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Deformation analysis of a non-prismatic beam with corrugated steel webs in the elastic stage

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ABSTRACT

Based on the concept of isoparametric mapping, a generic approach for investigating the bending and shear deformation in a non-prismatic elastic beam with corrugated steel webs (CSWs) was presented in this study. The strain field of an actual element (namely, the non-prismatic beam segments) is expressed as a function of the local coordinates in the parent element. Continually, the solution of the bending and shear deformation of the non-prismatic beam segment can be transformed into the integration of strain in the parent element under local coordinates. Since it is usually laborious to solve the displacement field by direct integration of strain in a non-prismatic beam segment using global coordinates. In addition, this study found that shear deformation cannot be ignored in the actual design of this type of structure because the thin-walled section has a small shear stiffness. In contrast, for a composite beam with CSWs, shear deformation occurs beyond bending deformation and becomes a major contributor of total deformation in some critical sections. Finally, experimental study of the mechanical properties of a non-prismatic beam with CSWs is conducted for the first time. The experimental results further demonstrate the validity of the proposed theoretical analysis methods.

1. Introduction

The box girder with corrugated steel webs (CSWs) is a new type of composite steel-concrete structure, which makes full use of the material characteristics of concrete and steel, and significantly reducing the weight of the structure. The most important characteristic of this type of bridge is that CSWs have replaced the traditional flat concrete webs. Compared with conventional concrete box girder bridges, in addition to completely avoiding web cracking, this structure has many other advantages, such as the definite force, aesthetic appeal, and convenience for construction. The first composite box girders with CSWs originated in France in the 1980s and were widely applied in Japan soon after [1]. Over the past three decades, it has been widely used in small- and medium-span bridges. As the manufacturing processes, construction technology, and design theory of box girders with CSWs have increasingly matured, this type of bridge has begun to offer significant competition to the modern larger span bridges. For long-span bridges, beams of variable depth are inevitably used, considering economic and technological factors. However, through literature investigation, the authors found that most scholars have focused on the buckling behavior of prismatic beams with CSWs, and very few studies have been conducted to investigate the bending and shear deformation of non-prismatic beams with CSWs. It should be noted that the sectional shear stiffness of the box girder with CSWs would be reduced compared with conventional box girders with concrete webs (approximately 8% of the latter [2]). The influence of shear deformation may not be ignored in its deflection calculation. In addition, the value and distribution of shear stress in a non-prismatic beam is quite different than that of a prismatic beam due to the effect of variable cross sections [3]. Therefore, it is of great significance to determine the proportion of shear deformation and total deformation with respect to theory and engineering.

The current progress in research of beams with CSWs in regard to deformation or the effect of variable cross sections is briefly stated as follows. As is well known, shear buckling has become a key controlling factor in the design of this structure. Many scholars have focused on the global and local buckling of prismatic I- or box girders with CSWs [4–11]. In addition, some scholars have conducted basic research works on the deformation analysis in prismatic beams with CSWs, which are related to this study. Machimdamrong [12] asserted that errors result when the Euler–Bernoulli beam theory is applied to stress and deformation analysis of box girders with CSWs. A more refined beam theory that accounts for shear deformation is derived from the application of the variational principle. Based on the displacement field assumption, internal force equilibrium equations, and the deformation compatibility condition, He [13] presented the elastic bending theory

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Nomenclature

$\rho(x)$	the radius of curvature
γ_{xy}	shear strain of the infinitesimal segment
θ	the central angle
ε_{pq}	the compressive of the upper fiber layer
ε_{mn}	the tensile strain of the lower fiber layer
h	the height of the infinitesimal segment
Ni	the shape functions of 4 nodes isoparametric element
ξ and η	coordinates of an arbitrary point under the local coordinate system
u and v	the horizontal and vertical displacement
ε	the element strain fields
J	denotes the Jacobian matrix
w_b and w_s	bending and shear deformations

by taking shear deformation for a composite bridge with CSWs. By introducing a shear rotation function accounting for the shear deformation in the webs, Nie [14] introduced a beam theory model of the corrugated web girder, where the flexural behavior of the corrugated web girder is modeled as the combination of truss action and bending action between the top and bottom flange. Li [15] noted that it is not reasonable to consider that all vertical shear force is supported by the CSWs outside the concrete top slab and bottom slab. It would be conservative to calculate the shear stress in beam bridges by ignoring the ability of the concrete slab, especially for variable cross sections. Hassanein [16–18] performed some theoretical research, first on the shear buckling behavior of tapered bridge girders with CSWs, and introduced a design strength formula for the tapered CSWs. Zhou [3] provides a strict derivation of the general formula for shearing stress in a non-uniform box girder with corrugated steel webs in the elastic stage.

From the above-mentioned studies, it can be concluded that studies on the deflection of non-prismatic beams with CSWs in the elastic stage remain insufficient. However, the shear deformation is especially noticeable in these thin-walled structures. Additionally, the mechanical behavior of a non-prismatic beam is very different from that of a prismatic beam due to the effect of the variable section. As a result, it is difficult to solve for the bending and shear deformation in a non-prismatic beam. To quantitatively study the proportional relation of bending deformation and shear deformation, the authors conducted experimental and theoretical studies on the deformation of a non-prismatic scaled model with CSWs in this study.

2. Experiment

2.1. Experimental program

To investigate the proportional relationship between bending and shear deformation and determine an adapted method to separate the shear deformation from the total deformation in a non-prismatic I type beam with CSWs, an experiment of a simply supported beam with a cantilever in the elasticity range was conducted to verify the theoretical calculation method proposed in this study. The general introduction of

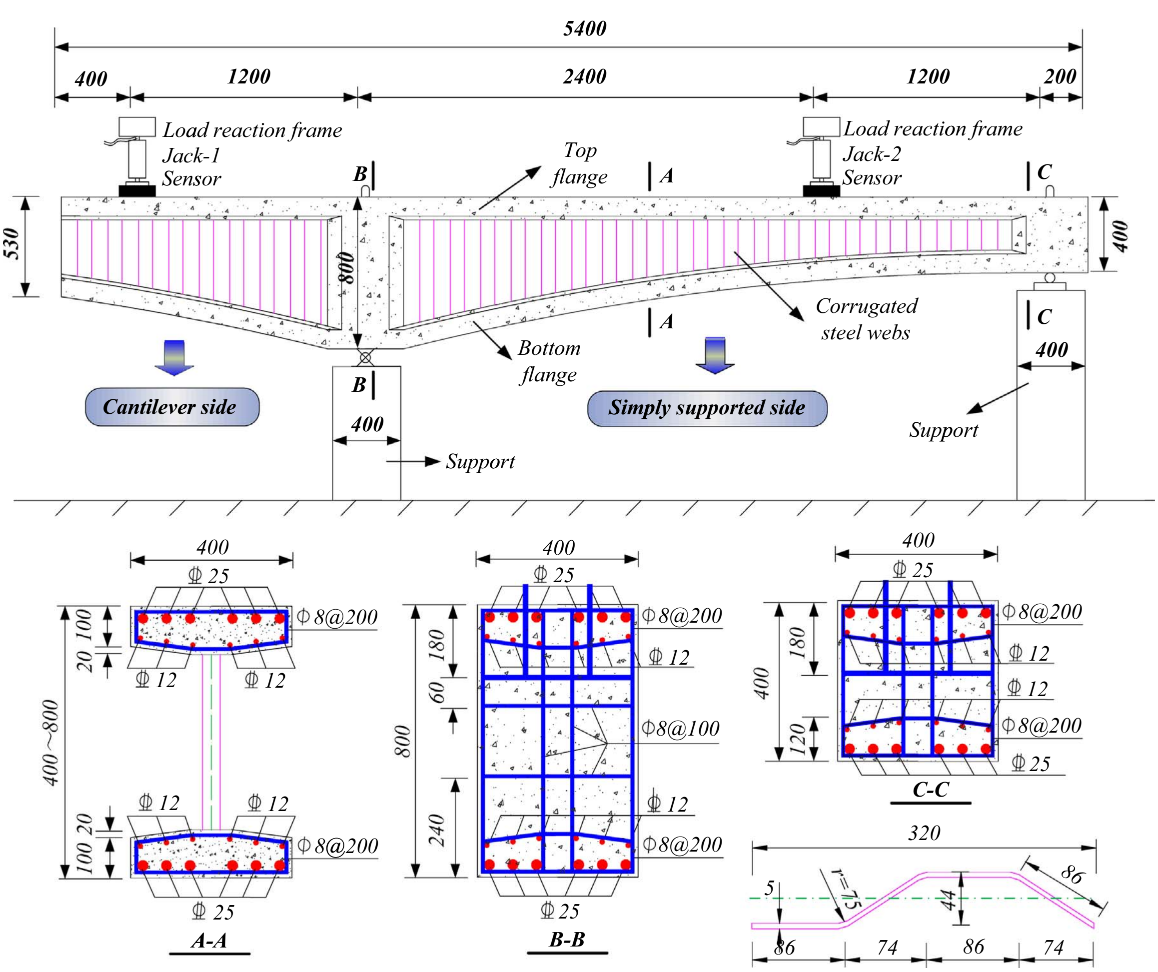

Fig. 1. Dimension and reinforcement of the I-girder with CSWs (unit: mm).