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Shear capacity of a novel joint between corrugated steel web and concrete lower slab

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HIGHLIGHTS

- A new joint structure with perforated plate connectors was proposed.
- Push-out tests on proposed joint structure were carried out.
- A parametric study was performed using verified 3D FEM to examine the effects on ultimate shear strength.
- Prediction equations of shear strength were proposed and verified by experimental and numerical results.

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ABSTRACT

Composite girder with corrugated steel web is one of the promising concrete-steel hybrid structures with superior properties and cost effectiveness widely applied in highway and railway bridges. The connection between concrete slabs and corrugated steel web is an important part of such composite structure. In order to improve pouring quality and durability of concrete for joint structure between corrugated steel webs and concrete lower slab, the validity of placing lower slab on the inner side of corrugated steel webs was confirmed and a new joint structure with perforated plate connectors was proposed. Push-out tests on proposed joint structure with different parameters including the welding width and the plate thickness were carried out to study their shear strength, shear stiffness, failure modes and relative slip characteristics. Subsequently, three-dimensional finite element models taking material non-linearity and nonlinear contact between steel and concrete interface into consideration were built and validated by the push-out tests. Afterwards, parametric studies were performed to further investigate the influences of geometrical parameters (such as width, height and thickness of perforated steel plate) and material parameters including steel yielding strength and concrete compressive strength on ultimate shear strength and failure mode of the joint structure. Analytical results indicate that the shear loading capacity is increased with the thickness, the width and height of perforated plate, and the compressive strength of concrete. However, steel yielding strength, presence or absence of perforating rebar, have a negligible effect on ultimate shear strength of the joint structure. Finally, prediction equations of shear capacity were provided and compared with experimental and numerical results. The calculated shear capacity agrees well with experimental and numerical ones, indicating provided analytical equations can accurately predict shear capacity for such novel joint structure.

1. Introduction

A composite girder with corrugated steel web, including corrugated steel webs, reinforced concrete or pre-stressed concrete slabs, is one of the promising concrete-steel hybrid structures applied to railway and highway bridges. Because of using corrugated steel webs instead of concrete webs, no restraint between the concrete slabs and corrugated steel webs exists, resulting in reduction of effects on structural responses due to shrinkage and creep of concrete, temperature differences between webs and slabs. In addition, the "accordion effect" of the corrugated steel webs allows pre-stressing efficiently introduced into concrete slabs [1,2]. Since the first composite bridge with corrugated steel webs-Cognac Bridge built at France in 1986, a large number of this

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type composite bridge has been constructed, and their mechanic behaviors such as shear, flexural, torsional behavior, fatigue performance and so on have been experimentally and analytically studied [3–9].

The connection between concrete and steel is an important part of composite structure. The shear studs, Perfo-Bond Strip (PBL) connectors and angle shear connectors welded on steel flange or the corrugated steel web directly embedded in concrete slab are generally used for the joint part as shown in Fig. 1. He et al. [10] investigated composite bridges with corrugated webs domestic and abroad to analyze the number and proportion of different kind connectors, and found that headed studs were adopted most for corrugated web bridge in early time [11–13], such as Shinkai Bridge [14] in Japan and Altwipfergrund Bridge [15] in Germany. Angel connector [16] (Fig. 1d) was the most popular one used in France and Japan, the U-shaped reinforcements welded on the angel help the connector deform ductile, while the longitudinal reinforcements bear out-of-plane bending moment.

In the eighties of last century, the PBL connector was developed for the design of the third bridge over the Caroni River in Venezuela by a German company [17]. PBL shear connectors showed better fatigue strength in comparison to welded studs from push-out test results [18]. However the out-of-plane bending moment performance for single perforated plate is not so good, therefore studs are welded on both sides of perforated plate in Fig. 1(c) or Twin PBL connectors (in Fig. 1b) are used to improve transversal bending moment resistance. Ebina et al. [19,20] conducted an extensive research using normal and high performance concrete to obtain the mechanical characteristics (shear and out-plane bending behavior) of twin PBL connectors. Corrugated steel webs have very low axial rigidity, which requires relatively flexible shear connectors. A type of shear connector without using a steel flange was proposed. Corrugated steel web embedded in the concrete as shear connector was initiated in Hondani Bridge. Nakasu et al. [21] carried out the experiments and finite element analysis for several types of specimens changing plate thicknesses and embedded depths of corrugated steel webs to investigate a long-term behavior of embedded connector. Kosa et al. [22] conducted experimental and analytical investigations on shear and flexural behavior of composite girders with corrugated steel webs to understand failure mechanism of embedded connection. Taira et al. [23] investigated the stress distribution in embedded connection zone by finite element method considering the effects of embedded depth, thickness of corrugated steel plate, and the direction of wedding joint. Novák & Röhm [24], Röhm & Novák [25] investigated the load-carrying capacity of an embedded corrugated steel web with concrete dowels under longitudinal shear force and transverse bending moment respectively. Based on these studies, simplified design methods for shear connection at ultimate limit state were proposed. Kim et al. [26] carried out push-out test of corrugated perfo-bond rib shear connections. Test results showed that the failure was determined by concrete at inclined panel with small deformations, and shear strength increased much in comparison to standard perfo-bond rib connector due to the shear resistance of the inclined rib panel.

When stud or embedded connections used for the joints between corrugated steel webs and concrete lower slab, the designer and constructor must take care about the construction quality of concrete and waterproofing of the joints. With a view to these problems, Ono et al. [27] prepared some specimens of the embedded connection and carried out accelerated corrosion tests of these specimens. The results showed that durability of the embedded connection was improved by sealing the border between steel and concrete and by painting embedded connection in concrete. Shiji et al. [28] and He et al. [10] adopted the joint structures with headed studs and perforated plate connector as shown in Fig. 2, the validity of placing lower slab on the inner side of corrugated steel webs was confirmed. It was proved that the bottom flange was beneficial to concrete construction quality, as well as the durability of the interface between concrete slab and corrugate web. This study only focuses on the shear behavior of joint structure with perforated plate connector.

Since shear loading capacity, failure modes and relative slip characteristics of proposed joint structures are different from those of conventional ones. Therefore, standard push-out tests are conducted to investigate the influence of different parameters

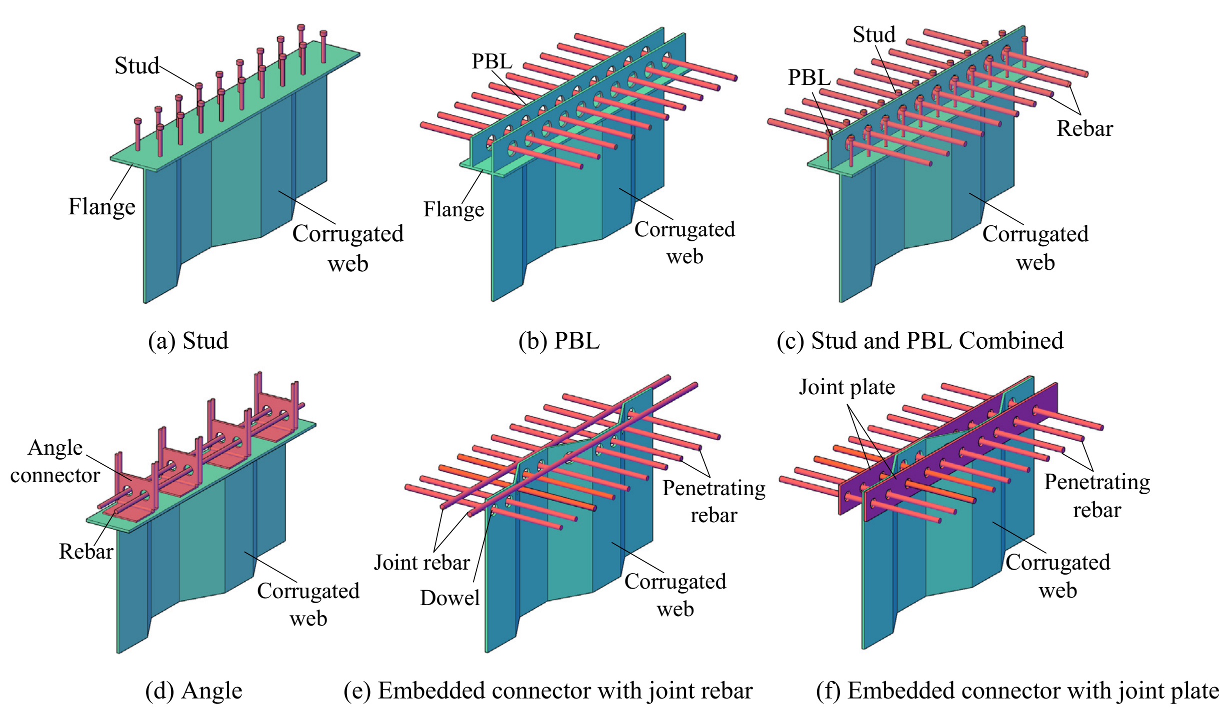

Fig. 1. Conventional joint structure of composite bridge with corrugated steel web.