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Equivalent computational models and deflection calculation methods of box girders with corrugated steel webs

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ABSTRACT

This study found that it is improper to use equivalent concrete webs (ECWs) to replace corrugated steel webs (CSWs) in the MIDAS Civil. To reflect the mechanical performance difference of CSWs in different directions, a more precise theoretical model, the assimilated orthotropic plate (AOP), is presented to simulate CSWs. 3D Finite element analysis demonstrates that the AOP model can yield a more precise description of CSWs compared with the ECW model in MIDAS. In addition, this paper presents a unified calculation method for bending deformation suitable for the analysis of beams with equal-area or variable-area cross-sections, in which the non-prismatic beam is made equivalent to the prismatic beam by introducing the concept of equivalent inertia moment. Additionally, the formula of shear deformation in a non-prismatic box girder with CSWs is also derived with Timoshenko beam theory. These derived formulas for non-prismatic box girder with CSWs agree well with the numerical and measured data.

1. Introduction

As a new type of composite structure, box girders with CSWs originated in France in the 1980s and were soon after widely applied in Japan. In the last 15 years, PC girders with CSWs have been vigorously promoted in China [1]. However, there is no specialized 3D finite element software or universal standard method for this new structure in China. Generally, the finite element software MIDAS Civil is adopted to check and analyze the design of such structures. As a professional design software application, MIDAS Civil has been widely used in South Korea, China and other countries (more than 150 countries). The spatial beam element is adopted to simulate the composite box girder with CSWs in MIDAS Civil. In the program, the folded steel webs are equivalent to the usual concrete flat webs according to the principle of equivalent stiffness. This program uses two basic assumptions: (1) The ECWs bear all vertical shear force in the section; (2) Only the area of the ECWs is included in the calculation of the effective shear area of the cross section; namely, the shear stiffness and the shear deformation of the concrete flanges are ignored. These assumptions are obviously inappropriate for non-prismatic box girders with CSWs. The reasons for this are as follows: The inclined bottom concrete flange will share a significant part of the shearing force; therefore, the shearing force of the web calculated by MIDAS are larger than the accurate results if the shear capacity of the concrete flanges is ignored. Second, the ECWs are nearly 6 times (the ratio of the elastic modulus of steel to that of concrete) the thickness of the CSWs; thus, the shear stress in the ECWs calculated by MIDAS is only 1/6 of the stress of the CSWs. In addition, the accordion effect of CSWs cannot be reflected in the ECW model. Because the ECW beam model includes many assumptions and cannot accurately reflect the mechanical behavior of the CSWs, seeking a reasonable, simple and accurate model is needed to reflect the features of CSWs represents an urgent matter.

Accordingly, a comparison of the solid model in ABAQUS (CSW model) and the beam model in MIDAS (ECW model) is presented, and the 3-D CSW solid model is used as a standard reference model to evaluate the accuracy of the stress and deformation of the ECW beam model. However, the space effect and analysis of local stress cannot be analyzed using the MIDAS beam model. To reflect the characteristics of the CSWs more exactly, a more accurate simulation model—AOPs model—is developed. In this paper, a long-span non-prismatic box girder bridge with CSWs is chosen as the project background. The solid models of CSW, ECW and AOP are established in ABAQUS. Through comparative analysis and study of the three models, a more reasonable equivalent analysis model of the CSWs is presented. In addition, the calculation and distribution of shear stress in the non-prismatic box girder with CSWs will be

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quite different from the prismatic member; the calculated shear stress in the webs would be overly conservative if the shear capacity of concrete flanges was ignored. Compared with the ordinary prestressed concrete box girder, the shear stiffness of the composite box girder with CSWs is substantially smaller [2] (approximately 8% of the former), which means that the shear deformation in this structure is also been quite pronounced. The mechanical performances of the non-prismatic box girder with CSWs have received little scientific attention in previous studies. Many scholars thoroughly studied prismatic I- or box girders with CSWs. The shear stress and shear deformation were usually studied via experimental and finite element methods but lacked an analytical expression for computing the stress and deformation of the non-prismatic box girder with CSWs. Therefore, the theoretical study of the basic mechanical properties of a non-prismatic beam with CSWs represents a research direction worthy of academic attention.

Current research progress on CSWs is now briefly discussed. Because shear bucking is a key issue in the design of such a structure, many scholars have focused on the global and local buckling of prismatic I- or box girders with CSWs [3–16]. Hassanein and Zevallos [17,18] have done some theoretical research, first on the shear buckling behavior of tapered bridge girders with CSWs, and put forward a design strength formula for the tapered CSWs. In addition, some scholars have conducted basic research on shear stress and shear deformation related to this study. Through experimental study and theoretical analysis, Hamilton [3] and Johnson et al. [19] found that shear forces are resisted mainly by the CSWs, and the longitudinal bending moment is resisted mostly by axial forces in the concrete flanges. Shitou et al. [20] experimentally determined that the load sharing ratio of the CSWs to shear increased with crack propagation in the concrete flanges but decreased when the steel reached the yielding strength. Machimdamrong et al. [21] asserted that errors result when the Euler–Bernoulli beam theory is applied to stress and deformation analysis of box girder with CSWs. A more refined beam theory that accounts for shear deformation is derived by the application of the variational principle. Based on the displacement field assumption, internal force equilibrium equations, and the deformation compatibility condition, He et al. [22] presented the elastic bending theory by considering shear deformation for a composite bridge with CSWs.

From the above-mentioned studies, it can be concluded that studies on the shear stress and deflection of non-prismatic box girders with CSWs in the elastic stage remain insufficient. However, considering economic and construction feasibility, the non-prismatic box girder is one of the most popular structure types in bridge design. The mechanical behavior of the non-prismatic beam is very different from that of the prismatic beam owing to the effect of variable section. The ultimate bearing capacity of this structure is dominated by the shear buckling failure of the CSWs. However, a bridge is usually in the elastic stage during construction and service. The control of vertical deflection in the elastic stage is also crucial to satisfy the requirements of the servicing limit states in bridge design. Accordingly, the static analysis of the non-prismatic box girders with CSWs at the elastic stage is significant in theory and practice.

2. Comparison of multiple equivalent analytical models of CSWs

2.1. The project background

The Fenghua River bridge, which is one of the longest span non-prismatic box girders with CSWs under construction in China, was selected as the study object. The superstructure of the Fenghua River bridge is a three-span PC composite continuous box girder with a main span of 160 m. The cantilever construction method is used, and the main girder is divided into many sections and steps of pouring and prestressing. Because balanced cantilever construction is adopted, the bridge must undergo the longest cantilevered stage, which is the most adverse load case during the construction stage. Therefore, the 80-m cantilever beam in the largest single-cantilever state of the middle span was chosen for this study, and the dimensions of the section are shown in Fig. 1.

2.2. Discussion of the equivalent model of CSW in MIDAS Civil

2.2.1. The FE model of MIDAS Civil and ABAQUS

As mentioned above, the spatial beam element is adopted to simulate the box girder with CSWs in MIDAS Civil. The CSWs are replaced with ECWs according to the conversion elastic modulus of steel and concrete, as shown in Fig. 2a. For the beam model of the box girder with CSWs, only the contribution of the concrete flanges is considered in the bending stiffness, as shown in Fig. 3b. And only the area of ECWs is assumed as the effective shear area. The user can choose whether or not to consider shear deformation in the calculation of beam deflection by the option button. Under the assumption of quasi-plane section, the normal stress at the concrete flanges presents linear distribution, as shown in Fig. 3c. The ECWs are assumed to bear all vertical shear force in section and the shear stress in the thin CSWs presents an even distribution, as shown in Fig. 3c. To evaluate the computation results obtained by MIDAS Civil, two 3D finite element models were established in ABAQUS, as shown in Fig. 2b and c. Among them, model-2 is highly similar to model-1, except that the former is a more accurate solid model, and the latter was established based on the beam element. By comparing model-1 and model-2, some assumptions in the analysis module of MIDAS Civil can be verified. Model-3 is established in accordance with the actual dimensions of the bridge and can be used to validate the results when the ECWs replace the CSWs in MIDAS Civil. For model-3, the concrete flanges and folded steel webs are simulated by C3D8R solid elements and S4R shell elements, respectively. The concrete flanges and steel webs are merged using Boolean operations to make the mesh nodes follow the same deformation under loading. In the elastic stage, the constitutive relation for the concrete and steel follow a linear elastic constitutive relation. Both concrete and steel are considered to be homogeneous materials in the finite element model. The parameters of each model are shown in Table 1.

2.2.2. The loading conditions and contrast analysis results

Following the construction process, two types of load conditions are discussed: gravity and the concentrated load (simulation of the hanging basket, 500 kN). Taking model-3 (CSW in Fig. 4) of ABAQUS as the standard model, this part attempts to realistically appraise the applicability of the MIDAS model. The contrastive research was conducted based on four aspects: the stress of the webs, the load sharing ratio of the webs, the total deflection, and the shear deformation and its proportion of the total deformation. The comparison results of each calculated section obtained by MIDAS and ABAQUS are as follows.

From the perspective of shear stress in the webs and the proportion of the total load in the section, it is unreasonable that the folded steel webs were assumed to carry all shearing force of the non-prismatic box girder with CSWs. From Fig. 4, the shear stress in ECWs in the MIDAS model is nearly one-sixth of the stress in CSWs calculated using the CSW model in ABAQUS. The proposed reason for this is that the ECWs are nearly six times thicker than the CSWs converted based on the elastic moduli of the steel and concrete. On further analysis, the shear stress calculated using the MIDAS beam model is greater than that of the ECW model established in ABAQUS (the CSWs are all equivalent to the concrete