions. Further, it goes without saying that the configurations described in each embodiment can be used in combination as appropriate.

For example, in the evaluation method according to the embodiment, it is not necessary to transition to the solution setting step S28 or the temporary design step based on the determination in the determination step S26. In this case, the storage step S20 is not performed in the evaluation method.

[0156]

In the beam 13, the bending stiffness of sagging bending and the bending stiffness of hogging bending may be equal to each other.

It is assumed that the end support portion is the second large beam 31. On the other hand, the end support portion may be a rigid body such as another building.

[0157]

(Second Embodiment)

Next, a method of evaluating a composite beam according to a second embodiment of the present invention will be described with reference to FIG. 15 to FIG. 24. The same portions as those of the embodiment are denoted by the same reference numerals, and a description thereof will be omitted. Only differences will be described.

[0158]

[1. Composite Beam of which Both Ends are Semi-Rigidly Jointed]

A method of evaluating a composite beam according to the present embodiment is used for evaluating, for example, a composite beam 211 of a building 201 shown in FIG. 15.

In the example, the composite beam 211 includes a floor 212 and a beam (small beam) 213. It is noted that the configuration of the composite beams 211 is not limited to the example.

The floor 212 is a so-called composite slab, and is supported from below by the beam 13. The floor 212 includes a deck plate 216 and a reinforced concrete (RC) slab 217 disposed on the deck plate 216.

An uneven shape of the deck plate 216 extends in a direction along a horizontal plane and in a direction orthogonal to a direction in which the beam 213 extends.

The RC slab 217 includes a concrete 218 and a reinforcement bar 219. The concrete 218 is formed in a plate shape in which a vertical direction is a thickness direction. The concrete 218 is supported from below by the deck plate 216.

The reinforcement bar 219 extends along the horizontal plane, and is buried in the concrete 218. For example, the reinforcement bar 219 is disposed in a lattice shape in a plan view.

[0159]

The beam 213 is made of H-section steel, and extends along the horizontal plane. A lower end portion of a stud 221 is fixed to an upper flange of the beam 213. The stud 221 penetrates the deck plate 216. An upper end portion of the stud 221 is embedded in the concrete 218.

The both ends of the beam 213 are semi-rigidly jointed to the large beam 224 extending along the horizontal plane. The large beam 224 extends in a direction orthogonal to the beam 213. The semi-rigid joint between the beam 213 and the large

beam 224 is performed by, for example, a shear plate 225 and a bolt 226.

The end portion of the large beam 224 is supported from below by columns 228.

[0160]

Hereinafter, an evaluation method of the composite beam 211 configured in this way will be described.

[0161]

[2. Differential Equation of Deflection of Composite Beam of which Both Ends are Semi-Rigidly Jointed (Exact Solution)]

The following examinations are all limited to an elastic property range of the composite beam.

As shown in FIG. 16, the composite beam is modeled.

A coordinate x (mm) is defined in a right direction along the composite beam. A position of a left end of the composite beam is defined as the origin of the coordinate x. It is assumed that a length of the composite beam is L (mm). As boundary conditions (preconditions), it is assumed that both ends of the composite beam are semi-rigidly jointed. It is assumed that a downward uniformly-distributed load w (N/mm: Newton per millimeter) acts on the composite beam over the entire length.

It is assumed that a rotational rigidity of a joint portion at both ends of the composite beam is S_j (Nmm/rad: Newton millimeter per radian) and a rotation angle of the end of the composite beam is θ_j (rad: radian) when the clockwise direction in a front view shown in FIG. 16 is positive.

At this time, an absolute value of the bending moment at the end of the composite beam (moment of the semi-rigid joint portion of the end portion, hereinafter, referred to as a semi-rigid joint moment) M_j (Nmm) is represented by Expression (111).

[0162]

$$M_j = S_j \left| \theta_j \right| \qquad \cdots(111)$$

[0163]

Assuming that the bending moment when a tensile stress acts on a lower flange of the beam of the composite beam is positive, a distribution of the bending moment M (x) (Nmm) along the coordinate x of the composite beam is represented by Expression (112) from a force balance condition.

[0164]

$$M(x) = \frac{wL}{2}x - \frac{w}{2}x^2 - M_j \qquad \cdots(112)$$

[0165]

A curvature φ (rad/mm) of the composite beam is represented by using the bending moment M (Nmm) acting on the composite beam and the bending stiffness EI (Nmm^2) of the composite beam. In the composite beam, a bending stiffness of sagging bending (downward protrusion) and a bending stiffness of hogging bending (upward protrusion) are different from each other due to action of concrete. Thus, it is assumed that the bending stiffness of sagging bending of the composite beam is EI_s (Nmm^2) and the bending stiffness of hogging bending of the composite beam is EI_h (Nmm^2). As shown in FIG. 17, it is assumed that the composite beam is in a hogging bending state in a range where the coordinate x is equal to or larger than 0 and equal to or smaller than L_1 and in a range where the coordinate x is equal to or larger than L_2 and equal to or smaller than L. Here, L_1 is larger than 0, and L_2 is larger than L_1 and smaller than L. It is assumed that the composite beam is in a sagging bending state in a range where the coordinate x is equal to or larger than L_1 and equal to or smaller than L_2.

At this time, solutions of x when Expression (112) becomes 0 are L_1 and L_2.

The curvature φ of the composite beam is divided into a region where the composite beam is in a sagging bending state and a region where the composite beam is in a hogging bending state, and is represented by Expression (113) and Expression (114).

[0166]

$$\phi(x)=\frac{1}{EI_s}\left(\frac{wL}{2}x-\frac{w}{2}x^2-M_j\right) \qquad (L_1\le x\le L_2) \qquad \cdots(113)$$

$$\phi(x)=\frac{1}{EI_h}\left(\frac{wL}{2}x-\frac{w}{2}x^2-M_j\right) \qquad (0\le x\le L_1, L_2\le x\le L) \qquad \cdots(114)$$

[0167]

When Expression (112) of which the right side is equal to 0 is solved for x, L_1 and L_2 are obtained by Expression (115) and Expression (116).

[0168]

$$L_1=\frac{L}{2}\left(1-\sqrt{1-\frac{8M_j}{xL^2}}\right) \qquad \cdots(115)$$

$$L_2=\frac{L}{2}\left(1+\sqrt{1-\frac{8M_j}{xL^2}}\right) \qquad \cdots(116)$$

[0169]

Next, assuming that clockwise rotation with respect to the horizontal plane is positive (+), the rotation angle θ (x) (rad) of the composite beam will be described. The rotation angle θ (x) is obtained by integrating the curvature φ of Expression (113) and Expression (114) for the coordinate x. Further, the rotation angle θ (x) is represented by Expression (120) to Expression (122) using Expression (119) in

consideration of the boundary conditions that the rotation angle θ becomes θ_j when the coordinate x is 0.

[0170]

$$A(x)=\frac{w}{6}x^3-\frac{wL}{4}x^2+M_j x \qquad \cdots(119)$$

$$\theta(x)=\frac{1}{EI_h}A(x)\Big|_{x=x}+\theta_j \qquad (0\le x\le L_1) \qquad \cdots(120)$$

$$\theta(x)=\frac{1}{EI_s}A(x)\Big|_{x=x}+\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)A(x)\Big|_{x=L_1}+\theta_j \qquad (L_1\le x\le L_2) \qquad \cdots(121)$$

$$\theta(x)=\frac{1}{EI_h}A(x)\Big|_{x=x}+\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)\left\{A(x)\Big|_{x=L_1}-A(x)\Big|_{x=L_2}\right\}+\theta_j \qquad (L_2\le x\le L) \qquad \cdots(122)$$

[0171]

Next, assuming that the vertical downward direction is positive (+), the deflection δ (x) (mm) generated on the composite beam will be described. The deflection δ (x) is obtained by integrating the rotation angle θ of Expression (120) to Expression (122) for the coordinate x. Further, the deflection δ (x) is represented by Expression (127) to Expression (129) using Expression (125) and Expression (126) in consideration of the boundary conditions that the deflection δ (x) becomes 0 when the coordinate x is 0.

[0172]

$$B(x)=\frac{w}{24}x^4-\frac{wL}{12}x^3+\frac{M_j}{2}x^2 \qquad \cdots(125)$$

$$C(x)=\frac{w}{8}x^4-\frac{wL}{6}x^3+\frac{M_j}{2}x^2 \qquad \cdots(126)$$

$$\delta(x)=\frac{1}{EI_h}B(x)\Big|_{x=x}+\theta_j x \qquad (0\le x\le L_1) \qquad \cdots(127)$$

$$\delta(x)=\frac{1}{EI_s}B(x)\Big|_{x=x}+\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)\left\{\left(A(x)\Big|_{x=L_1}\right)x-C(x)\Big|_{x=L_1}\right\}+\theta_j x$$
$$(L_1\le x\le L_2) \qquad \cdots(128)$$

$$\delta(x)=\frac{1}{EI_s}B(x)\Big|_{x=x}$$
$$+\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)\left\{\left(A(x)\Big|_{x=L_1}-A(x)\Big|_{x=L_2}\right)x-C(x)\Big|_{x=L_1}+C(x)\Big|_{x=L_2}\right\}+\theta_j x$$
$$(L_2\le x\le L) \qquad \cdots(129)$$

[0173]

Expression (127) to Expression (129) obtained above are represented in a form including the semi-rigid joint moment M_j and the rotation angle θ_j. On the other hand, in the form, the semi-rigid joint moment M_j and the rotation angle θ_j cannot be uniquely determined for a rotational rigidity S_j. Here, in a case where a distortion compatibility condition that the rotation angle θ becomes 0 rad when the coordinate x is (L/2) is used, a relationship between the rotational rigidity S_j and the rotation angle θ_j is represented by Expression (130) using Expression (111) and Expression (121).

[0174]

$$\theta(x)\Big|_{x=\frac{L}{2}}=\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)\left(\frac{wL^3}{24}-\frac{L}{3}S_j\theta_j\right)\sqrt{1-\frac{8S_j\theta_j}{wL^2}}$$
$$-\frac{1}{EI_h}\left(\frac{wL^3}{24}-\frac{L}{2}S_j\theta_j\right)+\theta_j=0 \qquad \cdots(130)$$

[0175]

Further, a distortion compatibility condition that the deflection δ (x) becomes 0 when the coordinate x is L is used. In this way, from Expression (111) and Expression (129), the relationship between the rotational rigidity S_j and the rotation angle θ_j is represented by Expression (131).

Expression (130) is equivalent to Expression (131).

[0176]

$$\left(\frac{1}{EI_h}-\frac{1}{EI_s}\right)\left(\frac{2L^2}{3}S_j\theta_j-\frac{wL^4}{24}-\frac{8}{3w}S_j{}^2\theta_j{}^2\right)+\frac{1}{EI_h}\sqrt{1-\frac{8S_j\theta_j}{wL^2}}\left(\frac{wL^4}{24}-\frac{L^2}{3}S_j\theta_j\right)$$
$$-\theta_j L\sqrt{1-\frac{8S_j\theta_j}{wL^2}}=0 \qquad \cdots(131)$$

[0177]

A maximum value δ_{max} of the deflection generated on the composite beam is a value when the coordinate x is (L/2) in Expression (128).

In order to calculate the maximum value δ_{max} of the deflection using Expression (130) or Expression (131), it is necessary to calculate the rotation angle θ_j by performing convergence calculation using Expression (130) or Expression (131). Further, it is necessary to calculate the deflection δ (x) when the coordinate x is (L/2) by using Expression (128).

[0178]

[3. Approximation Expression for Deflection of Composite Beam of which Both Ends are Semi-Rigidly Jointed]

The inventors have found that the following results are obtained by evaluating the maximum value δ_{max} of the deflection based on a nondimensional rotational rigidity and a nondimensional bending stiffness which are nondimensional values. That is,

regardless of specifications of the composite beam, it is possible to calculate the bending moment at supports and the maximum value δ_{max} of the deflection with high flexibility and with high accuracy without performing convergence calculation.

In the following, an approximation expression capable of calculating the bending moment at supports and the maximum value of the deflection by explicit functions will be described.

[0179]

As in Expression (135) and Expression (136), the nondimensional bending stiffness α_s and the nondimensional rotational rigidity α_j are defined.

[0180]

$$\alpha_s = \frac{\left(\frac{EI_s}{L}\right)}{\left(\frac{EI_h}{L}\right)} = \frac{EI_s}{EI_h} \quad \cdots(135)$$

$$\alpha_j = \frac{S_j}{\left(\frac{EI_h}{L}\right)} = \frac{S_j L}{EI_h} \quad \cdots(136)$$

[0181]

That is, the nondimensional bending stiffness α_s is defined as a ratio of the bending stiffness of sagging bending of the composite beam and the bending stiffness of hogging bending of the composite beam. In the example, the nondimensional bending stiffness α_s is defined as a ratio of the bending stiffness EI_s of sagging bending of the composite beam to the bending stiffness EI_h of hogging bending of the composite beam. In this case, the nondimensional bending stiffness α_s generally has a value equal to or larger than one. This is because the floor is usually above the beam in the vertical direction and the concrete of the floor has a compressive resistance larger than a tensile resistance. Thus, as compared with the hogging bending in which the concrete of the

floor is pulled, in the sagging bending in which the concrete of the floor is compressed, the resistance of the floor increases. In specifications of a general composite beam, the nondimensional bending stiffness α_s is equal to or smaller than 10. In a composite beam which is more commonly used, the nondimensional bending stiffness α_s is equal to or smaller than three.

The nondimensional bending stiffness α_s may be defined as a ratio of the bending stiffness EI_h of hogging bending of the composite beam to the bending stiffness EI_s of sagging bending of the composite beam.

The nondimensional rotational rigidity α_j is a value obtained by dividing the rotational rigidity of the end of the composite beam by the bending stiffness per unit length of the composite beam.

[0182]

Further, a pin joint moment M_o, a semi-rigid joint moment M_j, a rigid joint moment M_{jr}, a nondimensional joint moment β_{Mj}, and a nondimensional rigid joint moment $\beta_{Mj, rigid}$ are defined.

The pin joint moment M_o is defined when it is assumed that, in a composite beam in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are different from each other, the both ends are pin-jointed and an uniformly-distributed load acts over the entire length. The pin joint moment M_o means the maximum value of the bending moment acting on the composite beam. The pin joint moment M_o is represented by Expression (137).

The pin joint moment M_o is equal to the following value in a beam in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are equal to each other. The pin joint moment M_o is equal to the bending moment acting on the end of the beam in a case where the both ends are pin-jointed and an uniformly-

distributed load acts over the entire length. Specifically, the pin joint moment M_o is a value obtained by Expression of ($wL^2/8$).

[0183]

$$M_0 = \frac{wL^2}{8} \qquad \cdots(137)$$

[0184]

The semi-rigid joint moment M_j is an absolute value of the bending moment of the end of the composite beam as described above. More specifically, in the composite beam in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are different from each other and of which the both ends are semi-rigidly jointed and an uniformly-distributed load acts over the entire length, the semi-rigid joint moment M_j means the bending moment acting on the end of the composite beam. The semi-rigid joint moment M_j is represented by Expression (138) using the rotation angle θ_j calculated by performing convergence calculation using Expression (130) or Expression (131).

[0185]

$$M_j = S_j \left| \theta_j \right| \qquad \cdots(138)$$

[0186]

The rigid joint moment M_{jr} means the following value in the composite beam in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are different from each other. The rigid joint moment M_{jr} means the bending moment acting on the end of the composite beam in a case where the both ends are rigidly-jointed and an uniformly-distributed load acts over the entire length.

The composite beam according to the present embodiment is a beam in which

the bending stiffness of sagging bending and the bending stiffness of hogging bending are different from each other. For convenience of explanation, a beam according to Comparative Example in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are equal to each other is assumed. In the beam according to Comparative Example, in a case where the both ends are rigidly jointed and an uniformly-distributed load acts over the entire length, the rigid joint moment M_{jr} is a value obtained by Expression of $(wL^2/12)$.

The nondimensional joint moment β_{Mj} is a value obtained by dividing the semi-rigid joint moment M_j by the pin joint moment M_o, and is represented by Expression (139).

[0187]

$$\beta_{Mj} = \frac{M_j}{M_0} \qquad \cdots(139)$$

[0188]

The nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is a value obtained by dividing the rigid joint moment M_{jr} by the pin joint moment M_o, and is represented by Expression (140).

[0189]

$$\beta_{Mj,rigid} = \frac{M_{jr}}{M_0} \qquad \cdots(140)$$

[0190]

Here, indexes such as the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s are evaluated. Thus, for the composite beams according to the specifications of Case 1 to Case 6 shown in Table 9, the nondimensional joint moment β_{Mj} is trially calculated by changing the nondimensional

rotational rigidity α_j and the nondimensional bending stiffness α_s.

In Case 1 to Case 5, the both ends of the composite beam are semi-rigidly jointed, and in Case 6, the both ends of the composite beam are rigidly jointed.

[0191]

[Table 9]

Case	Length of Composite Beam	Bending Stiffness of Hogging Bending	Uniformly-Distributed Load	Pin Joint Moment	Nondimensional Rotational Rigidity			Nondimensional Bending Stiffness		
	L	EI_h	w	M_o	α_j			α_s		
	m	kNm^2	kN/m	kNm	-			-		
					Minimum Value	Maximum Value	Increments	Minimum Value	Maximum Value	Increments
1	10.0	229397	28.6	357	0.00	50.00	1.00	1.00	6.00	0.10
2	15.0	229397	28.6	803	0.00	50.00	1.00	1.00	6.00	0.10
3	15.0	229397	28.6	803	0.00	50.00	0.01	1.00	1.06	0.01
4	8.4	214311	28.6	252	0.00	100.00	0.50	1.00	1.30	0.05
5	13.8	229397	28.6	680	0.00	100.00	0.50	1.00	4.00	0.50
6	15.0	229397	28.6	803	∞	∞	-	1.00	51.00	0.10

[0192]

In Case 1, it is assumed that the length L of the composite beam is 10.0 m (10000 mm). Assuming that the bending stiffness EI_h of hogging bending is 229397 kNm^2 and the uniformly-distributed load w is 28.6 kN/m (28.6 N/mm), the pin joint moment M_o is calculated to 357 kNm from Expression (137). In Case 1, the Nondimensional rotational rigidity α_j is changed to 51 different values from a minimum value of 0.00 to a maximum value of 50.00 in increments of 1.00. That is, the Nondimensional rotational rigidity α_j is set to values of 0.00, 1.00, 2.00, ··, 50.00. The nondimensional bending stiffness α_s is changed to 51 different values from a minimum value of 1.00 to a maximum value of 6.00 in increments of 0.10. That is, the nondimensional bending stiffness α_s is set to values of 1.00, 1.10, 1.20, ··, 6.00. In Case 1, trial calculation is performed for 2601 (51 × 51) cases obtained by changing the values of the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

[0193]

In Case 2, with reference to Case 1, the length L of the composite beam is changed to 15.0 m. The pin joint moment M_o is calculated to 803 kNm from Expression (137). In Case 2, as in Case 1, trial calculation is performed for 2601 cases obtained by changing the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

In Case 3, a scale of the nondimensional rotational rigidity α_j, and a maximum value and a scale of the nondimensional bending stiffness α_s in Case 2 are changed. That is, in Case 3, the nondimensional rotational rigidity α_j is changed to 5001 different values from a minimum value of 0.00 to a maximum value of 50.00 in increments of 0.01. That is, the nondimensional rotational rigidity α_j is set to values of 0.00, 0.01,

0.02, ··, 50.00. The nondimensional bending stiffness α_s is changed to 7 different values from a minimum value of 1.00 to a maximum value of 1.06 in increments of 0.01. That is, the nondimensional bending stiffness α_s is set to values of 1.00, 1.01, 1.02, ··, 1.06. In Case 3, trial calculation is performed for 35007 (5001 × 7) cases obtained by changing the values of the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s. In Case 3, trial calculation is performed in more detail for a part of the ranges of the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s in Case 2.

[0194]

In Case 4, with reference to Case 1, the length L of the composite beam is changed to 8.4 m. Assuming that the bending stiffness EI_h of hogging bending is 214311 kNm^2, the pin joint moment M_o is calculated to 252 kNm from Expression (137). In Case 4, the nondimensional rotational rigidity α_j is changed to 201 different values from a minimum value of 0.00 to a maximum value of 100.00 in increments of 0.50. That is, the nondimensional rotational rigidity α_j is set to values of 0.00, 0.50, 1.00, ··, 100.00. The nondimensional bending stiffness α_s is changed to 7 different values from a minimum value of 1.00 to a maximum value of 1.30 in increments of 0.05. That is, the nondimensional bending stiffness α_s is set to values of 1.00, 1.05, 1.10, ··, 1.30. In Case 4, trial calculation is performed for 1407 (201 × 7) cases obtained by changing the values of the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

[0195]

In Case 5, with reference to Case 1, the length L of the composite beam is changed to 13.8 m. The pin joint moment M_o is calculated to 680 kNm from Expression (137). In Case 5, the value of the nondimensional rotational rigidity α_j is

changed in the same manner as in Case 4. The nondimensional bending stiffness α_s is changed to 7 different values from a minimum value of 1.00 to a maximum value of 4.00 in increments of 0.50. That is, the nondimensional bending stiffness α_s is set to values of 1.00, 1.50, 2.00, ··, 4.00. In Case 5, trial calculation is performed for 1407 (201 × 7) cases obtained by changing the values of the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

In Case 1 to Case 5, trial calculation is performed for a total of 43023 cases.

[0196]

In Case 6, a maximum value of the nondimensional rotational rigidity α_j and a maximum value of the nondimensional bending stiffness α_s in Case 2 are changed. In Case 6, the nondimensional rotational rigidity α_j is set to infinity (∞), that is, the rotational rigidity S_j is set to infinity, and it is assumed that both ends of the composite beam are rigidly jointed. The nondimensional bending stiffness α_s is changed to 501 different values from a minimum value of 1.00 to a maximum value of 51.00 in increments of 0.10. That is, the nondimensional bending stiffness α_s is set to values of 1.00, 1.10, 1.20, ··, 51.00.

[0197]

FIG. 18 shows a relationship between the nondimensional rotational rigidity α_j and the nondimensional joint moment β_{Mj} in Case 1 to Case 5. In FIG. 18, a horizontal axis represents the nondimensional rotational rigidity α_j, and a vertical axis represents the nondimensional joint moment β_{Mj}.

A straight line L11 is a nondimensional rigid joint moment $\beta_{Mj, rigid, u}$ in a normal beam in which the bending stiffness of sagging bending and the bending stiffness of hogging bending are equal to each other. In a normal beam, it is assumed that a length is L (mm) and an uniformly-distributed load is w (N/mm). In this case, in

a normal beam, the rigid joint moment M_{jr} is ($wL^2/12$), and the pin joint moment M_o is ($wL^2/8$). Thus, the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,u}$ is a value of 2/3 (approximately 0.667) by an expression of $\{(wL^2/12)/(wL^2/8)\}$.

[0198]

The trial calculation result of Case 1 is represented by a white square mark. Similarly, the trial calculation result of Case 2 is represented by a white triangle mark, and the trial calculation result of Case 3 is represented by a white circle mark. The trial calculation result of Case 4 is represented by a white diamond mark, and the trial calculation result of Case 5 is represented by a cross mark.

As the nondimensional rotational rigidity α_j on the horizontal axis increases, the joints at both ends of the composite beam approach rigid joints. As the nondimensional bending stiffness α_s approaches 1, the nondimensional joint moment β_{Mj} approaches a curve L12, which is an upper envelope in Case 1 to Case 5.

Further, as the nondimensional rotational rigidity α_j increases, the joints at both ends of the composite beam approach rigid joints. In this way, the nondimensional joint moment β_{Mj} converges to a value of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ represented by the straight line L11, which is an upper limit value.

It is considered that the nondimensional joint moment β_{Mj} represented by the curve L12 can be approximated by Expression (142) in consideration of a shape of the function and a limit of the nondimensional joint moment β_{Mj} when the nondimensional rotational rigidity α_j becomes 0 and infinity. Here, e is Napier's number (2.718··).

[0199]

$$\beta_{Mj} = \frac{\beta_{Mj,rigid}}{e^{\{k(log_{10}\alpha_j - log_{10}\alpha_{j,T})\}} + 1} \quad \cdots(142)$$

[0200]

In Expression (142), k is a coefficient. A variable $\alpha_{j,T}$ is the nondimensional rotational rigidity α_j when the nondimensional joint moment β_{Mj} has a value corresponding to a half of the nondimensional rigid joint moment $\beta_{Mj,rigid}$. In the following, a method of identifying the nondimensional rigid joint moment $\beta_{Mj,rigid}$, the coefficient k, and the variable $\alpha_{j,T}$ is proposed.

[0201]

[4. Identification of Approximation Expression]

[4.1. Control Variable of Nondimensional Rigid Joint Moment]

In Expression (130), in a case where both ends of the composite beam are rigidly jointed, it is assumed that the rotational rigidity S_j is infinite (nondimensional rotational rigidity α_j is infinite). Further, in a case where the Equation is represented by using the nondimensional rigid joint moment $\beta_{Mj,rigid}$, the nondimensional bending stiffness α_s, and the pin joint moment M_o, Expression (146) is obtained.

[0202]

$$\frac{L}{EI_h}\left(1-\frac{1}{\alpha_s}\right)\left(\frac{M_0}{3}-\frac{\beta_{Mj,rigid}M_0}{3}\right)\sqrt{1-\beta_{Mj,rigid}}-\frac{L}{EI_h}\left(\frac{M_0}{3}-\frac{\beta_{Mj,rigid}M_0}{2}\right)=0 \quad \cdots(146)$$

[0203]

Expression (146) is transformed to Expression (147) and Expression (148). Further, Expression (147) and Expression (148) are transformed to Expression (150) by using Expression (149).

[0204]

$$\left(1-\frac{1}{\alpha_s}\right)\left(1-\beta_{Mj,rigid}\right)\sqrt{1-\beta_{Mj,rigid}}=\left(1-\frac{3}{2}\beta_{Mj,rigid}\right) \quad \cdots(147)$$

$$\overline{\alpha_s}^2\left(1-\beta_{Mj,rigid}\right)^3=\left(1-\frac{3}{2}\beta_{Mj,rigid}\right)^2 \quad \cdots(148)$$

$$\overline{\alpha_s}=\left(1-\frac{1}{\alpha_s}\right) \quad \cdots(149)$$

$$\beta_{Mj,rigid}{}^3+3\left(\frac{3}{4\overline{\alpha_s}^2}-1\right)\beta_{Mj,rigid}{}^2-3\left(\frac{1}{\overline{\alpha_s}^2}-1\right)\beta_{Mj,rigid}+\left(\frac{1}{\overline{\alpha_s}^2}-1\right)=0 \quad \cdots(150)$$

[0205]

From the above, it is found that the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is, strictly speaking, a solution of a cubic differential equation according to Expression (150). Further, it is found that a solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ depends only on the nondimensional bending stiffness α_s and does not depend on the length L of the composite beam and the uniformly-distributed load w. Thus, solutions of Expression (50) can be obtained by using Cardano's formula, which is a solution of a cubic equation, and an exact solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ can be obtained from a real solution among the obtained solutions.

A relationship between the trial calculation results of the nondimensional bending stiffness α_s and the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ for Case 6 is shown in FIG. 19. In FIG. 19, a horizontal axis represents the nondimensional bending stiffness α_s. A vertical axis represents the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$.

[0206]

[4.2. Approximation Expression of Nondimensional Rigid Joint Moment]

Strictly speaking, the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ can be obtained as a real solution of the cubic equation by Expression (150). On the other hand, as shown in FIG. 19, in a range where the nondimensional bending stiffness α_s is

approximately equal to or smaller than 10, it is considered that the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ can be approximated by a linear form of a common logarithm of the nondimensional bending stiffness α_s.

As described above, the nondimensional bending stiffness α_s is equal to or smaller than 10 in a case where a thickness of a slab of a general composite beam is used. Therefore, in FIG. 19, the range in which the nondimensional bending stiffness α_s is equal to or smaller than 10 is approximated in a linear form, and the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is approximated by Expression (153).

[0207]

$$\beta_{Mj,rigid} = -\frac{15}{48} log_{10}\,\alpha_s + \frac{2}{3} \quad \cdots(153)$$

[0208]

In Expression (153), the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is calculated by an explicit function based on the nondimensional bending stiffness α_s.

Expression (153) is shown by a straight line L14 in FIG. 19. In the range where the nondimensional bending stiffness α_s is equal to or smaller than 10, the straight line L14 overlaps with the trial calculation result.

In Case 6, FIG. 20 shows a result obtained by comparing the approximation solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ by Expression (153) with the exact solution by Expression (150). In FIG. 20, a horizontal axis represents an approximation solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ by Expression (153), and a vertical axis represents an exact solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ (the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$) by Expression (150). In a case where the approximation solution and the exact solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ match each other, the trial calculation result

is plotted on the straight line L16.

The approximation solution and the exact solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ approximately match each other in a case where the approximation solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ exceeds 0.4. On the other hand, in a case where the approximation solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is equal to or smaller than 0.4, the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ may be corrected by Expression (154). Expression (154) is shown by a curve L17 in FIG. 20 in a state where the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is shown on the horizontal axis and the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ is shown on the vertical axis. The nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ overlaps with the exact solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$.

[0209]

$$\beta_{Mj,rigid,Theo} = -\frac{781}{1000}\beta_{Mj,rigid}{}^{3} + \frac{1702}{1250}\beta_{Mj,rigid}{}^{2} + \frac{1189}{5000}\beta_{Mj,rigid} + \frac{1369}{10000} \quad \cdots(154)$$

[0210]

That is, in a case where the approximation solution of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is equal to or smaller than 0.4, in Expression (142), instead of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$, the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ calculated by Expression (154) based on the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ may be used.

Next, an approximation expression of the coefficient k and the variable $\alpha_{j,\,T}$ is obtained.

For each nondimensional bending stiffness α_s, the coefficient k is obtained by the differential evolution method. FIG. 21 shows a relationship between the obtained coefficient k and the nondimensional bending stiffness α_s. The coefficient k depends

on the nondimensional bending stiffness α_s at a higher order, and is approximated by Expression (155).

Similarly, for each nondimensional bending stiffness α_s, the variable $\alpha_{j,T}$ is obtained by the differential evolution method. FIG. 22 shows a relationship between the obtained variable $\alpha_{j,T}$ and the nondimensional bending stiffness α_s. The variable $\alpha_{j,T}$ depends on the nondimensional bending stiffness α_s at a higher order, and is approximated by Expression (156).

[0211]

$$k = \frac{1}{5000}{\alpha_s}^6 - \frac{1}{250}{\alpha_s}^5 + \frac{196}{5000}{\alpha_s}^4 - \frac{1985}{10000}{\alpha_s}^3 + \frac{5549}{10000}{\alpha_s}^2 - \frac{4138}{5000}\alpha_s - \frac{18681}{10000} \quad \cdots(155)$$

$$\alpha_{j,T} = \frac{7}{1000}{\alpha_s}^3 - \frac{1343}{10000}{\alpha_s}^2 + \frac{7614}{5000}\alpha_s + \frac{6217}{10000} \quad \cdots(156)$$

[0212]

Expression (155) is shown by a curve L18 in FIG. 21. In the examination range, the trial calculation result is properly approximated by the curve L18. Similarly, Expression (156) is shown by a curve L19 in FIG. 22. In the examination range, the trial calculation result is properly approximated by the curve L19.

As described above, in a case where the nondimensional rigid joint moment $\beta_{Mj,rigid}$, the coefficient k, and the variable $\alpha_{j,T}$ are calculated by the nondimensional bending stiffness α_s, the nondimensional joint moment β_{Mj} is calculated by Expression (142). That is, based on the calculated nondimensional bending stiffness α_s, the nondimensional rotational rigidity α_j, and the nondimensional rigid joint moment $\beta_{Mj,rigid}$, the nondimensional joint moment β_{Mj} is calculated by the explicit function of Expression (142). More specifically, the nondimensional joint moment β_{Mj} is calculated by Expression (142) using Expression (153), Expression (155), and Expression (156). Alternatively, instead of Expression (153), the nondimensional joint

moment β_{Mj} may be calculated by substituting the nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ calculated using Expression (153) and Expression (154) into the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$.of Expression (142).

[0213]

[5. Calculation Expression of Maximum Value of Deflection using Approximation Expression]

Next, using a derived deflection function, the maximum deflection (maximum value of deflection) δ_{max} at the center of the composite beam is converted into Expression of the nondimensional joint moment β_{Mj} and the pin joint moment M_o.

First, a deflection function of a sagging bending region including the center of the composite beam is given by Expression (128). The maximum value δ_{max} of deflection is a value by Expression (128) when x = (L/2).

Here, L_1 and L_2 in Expression (115) and Expression (116) are represented by, as in Expression (160) and Expression (161), Expressions of the nondimensional joint moment β_{Mj}, pin joint moment M_o, and the semi-rigid joint moment M_j. Here, L_1 and L_2 are points where the bending moment of the composite beam becomes zero, and satisfy Expression (162).

[0214]

$$L_1 = \frac{L}{2}\left(1 - \sqrt{1 - \frac{8M_j}{wL^2}}\right) = \frac{L}{2}\left(1 - \sqrt{1 - \frac{M_j}{M_0}}\right) = \frac{L}{2}\left(1 - \sqrt{1 - \beta_{Mj}}\right) \quad \cdots(160)$$

$$L_2 = \frac{L}{2}\left(1 + \sqrt{1 - \frac{8M_j}{wL^2}}\right) = \frac{L}{2}\left(1 + \sqrt{1 - \frac{M_j}{M_0}}\right) = \frac{L}{2}\left(1 + \sqrt{1 - \beta_{Mj}}\right) \quad \cdots(161)$$

$$0 \le L_1 < L_2 \le L \quad \cdots(162)$$

[0215]

In a case where Expression (128) is represented by the nondimensional

bending stiffness α_s, the nondimensional rotational rigidity α_j, and the nondimensional joint moment β_{Mj}, Expression (128) is represented as Expression (164).

[0216]

$$\delta_{(x)} = \frac{1}{\alpha_s EI_h} B_{(x)} + \frac{1}{EI_h}\left(1 - \frac{1}{\alpha_s}\right)\left\{\left(A_{(x)}\big|_{x=L_1}\right)x - C_{(x)}\big|_{x=L_1}\right\} + \frac{\beta_{Mj} M_0 L}{\alpha_j EI_h} x \quad \cdots(164)$$

[0217]

By substituting Expression (160) into Expression (119) and Expression (126), Expression (166) and Expression (167) are obtained. By substituting x = (L/2) into Expression (125), Expression (168) is obtained.

[0218]

$$A_{(x)}\big|_{x=L_1} = \frac{wL^3}{48}\left(1 - \sqrt{1-\beta_{Mj}}\right)^3 - \frac{wL^3}{16}\left(1 - \sqrt{1-\beta_{Mj}}\right)^2 + \frac{L}{2} M_j \left(1 - \sqrt{1-\beta_{Mj}}\right)$$
$$= \frac{M_0 L}{2}\left\{\frac{\left(1-\sqrt{1-\beta_{Mj}}\right)^3}{3} - \left(1 - \sqrt{1-\beta_{Mj}}\right)^2 + \beta_{Mj}\left(1 - \sqrt{1-\beta_{Mj}}\right)\right\} \quad \cdots(166)$$

$$C_{(x)}\big|_{x=L_1} = \frac{wL^4}{128}\left(1 - \sqrt{1-\beta_{Mj}}\right)^4 - \frac{wL^4}{48}\left(1 - \sqrt{1-\beta_{Mj}}\right)^3 + \frac{L^2}{8} M_j \left(1 - \sqrt{1-\beta_{Mj}}\right)^2$$
$$= \frac{M_0 L^2}{2}\left\{\frac{\left(1-\sqrt{1-\beta_{Mj}}\right)^4}{8} - \frac{\left(1-\sqrt{1-\beta_{Mj}}\right)^3}{3} + \frac{\beta_{Mj}\left(1-\sqrt{1-\beta_{Mj}}\right)^2}{4}\right\} \quad \cdots(167)$$

$$B_{(x)}\big|_{x=\frac{L}{2}} = \frac{wL^4}{384} - \frac{wL^4}{96} + \frac{L^2}{8} M_j$$
$$= \frac{M_0 L^2}{8}\left(\beta_{Mj} - \frac{1}{2}\right) \quad \cdots(168)$$

[0219]

By setting x = (L/2) in Expression (164) and using Expression (166) to Expression (168), the maximum value δ_{max} of the deflection can be obtained by Expression (170).

[0220]

$$\delta_{\max} = \frac{M_0 L^2}{2EI_h}\left[\frac{2\beta_{Mj}-1}{8\alpha_s} - \left(1-\frac{1}{\alpha_s}\right)\left\{\frac{\left(1-\sqrt{1-\beta_{Mj}}\right)^4}{4} - \left(1-\sqrt{1-\beta_{Mj}}\right)^3 + \left(1+\frac{\beta_{Mj}}{2}\right)\left(1-\sqrt{1-\beta_{Mj}}\right)^2 - \beta_{Mj}\left(1-\sqrt{1-\beta_{Mj}}\right)\right\} + \frac{\beta_{Mj}}{\alpha_j}\right] \quad \cdots(170)$$

[0221]

By using Expression (170), it is possible to calculate the maximum value δ_{max} of the deflection based on the calculated nondimensional bending stiffness α_s, the nondimensional rotational rigidity α_j, and the nondimensional joint moment β_{Mj} by an explicit function.

On the other hand, by substituting the obtained bending moment M_j (semi-rigid joint moment M_j) at the end of the composite beam into Expression (112), a function of a moment distribution of the composite beam is obtained.

The bending moment at supports, which is a bending moment acting on the end of the composite beam, is a value obtained by substituting x = 0, L into the function of the moment distribution of the composite beam. Specifically, the bending moment M_j can be directly obtained from Expression (171) obtained by transforming Expression (139).

[0222]

$$M_j = \beta_{Mj} \times M_0 \quad \cdots(171)$$

[0223]

The nondimensional joint moment β_{Mj} and the pin joint moment M_o can be calculated by explicit functions such as Expression (142) and Expression (137), by using the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s, which are the given conditions, and the length L of the composite beam and the uniformly-distributed load w, which are design requirement values (given conditions).

Further, the coefficient k, the variable $\alpha_{j,T}$, and the nondimensional rigid joint moment $\beta_{Mj,rigid}$ in Expression (142) can be calculated by explicit functions in Expression (155), Expression (156), and Expression (153).

In a case where the nondimensional rigid joint moment $\beta_{Mj,rigid}$ calculated by Expression (153) is equal to or smaller than 0.4, in Expression (142), instead of the nondimensional rigid joint moment $\beta_{Mj,rigid}$, the nondimensional rigid joint moment $\beta_{Mj,rigid,Theo}$ calculated by Expression (154) based on the nondimensional rigid joint moment $\beta_{Mj,rigid}$ may be used.

The maximum value δ_{max} of the deflection, which is the maximum deflection at the center of the composite beam, can be explicitly obtained by substituting the nondimensional joint moment β_{Mj} calculated by Expression (142) and the given condition into Expression (170).

[0224]

As described above, in the evaluation method of the composite beam according to the present embodiment, the bending moment at supports and the maximum value δ_{max} of the deflection are calculated by explicit functions based on the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

[0225]

[6. Accuracy Verification of Approximation Expression]

For Case 1 to Case 5 in Table 9, FIG. 23 shows a result obtained by comparing the approximation solution of the nondimensional joint moment β_{Mj} by Expression (142) with the exact solution of the nondimensional joint moment β_{Mj} by Expression (153), Expression (155), and Expression (156). In FIG. 23, a horizontal axis represents the exact solution of the nondimensional joint moment β_{Mj}. A vertical axis represents the approximation solution of the nondimensional joint moment β_{Mj}. In a

case where the approximation solution and the exact solution of the nondimensional joint moment β_{Mj} match each other, the trial calculation result is plotted on the straight line L21. From the results shown in FIG. 23, it can be seen that the approximation solution and the exact solution of the nondimensional joint moment β_{Mj} match each other with sufficient accuracy for practical use.

Further, FIG. 24 shows a result obtained by comparing the approximation solution of the maximum value δ_{max} of the deflection with the exact solution of the maximum value δ_{max} of the deflection, the approximation solution being obtained by Expression (170) using the approximation solution of the nondimensional joint moment β_{Mj}. FIG. 24 also shows the trial calculation result of Case 6. The trial calculation result of Case 6 is represented by a white rectangular mark. From the results shown in FIG. 24, it can be seen that the approximation solution and the exact solution of the maximum value δ_{max} of the deflection match each other with sufficient accuracy for practical use.

As described above, the maximum value δ_{max} of the deflection is evaluated based on the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s. As a result, it can be seen that the maximum value δ_{max} of the deflection can be calculated with high flexibility and high accuracy regardless of specifications of the composite beam 211.

[0226]

A new composite beam may be designed based on the bending moment at supports and the maximum value of the deflection which are calculated by the evaluation method of the composite beam according to the present embodiment. That is, by using the evaluation method of the composite beam according to the present embodiment, a composite beam design method may be performed.

[0227]

As described above, in the evaluation method of the composite beam according to the present embodiment, the bending moment at supports and the maximum value δ_{max} of the deflection are evaluated by the inventors based on the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s. As a result, it is found that the bending moment at supports and the maximum value δ_{max} of the deflection can be calculated with high flexibility and high accuracy by the explicit functions regardless of specifications of the composite beam 211.

By calculating the bending moment at supports and the maximum value δ_{max} of the deflection of the composite beam 211 by explicit functions based on the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s, it is possible to calculate the bending moment at supports and the maximum value δ_{max} of the deflection of the composite beam 211 without performing convergence calculation.

[0228]

In addition, the nondimensional rigid joint moment $\beta_{Mj, rigid}$ is calculated by an explicit function based on the nondimensional bending stiffness α_s and Expression (153), and the nondimensional joint moment β_{Mj} is calculated by an explicit function based on the calculated nondimensional rigid joint moment $\beta_{Mj, rigid}$, the nondimensional rotational rigidity α_j, the nondimensional bending stiffness α_s, and Expression (142). Further, the bending moment at supports and the maximum value δ_{max} of the deflection are calculated by explicit functions based on the calculated nondimensional joint moment β_{Mj} and Expression (170). Thereby, it is possible to calculate the bending moment at supports and the maximum value δ_{max} of the deflection of the composite beam 211 without performing convergence calculation.

The nondimensional joint moment β_{Mj} is calculated by Expression (142) using

Expression (153), Expression (155), and Expression (156). Therefore, it is possible to calculate the nondimensional joint moment β_{Mj} by Expressions with high accuracy without performing convergence calculation. Therefore, it is possible to appropriately evaluate the deflection.

[0229]

In a case where the nondimensional rigid joint moment $\beta_{Mj, rigid}$ is equal to or smaller than 0.4, in Expression (142), instead of the nondimensional rigid joint moment $\beta_{Mj, rigid}$, the nondimensional rigid joint moment $\beta_{Mj, rigid, Theo}$ calculated by Expression (154) based on the nondimensional rigid joint moment $\beta_{Mj, rigid}$ is used. In a case where the nondimensional rigid joint moment $\beta_{Mj, rigid}$ is equal to or smaller than 0.4, the nondimensional rigid joint moment $\beta_{Mj, rigid}$ has a large error with respect to an exact solution. Even in this case, by using the nondimensional rigid joint moment $\beta_{Mj, rigid, Theo}$ instead of the nondimensional rigid joint moment $\beta_{Mj, rigid}$, it is possible to calculate the nondimensional rigid joint moment with high accuracy.

Further, for example, in convergence calculation for dynamic analysis of a structure including a plurality of composite beams, convergence calculation for calculating the bending moment of the composite beam which is a member of the structure is not necessary. Therefore, it is not necessary to perform double convergence calculation for dynamic analysis of the structure, and thus a calculation time can be significantly shortened. Further, for example, assuming that a cross-sectional area of the composite beam is set as an objective function and design conditions such as the deflection and the bending moment are set as constraint conditions, in a case of performing optimization calculation that minimizes the objective function, the following advantages can be obtained. That is, convergence calculation for calculating the deflection and the bending moment, which are constraint

conditions, is not required, and thus it is not necessary to perform double convergence calculation for optimization of the objective function. Therefore, a calculation time can be significantly shortened.

[0230]

As described above, the second embodiment of the present invention has been described in detail with reference to the drawings. On the other hand, the specific configuration is not limited to the embodiment, and modifications, combinations, and deletions in the configuration may be made without departing from the scope of the inventions.

For example, in the evaluation method of the composite beam according to the embodiment, the bending moment M_j and the maximum value δ_{max} of the deflection may be calculated by explicit functions based on the nondimensional rotational rigidity α_j and the nondimensional bending stiffness α_s.

At that time, the following procedure may be performed. That is, the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ may be calculated by an explicit function based on the nondimensional bending stiffness α_s. Based on the calculated nondimensional rigid joint moment $\beta_{Mj,\,rigid}$, the nondimensional rotational rigidity α_j, and the nondimensional bending stiffness α_s, the nondimensional joint moment β_{Mj} is calculated by an explicit function. The bending moment M_j and the maximum value δ_{max} of the deflection are calculated by explicit functions based on the calculated nondimensional joint moment β_{Mj}.

[0231]

As described above, the first embodiment and the second embodiment of the present invention have been described in detail with reference to the drawings. On the other hand, the specific configuration is not limited to the embodiments, and

modifications, combinations, and deletions in the configuration may be made without departing from the scope of the inventions. Further, it goes without saying that the configurations described in each embodiment can be used in combination as appropriate.

[Industrial Applicability]

[0232]

According to the present invention, it is possible to provide a method of evaluating a continuous beam, a program of evaluating a continuous beam, and a method of evaluating a composite beam. Therefore, the industrial applicability is high.

[Brief Description of the Reference Symbols]

[0233]

11: continuous beam

12a: intermediate fulcrum

12b: end fulcrum

13: beam (small beam)

27: first large beam (intermediate support portion)

31: second large beam (end support portion)

101: evaluation apparatus

112: solution determination unit

211: composite beam

M_j: semi-rigid joint moment

M_{jr}: rigid joint moment

M_o: pin joint moment

S11, S36, S46, S56, S66, S76: evaluation method (method of evaluating continuous beam)

S12, S37, S47, S57, S67, S77: solution determination step

S14: first design step

S16, S39, S49, S59, S69, S79: second design step

S18, S41, S51, S61, S81: temporary design step

S20: storage step

S22: solution calculation step

S24: residual calculation step

S26: determination step

α_j: nondimensional rotational rigidity

α_s: nondimensional bending stiffness

β_{Mj}: nondimensional joint moment

$\beta_{Mj,\ rigid}$, $\beta_{Mj,\ rigisd,\ Theo}$: nondimensional rigid joint moment

[Document Type] CLAIMS

1. A method of evaluating a continuous beam including n, which is a natural number equal to or larger than two, beams which are disposed side by side in a longitudinal direction and of which end portions adjacent to each other in the longitudinal direction are semi-rigidly jointed to each other to be intermediate fulcrums, both ends of the entire continuous beam being a pair of end fulcrums, the method comprising:

a solution determination step of obtaining a plurality of bending moments at the intermediate fulcrums and the pair of end fulcrums and a plurality of rotation angles at the pair of end fulcrums based on given conditions,

wherein the given conditions include

a length and a bending stiffness of each of the n beams,

a plurality of rotational rigidities at the intermediate fulcrums and the pair of end fulcrums,

vertical loads acting on the n beams, and

a plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums, and

wherein, in a case where the plurality of bending moments and the plurality of rotation angles are defined as a plurality of unknown quantities and a relational expression between the plurality of rotational rigidities, the plurality of bending moments, and the plurality of rotation angles and a relational expression between the plurality of vertical displacements are defined as a plurality of first boundary conditions having the same number as the number of the plurality of unknown quantities, in the solution determination step, the bending moments and a deflection distribution of the continuous beam are evaluated by solving the plurality of unknown quantities such that

the plurality of unknown quantities satisfy the plurality of first boundary conditions.

2. The method of evaluating a continuous beam according to claim 1,

wherein the solution determination step includes

a first design step of giving design values including the plurality of vertical displacements,

a second design step of giving second boundary conditions to the pair of end fulcrums according to joint states at the pair of end fulcrums,

a temporary design step of giving temporary design values including the bending moments acting on the pair of end fulcrums and the intermediate fulcrums according to the joint state at the pair of end fulcrums,

a solution calculation step of calculating, based on the temporary design values, calculation values including calculation results of the vertical displacements at the intermediate fulcrums so as to satisfy the plurality of first boundary conditions and the plurality of second boundary conditions,

a residual calculation step of obtaining a displacement residual which is a residual between the design value and the calculation value, and

a determination step of determining whether or not the displacement residual is smaller than a predetermined threshold value.

3. The method of evaluating a continuous beam according to claim 2,

wherein the solution determination step further includes a storage step of storing the temporary design values after the temporary design step,

wherein, in the determination step, in a case where the displacement residual is equal to or larger than the threshold value, giving other new temporary design values in the temporary design step instead of the temporary design values stored in the storage step and performing the solution calculation step, the residual calculation step, and the

determination step based on the new temporary design values are performed as a set, and the set is repeatedly performed until it is determined in the determination step that the displacement residual is smaller than the threshold value, and

wherein the bending moments of the temporary design values in a case where it is determined in the determination step that the displacement residual is smaller than the threshold value are defined as the bending moments acting on the intermediate fulcrums, and the plurality of rotation angles are obtained based on the bending moments.

4. The method of evaluating a continuous beam according to claim 2 or 3,

wherein, in the solution calculation step, for a natural number i equal to or larger than one and equal to or smaller than n, among the n beams, for an i-th beam from a first end fulcrum which is one of the end fulcrums of the continuous beam toward a second end fulcrum which is the other of the end fulcrums of the continuous beam,

the vertical displacements δ_{0i} (m) of the i-th beam at the intermediate fulcrums or the end fulcrums on a first end fulcrum side are defined as the given conditions, and

calculation results $\delta_{i,\,calc}$ (m) of the vertical displacements of the i-th beam at the intermediate fulcrums or the end fulcrums on a second end fulcrum side are calculated by Expression (9) obtained based on Expression (1) to Expression (8), the calculation results being included in the calculation values, and

wherein, in the residual calculation step, for a natural number i equal to or larger than one and equal to or smaller than (n-1), in a case where a residual between the vertical displacements $\delta_{0(i+1)}$ of the (i+1)-th beam at the intermediate fulcrums on the first end fulcrum side and the calculation results $\delta_{i,\,calc}$ of the vertical displacements of the i-th beam at the intermediate fulcrums on the second end fulcrum side is defined as

an i-th residual,

an intermediate residual which is a sum from the first residual to the (n-1)-th residual is calculated,

a residual at the second end fulcrum is calculated, the residual at the second end fulcrum being a residual between the vertical displacements δ_n at the second end fulcrum which are the given conditions and the calculation results $\delta_{n,\,calc}$ of the vertical displacements of an n-th beam at the second end fulcrum, and

the displacement residual is calculated, the displacement residual being a sum of the intermediate residual and the residual at the second end fulcrum,

$$V_{jl,i} = \frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2} \quad \cdots (1)$$

$$V_{jr,i} = w_i \cdot L_i - V_{jl,i} = \frac{w_i \cdot L_i}{2} - \frac{M_{j,i-1} - M_{j,i}}{L_i} \quad \cdots (2)$$

$$x_{h,i} = \frac{1}{w_i}\left\{V_{jl,i} - \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{j,i-1}}\right\} \quad \cdots (3)$$

$$x_{s,i} = \frac{1}{w_i}\left\{V_{jl,i} + \sqrt{{V_{jl,i}}^2 - 2w_i \cdot M_{j,i-1}}\right\} \quad \cdots (4)$$

$$f_{(x_i)} = \left(\frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^2}{2} - \frac{w_i \cdot {x_i}^3}{6} - M_{j,i-1} \cdot x_i \quad \cdots (5)$$

$$F_{(x_i)} = \left(\frac{M_{j,i-1} - M_{j,i}}{L_i} + \frac{w_i \cdot L_i}{2}\right) \cdot \frac{{x_i}^3}{6} - \frac{w_i \cdot {x_i}^4}{24} - \frac{M_{j,i-1}}{2} \cdot {x_i}^2 \quad \cdots (6)$$

$$\varphi_{c(x_i)}\big|_{x_i=L_i} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\left(f_{(x_i)}\big|_{x_i=x_{h,i}} - f_{(x_i)}\big|_{x_i=x_{s,i}}\right) - \frac{1}{EI_{h,i}} f_{(x_i)}\big|_{x_i=L_i} + \varphi_{0i} \quad \cdots (7)$$

$$\varphi_{0i} = \left(\frac{1}{S_{jr,i-1}} + \frac{1}{S_{jl,i}}\right) M_{j,i-1} + \varphi_{c(x_{i-1})}\big|_{x_{i-1}=L_{i-1}} \quad \cdots (8)$$

$$\begin{aligned}\delta_{i,calc} = -\left(\frac{1}{EI_{h,i}} - \frac{1}{EI_{s,i}}\right)\Big\{&F_{(x_i)}\big|_{x_i=x_{h,i}} - F_{(x_i)}\big|_{x_i=x_{s,i}} + f_{(x_i)}\big|_{x_i=x_{h,i}}\left(L_i - x_{h,i}\right) \\ &- f_{(x_i)}\big|_{x_i=x_{s,i}}\left(L_i - x_{s,i}\right)\Big\} - \frac{1}{EI_{h,i}} F_{(x_i)}\big|_{x_i=L_i} + \varphi_{0i} \cdot L_i + \delta_{0i} \quad \cdots (9)\end{aligned}$$

here, for a natural number i equal to or larger than one and equal to or smaller than n, a length of the i-th beam is defined as L_i (m), a coordinate of the i-th beam is defined as x_i (m) in a case where an end of the i-th beam on the first end fulcrum side is

set as an origin and a direction from the first end fulcrum toward the second end fulcrum is set as positive, a vertical load acting on the i-th beam is defined as w_i (N/m), a rotational rigidity of the end of the i-th beam on the first end fulcrum side is defined as $S_{jl,\,i}$ (Nm/rad), a rotational rigidity of an end of the i-th beam on the second end fulcrum side is defined as $S_{jr,\,i}$ (Nm/rad), a bending stiffness of sagging bending of the i-th beam is defined as $EI_{s,\,i}$ (Nm^2), a bending stiffness of hogging bending of the i-th beam is defined as $EI_{h,\,i}$ (Nm^2), and a bending moment of the i-th beam at the intermediate fulcrums or the end fulcrums on the second end fulcrum side is defined as $M_{j,\,i}$ (Nm), and a bending moment $M_{j,\,0}$ (Nm) of a first beam at the first end fulcrum is 0 in a case where the first end fulcrum is pin-jointed and is an unknown quantity in a case where the first end fulcrum is rigidly jointed or semi-rigidly jointed, and a rotation angle φ_{01} (rad) of the first beam at the first end fulcrum is 0 in a case where the first end fulcrum is rigidly jointed and is an unknown quantity in a case where the first end fulcrum is pin-jointed or semi-rigidly jointed, the bending moment $M_{j,\,0}$ (Nm) and the rotation angle φ_{01} (rad) of the first beam being included in the second boundary conditions.

5. A program for an evaluation apparatus that evaluates a continuous beam including n, which is a natural number equal to or larger than two, beams which are disposed side by side in a longitudinal direction and of which end portions adjacent to each other in the longitudinal direction are semi-rigidly jointed to each other to be intermediate fulcrums, both ends of the entire continuous beam being a pair of end fulcrums, the program causing the evaluation apparatus to function as:

a solution determination unit that obtains a plurality of bending moments at the intermediate fulcrums and the pair of end fulcrums and a plurality of rotation angles at the pair of end fulcrums based on given conditions,

wherein the given conditions include

a length and a bending stiffness of each of the n beams,

a plurality of rotational rigidities at the intermediate fulcrums and the pair of end fulcrums,

vertical loads acting on the n beams, and

a plurality of vertical displacements at the intermediate fulcrums and the pair of end fulcrums, and

wherein, in a case where the plurality of bending moments and the plurality of rotation angles are defined as a plurality of unknown quantities and a relational expression between the plurality of rotational rigidities, the plurality of bending moments, and the plurality of rotation angles and a relational expression between the plurality of vertical displacements are defined as a plurality of first boundary conditions having the same number as the number of the plurality of unknown quantities,

the solution determination unit evaluates the bending moments and a deflection distribution of the continuous beam by solving the plurality of unknown quantities such that the plurality of unknown quantities satisfy the plurality of first boundary conditions.

6. A method of evaluating a composite beam by calculating bending moment at supports which are bending moments acting on both ends of the composite beam and a maximum value of a deflection generated on the composite beam, in which a bending stiffness of sagging bending and a bending stiffness of hogging bending are different from each other, of which both ends are semi-rigidly jointed, and on which a uniformly-distributed load acts over an entire length, the method comprising:

calculating the bending moment at supports and the maximum value of the deflection by explicit functions based on a nondimensional rotational rigidity and a nondimensional bending stiffness,

in a case where a value obtained by dividing a rotational rigidity of the end of

the composite beam by a bending stiffness per unit length of the composite beam is defined as the nondimensional rotational rigidity, and

a ratio between the bending stiffness of the sagging bending of the composite beam and the bending stiffness of the hogging bending of the composite beam is defined as the nondimensional bending stiffness.

7. The method of evaluating a composite beam according to claim 6, further comprising:

calculating a nondimensional rigid joint moment by an explicit function based on the nondimensional bending stiffness;

calculating a nondimensional joint moment by an explicit function based on the calculated nondimensional rigid joint moment, the nondimensional rotational rigidity, and the nondimensional bending stiffness; and

calculating the bending moment at supports and the maximum value of the deflection by explicit functions based on the calculated nondimensional joint moment,

in a case where a bending moment acting on the end of the composite beam when it is assumed that the both ends are rigidly jointed and a uniformly-distributed load acts over the entire length is defined as the rigid joint moment,

a maximum value of the bending moment acting on the composite beam when it is assumed that the both ends are pin-jointed and an uniformly-distributed load acts over the entire length is defined as a pin joint moment,

a bending moment acting on the end of the composite beam when it is assumed that the both ends are semi-rigidly jointed and an uniformly-distributed load acts over the entire length is defined as a semi-rigid joint moment,

a value obtained by dividing the semi-rigid joint moment by the pin joint moment is defined as the nondimensional joint moment, and

a value obtained by dividing the rigid joint moment by the pin joint moment is defined as the nondimensional rigid joint moment.

8. The method of evaluating a composite beam according to claim 7,

wherein, in a case where the nondimensional rigid joint moment is defined as $\beta_{Mj,\,rigid}$, the nondimensional rotational rigidity is defined as α_j, and the nondimensional bending stiffness is defined as α_s,

the nondimensional joint moment β_{Mj} is calculated by Expression (13) using Expressions (10) to (12),

$$k = \frac{1}{5000}\alpha_s^{\,6} - \frac{1}{250}\alpha_s^{\,5} + \frac{196}{5000}\alpha_s^{\,4} - \frac{1985}{10000}\alpha_s^{\,3} + \frac{5549}{10000}\alpha_s^{\,2} - \frac{4138}{5000}\alpha_s - \frac{18681}{10000} \quad \cdots(10)$$

$$\alpha_{j,T} = \frac{7}{10000}\alpha_s^{\,3} - \frac{1343}{10000}\alpha_s^{\,2} + \frac{7614}{5000}\alpha_s + \frac{6217}{10000} \quad \cdots(11)$$

$$\beta_{Mj,rigid} = -\frac{15}{48}\log_{10}\alpha_s + \frac{2}{3} \quad \cdots(12)$$

$$\beta_{Mj} = \frac{\beta_{Mj,rigid}}{e^{\left\{k\left(\log_{10}\alpha_j - \log_{10}\alpha_{j,T}\right)\right\}} + 1} \quad \cdots(13)$$

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9. The method of evaluating a composite beam according to claim 8,

wherein, in a case where the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is equal to or smaller than 0.4, in Expression (13), instead of the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$, a nondimensional rigid joint moment $\beta_{Mj,\,rigid,\,Theo}$ calculated by Expression (14) based on the nondimensional rigid joint moment $\beta_{Mj,\,rigid}$ is used,

$$\beta_{Mj,rigid,Theo} = -\frac{781}{1000}\beta_{Mj,rigid}^{\,3} + \frac{1702}{1250}\beta_{Mj,rigid}^{\,2} + \frac{1189}{5000}\beta_{Mj,rigid} + \frac{1369}{10000} \quad \cdots(14)$$

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