Beam-Truss Model of Steel-Concrete Composite Box-Girder Bridges I: theory and calculation

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Abstract: In this paper, modeling strategy for member and section level is firstly established based on shear-flexible grillage theory cellular decks. In addition, modal analysis and static analysis under the dead and live load are conducted for composite simply supported and continuous box girder bridges, the alignment of which includes straight and curve. High accuracy and good applicability of beam-truss model of composite box-girder bridge can be verified due to good correlation of numerical results between elaborate and beam FE model. The research in this paper has laid the foundation for the further application of beam-truss models in the design analysis of actual composite box-girder bridge.

1. Introduction
Steel-concrete composite girder bridges are widely used due to their high stiffness, high strength and low self-weight. Compared with other types of bridges, it has superior economic performance. Numerical models often play a very important role in the design analysis of bridges. In general, numerical models are usually divided into two groups: fine models and beam truss models. Compared with the beam truss numerical model composed of beam and truss elements, the fine numerical model consisting of the shell and the solid element takes more time and effort in modeling, but has good visual effect and high simulation precision. More in line with the actual situation. The advantages of the beam truss model are: easy modeling and high computational efficiency. Therefore, the beam truss model has always been a powerful tool for bridge design analysis.

2. Modeling Implementation
The important theoretical basis for the implementation of the beam truss model is provided by the analysis of shear flexible grids. Theory should follow the principle of membership and cross-sectional level.

2.1. Principle on Level of Member
The two lattice members representing the concrete slab and the steel beam respectively should be modeled at the same position in the finite element. Moreover, since the method of full shear connection is employed, the slip effect between the concrete and steel interfaces is neglected, which is present in the actual bridge. The lattice members establish a finite element model in the plane of the main bending axis of the entire deck. For longitudinal members, their position should be consistent with the position of the longitudinal web so that the shearing force of the web can be directly represented by the shear force of the lattice members at the same location on the cross-section.
cross members, the spacing of the cross members should be less than 1/4 of the distance between the inflection points and the position of the diaphragm in the straight bridge. Compared to straight bridges, in curved bridges, the spacing of the cross members should be shorter, in order to more accurately simulate the bending and torsion coupling effect of the curved bridge.

2.2. Principle on Level of Cross-Section

The combination of the two materials of the steel-concrete composite girder bridge results in the computation of complexity of various cross-sectional properties, particularly involving nominal conversion between steel and concrete materials. This is more complicated, compared to concrete or steel girder bridges made up of a single material. For example, to obtain the cross-section shown in Figure 1, after describing the cross-section of the cut form, a corresponding calculation of various cross-sectional characteristics, including properties related to axial, bending, shearing, and torsional actions, is explained, as shown in Fig 2.

![Fig. 1 Geometric notations of cross-section](image1)

![Fig. 2 Cutting forms of cross-section](image2)

3. Modeling Analysis

3.1. FE Models

In the modeling analysis of engineering examples, the research mainly focuses on composite simply supported beams and continuous box girder bridges. The alignment of simply supported beams and continuous bridges includes both straight lines and curves. The calculation accuracy of the beam truss model is studied by using the comparison between the finite element model of the fine and beam truss. Based on the commercial FE package ANSYS12.0 (2009), the finite element model of the composite and beam truss of the composite simply supported beam and the continuous box girder bridge is established. In addition, the details of FE modeling are described below:

(a) Almost all large commercial finite element programs do not provide curved beam elements, taking into account the bending and torsion coupling effects. The curved beam element can be used to calculate the mechanical behavior of the curved bridge.

(b) The width of the cross member at the outer support should be half the width of the cross member at other locations, and the center of mass of the lateral lattice member has an offset from the position at the outer support.

(c) The width of the cross member varies in the radial direction of the curved bridge.

(d) Principle of the offset of the centroid of the cross section.

(e) The prestressed load applied to the deck at the time of travel is simulated by the equivalent load method.

3.2. Analysis of Composite Simply Supported Box-Girder Bridges

In the following, numerical analysis is carried out, including modal analysis and static analysis under the combined action of gravity and live loads, to predict the mechanical behavior of composite simply supported box girder bridges using fine and beam truss finite element models. For ease of discussion, the predictions obtained using the fine and beam truss models are named EM and BM, respectively.

(a) mode and natural frequency

The results of the modal analysis can reflect the overall mass and stiffness distribution of the deck. As shown in Fig. 3 and Fig. 4, the comparison of the prediction mode and the natural frequency of the two
models of the straight line and the 60° central angle curved simply supported bridge are respectively given.

![Fig. 3 Comparison on predicted mode and natural frequency from two models for straight simply supported bridge](image)

![Fig. 4 Comparison on predicted mode and natural frequency from two models for curved simply supported bridge with 60° central angle](image)

(b) Gravity Load

In highway bridges, gravity loads are often dominated by total vertical loads. Under the action of gravity load, the reaction of the inner and outer supports of the curved bridge with horizontal curvature and lateral asymmetry is different. Table 1 compares the predicted responses of the two models of curved simply supported bridges with different central angles under gravity loading, where positive and negative values indicate support in compression and stretching, respectively.

| Central angle (°) | Reaction of inside support (kN) | Reaction of outside support (kN) |
|------------------|-------------------------------|-------------------------------|
|                  | EM               | BM          | BM/EM  | EM               | BM          | BM/EM  |
| 20               | 204.78           | 204.29      | 1      | 543.01           | 541.03      | 1      |
| 50               | -78.06           | -77.32      | 0.99   | 825.85           | 822.63      | 1      |
| 80               | -455.88          | -453.49     | 0.99   | 1203.66          | 1198.80     | 1      |
| 110              | -1082.57         | -1077.49    | 1      | 1830.35          | 1822.78     | 1      |
| 140              | -2552.6          | -2541.24    | 1      | 3300.37          | 3286.52     | 1      |

3.3. Analysis of Composite Continuous Box-Girder Bridges

Different from composite simple box girder bridges. In order to avoid the concrete being stretched in the continuous bridge, a prestressed load should be applied under the concrete slab. Therefore, for composite continuous box girder bridges, the static analysis under prestressed loads is supplemented.

(a) Mode and Natural Frequency

Fig. 5 and Fig. 6 plot the comparison on predicted mode and natural frequency from two models for straight and 140° central angle curved continuous bridges, respectively.

![Fig. 5 Comparison on predicted mode and natural frequency from two models for straight continuous bridge](image)

![Fig. 6 Comparison on predicted mode and natural frequency from two models for 140° central angle curved continuous bridge](image)
Fig. 6 Comparison on predicted mode and natural frequency from two models for curved continuous bridge with 140° central angle

(b) Gravity Load
Table 2 compares the predicted responses of the two models of curved composite continuous beams with different central angles under gravity loading. A good correlation between the predictions obtained using the two models can be observed by comparison.

Table 2 Comparison on predicted reaction of support from two models for curved continuous bridges with different central angle under gravity load

| Central angle (°) | Reaction of inside exterior support (kN) | Reaction of inside interior support (kN) | Reaction of outside exterior support (kN) | Reaction of outside interior support (kN) |
|------------------|-----------------------------------------|----------------------------------------|------------------------------------------|-----------------------------------------|
|                  | EM BM BM/EM EM BM BM/EM EM BM BM/EM EM BM BM/EM | EM BM BM/EM EM BM BM/EM EM BM BM/EM EM BM BM/EM | EM BM BM/EM EM BM BM/EM EM BM BM/EM EM BM BM/EM |
| 70               | 119.2 119.4 1.00 623.0 622.4 1.00 149.9 150.0 1.00 600.2 597.0 0.99  |
| 140              | 104.7 104.3 1.00 654.8 653.6 1.00 159.0 159.1 1.00 573.5 571.7 1.00 |
| 210              | 95.61 94.24 0.99 719.0 718.3 1.00 160.9 160.9 1.00 516.0 515.3 1.00 |
| 280              | 94.93 92.18 0.97 822.7 833.0 1.01 154.5 153.4 0.99 418.7 410.1 0.98 |

(c) Prestressing Load
The equivalent load method is used to simulate the effects of prestressed tendons. Figure 7 depicts a comparison of predicted deflections and stresses for two models of linear continuous beams under prestressed loads.

Fig. 7 Comparison on predicted deflection and stress from two models for straight continuous bridge under prestressing load

4. Conclusions
Using the existing powerful research and design tools, the beam truss model was introduced into the design analysis of the composite box girder bridge. This paper carried out a comprehensive research plan for the beam truss model. These include modeling implementation, modeling analysis, and modeling applications. From the research in this paper, we can draw the following conclusions:

Shear flexible grid theory has traditionally been used for the design analysis of cellular bridge decks, such as box girder bridge decks, composite box girder bridges - truss model modeling strategies, including the principles of component and cross-sectional levels, and formulation. On the principle of component level, the reasonable arrangement of the lattice members of the straight bridge and the curved bridge is described, and in the principle of the horizontal level of the section, the various cross-sectional characteristics of the axial, bending, shearing and torsion effects of the deck are explained.
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