Journal of Constructional Steel Research 150 (2018) 415–429

Contents lists available at ScienceDirect

Journal of Constructional Steel Research

Push-out test of large perfobond connectors in steel–concrete joints of hybrid bridges

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ARTICLE INFO

Article history:
Received 26 September 2017
Received in revised form 7 January 2018
Accepted 1 September 2018
Available online xxxx

Keywords:
Steel–concrete joints
Perfobond connector
Shear capacity
Large
Push-out test

ABSTRACT

The size of perfobond connectors in steel–concrete joints of hybrid bridges is typically less than 75 mm. Given the limited capacity of connectors, it is essential to tightly arrange the connectors for transmitting large internal forces. Large-sized perfobond connectors with increased capacity act as an excellent alternative to reduce the number of connections, thereby simplifying the structure in steel–concrete joints. Additionally, an increased diameter can contribute to the flow of concrete coarse aggregate. To verify the mechanical properties of large perfobond connectors, 13 groups of 39 push-out specimens are introduced. The effects of hole size, hole shape, perforating rebar, concrete strength, and lateral confinement are investigated on the failure modes and load–slip curves of large perfobond connectors. The test results indicated that, under a high level of confinement of a concrete dowel, increases the geometrical size of the hole significantly improve its bearing capacity without weakening its ductility. Finally, an empirical formula is proposed for the shear capacity considering various influencing factors.

1. Introduction

Perfobond connectors, were first proposed in 1987 [1] and are widely used in composite bridges and hybrid bridges owing to their ease of installation and excellent fatigue resistance. Studies on perfobond connectors have attracted increasing attention from researchers and designers in the past decade. Several factors affect the mechanical properties and a complex mechanism exists for force transfer, and thus, the performance of perfobond connectors is extensively examined. Currently, the main research methods include push-out tests, model tests, and numerical analysis. Model tests, including steel–concrete composite beams [2,3], steel–concrete composite plates [4], and steel–concrete joint tests [5–7] reflect the actual force state of the connection accurately. However, the cost of a model test is high, and it is difficult to obtain the mechanical characteristics of the connector directly. Numerical analysis [8–10] can aid the study of the shear mechanism of connectors and obtain the stress state of any part of the connection. However, numerical analysis is not reliable without experimental verification. Therefore, the push-out test is the most important mean of evaluating connectors due to its economy and reliability.

Currently, as shown in Fig. 1(a), most push-out specimens are based on a standard separated type of specimen recommended in EC. 4 [11]. The structure of the specimen is similar to that of the connectors in composite beams and composite plates. The specimen shown in Fig. 1(a) is termed as a *superposed perfobond connector* in the study. Test results indicate that the mechanical properties of superposed perfobond connector are mainly influenced by the perforating rebar and concrete dowel [12]. The capacity of the perforating rebar is mainly dependent on the sectional area and yield strength. The failure modes of concrete dowel are relatively complex and include shearing, local crushing, and splitting failures [13–15]. Therefore, in addition to the concrete dowel area and strength, confinement of the concrete dowel also significantly affects its mechanical properties [16,17]. Given the weak confinement of the concrete dowel in the superposed perfobond connector the load declines rapidly after reaching the peak load due to concrete dowel failure. A typical load–slip curve for the superposed perfobond connector is shown in Fig. 2.

The perfobond connectors in steel–concrete joints of hybrid bridges are typically wrapped in a steel box, and the concrete dowel is strongly confined, thereby leading to a higher capacity and even different failure modes. Given the weak confinement of the concrete dowel, the use of a superposed push-out specimen may underestimate the capacity of the perfobond connector in steel–concrete joints. Therefore, Zhang et al. [18] and Lin Xiao et al. [19] designed a new push-out specimen to investigate the mechanical behavior of perfobond connectors in steel–concrete joints, as shown in Fig. 1(b). The specimen shown in Fig. 1(b)

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https://doi.org/10.1016/j.jcsr.2018.09.002

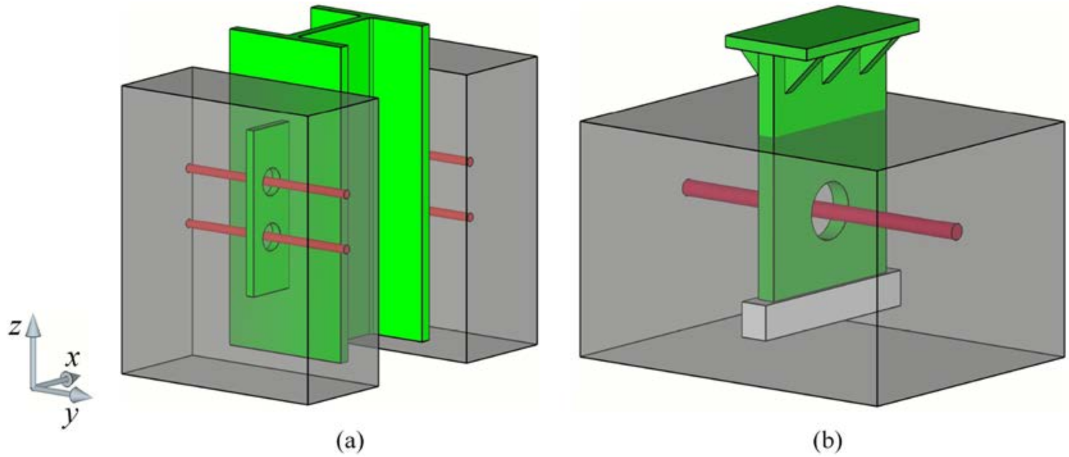

Fig. 1. (a) Superposed perfobond connector push-out specimen. (b) Encased perfobond connector push-out specimen.

is termed as a *encased perfobond connector* in the study, and the typical load–slip curve for the encased perfobond connector is shown in Fig. 2. In an encased perfobond connector specimen, the perforated plate is embedded in concrete, and an intensive transverse reinforcement is placed to ensure a high level of concrete confinement. Zhang et al. [18] conducted seven groups of 31 tests. The results revealed that the test on superposed perfobond connector push-out specimens significantly underestimate the shear capacity of the perfobond connector in steel–concrete joints. The use of push-out specimen which has the same stress state as the real structure was recommended. The test results obtained by Xiao et al. [19] indicated that the encased perfobond connector exhibits good ductility and high shear capacity. In the elastic phase, the load is mainly borne by the concrete dowel while the ultimate capacity is controlled by the transverse rebar. The test results also revealed significant differences between single-row and multi-row connectors, but the author ignores the relatively weak constraint states for a single connector of multiple rows of connectors. Xiao et al. [20] proposed a shear capacity formula to consider the influence of the concrete dowel, perforating rebar, stirrup reinforcement ratio, and thickness of the perfobond plate. The thickness of perfobond plate has effect on the failure mode, shear capacity and stiffness of the connectors. Xiao et al. [21] conducted a comparative study on the two types of connectors. The test results revealed that significant differences exist in the failure process as follows: the failure mode and the load–slip curve between the two connectors and the bond/friction between the perfobond plate and concrete do not significant affect the capacity. However, this study does not give the main reason for the difference. Based on the test results of 78 specimens in 24 groups, Wang et al. [22] fitted the load–slip curve of the encased perfobond connector, and presented an analytic expression of the curve which help to analyze the distribution of slip and shear forces on steel-concrete interface. However, the analytic expression applies only to circular hole connectors and the number of test data is limited. He et al. [23] conducted 6 groups of 12 push-out tests, and the results indicated that the capacity of the encased perfobond connector is mainly depends on the concrete dowels, transverse rebar, and bond/friction between the perfobond plate and concrete. The fore-mentioned capacity formulae of the superposed perfobond connector are used to obtain the relevant predictive errors between the calculated and measured capacities ranged from 19% to 51%. He et al. [24] tested 24 push-out specimens of an encased perfobond connector with ultra-high- performance concrete (UHPC). The experimental results indicated that the use of UHPC effectively avoids brittle cracking of concrete and enhances the shear capacity. It should be noted that although the shape of the novel push-out specimen proposed by Su et al. [25,26] is similar shape to that of the encased perfobond connector, the test results are similar to those of the superposed perfobond connector due to its weak confinement.

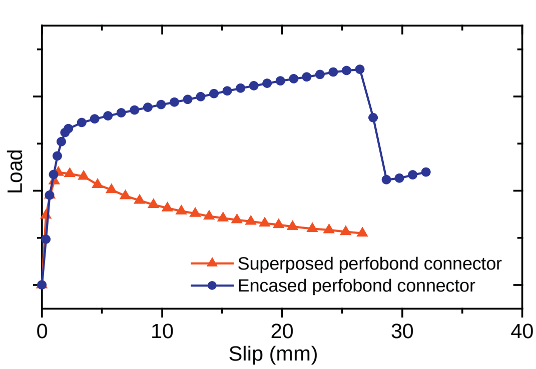

Fig. 2. Typical load–slip curves of two connector types.

To transmit large internal forces in steel–concrete joints of beams or columns in long-span bridges, it is generally necessary to tightly arrange the connectors, and this increases the complexity in the manufacturing and construction of steel–concrete joints. Large-diameter perfobond connectors with higher capacity act as an excellent alternative to reduce the number of required connections. The concrete dowel is a main component that contributes to the shear capacity of the connector, and thus, increasing the hole size is a cost-effective solution to increase the shear capacity. Additionally, large holes contribute to the flow of coarse concrete aggregate, and this facilitates concrete pouring. The test results obtained by Zheng et al. [15] indicated that increasing the hole size of superposed perfobond connectors does not significantly affect the increase in the load capacity of the concrete dowels and even leads to a decrease in ductility. This suggests that with respect to superposed perfobond connectors with relatively weak confinement, the load capacity is mainly controlled by confinement when the hole size exceeds a particular range. However, with respect to encased perfobond connectors with strong confinement, there is a paucity of studies on the effect of increase in the hole size.

This study aims at evaluating the mechanical behavior of large connectors in steel–concrete joints of hybrid bridges, and a total of 39 encased push-out specimens with strong confinement are tested. Specifically, hole size, hole shape, perforating rebar, concrete strength, and lateral confinement were considered as test parameters to study the reasonable hole size and hole shape, and to quantify the effect of perforating rebar, concrete strength and confinement. Finally, based on the push-out test results, an improved empirical formula for shear capacity considering various influencing factors is proposed and compared with existing formulas.