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Shear behavior of partially encased composite I-girder with corrugated steel web: Numerical study

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ABSTRACT

Shear behavior of partially encased composite I-girders with corrugated web has been investigated analytically and numerically in this paper. A 3-D finite element model with geometric and material nonlinearity is established and verified by the experiments. Subsequently, a parametric study is carried out to examine the effects of geometric and material properties on the shear behavior which includes corrugation, height, thickness, connection degree between steel web and concrete encasement. It is found that the ultimate shear strength of steel I-girders is improved with increases in the thickness, height and yield strength of corrugated web, while the ultimate shear strength of partially encased composite I-girders increases with the thickness, yield strength of corrugated web and the thickness, compressive strength of concrete encasement. However, the stud stiffness has little influence on the ultimate shear strength. Moreover, the concrete encasement improves the shear strength of steel I-girders, the degree of improvement increases with the thickness and compressive strength of the concrete, but decreases drastically with the thickness of corrugated web. Therefore, it is suggested that concrete should be poured on the corrugated web with thin thickness or low yield strength to prevent buckling occurrence before yielding of steel web. Finally, shear strength prediction equations are proposed and verified by numerical results. The calculated shear strength agree well with the numerical results for steel I-girders before and after composite with concrete, which indicates that the proposed analytical equations can be applied to predict the shear strength of such partially encased composite girders with corrugated web.

1. Introduction

Prestressed concrete girder with corrugated steel webs is one of the promising steel–concrete hybrid structures applied to highway bridges, which is composed of concrete slabs, corrugated steel webs and internal or external tendons. The way to substitute corrugated steel webs for concrete webs of composite girders will result in no restraint among the upper or lower slab and the webs, which will alleviate influence on the structure due to concrete creep, drying shrinkage and temperature differences. Prestressing can be efficiently introduced into the top and bottom concrete slabs due to the so-called “accordion effect” of corrugated webs. The strength, stability of structures and material efficiency can be improved by concrete slabs combined with corrugated steel webs [1–3].

Corrugated steel plates can ensure higher resistibility against shear buckling, leading to elimination of stiffeners. The shear behavior of corrugated steel plates has been extensively studied: Shimada [4] was the first researcher who studied the shear strength of steel plate girders with folded web plate. Easley [5,6] proposed the global shear buckling equation of corrugated web by treating the corrugated web as an orthotropic flat web. The corrugated steel web is assumed to provide the shear capacity of the girder where the shear strength is controlled by buckling and/or shear yielding of the web [7–11]. Lindner and Aschinger [12] presented test results for the shear strength of steel trapezoidal corrugated webs and suggested using 70% of the shear buckling stress as the nominal shear strength for design. Luo and Edlund [13,14] analyzed the buckling of trapezoidally corrugated panels under in-plane loading by spline finite strip method and finite element method. Elgaaly et al. [15] presented experimental and analytical results of steel beams with trapezoidal corrugated webs loaded predominantly in shear. Yamazaki [16] described some formulas for estimating buckling strength of corrugated steel web in comparison with the test results of 6 full-scale models for bridge girders. Driver et al. [17] tested full-scale corrugated web girders made of HPS 485W steel, assessed the effect of web initial geometric imperfections through measurements of the out-of-plane displacements, and proposed a lower bound equation for design that accounts for both local and global buckling of the web in the elastic and inelastic domains. Watanabe et al. [18,19] presented the test results using four different trapezoidal corrugation configurations to study the shear capacity with and without local heating history. Yi et al. [20] studied the nature of the interactive shear buckling of corrugated web, and concluded that the first order interactive shear buckling equation

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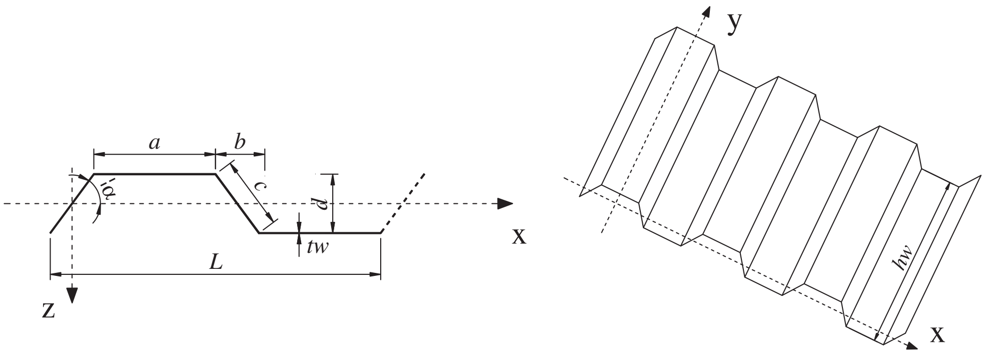

Fig. 1. Profile of corrugated steel web.

without considering material inelasticity and material yielding provided a good estimation of the shear strength of corrugated steel web by comparison with 15 tests and FEA results. Sause and Braxtan [21] summarized previously developed formulas for predicting the shear strength of steel trapezoidal corrugated web, along with the corresponding theory, and a new formula was developed.

Based on the design and construction data of all completed composite bridges with corrugated steel webs in Japan, continuous and rigid frame bridges with the main span length from 50 m to 150 m account for about 80% of the total number, which means these two kinds of structural configurations are suitable for composite bridges with corrugated steel webs. However, at the intermediate supports, large bending moment and shear force exist in continuous and rigid frame bridges; the concrete slab is in tension due to hogging moment and does not contribute to the bending strength. The lower flanges and lower parts of webs are in compression, which are vulnerable to lateral-torsional buckling. Thus, there are weak points with regard to durability and strength. Especially, concrete cracking affects the durability and service life of bridges. In order to improve the structural performance of continuous composite girders under hogging moment, Nakamura [22,23] proposed the use of partially encased composite I-girders and partially concrete filled steel box girders around support parts, and the authors [24] proposed partially encased composite I-girders with corrugated steel web. Concrete is poured in the area surrounded by the upper flange, lower flange and web around the intermediate supports. The concrete encasement is expected to prevent buckling of the web in compression and the concrete itself also contributes to the bending and shear strength.

At present, there are few reports about design specifications for partially encased composite girders with corrugated steel web, He et al. [24] tested steel and composite I-girders with corrugated web to investigate the shear performance, the varying parameters such as the thickness of steel web, connection degree between the steel web and the concrete were considered in the test. This paper pays more attention to the analytical and numerical studies of the shear behavior for steel and composite girders with corrugated web. Firstly, analytical models of the shear strength were reviewed and developed. Secondly, on the basis of experimental works by the authors, numerical FE models were established. Accordingly, parametric analyses were performed by the validated FE models to examine the effects of geometric and material properties on the shear strength. Finally, analytical equations of the shear strength were verified through comparisons with numerical studies. The present overall investigation can serve as a basis for shear design of partially encased composite I-girders with corrugated web.

2. Analytical study

2.1. Shear capacity of steel I-girder with corrugated web

Shear strength of steel I-girder is controlled by buckling and/or shear yielding of the corrugated web. Shear buckling of corrugated web is often classified as either local buckling or global buckling. Global buckling involves multiple folds and the buckled shape extends diagonally over the height of the web. Local buckling is controlled by deformations within a single flat panel or "fold" of the web. The local buckling deformations can propagate into adjacent folds simultaneously.

Plate buckling theory [25] can be used to predict the local shear buckling stress of a corrugated web. A single fold (longitudinal or inclined, Fig. 1) is assumed to be supported by the adjacent folds along its vertical edges and by the flanges along its horizontal edges. The corresponding local elastic shear buckling stress $\tau^e_{cr,L}$ is:

$$\tau^e_{cr,L} = k_L \frac{\pi^2 E}{12(1-\upsilon^2)} \left(\frac{t_w}{w}\right)^2 \quad (1)$$

where k_L is the local shear buckling coefficient that depends on the boundary conditions and fold aspect ratio, k_L lies between 5.34 (assuming simply supported edges) and 8.98 (assuming fixed edges). E and υ are Young's modulus and Poisson's ratio respectively, w is the fold width, and t_w is the web thickness. For buckling of an inclined fold $w = c$ and for buckling of a longitudinal fold $w = \alpha$ (Fig. 1). To determine the smallest value of $\tau^e_{cr,L}$, w is taken as the larger of c and α.

An expression for the global elastic shear buckling stress of a corrugated plate $\tau^e_{cr,G}$ was developed by Easley [6] using the orthotropic plate theory:

$$\tau^e_{cr,G} = k_G \frac{D_y^{1/4} D_x^{3/4}}{t_w h_w^2} \quad (2)$$

where, k_G is the global shear buckling coefficient that depends upon the boundary conditions. Elgaaly et al. [15] suggested that k_G should

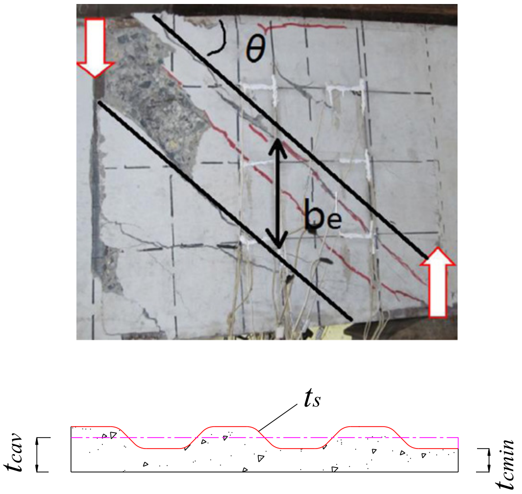

Fig. 2. Shear failure of partially encased composite I-girder with corrugated steel web.