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Push-out tests for perfobond strip connectors with UHPC grout in the joints of steel-concrete hybrid bridge girders

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ABSTRACT

This paper aims at examining the structural behavior of perfobond strip (*PBL*) connectors for steel-concrete joint of hybrid girders with ultra-high performance concrete (*UHPC*) as grout for such connectors. Twenty-four push-out specimens fabricated according to the design used for the connectors in the steel-concrete joint in a hybrid cable-stayed bridge have been investigated. Effects of several parameters such as (i) the interface bond between perforated plate and concrete, (ii) dowels inside the holes in the plate, and (iii) volume of steel fibers in the UHPC on the behavior of PBL were discussed in depth. Experimental results indicated that the use of a 2% volume fraction of steel fibers in the UHPC, increased the average bond strength at the plate/concrete interface and the shear resistant-capacity of concrete dowel by 82% and 50%, respectively, as compared to UHPC specimens without the fibers. The concrete dowel played an important role in developing the desired loading resistant-capacity of the PBL, and about 34–41% of the overall resistance of a standard PBL embedded in UHPC were supplied by the concrete dowel surrounding transverse rebar. The source of the achieved ductility of PBL was mainly determined by the action of transverse rebars, and the ductility in the specimens having transverse rebars was about eleven times the ductility of similar specimens without the rebars. Furthermore, the experimental ultimate strength values of PBL were compared with available equations in literatures published recently, and an analytical model for PBL/UHPC was developed and appropriate parameters were derived from present data and used to provide reliable prediction of ultimate resistant-capacity of PBL in the hybrid girders' steel-concrete joints.

1. Introduction

Due to the excellent economical, constructional, and mechanical advantages, steel/concrete composite structures have been widely used in civil infrastructural applications. The most common composite structural system is comprised of a steel girder topped with a reinforced concrete (*RC*) slab for both buildings and bridge applications. Another form of composite structure that attracted engineers' attention nowadays is the steel-concrete hybrid girders. These hybrid girders have remarkable advantages in terms of structural behavior. Compared with the conventional superimposed beams, a hybrid girder consists of both steel and RC girders that are connected in series via a steel-concrete joint. In this case, shear connectors are required for transmitting forces between steel and RC girders. One of the most popular connectors is the headed steel studs due to their rapid application and their efficient structural behavior. The performance of steel studs in composite structure has been extensively investigated in recent years [1–3]. However, the insufficient fatigue property and harsh requirements on installation equipment of steel stud connectors has limited their further application [4].

In 1980s, Leonhardt [5] proposed the Perfobond strip (PBL) connector that is composed of perforated steel plates and reinforced concrete dowels as shown in Fig. 1. The ease of construction coupled with their superior mechanical performance made PBL connectors to be widely used. These connectors can be used in lieu of traditional steel studs for shear transfer in steel-concrete composite structures.

The main differences between the PBLs in superimposed beams and those in steel-concrete joints of hybrid girders are in their failure modes and mechanical properties. In superimposed beams, PBLs are embedded in a relatively thin RC floor slabs or bridge deck that typically the failure usually occurs due to cracking of slabs. In comparison, PBLs in steel-concrete joint of hybrid girders are plugged deeply in concrete blocks and their failure modes

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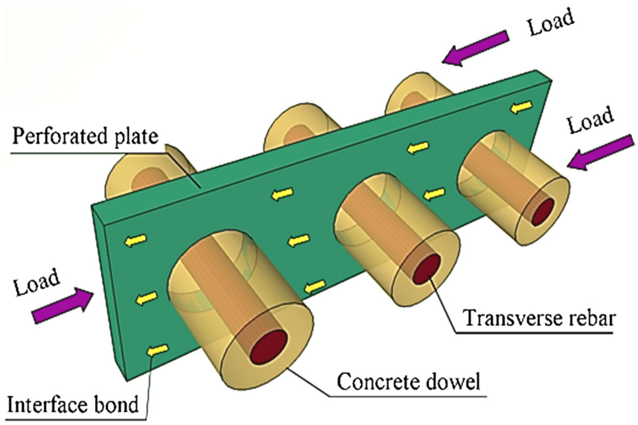

Fig. 1. Load transfer principle of perfobond strip connectors.

generally governed by fracture of the dowels by the holes. Meanwhile, PBLs in hybrid girders have much stronger interfacial restraints and the interfacial bond at the contact surface between perforated plate and concrete is more significant as compared with those in the superimposed beams [6]. As sufficient quantity of PBLs are used to transfer the major shear forces between steel components and concrete in hybrid girders, the effect of local concrete at the end of the perforated plate is small and can be negligible [7–9].

Mechanical behavior of PBL in superimposed beams with the use of conventional concrete has been experimentally and numerically assessed by several researchers. For example, Leonhardt et al. [5] and Hans-Peter [10] performed push-out tests of PBL to determine the performance of the connector. The experimental results indicated that PBL resistance was primarily influenced by concrete strength and hole diameter in perforated plate. Oguejiofor and Hosain [11,12] reported the results of an experimental study performed on sixty-one push-out specimens and conducted comprehensive numerical simulations for predicting the capacity of PBL embedded in concrete slabs. Based on their study, it was found that the interlock effect of adjacent holes in perforated plate could be eliminated by spacing larger than 2.25 times the hole diameter. Ahn et al. [13] performed fourteen push-out tests involving the arrangement of perforated plate, type and strength of concrete, and presence of transverse rebar. In this study, equations for determining the PBL capacity for structural design of the connectors in superimposed beams were presented. Studnicka et al. [14] performed sixty-one push-out tests to evaluate the capacity and behavior of PBL embedded in both normal and lightweight concrete slabs. Based on this study, it was shown that the shear capacity of PBL was significantly affected by both the compressive strength and the modulus of elasticity of concrete. Similar conclusions were reported by Valente et al. [15,16]. Medberry et al. [17] performed a total of twenty-eight push-out tests to examine the effects of chemical bond between the steel girder flange and the concrete slab. The contribution of chemical bond to shear capacity of PBL was considered in their proposed equation for evaluating the shear resistance. Al-Darzi et al. [18] proposed a numerical model using the finite element method to simulate the push-out tests. The effectiveness of the model was verified by the experimental results. A comprehensive discussion on the behavior of PBL embedded in concrete slabs was presented by Candido-Martins et al. [19]. Further experimental and numerical studies varying with the concrete strength, number of holes, and the concrete slab thickness were performed by Vianna et al. [20], and an equation to predict the shear capacity of PBL with different concrete strength was proposed.

In the past few years, research studies on the behavior of PBL with conventional concrete in steel-concrete joint of hybrid girders were performed. Wang et al. [6] performed twenty-four push-out tests to study the mechanical behavior of PBL in hybrid girders. It was shown that the interface bond between perforated plate and surrounding concrete substantially increased due to the strong restraints on the plate resulted from the reinforcements in concrete blocks. He et al. [7] conducted six push-out tests and a large-scale model test to examine the shear strength and reliability of PBL in steel-concrete joint of hybrid girders. The results revealed that the shear resistance of a PBL in a twin configuration was about 80% of that of a single independent PBL and the connectors effectively transferred the forces in steel-concrete joint. Zheng et al. [21] presented results from twenty-one push-out tests of PBL embedded in conventional concrete involving both hole diameter and shape. It was concluded that the shear stiffness of the connector was improved with the increase of hole diameter. An analytical model to determine the shear capacity of PBL regardless of the hole geometry was suggested by the authors. He et al. [22] performed twelve push-out tests to study the load transferring mechanism of PBL embedded in conventional concrete in steel-concrete joint. Results of the study indicated that the mechanical properties of PBL in hybrid girders were improved due to the bond at plate/concrete interface, and corresponding equation for determining the shear capacity of PBL with conventional concrete in hybrid girders was proposed.

In the recent years, studies on the behavior of PBL in ultra-high performance concrete (UHPC) have also been found in literature. For example, Hegger et al. [23,24] investigated the behavior of puzzle strip connectors using UHPC slabs with compressive strength of 180 MPa. It was found that the continuous type of shear connectors like the puzzle strip were appropriate for the UHPC by carrying high shear loads with appropriate ductility. Kang et al. [25] performed tests on fourteen push-out specimens of PBL with UHPC slabs. The results indicated that the shear capacity of PBL in superimposed beams was improved by increasing the strength of UHPC. Wirojjanapirom et al. [26] investigated the efficiency of using UHPC to improve the shear capacity of PBL by twelve pre-stressed short-beam tests. Results of the study showed an increase of PBL shear capacity due to the application of pre-stressing force.

Concrete-filled steel-concrete joint in hybrid girders should have sufficient strength and durability to ensure the shear capacity of connectors in the joint. However, with the extensive use of conventional concrete in steel-concrete joints, many problems arise. For example, the quality of poured concrete with coarse aggregate in the joint is difficult to be guaranteed due to the heavy reinforcements and the presence of pre-stressing tendons in the steel-concrete joint zone. In addition, the separation between steel plate and concrete is difficult to be avoided due to the shrinkage of conventional concrete at the joint zone. These two issues are harmful to the integrity of the connectors. The use of UHPC can be a way to solve these problems. UHPC has many remarkable advantages such as ultra-high strength, better ductility, and excellent durability owing to its homogenized microstructure and the incorporation of fibers. The less creep and shrinkage characteristics of UHPC may result in better bond between joint steel components and concrete, and the higher strength of UHPC and absence of coarse aggregates may also contribute to reducing the required number of PBLs in addition to the ease of placing the concrete at the joint zone.

Recently, UHPC has been successfully applied to the steel-concrete joint of Nujiang Bridge, which is a steel-concrete hybrid cable-stayed bridge with a span arrangement of 81 m + 175 m, located in Yunan, China. Although some studies were carried out on performance of PBL using UHPC in superimposed beams, however, few studies reported the behavior of PBL with UHPC in