THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

2010

5(2): 98–103

SPACE FRAME LATTICE MODEL FOR STRESS ANALYSIS OF BRIDGE

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Abstract. The space frame lattice model, which is suitable for the analysis of stress of entire cross-section of bridge, is presented. It is suitable for the analysis of stress of entire cross-section of bridge. The relatively weaker position of stress in box-girder section was analyzed. By using the presented space frame lattice model, the shear stress and principle tensile stress of the box girder cross-section in Xintan Bridge, which is a continuous prestressed concrete rigid frame with the 75+130+75 m span, was calculated and analyzed. An innovative layout method of mixed internal and external prestressed tendons was adopted. In addition, the space frame lattice model is worth to be further investigated. It can be applied to more bridge patterns.

Keywords: space frame lattice model, stress analysis, mixed tendon layout method, long-span continuous rigid frame bridge, shear stress, principle tensile stress.

1. Introduction about space frame lattice model

At present, the common integral calculation models for bridge structure are as following: 3-freedom plane straight beam model, 6-freedom (or 7-freedom) space beam element model, and *Hambly Shear Flexible* plane grillage model (Hambly 1991). The above models can meet the design need in some degree. Here is another model: space frame lattice model. Basically, all the complicated bridge structures can be separated into "plates". For example, a box girder can be separated into the top slab, web and many bottom slabs, as shown in Fig. 1. These plates can be made of steel, concrete, or any other material. Then, these plates can compose all-concrete section, all-steel section, both steel and concrete (steel-concrete composite girder) section, or any other different material section. A plate element can be made up of the orthogonal grids. An orthogonal grid is just like a "net", and there are as many pieces of plates as the number of "nets" composed of grids in a structure. In this way, the space bridge structure can be figured by the space frame lattice (Chao *et al.* 2009; Xu 2008).

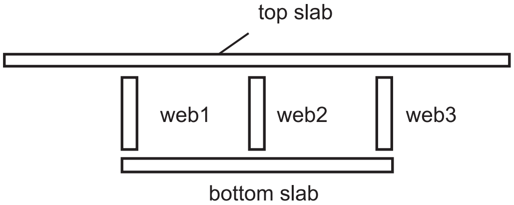

Fig. 1. A double-cell box section expressed by "plates"

Fig. 2 shows a space frame lattice model for a prestressed concrete cable-stayed bridge. As mentioned above, the three calculation models and the space-frame lattice model can simulate the cantilever construction, the tension of prestressed tendons to completion of bridge, and the whole process of live loading on the bridge (Grigorjeva *et al.* 2008; Marzouk *et al.* 2007; Marzouk *et al.* 2008; Kaklauskas *et al.* 2008; Podolny, Muller 1982). In addition, the spatial distribution of temperature variation can be conveniently considered as well at the space-frame lattice model. The model can accurately simulate the stress in every part of bridges because it takes all the spatial effects, except for Poisson's ratio, into account.

2. Concerned position on box-girder section

Fig. 3 shows flexural shear flow, free torsional shear flow and restraining torsional shear flow of a box girder with single-box and single-cell (Du 1994; Guo, Fang 2008; Xiang 2001).

From Fig. 3 could be concluded that the shear design of box-girder is not only for the web, but also for the entire cross-section of box-girder including top slab and bottom slab.

The principal tensile stress of concrete in the vertical web of box-girder is composed of the shear stress and normal stress and it can be counteracted by the vertical compressive stress provided by vertical prestressed bars. At the same time, the shear cracking of concrete does not happen at top slab of box-girder usually because the transverse prestressed tendons or strong transverse reinforcements,

ISSN 1822-427X print / ISSN 1822-4288 online
doi: 10.3846/bjrbe.2010.14
http://www.bjrbe.vgtu.lt

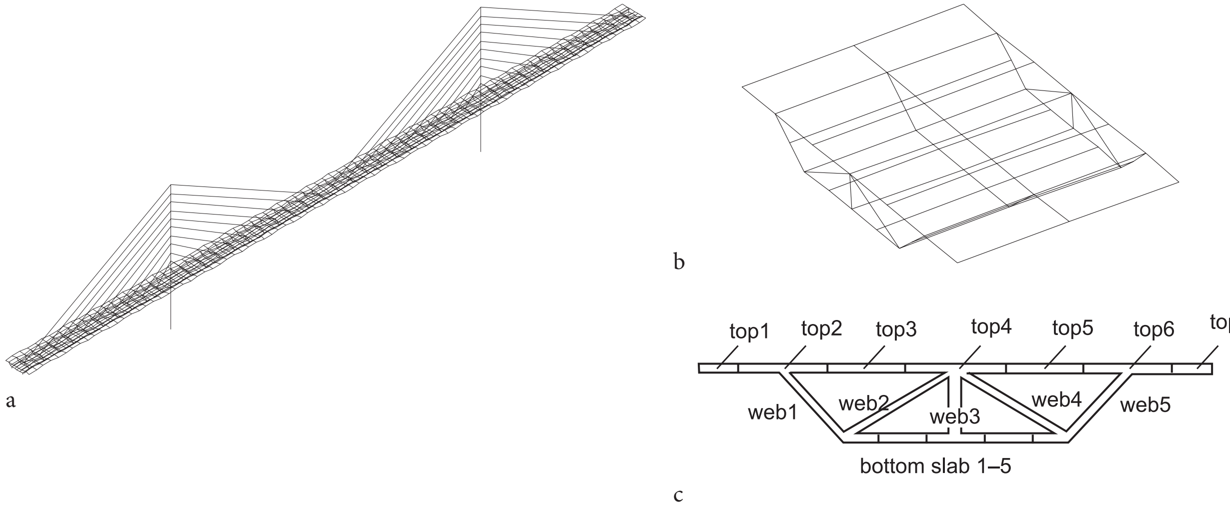

Fig. 2. Space frame lattice model of prestressed concrete cable-stayed bridge: a – space frame lattice model of whole bridge; b – a segment; c – section divided

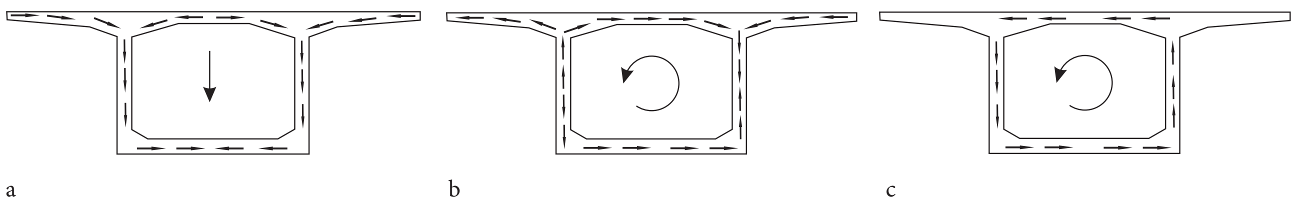

Fig. 3. Shear flow of cross-section: a – flexural shear flow; b – free torsional shear flow; c – restraining torsional shear flow

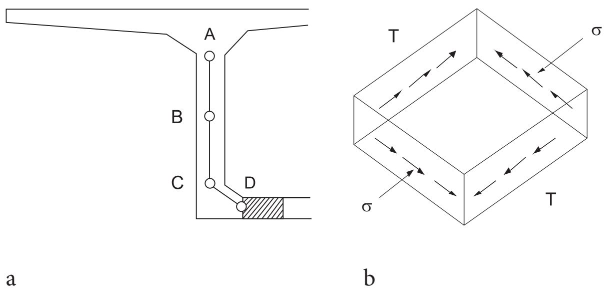

Fig. 4. Stress position (a); D point stress in plane (b)

which have the same direction with shear flow, are usually laid inside the top slab of box-girder. The bottom slab of box-girder, inside which are generally laid constructional reinforcements only, is relatively weaker and should be concerned. At the same time, the calculation and design method about the bottom slab of box-girder are relatively weaker. Could be imagined that the shear stress value of bottom slab is even more than that of the web. The principal tensile stress of the D point in Fig. 4 is in horizontal plane and the vertical prestressing can not influence the D point. The shear stress (principal tensile stress) at this place can be reduced only through optimizing the longitudinal prestressed tendons in order to reduce the flexural shear flow of bottom slab by reducing the shear of box girder cross-section. But now it is even worse because of the use of the bigger prestressed strands, the anchoring force is so large that can generate bigger stress concentration in anchor block. Because of the anchoring of internal prestressed tendons in bottom slab, the bigger horizontal shear in plane of bottom slab will be generated and it can be combined with shear flow in bottom slab each other. If the combined principal tensile stress exceeds the actual concrete ultimate tensile strain, inclined cracking will occur in the plane of bottom slab. If insufficient constructional reinforcements of bottom slab cause its own yielding and the movement among the concrete, the longitudinal stress and deformation of the box girder can be influenced significantly. Once the above situation happened, the effect of longitudinal prestressing in the bottom slab cannot be accurately transferred to the web, and then the cracking in web will occur because the principal tensile stress of web is too large.

3. Application of space frame lattice model in wwa box-girder bridge

3.1. Project overview

Xintan Bridge over the Qijiang River in Chongqing China is a practice bridge for the research project of Design

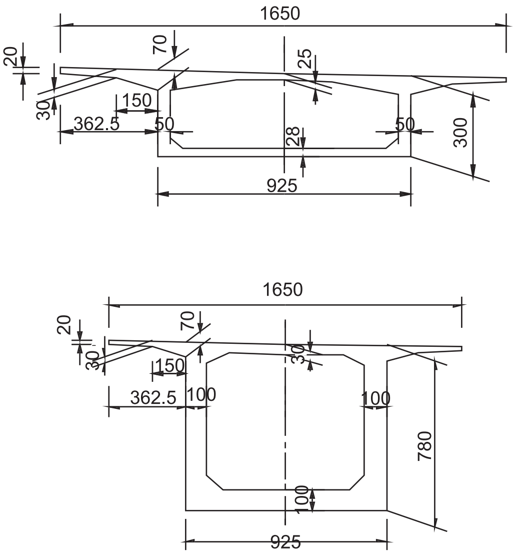

Fig. 5. Section at mid-span (a); section at support (b), cm

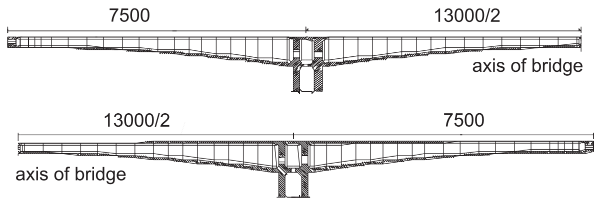

Fig. 6. Longitudinal profile of bridge, cm

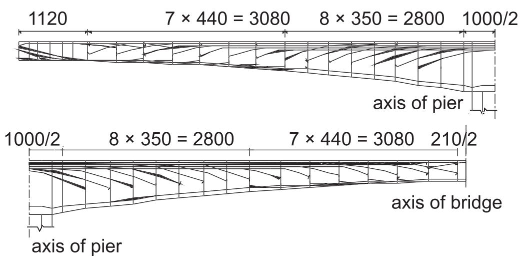

Fig. 7. Layout of the internal prestressing system of the left-deck bridge, cm

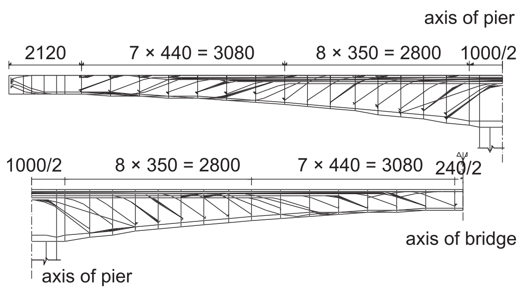

Fig. 8. Layout of the internal prestressing system in the right-deck bridge, cm

and Construction of Externally Prestressed Bridges in the Western Communication Technology Research Program in China. It was finished by the end of 2008. The main bridge is a continuous prestressed concrete rigid frame with the 75+130+75 m span. The bridge is divided into left and right twin-decks, each 16.75 m wide. The difference between them is that the left-deck bridge used the all internal prestressing system, i.e. tri-directional prestressing system of longitudinal, transverse and vertical directions (Fig. 7); while a new prestressed tendon layout method including mixed internal and external prestressed tendons is applied in the right-deck bridge, in which the first-stage prestressing is internal while the second-stage prestressing is external (Figs 8, 9). There are not vertical prestressed bars in the right-deck bridge. The main girder with single box and single cell is shown in Fig. 5, and longitudinal profile of bridge is shown in Fig. 6. The height of box-girder at pier is 7.8 m, while the height of box-girder at the mid-span and the end of side span is 3.0 m, which changes by 1.8-time parabola.

The normal stress, shear stress and principle tensile stress in the box girder cross-section of Xintan Bridge is calculated and analyzed by the space frame lattice model.

3.2. Calculation model

It totals to 1674 nodes and 3222 units in the space frame lattice model of the left-deck bridge, while there are 1774 nodes and 3310 units in the right one totally, in which there are more external prestressed units. External prestressed tendon is regarded as a unattached member in the model. A rigid arm is placed between the deviator and the beam axis, while the rubber element, which can adjust the frictional coefficient between external tendon and deviator, is set in the node between the rigid arm and beam axis. For example, the calculation model of a 30 m simply-supported bridge is shown in Fig. 11 (Chao *et al.* 2005).

The beam structure between left-deck and right-deck is the same, as the space frame lattice model of the right-deck bridge is shown in Fig. 12. The top slab of box girder section is divided into nine longitudinal grids, while the bottom slab of box girder section is divided into seven longitudinal beam grids. In order to ensure the layout of internal prestressed tendons, the web is divided into one longitudinal grid. The longitudinal grid in the junction of

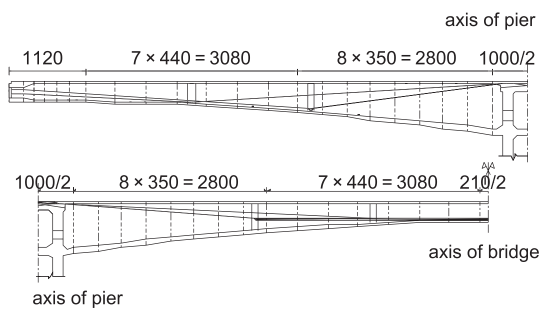

Fig. 9. Layout of the external prestressing system in the right-deck bridge, cm

the web, the top slab and the bottom slab is figured to an imaginary grid without weight, which only plays the role of load transfer and the internal force of which is not analyzed. The actual stress of the box-girder at the imaginary grid is analyzed according to the stress at the upper and lower edge of web. The cross-section divided is shown in Fig. 13.

3.3. Construction process

The bridge was constructed by cantilever casting method. The true construction process was considered in the calculation model, including the casting of concrete, tension of internal prestressed tendons, installation, movement, removal of traveler, closure of mid-span and side span, tension of external prestressed tendons, paving of bridge deck and creep of 30 years, etc.

3.4. Comparison of calculation results

According to the actual construction stage, stress at 4 points as shown in Fig. 4a, i.e., the point A at the upper edge of the section, the point C at the lower edge of the section, the central point B of web and the point D at the intersection between the auxiliary and the bottom slab, are selected to be calculated and analyzed by the space frame lattice model. In the following charts the tension stress is positive value, while the compressive stress is negative value.

The results listed below are all for construction condition of bridge after completion of 30 years creeping.

3.4.1. Comparison of the calculation results of shear stress under dead load

The comparison of the calculation results of shear stress under dead load at A, B, C, D points of cross-sections between the left-deck and right-deck of the bridge is shown in Fig. 14. Among them, the numerical value of shear stress of A, B, C points in webs is regarded as the same approx.

From Fig. 14 could be concluded the shear stress of web and D point in box-girder under dead load in right-deck bridge with mixed internal and external prestressed tendons is significantly less than that in left-deck bridge with all internal prestressing system.

3.4.2. Comparison of the calculation results of principal tensile stress

The comparison of the calculation results of principal tensile stress between the left-deck and right-deck of the bridge is shown in Fig. 15. The principal tensile stresses of D point and the max one among A, B, C of cross-sections are compared separately. The effects of dead load, live load, temperature and settlement of supports are taken into account and combined in the results of calculation.

From Fig. 15 could be concluded that the max principal tensile stresses of webs in whole left-deck bridge are all compressive due to the effect of vertical prestressing, but the one of D point is tensile as the vertical prestressed bars have not action on this place. At the same time, the max principal tensile stresses of webs in whole right-deck bridge are all tensile, but do not exceed the 0.5 MPa. Obviously, the principal tensile stresses of D point in whole right-deck bridge are significantly lower than that in left-deck bridge due to the use of mixed internal and external prestressing system.

Fig. 10. Xintan Highway Bridge over the Qijiang River: a – bridge at construction stage; b – deviators and external tendons; c – longitudinal profile of bridge(from Xiaodong Guo)

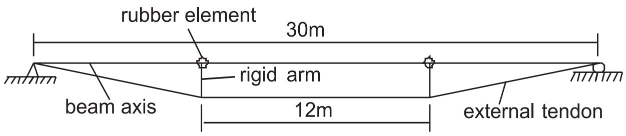

Fig. 11. Calculation model of a 30 m simply supported bridge

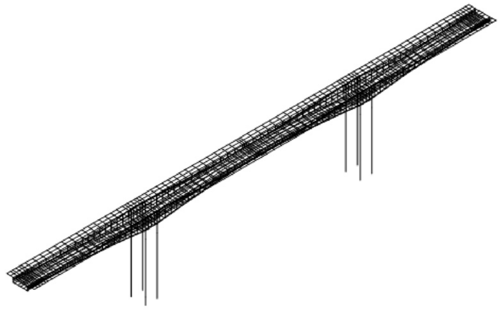

Fig. 12. Space frame lattice model of bridge

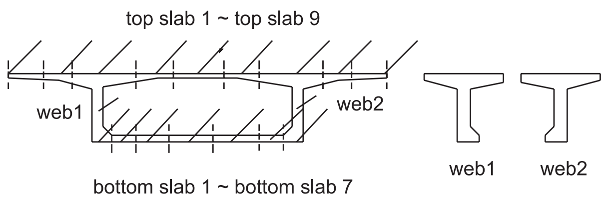

Fig. 13. Section divided

3.5. Analyses

From above it could be concluded that the shear stress in the right-deck bridge is significantly lower than that in the

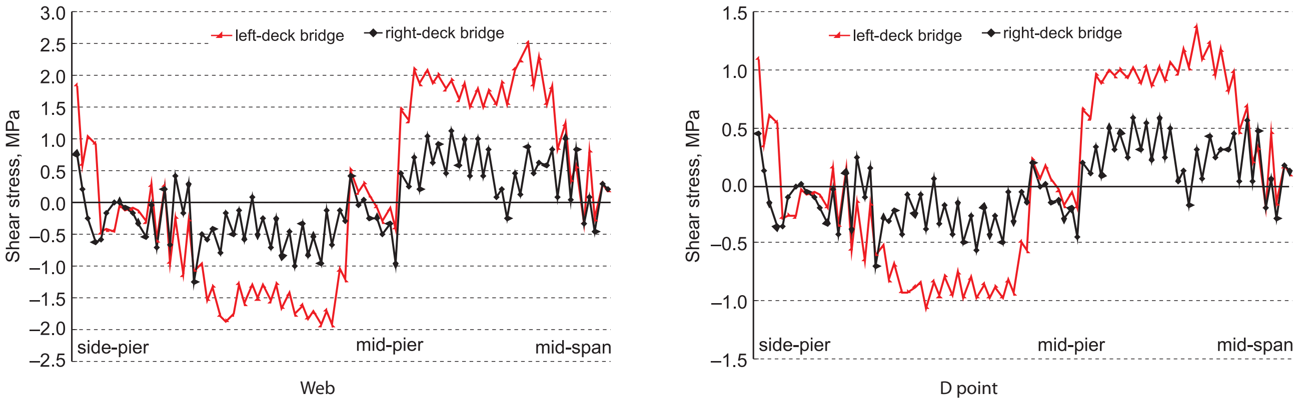

Fig. 14. The comparison of the calculation results of shear stress under dead load between the left-deck and right-deck of the bridge

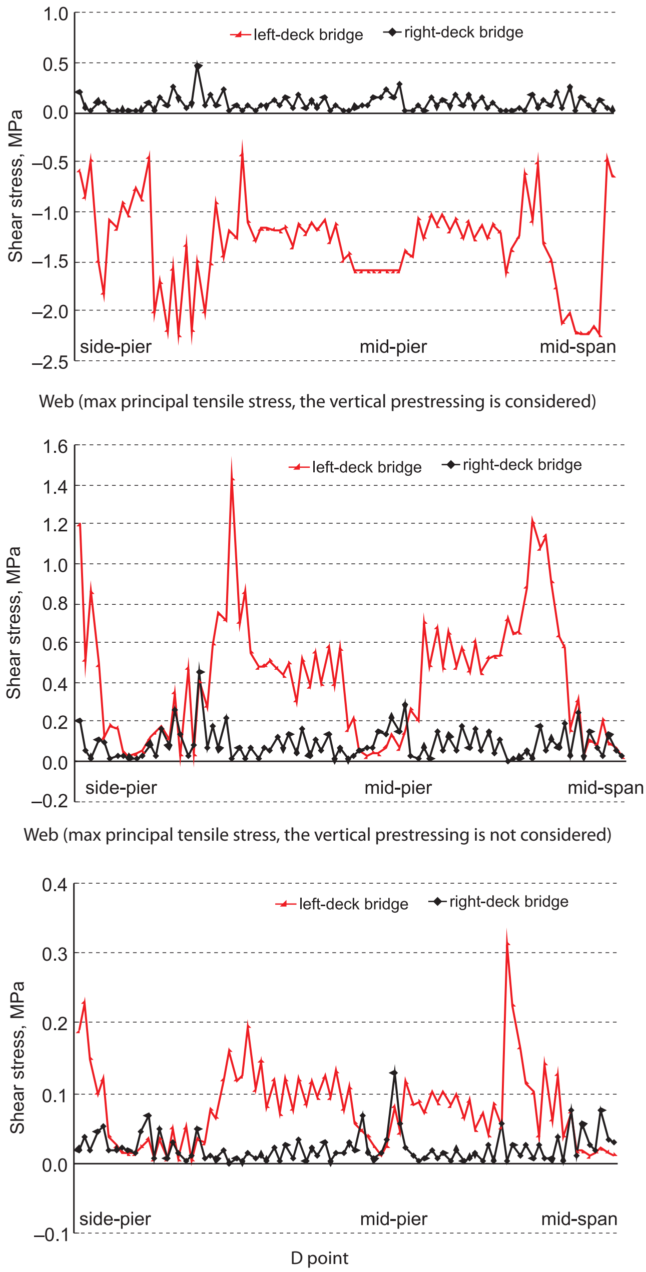

Fig. 15. The comparison of the calculation results of principal tensile stress under dead load between the left-deck and right-deck of the bridge

left-deck bridge. The principal tensile stress in webs and bottom slabs is significantly reduced by using mixed internal and external prestressed tendons. The reduction of the principal tensile stress is due to the use of more reliable external longitudinal prestressed tendons that provided the vertical shear. On condition without the vertical prestressed bars, the calculation results of principal tensile stress can completely meet the design requirements (*JTJ D62-2004: 2004 Chinese Code for Design of Highway Reinforced Concrete and Prestressed Concrete Bridges and Culverts*), so the layout method of mixed prestressed tendons without vertical prestressed bars is feasible and rational. Furthermore, it is more convenient to adjust the layout of the internal and external prestressed tendons, and structural form of box-girder is easier. Thus, this mixed tendon layout method without vertical prestressed bars can be extended to longer continuous rigid frame bridges.

4. Conclusions

The stress state of bridge can be calculated and analyzed accurately by space frame lattice model.

Xintan Bridge over Qijiang River in Chongqing adopts an innovative layout method of mixed internal and external prestressed tendons. The innovation is not only application of the external prestressed tendons, but of following two important features: First, the external prestressed tendons which can be replaced and detected are used as many as possible for convenient construction and more durable structures; Second, the combination of the vertical pre-shear provided by the external prestressed tendons and by internal prestressed tendons that bends downward in each segment and upwards in the bottom slab of closure at the side-span and mid-span can reduce the shear force of the whole bridge under dead load, thus can reduce the shear stress and principal tensile stress of the full-section of box girder under dead load.

The space frame lattice model is worth to be further investigated. It can be applied to more bridge patterns. In addition, it can simulate the whole process of the long-term crack and deflection of large-span prestressed concrete girder bridges. This will be studied in the future.

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Received 03 April 2009; accepted 14 May 2010