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Experimental and analytical investigation of innovative wing plate headed stud shear connector in composite structures

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Abstract

The most widely employed components in concrete-steel composite constructions to achieve composite action are headed stud shear connectors. Although headed studs are widely employed, their behaviour causes shank failure at the interface, and incomplete composite action is unfair due to unused residual concrete strength. This study intended to enhance the shear capacity of the stud by enlarging its bearing area by introducing triangular-shaped steel wing plates at the base of the stud on either side of it. The effectiveness of integrating wing plates to the headed stud on the shear carrying capacity of composite connection was evaluated using experimental testing on ten pushout specimens. Ultimate shear capacity, ductility, stiffness, and modes of failure were investigated. Furthermore, the ABAQUS dynamic-explicit has been used to analyse the pushout specimens. A proposed modelling strategy used for further parametric analysis was validated with the test results. For the parametric research, two different grades of concrete and wing plate sizes were evaluated. The innovative stud's performance was compared with the traditional stud, demonstrating that the suggested studs give 34–74 per cent greater shear capacity, increased stiffness, and slip with superior ductility. Finally, based on the FE parametric and regression analysis, two equations for predicting the shear strength of the wing plate headed stud shear connector was developed and proposed for composite constructions.

Introduction

The construction of composite bridge structures started in the early 1920. However, more emphasis was brought on these types of structures after 1950. The use of shear connectors between steel and concrete elements of bridge deck-girder was recommended to achieve composite action and avoid shear failure. Many different shear connectors are used in today's composite construction practice; a few examples of commonly used shear connectors are headed stud, channel, perfobond rib, *T*-rib, angle, and demountable

[1], [2], [3], [4], [5], [6], [7], [8], [9], [10]. These shear connectors can be broadly classified into two categories, i.e., flexible and rigid. Flexible shear connectors resist forces by bending action, whereas rigid connectors rely on the bearing pressure of the concrete to resist the horizontal loading [11]. The commonly observed type of failure in a flexible connector is stud failure under shear. In comparison, utilisation of rigid connectors in composite structures shows concrete failure. The headed stud and channel are the most frequently used shear connectors among all these types. The headed stud comprises a circular shank and circular head over it. These shear connectors are responsible for resisting horizontal shear and vertical uplift [12]. Various researchers have studied the impact of various parameters on the shear capacity of headed stud. The stud's tensile strength, shank diameter, and height are the main responsible parameter for resisting the acting shear force [5], [13], [14]. Moreover, concrete properties such as modulus of elasticity and compressive strength also resist the acting shear force on composite connection [15]. Furthermore, research has also been done to study the effect of reinforcement in the concrete slab on the shear carrying capacity of the stud [16]. Reinforcement in concrete slab does not carry any acting load; however, reinforcement gives confining the action to concrete, enhancing the shear strength carrying capacity of the connectors [16]. Results concluded that the addition of reinforcement enhances the shear strength carrying capacity by 10% [17]. Effects of different types of concrete like engineering cementitious concrete (ECC) [18], fibre reinforced concrete (FRC) [18], ultra-high-performance concrete (UHPC) [19], lightweight concrete (LWC) [15] on the shear capacity of stud in composite connection are also studied in recent years.

As stated earlier, the commonly observed type of failure in the flexible connector is a shear failure. Headed studs are the category of the flexible shear connector, and it mostly shears off at its root [17]. The maximum shear stress concentration has been seen on the bottom face of the headed shear connectors, leading to the shear failure of studs [1]. Moreover, efforts have been made to enhance a stud's shear capacity and reduce the number of studs required in the composite connection. Here, the addition of triangular shaped wing plates to the headed stud as a re-strainer has been proposed in Fig. 1. The present study intends to vary the bottom to top geometrical configuration of the shank of the headed stud. The influence of triangular wing plates on the ultimate shear capacity of the 19mm stud was investigated.

In order to increase the bearing area of headed stud shear connectors along the length of the shank, wing plates of different dimensions were welded to the bottom portion shank. In this research, the effects of different dimensions of wing plate like thickness, width and height, and orientation have been studied. Seven different specimens were prepared for the experimental evaluation of the addition of wing plates to the shank of the headed stud. Xue et al. [17] suggested that the bending length of the headed stud varied based on the type of failure of the sample. Maghaghi [20] showed that the increase in length of the channel shear connector increased the bearing area of concrete. Moreover, the bending length of the headed stud varied from 0.18 to 0.33 times the height of the shear connector [17]. In order to enhance the stiffness of the headed stud shear connector, the wing plates of two different dimensions were opted for stiffening this bending length. In the present study, a headed stud of a total height of 100mm has opted. Considering the head stud's minimum and maximum bending length, two different heights of 20mm and 40mm have been opted based on studies carried out by Xue et al. [17] study. Wing plates of 20mm dimension was opted to stiffen the minimum bending height, whereas 40mm dimension wing plates were used to stiffen the maximum bending height.

Section snippets

Experimental setup

The specific pushout test as per Eurocode 4 [21] was used in this research to appraise the shear strength and stiffness behaviour of wing plate headed stud. The test setup consists of two concrete slabs placed on both sides of the flange of I section parallel plate steel beam and connected using a stud. The I-beam section was rolled out by a welding 10 mm thick web steel plate to a 20 mm thick flange. The bottom of the headed stud shear connectors was welded to the surface of the steel beam's…

Headed stud shear connector

Mechanical properties of studs were evaluated to ensure the tensile strength and modulus of elasticity. The ultimate evaluated strength of studs from the curve, as shown in Fig. 6(a), was 491 $N/mm^{2,}$ and yield strength was 425 N/mm^2. The mechanical properties were validated with Eurocode 4, where the ultimate strength of studs is considered up to 500 MPa for calculation of the ultimate capacity of studs in the equation given by Eurocode 4 (2004).…

Wing plate properties

Fig. 7 shows the preparation and testing of wing…

Results and discussion

The shear connector's performance is assessed using various pushout test results written in Table 2. The addition of 3 mm and 5 mm thick wing plates with dimensions 40×40 mm to the regular headed studs adds a volume of 4800 mm^3 and 8000 $mm^{3,}$ respectively, in comparison with regular headed studs, which have volume of 34600 mm^3. The addition of 3 mm and 5 mm wing plates of dimension 40×40 mm added 13.87% and 23.13% extra volume respectively to the initial volume of the headed stud, as shown …

Taguchi method for evaluation of number of analytical specimen

The Taguchi method were used to optimize the design parameters as this systematic approach can significantly minimize the cost of the experiments. In this research total three variables are applied out of which two variables have two levels and one variable have one level. That is, two levels of compressive strength of concrete (48, 58), two levels of plate height (20, 40 mm), and three levels of plate thickness (2, 3, and 5 mm), was used as parameters, as given in Table 3. Taguchi method uses…

Validation of finite element modelling results

The results of two FE models were validated using the finite element analysis. Specimens S1-O1-3-40 and HS19 were considered for validation of the numerical model. Close behaviour of these curves was observed, as shown in Fig. 16. Results show that the FE model successfully validated the results of the experimental study. The observed behaviour of studs was also monitored using ABAQUS software; the deflected behaviour of studs in the pushout test was identical to the FE analysis failure pattern …

Parametric studies

Numerical studies were carried out to understand the detailed behaviour of the wing plate headed stud in remaining aspects that could not be studied experimentally. Wing plate headed stud embedded in a higher grade of concrete having compressive strength, 58 MPa was the main focus of the study along with the different parameters like thickness and orientation of wing plate in achieving higher shear capacity and stiffness of shear connector than it embedded in 48 MPa concrete. In numerical…

The capacity equation for wing plate shear connector

The strength of the wing plate varied with compressive strength, thickness, height and orientation of the plate. During the past year, various numerical formulas have been given based on the stud diameter, shear area, compressive strength and modulus of elasticity of concrete [6], [25]. Wing plate headed stud consists of circular headed stud and wing plate. In the case of a wing plate headed stud, the stud has a circular shear area, whereas the wing plate has a rectangular shear area at the…

Conclusions

The current study proposes a new wing plate headed stud shear connector for composite constructions as an alternative to typical headed studs. Wing plate headed stud shear connectors are restructured headed studs with triangular steel plates welded to the bottom of the shank. Under pushout test, Wing plate headed stud shear connector and typical headed stud was experimentally examined for shear capacity and displacement (slip) performance. FE analysis explored the impacts of changing the form…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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