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Analysis of corrugated steel web beam bridges using spatial grid modelling

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Abstract. Up to now, Japan has more than 200 corrugated steel web composite beam bridges which are under construction and have been constructed, and China has more than 30 corrugated steel web composite beam bridges. The bridge type includes the simply supported beam, continuous beam, continuous rigid frame and cable stayed bridge etc. The section form has developed to the single box and multi-cell box girder from the original single box and single chamber. From the stress performance and cost saving, the span range of 50~150 m is the most competitive. At present, the design mostly adopts the computational analytical method combining the spatial bar system model, plane beam grillage model and solid model. However, the spatial bar system model is short of the refinement analysis on the space effect, such as the shear lag effect, effective distribution width problem, and eccentric load factor problem etc. Due to the similarity of the plane beam grillage method in the equivalence principle, it cannot accurately reflect the shearing stress distribution and local stress of the top and bottom plates of the box type composite beam. The solid model is very difficult to combine with the overall calculation. Moreover, the spatial grid model can achieve the refinement analysis, with the integrity of the analysis and the comprehensiveness of the stress checking calculation, and can make up the deficiency of the analytical method currently. Through the example verification of the solid model and spatial grid model, it can be seen that the calculation results for the stress and the displacement of two models are almost consistent, indicating the applicability and precision of the spatial grid model.

Keywords: corrugated steel web; composite beam bridge; solid model; spatial grid model; refinement

1. Introduction

In the late 1980s, France firstly applied the steel web into the bridge structure, and built the first corrugated steel web beam bridge – Cognac Bridge. With the successful application of such structure, various countries successively constructed such type of the bridge, such as Maupre Bridge, Asterix Bridge, and Dole Bridge in France, Tronko Bridge in Norway, Caracas Bridge and Corniche Bridge in Venezuela. After introducing such structure, Japan constructed the first corrugated steel web composite simply supported box beam bridge – Xinkai Bridge of Japan in

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1993. At present, Japan is the country with the most extensive application of such structure in the world, and Japan has more than 200 corrugated steel web PC composite box beam bridges which are under construction and have been constructed. The box section form has developed to the multi-cell box girder from the original single box and single chamber. The bridge type have developed to the extra-dosed bridges now from the simply supported beam, continuous beam, and continuous rigid frame (Takaki *et al*. 2009, Jung *et al*. 2011, Okusumi 2008, He 2011).

China has nearly 30 corrugated steel web bridges which are under construction and have been constructed, including simply supported beam, continuous beam, continuous rigid frame, cable stayed bridge of PC composite box beam and other bridge types. Four bridges (the first one-box and seven-chamber corrugated steel web composite box beam bridge in China) involving Guo Shoujing Bridge and Gangtielu Bridge in Baiquan Avenue of Xingtai, Hebei, the $(70+11\times120+70)$ m corrugated steel web PC continuous box beam of Yellow River Bridge of Juancheng, Shandong, and $(60+5\times120+60)$ m corrugated steel web cable stayed bridge of Zhaoyang Bridge of Nanchang, Jiangxi under construction are the most typical (He 2011). The typical corrugated steel web composite beam bridge is shown as Fig. 1.

At present, for the analysis of the corrugated steel web composite beam bridge, it generally adopts the method combining the spatial bar system model, plane beam grillage method and local solid analysis (Chan *et al*. 2002). However, the spatial bar system model is short of the refinement analysis on the space effect, such as the plane cross-section assumption of wide box beam, effective distribution width, eccentric load factor, internal force distribution of each web, lateral distribution factor and other problems. Due to the similarity of the plane beam grillage method in the equivalence principle, it cannot accurately reflect the shearing stress distribution and local stress of the top and bottom plates of the box type composite beam. The solid model is very difficult to completely combine with the overall calculation. The analysis result is the overall stress result, and does not match with the internal force reinforcement design method as stipulated in force, which has always been applied in the local analysis.

(Chao and Xu 2010, 2012, Xu 2008, Xu and Yu 2012) described and applied the practical refinement analytical method – spatial grid model. The grid model deems the composite beam section as being composed of several plates, makes the beam grillage division for each plate, and equivalently replaces the stress of each plate by the divided beam grillage. Compared with the beam grillage method, the spatial grid division is finer. Due to denser division of the top plate, it can analyze the stress of the beam grillage of the top plate under the shear lag effect, without calculating the effective width. The rigidity torsion is reflected on the shearing stress of each beam grillage through the mutual combined action between the spatial grids, and also can achieve the distortion analysis of the cross section and the lateral bending deformation of each plate of the cross section under the load effect. It can analyze various deformation forms of the composite beam cross section under the eccentric load. The output result of the spatial grid model is the internal force, stress and displacement of each beam grillage, and can gain the stress state of various structural parts conveniently, and accordingly strengthen the constructional reinforcement specifically, which has important significance on the design analysis of the practical engineering.

Through the contrast of the calculation result between the spatial grid model and ANSYS solid finite element model, it can be seen that two models can be identical well in the aspects of the displacement and stress under three working conditions involving dead load, anti-symmetric load, and eccentric load. Thus, the calculation result of the spatial grid model is accurate, which can reflect the space stress characteristics of the box beam cross section authentically and acquire various complete index stresses as needed for concerning.

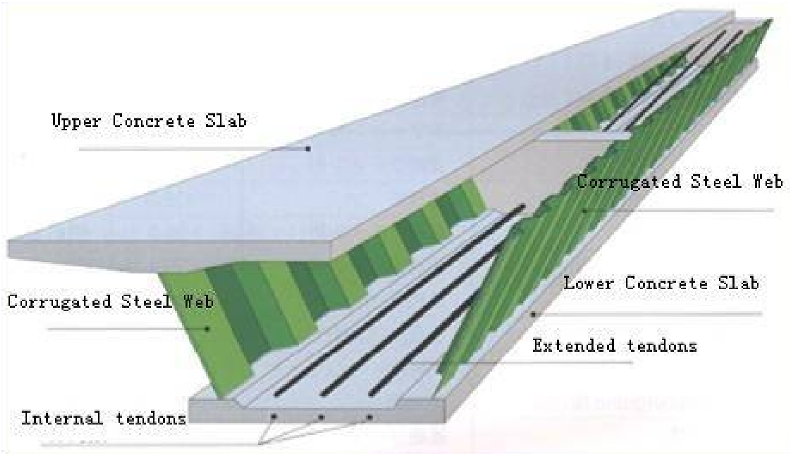


Fig. 1 Typical corrugated steel web bridge

2. Analysis situation of corrugated steel web bridge

At present, for the stress analysis of the corrugated steel web composite beam bridge, the common calculation method is the vertical calculation and lateral calculation respectively, to acquire the vertical and horizontal global effect of the structure. Then it calculates the local effect by adopting some large-scale general solid finite element software.

While calculating the vertical and horizontal global effect,it always adopts the plane bar system or spatial bar system for calculation. The full cross section of the composite beam is deemed as meeting the proposed plane cross section assumption (Valsa Ipe *et al*. 2013, Mo and Fan 2006, Machimdamrong *et al*. 2004). The encountered shear lag problems are generally solved by introducing the effective distribution width in the calculation, and the encountered live load and eccentric load also adopt the eccentric load factor for solving approximately. Various kinds of overall structure reaction and load effect can be reflected approximately in the general calculation in this mode, such as the function of the stayed cable, shrinkage and creep of the top plate and bottom plate in the steel – concrete superposed beam, local temperature difference of the bridge floor and other effects, with the calculation purpose of coordinating with the current specifications.

The purpose of building the full bridge model or local model by adopting the entity unit is to check some local stress situations in the steel – concrete superposed beam cross section, such as the stress situation of the steel plate, the local stability of the steel plate, and the distribution situation of the shearing force between the steel – concrete bridge floors.

The spatial bar system model is short of refinement analysis on the space effect. In the case of meeting the engineering accuracy, the plane beam grillage method is a convenient as well as applicable approach for the finite element design and analysis, and provides great convenience for the engineering technicians. However, due to the similarity of the equivalence principle, the calculation result can not accurately reflect the shearing stress distribution of the box type composite beam cross section. But adopting the entity analysis to make the supplementary calculation is difficult to combine with the overall calculation fully, and is also difficult to coordinate with the calculation of the design requirements such as the construction stage, creep and shrinkage, live load and acting load. Moreover, the analysis result is the overall stress result under various kinds of the deformations, and does not match with the internal force reinforcement design method in the current specification, which is difficult to strengthen the constructional reinforcement pointedly. In addition, the process of integrating the analysis result of the entity unit to gain the structure internal force is complex and tedious, restricts the extensive application in the design, and is only applied in the local analysis.

Thus, it is clear that utilizing the traditional analytical method is unable to fully reflect the stress characteristics of the corrugated web bridge, and is unable to solve the key problem of designing the corrugated web bridge. Therefore, it is necessary to break through the traditional method of the single beam analysis and design, utilize more comprehensive analytical method to carry out the stress analysis and design, and combine the current specification to finish the design work of the structure reinforcement while completing the structure internal force and stress analysis.

3. Introduction of spatial grid model

In the structural analysis, the complex bridge structure can be dispersed into the composition of several plates. Each plate element is composed of the crisscross orthogonal beam grillage, with the rigidity of the crisscross vertical and horizontal beams (6DOF beam unit) as the rigidity of the plate. An orthogonal beam grillage likes a “net”. The quantity of plates constitute a structure can indicate as the equal quantity of “nets” by the beam grillage. Thus, the spatial bridge structure can be indicated as the spatial grid. As shown in Fig. 2, the cross section of the single box and single chamber box girder can be decomposed into the top plate, bottom plate and several webs. “Plate” dispersed from the box cross section beam can be simulated by the orthogonal beam grillage model. Because these “plates” are located at different planes, the orthogonal beam grillages on behalf of them are in different planes (curved surface as for the bending beam bridge). The orthogonal beam grillages in different planes disperses the box cross section beam into a spatial “net” shape model, which can visually be called as “spatial grid” model (Xu 2008, Xu and Yu 2012).

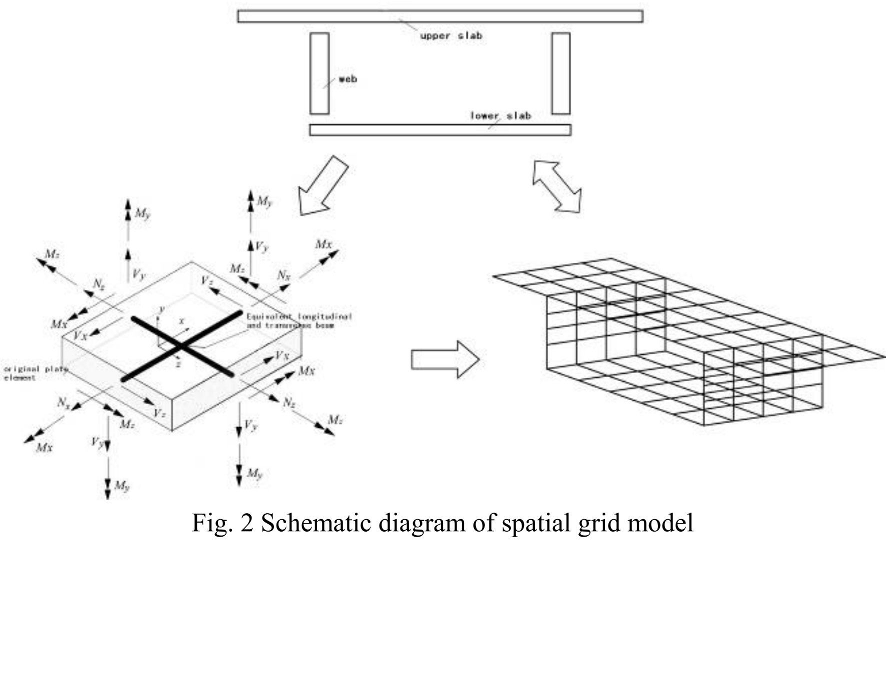
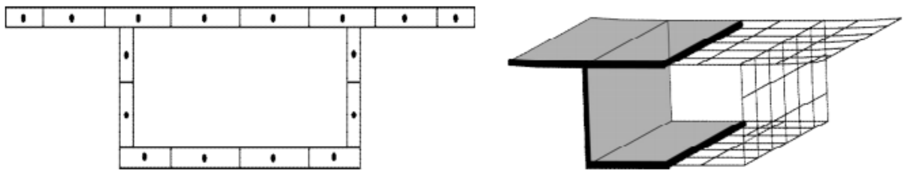


Fig. 2 Schematic diagram of spatial grid model



Grid model (adding the cross beam) divided and formed by top and bottom plates and webs

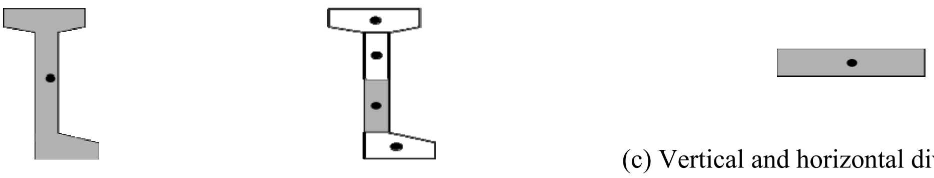
Fig. 3 Schematic diagram of cross section division mode of spatial grid model

3.1 Structural dispersing

While building the spatial grid model, it can be divided in accordance with the division mode of the single beam finite element longitudinally (i.e., the considered elements generally include the structural stress and natural construction division). The density degree of the internal division of the cross section should be determined in accordance with the cross section form and calculation requirements, which reflects the refinement degree of the space effect. While dividing the cross section of the spatial grid model, it partitions the webs. The webs and the top and bottom plates are divided. See Fig. 3 for the corresponding cross section division and grid model.

3.2 Calculation of cross section characteristics after dispersing

In the spatial grid model acquired from dispersing as per Fig. 3, the cross section mainly includes the following three types, such as global section of the web, division section of the web, and vertical and horizontal division section of top and bottom plates, as shown in Fig. 4. The



(a) Section of web (b) Division section of web (c) Vertical and horizontal division section of top and bottom plates

Fig. 4 Common cross section of spatial grid model

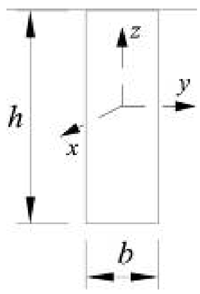


Fig. 5 Schematic diagram of calculation of common cross section characteristics in spatial grid model

calculation of these cross sections and characteristics is consistent with the cross section characteristics of the traditional beam element, which is calculated by the actual cross sectional dimension after dispersing.

Here take the rectangular cross section in Fig. 5 as an example, indicating the calculation method of the common cross section characteristics in the grid model.

$$\text{Axial direction area}: \quad A_x = bh \tag{1}$$

$$\text{Shearing area}: \quad A_y = A_z = bh \tag{2}$$

$$\text{Anti-bending moment of inertia}: \quad I_z = \frac{b^2 h}{12}; \quad I_y = \frac{bh^3}{12} \tag{3}$$

After the cross section division, the anti-torque moment of inertia of dividing the cross section has the fairly limited influence on the global section, so the anti-torque moment of inertia can adopt the following simplified formula for calculation.

$$I_T = \frac{4 I_z I_y}{\beta (I_z + I_t)}; \quad \beta = 1.3 \sim 1.6 \tag{4}$$

3.3 Effect calculation and expression means

The spatial grid model is to deem the thin walled box cross section as the composition of several plates, carry out the grid division for each plate, and equivalently replace the stress of each plate by the grid after dividing. Because the spatial grid model divides the top and bottom plates densely, it can analyze the shear lag effect of the top and bottom plates, without calculating the effective distribution width. The rigidity torsion effect of the box beam is reflected on the shearing stress distribution of each beam grillage through the mutual effect among the vertical and horizontal elements of the spatial grid. The spatial grid model can also achieve the distortion analysis of the cross section under the load effect and the horizontal bending deformation analysis of each plate of the cross section.

3.3.1 Space load effect calculation

While using the spatial grid model, the load effect of the cross section is borne as follows:

- The vertical effect (such as the axial force and bending moment) of the box beam cross section is borne by the vertical beam grillage.
- The horizontal effect (such as the distortion and horizontal effect of live load etc.) of the box beam cross section is borne by the horizontal beam grillage.
- The torsion and distortion effects of the box beam cross section are converted into the shearing force of the web beam grillage.

In the spatial grid model, it can gain the internal force (involving the axial force, bending moment, shearing force, and torque) of the cross section in each part (the global section of the web or the division section of the web) as the composition of the grid. The element internal force is distributed in accordance with the element rigidity. For different cross section forms, the calculation modes of the load effect are respectively as follows.

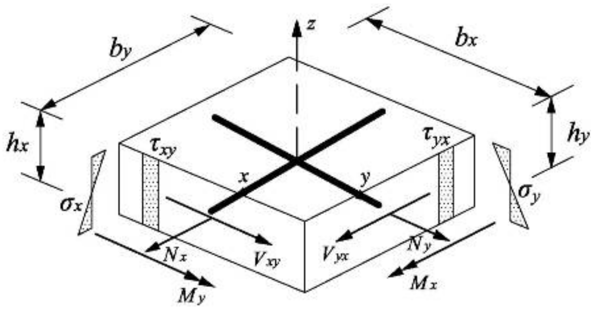


Fig. 6 Schematic diagram of “Division Section” effect calculation of spatial grid model

3.3.2 Division section

It is generally used for the top plate and bottom plate of the box beam in the simulated grid model, and mainly bears the axial force *Nx* and *Ny*, the in-plane shearing force *Vxy* and out-of-plane bending moment *Mx* and *My*. As shown in Fig. 6, the membrane effect distributing equally along the element thickness and the local load effect of the top and bottom plates (the out-of-plane bending normal stress with the linear change along the element thickness) can be fully reflected through “division section”.

(1) Out-of-plane normal stress

$$\sigma_x = \frac{M_y z}{I_y} \tag{5}$$

$$\sigma_y = \frac{M_x z}{I_x} \tag{6}$$

In the formula, σ_x − x direction normal stress of the cross section;
σ_y − y direction normal stress of the cross section;
z − Calculating the distance between the stress point and the gravity axis of cross section of the normal stress, and valuing the positive value above the gravity axis;
I_x, I_y − Inertia moment of the cross section around the gravity axis of each cross section perpendicular to y axis or x axis;
M_x, M_y − Bending moment of the cross section around the gravity axis of each cross section perpendicular to y axis or x axis

(2) In-plane normal stress

$$\sigma_{x-m} = \frac{N_x}{A_x} = \frac{N_x}{b_x h_x} \tag{7}$$

$$\sigma_{y-m} = \frac{N_y}{A_y} = \frac{N_y}{b_y h_y} \tag{8}$$

In the formula, $\sigma_{x\text{-}m}$ − x direction normal stress in the cross section;

$\sigma_{y\text{-}m}$ − y direction normal stress in the cross section;
b_x, b_y − Width of the cross section perpendicular to x axis or y axis in the cross section;
h_x, h_y − Height of the cross section perpendicular to x axis or y axis in the cross section

(3) In-plane shearing stress

$$\tau_{xy} = \frac{V_{xy}}{b_x h_x} \tag{9}$$

(4) The in-plane main tensile stress σ_t and the main compressive stress σ_c are calculated in the following formula

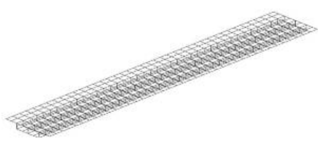
$$\begin{matrix}\sigma_t \\ \sigma_c\end{matrix} = \frac{\sigma_{x-m} + \sigma_{y-m}}{2} \pm \sqrt{\left(\frac{\sigma_{x-m} - \sigma_{y-m}}{2}\right)^2 + \tau_{xy}^2} \tag{10}$$

The spatial grid model can accurately analyze the space stress state of the complex structure. Also, the output data results (output in the mode of unit rod end force) are the internal force, stress and displacement of each beam grillage unit, which can acquire the stress state of different parts in the structure conveniently. It directly corresponds to the bridge design specifications currently in effect, and accordingly guides the reinforcement design in each part of the bridge pointedly, with the important significance for the design analysis of the practical engineering.

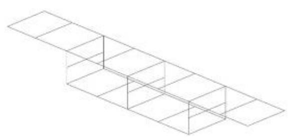
3.4 Application scope

The combined action of each "plate" in the spatial grid model constitutes the unique total cross section bending resistance, torsion resistance and shearing resistance rigidity of the box cross section beam. These plates can be made of steel, or concrete, or any other materials. Thus, these plate elements can be "combined" into all- concrete cross section, all- steel cross section, the cross

Fig. 7 Spatial grid model of large-span concrete box beam bridge with continuous rigid frame



(a) Full-bridge spatial grid model



(b) One section intercepted

Fig. 8 PC single box and double chamber box beam bridge – spatial grid model section with steel partly and concrete partly (steel- concrete superposed beam), and the cross section composed by other several different materials. Therefore, the spatial grid model is applicable to various kinds of bridge types such as curved bridge, skew bridge, wide bridge, and composite beam, without the limit of the specific structural form. See Figs. 7-8 for the structural model of the bridge established in the spatial grid method.

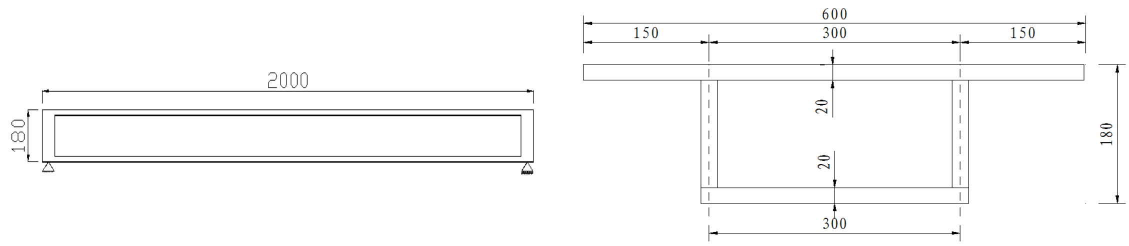
4. Parameter analysis and model verification analysis

Through the comparison of the analysis results of a simply supported corrugated web concrete composite box beam modelling by ANSYS solid model and spatial grid model, the rationality of the parameter determination and the accuracy of the analysis results in the spatial grid model is verified.

4.1 Model building and parameter description

The simply supported corrugated steel web composite box beam bridge has the span of 20 m, the top and bottom plates of box beam of C50 concrete (the modulus of elasticity of 3.45E4 MPa, gravity of 26 KN/m^3, and Poisson's ratio of 1/6), and the web of KL400 steel plate (the modulus of elasticity of 2.0E5 MPa, density of 78.5 KN/m^3, and Poisson's ratio of 0.3). See Figs. 9-10 for the dimension of each part in the box beam. The thickness of the steel web is 1 cm. The corrugated steel web is built by adopting the actual shape, and the central position coincides with the original web position.

It adopts the plate shell unit SHELL63 to simulate the box beam corrugated web, and utilizes Solid45 unit to simulate the concrete top and bottom plates of the box beam. See Fig. 11 for the



(a) (b)

Fig. 9 Elevation and sectional view of corrugated steel web composite box beam (Unit: cm)

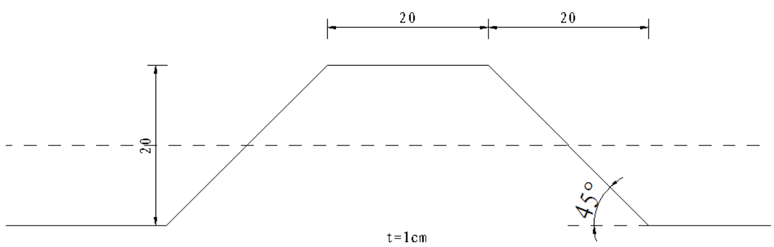
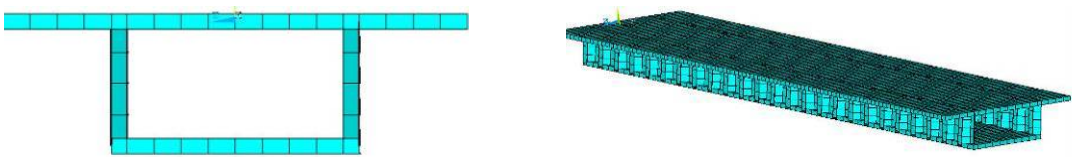


Fig. 10 Diagram of corrugated steel web dimension (Unit: cm)



(a) (b)

Fig. 11 Schematic diagram of ANSYS solid model

transverse section and the full-span grid division section in ANSYS.

(1) Modeling parameter description in ANSYS

Boundary constraint conditions: Under gravity, the constraint is applied at two sides of the transverse section, and the bottom plate node below the center of the corrugated web. At one end longitudinally, it constrains three direction degrees of freedom UX/UY/UZ of the node, and at the other end, it constrains UY/UZ. Under the effect of anti-symmetrical load and eccentric load, it constrains three direction degrees of freedom UX/UY/UZ for the above four nodes.

(2) Modeling parameter description of spatial grid model

While simulating the corrugated steel web by utilizing the spatial grid model, it is necessary to combine with the stress features of the corrugated steel web, and correct some cross section characteristic parameters of the corrugated web unit simulated by the spatial 6 degree of freedom beam grillage unit in the model. In allusion to the characteristics of dispersing of the spatial grid model, the correction of the parameters mainly focuses on the longitudinal web unit of embodying the longitudinal stress characteristics of the corrugated steel web and the vertical rob piece of simulating the web.

Upon understanding of the literatures (Maeda *et al*. 2007, Jiang *et al*. 2013, Huang *et al*. 2004), it can be seen that the common practice is to modify the longitudinal modulus of elasticity E0 of the corrugated steel web, adopt the mode of the effective modulus of elasticity Ex. The conversion process of the effective modulus of elasticity *Ex* is as follows. The corrugated steel web is equivalent to the plane steel web with equal altitude, and adopts the same condition as the axial deformation under the effect of the axial force of both, as shown in Fig. 12.

Under the effect of the axial force *P*, the axial deformation of the corrugated steel web can be obtained from Castigliano theorem, i.e.,

$$\delta_1 = \frac{P}{6E_0 I}\left(\frac{a^3}{2} + 3h^2 b\right) \tag{13}$$

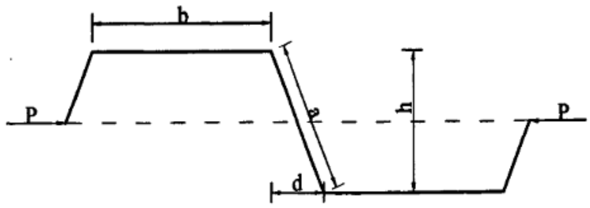


Fig. 12 Schematic diagram of geometrical parameters of corrugated web

The corrugated steel is equivalent to the plain plate with the equal length. Under the effect of the axial force *P*, the axial deformation is

$$\delta_2 = \frac{2P}{E_x A}(b+d) \tag{14}$$

From $\delta 1 = \delta 2$, it can acquire

$$Ex = \frac{E_0(b+d)}{a^3/2h^2+3b}\cdot\frac{t^2}{h^2} = E_0\cdot\alpha\cdot\frac{t^2}{h^2}$$

In the formula

$\alpha = \dfrac{b+d}{a^3/2h^2+3b}$, $I = t^2\cdot A/12$, A is the cross sectional area of steel plate.

The effective modulus of elasticity *Ex* for the axial direction of corrugated steel web is generally less one hundredth and even less one thousandth of the modulus of elasticity E_0 of the common steel plate. Thus it can be seen that the folding effect of the corrugated steel web makes the axial rigidity very small, and basically it does not bear the bending moment and axial force.

By utilizing the above theoretical formula, the specific value of the longitudinal effective modulus of elasticity *Ex* and the original modulus of elasticity E_0 as needed in the formula is calculated as $Ex/E_0 \approx 883$.

The above theoretical calculation is verified upon using the solid model of the corrugated steel established by ANSYS. While applying the tensile force and stress, calculate the specific value of the corrugated web and plain plate displacement under the effect of the same axial force. The result shows that the displacement of the corrugated web is 883 times than the plain plate displacement, thus it can be seen that the above formula is applicable.

In the spatial grid model, utilize the above theory to modify the longitudinal rigidity of the longitudinal unit on behalf of the corrugated steel web. The discount times calculated in accordance with the theoretical formula discount the unit axial rigidity area for 883 times, and other geometrical characteristics and material parameters shall not be modified.

In the grid model, the division mode of the box cross section transverse direction of bridge is as follows. The division spacing of the top and bottom plates is 0.3 m, and the division spacing of the web is 0.2 m. The longitudinal division spacing of the bridge is 0.2 m, and the division spacing of longitudinal beam of bridge is 0.2 m. The cross section of the vertical bar unit of web is two cross section types as shown in Fig. 13. The corresponding cross section of the vertical bar unit of web selected by the out-plane rigidity is shown as Fig. 14.

The established spatial grid model is shown as Fig. 15. The box type top plate is divided into 22 longitudinal bands (No. T1~T22) horizontally, and the bottom plate is dispersed as 12 longitudinal

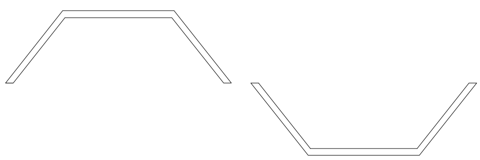


Fig. 13 Cross section of vertical bar unit

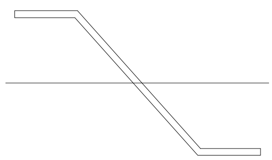


Fig. 14 Out-plane rigidity cross section of vertical bar unit

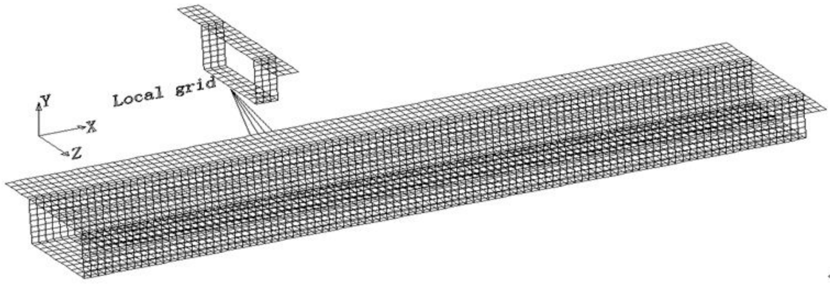
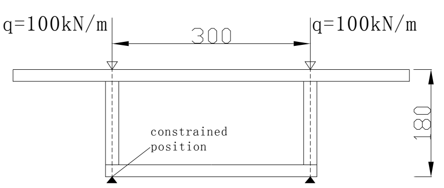
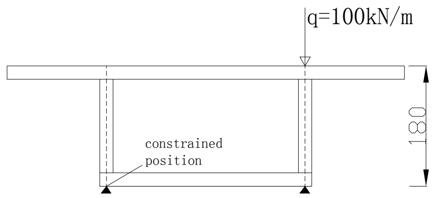


Fig. 15 Schematic diagram of spatial grid model



(a) Symmetrical loading



(b) Unilateral loading

Fig. 16 Schematic diagram of loading

bands (No. B1~B12). The web is simulated as 7 longitudinal bands (No. W1~W7). The box beam is divided into 100 sections longitudinally with each section of 0.2 m. The web unit and the wing plate unit are linked through the vertical rob piece, and delivers the load between the web and flange through the vertical rob piece.

The boundary constraint conditions of the spatial grid model correspond to the constraint conditions of ANSYS solid model, and the constraint is applied on the node connected between the web and bottom plate. Under the action of gravity, it constrains three direction degrees of freedom UX/UY/UZ of two nodes at one end, and it constrains two direction degrees of freedom UY/UZ at the other end. Under the effect of anti-symmetrical load and eccentric load, it constrains three direction degrees of freedom UX/UY/UZ for the above four nodes.

(3) Comparative analysis of working conditions

In order to consider the shear lag effect of the box beam in two different models, the stress analysis is made on the stress situation of the simply supported box beam under the action of gravity. In order to consider the thin-wall effect (statically indeterminate shearing stress distribution and warping normal stress distribution) of the box beam in two different models, the analysis is made on the stress situation of the simply supported box beam under the anti-symmetrical equally- wiring load (q = 100 kN/m) and eccentric load (q = 100 kN/m). See Fig. 16 for the loading position.

(4) Data comparison position

Compare the displacement of four points involving left side of top plate, middle part of top plate, middle part of bottom plate, and middle part of web. Compare the normal stress and shearing stress of the longitudinal quarter section and mid-span section. See Fig. 17 for the selection of the comparative points.

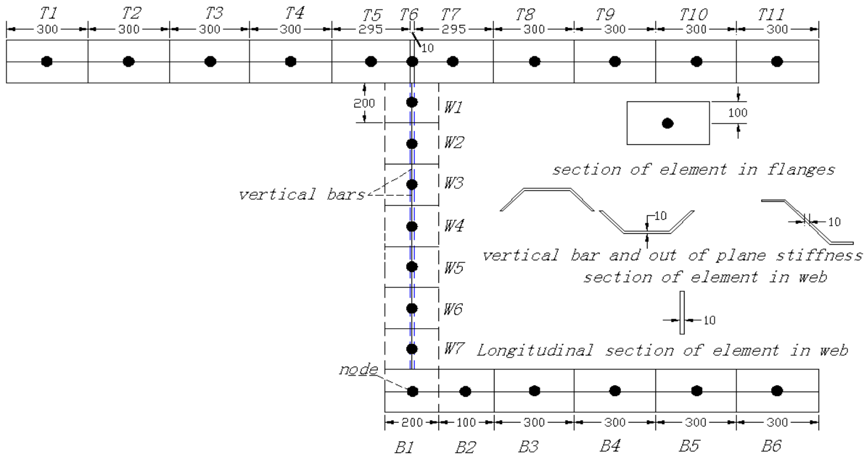
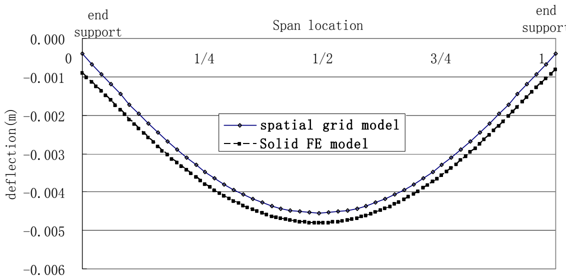
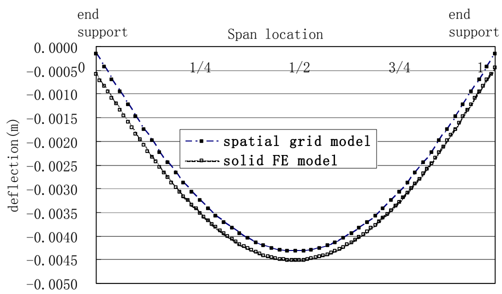


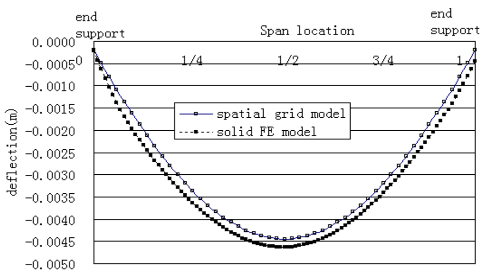
Fig. 17 Position of result comparison point (Unit: mm)



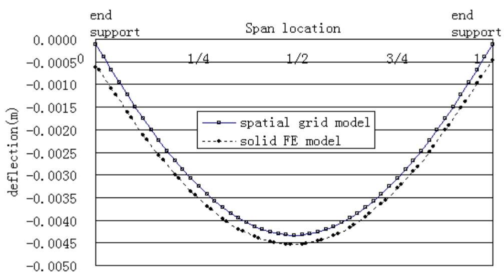
(a) Band T1



(b) Band T11



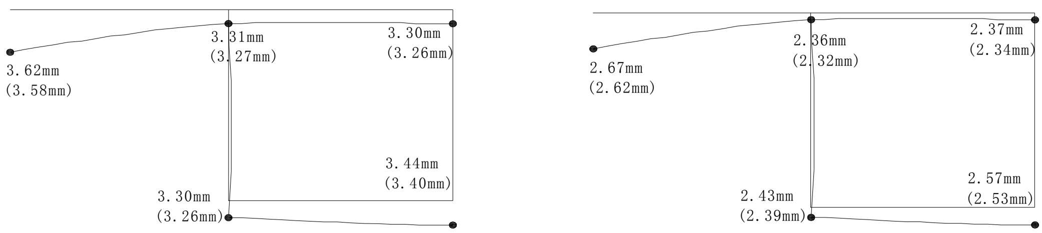
(c) Band B6



(d) Band W4

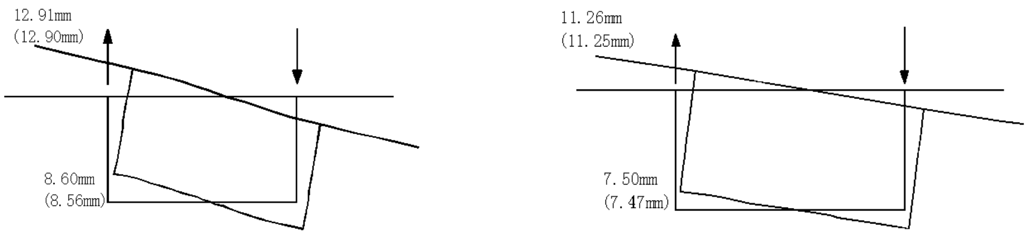
Fig. 18 Comparison of vertical deflection under self-weight (Unit: m)

Fig. 17 shows the comparison of vertical deflection for the position of four longitudinal bands (T1, W4, T11 and B6) along the direction of the span under gravity. Fig. 18 shows the comparison of vertical deflection for the mid-span and quartile point along the direction of the transverse section under gravity. Fig. 19 shows the comparison of deformation for the mid-span and quartile point transverse section under the effect of anti-symmetrical load. Fig. 20 shows the comparison of deformation for the mid-span and quartile point transverse section under the effect of eccentric load. The digits in the bracket indicate the calculation result of the solid finite element. From the



(a) Mid-span position (b) Quartile position

Fig. 19 Comparison of vertical deflection of transverse section under gravity (Unit: mm)

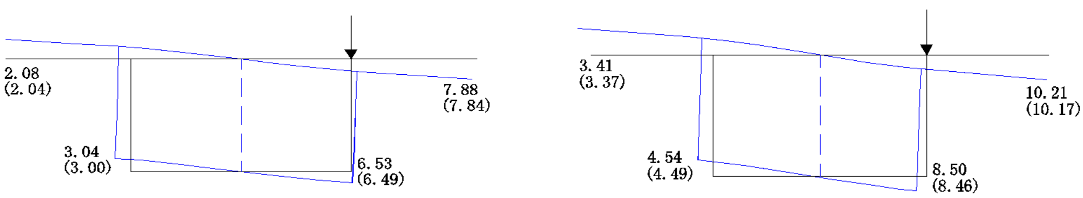


(a) Mid-span position (b) Quartile position

Fig. 20 Comparison of vertical deflection of transverse section under effect of anti-symmetrical load (Unit: mm)

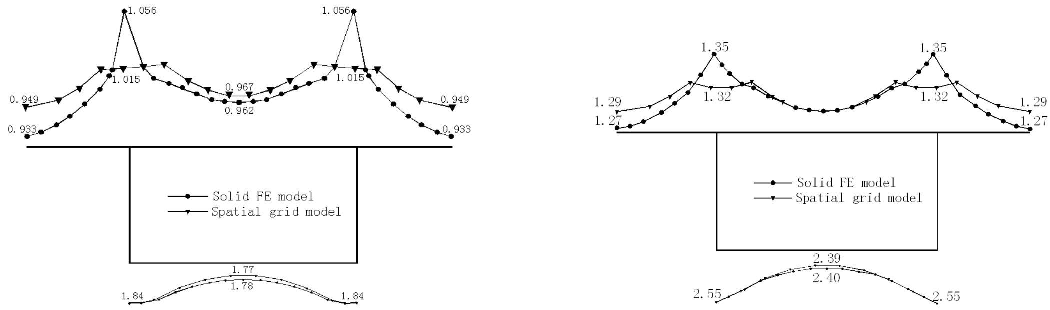
graphic comparison in the case of two loads, the maximum differences of the corresponding vertical displacement of the longitudinal bands T1, T11, B6 and W4 in two models under gravity are respectively 0.1 mm, 0.15 mm, 0.12 mm and 0.11 mm in Fig. 18. The maximum differences of the vertical displacement of the mid-span and quartile point transverse section in two models under gravity are respectively 0.04 mm and 0.05 mm in Fig. 19. The maximum differences of the vertical displacement of the mid-span and quartile point transverse section in two models under the effect of anti-symmetrical load are respectively 0.04 mm and 0.03 mm in Fig. 20. The maximum differences of the vertical displacement of the mid-span and quartile point transverse section in two models under the effect of eccentric load are respectively 0.04 mm and 0.05 mm in Fig. 21. Thus, it can be judged that the spatial grid model accurately simulates the structural rigidity.

The normal stress in the middle-plane spatial grid unit is mainly generated from the axial force, bending moment and cross section torsion. Here, the normal stress in the position of 0.1 m away



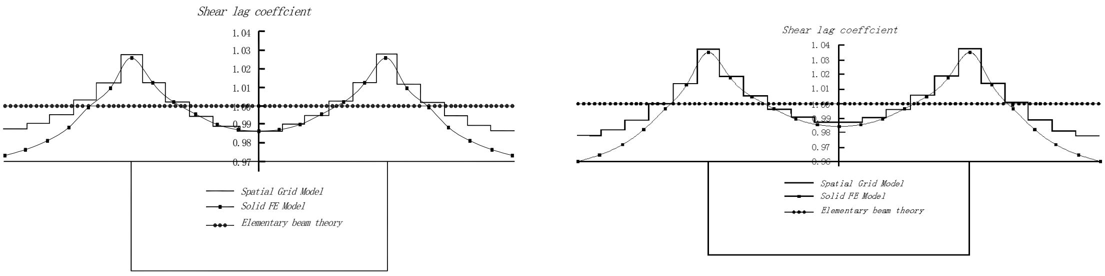
(a) Mid-span position (b) Quartile position

Fig. 21 Comparison of vertical deflection of transverse section under effect of eccentric load (Unit: mm)



(a) Mid-span position (b) Quartile position

Fig. 22 Comparison of normal stress of box beam cross section under gravity (Unit: Mpa)

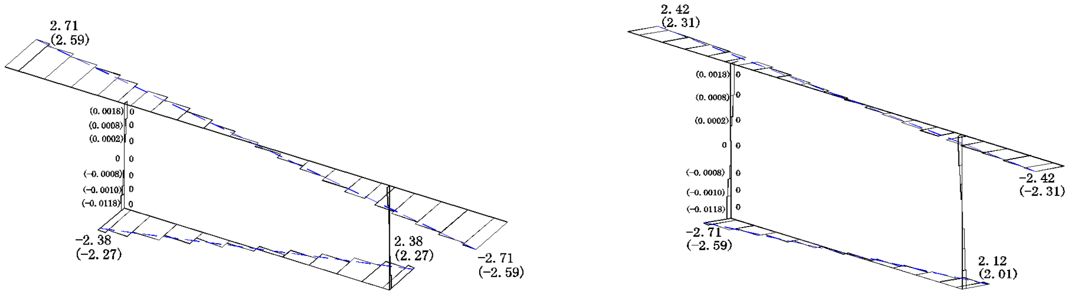


(a) Mid-span position (b) Quartile position

Fig. 23 Comparison of shear lag effect coefficient of box beam top plate under gravity

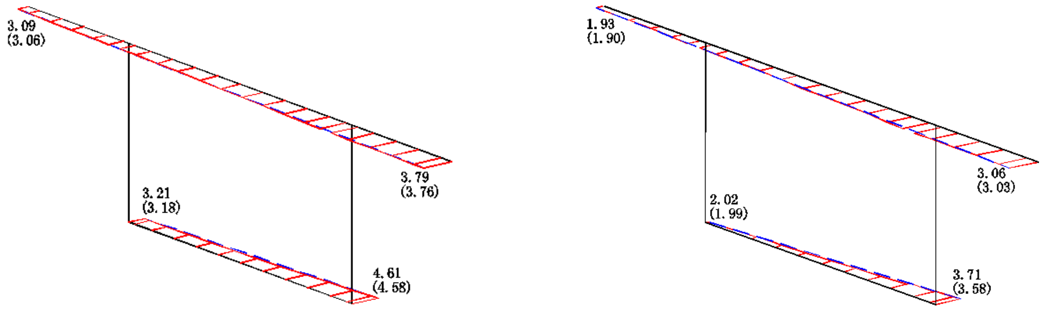
from the upper edge of the top plate and bottom plate is valued as the normal stress of the middle-plane plate unit for comparison. Fig. 22 shows the comparison of the normal stress (the tensile stress is positive) of the mid-span and quartile point transverse section under gravity. From the figure, it can be seen that the variation rule of the normal stress along the cross section width is the maximum stress in the junction of the web and flange and the minimum stress in the cantilever end of the wing plate and the center line of the box beam. In the junction of the web and the top plate in mid-span and quartile point section, the maximum differences of the stress are respectively 0.041 Mpa and 0.03 Mpa. For the stress in the junction of the web and the top plate, the grid model is a gentle transition, while the solid model has a protruding point, due to the rigidity differences near the junction arising out of the division unit in this place, but the difference of the peak value is only 3.8%. These shear lag effects are consistent with the conclusion in the literatures (Driver *et al*. 2006, Li and Wang 2013, Kosa *et al*. 2003). Fig. 23 compares the shear lag effect coefficient in two models, and the calculation results in two models are almost consistent. Thus, it can be seen that the spatial grid model can truly reflect the shear lag effect of the box beam cross section.

Figs. 24-25 show the comparison of warping normal stress (the tensile stress is positive) of mid-span and quartile point transverse section under the effect of anti-symmetrical load and eccentric load. In the figure, the result of the solid finite element model is indicated by the dotted line, and the calculation result of the grid model is indicated by the stair-step solid line. From the figure, it can be seen that the variation rule of the normal stress along the cross section width is as follows. Under the effect of anti-symmetrical load, the stress in the cantilever end of the mid-span



(a) Mid-span position (b) Quartile position

Fig. 24 Comparison of warping normal stress of box beam cross section under effect of anti-symmetrical load

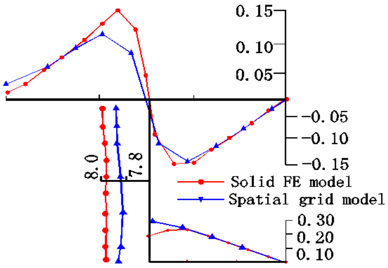


(a) Mid-span position (b) Quartile position

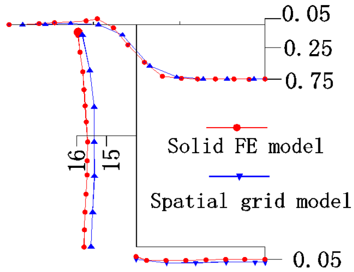
Fig. 25 Comparison of warping normal stress of box beam cross section under effect of eccentric load

and quartile point section is the maximum with the differences of 0.12 Mpa and 0.11 Mpa respectively, and the stress in the center line of the box beam is the minimum with the difference of nearly zero. Under the effect of eccentric load, the stress at the side of eccentric load is the relatively big, and the stress in the cantilever end of the mid-span and quartile point section is the maximum with the differences of 0.03 Mpa and 0.03 Mpa respectively, and the linear distribution along the top and bottom plates laterally. Under the effect of anti-symmetrical load and eccentric load, the normal stress of the web is nearly zero. Thus, it indicates that the calculation results of the solid and spatial grid model under various kinds of working conditions are identical relatively. The spatial grid model can accurately simulate the warping effect of the box beam cross section.

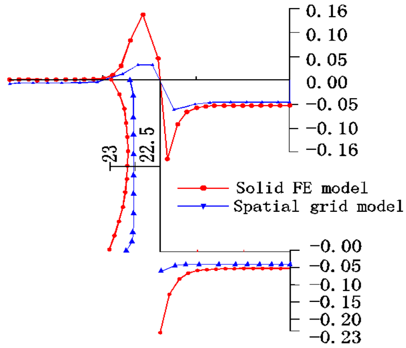
Fig. 26 shows the comparison of the shearing stress in the quartile position of the simply supported box beam. The shearing stress of the top and bottom plate of the box beam is valued as the shearing stress value in the central position of the plate thickness. In the figure, the calculation result of the solid finite element is indicated by the dotted continuous solid line, and the calculation result of the spatial grid model is indicated by the continuous solid line with triangle. From the figure, it can be seen that the top and bottom plates assume very small shearing stress compared with the web under gravity and the effect of anti-symmetrical load and eccentric load, accounting for about 4% of the shearing stress of the web. The web almost assumes all shearing forces. It is consistent with the conclusion in the literatures (Ko *et al*. 2013, Shitou *et al*. 2008, Kövesdi 2010b). The shearing stress distribution predicted by two models is very close. In the case



(a) Under the self-supporting effect



(b) Under the effect of anti-symmetrical load



(c) Under the effect of eccentric load

Fig. 26 Comparison of shearing stress in quartile position

of three working conditions, for the shearing stress distribution in the top and bottom plates, the slight differences in the joint of the web and top and bottom plates can be neglected, because it does not consider the contribution of shearing resistance in the top and bottom plates during calculating. The maximum difference of the shearing stress on the steel web is generated from the anti-symmetrical load, and is only 1 Mpa, accounting for 6% of the calculation result of the solid model, with very small influence.

5. Conclusions

This paper analyzes the current situation of the corrugated steel web composite beam bridge.After pointing out the deficiencies of single beam model, plane beam grillage model and solid model adopted by the design calculation, the paper accordingly introduces the practical and fine analytical method of spatial grid model. Through introducing the principles of the grid model and analyzing the process of the grid model simulating the corrugated steel web composite beam bridge, it comprehensively compares the calculation results of the stress and displacement of ANSYS solid model and spatial grid model, and can obtain the following conclusions.

(1) Bending resistance performance of corrugated steel web: The corrugated steel web is folding shape longitudinally, and can freely deform as the church organ. The axial modulus of elasticity Ex is generally less one hundredth and even less one thousandth of the modulus of elasticity E of the rolled steel, and hardly resists the axial force. Therefore,

in the beam structure, the contribution of bending resistance by the corrugated steel web is very small, and can be neglected, the bending moment is almost assumed by the top and bottom flange.

Shearing resistance performance: The corrugated steel web almost assumes all shearing forces in the beam. The bending resistance of the top and bottom flange plate and the shearing resistance of the corrugated steel web do not have the relevancy.

Torsion resistance performance: The longitudinal rigidity of the corrugated steel web is very small, so the distortion warping rigidity of restricting the distortion deformation is very weak. The distortion deformation of the cross section is almost coordinated by the top and bottom concrete plates fully.

(2) From the above diagram of the analysis and comparison, the displacement, normal stress and shearing stress distribution predicted by two models are very close under the effect of the self-weight load, anti-symmetrical load and eccentric load. Thus, the spatial grid model truly reflects the spatial stress characteristics of the box beam section. Conducting the structural analysis by utilizing the spatial grid model can acquire the complete stress of various indexes as needed for attention. The result is expressed by the means of the internal force of the unit rod end, and can be directly applied to the reinforcement design.

(3) The integrity of the spatial grid model analysis is applied to the stress analysis of the corrugated steel web composite beam bridge. It can be seen that the advantages are: (1) fully reflecting the torsion distortion of the cross section and the shear lag effect; (2) fully considering the construction process (creep shrinkage, and prestress); (3) loading of the space influence surface, accordingly solving the transverse stress and web stress distribution; (4) fully reflecting the integral calculation stress, especially the in-plane main tensile stress of the bridge deck and bottom plate; (5) closely combining current specification of the beam element and reinforcement design.

(4) The spatial grid model remedies the deficiency of the single beam model and plane beam grillage model. From the integrity of the analysis and the comprehensiveness of the calculation stress, the spatial grid model carries out the new thought for the fine design.

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