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Experimental assessment of angle shear connectors under monotonic and fully reversed cyclic loading in high strength concrete

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HIGHLIGHTS

- Required ductility was not achieved for angle shear connectors embedded in HSC.
- Angle connectors in HSC under low cyclic loading showed very low strength degradation (0.1%–1.4%).
- Angle connectors embedded in HSC, experienced angle fracture type of failure in both static and cyclic loading.
- The current equations estimated the shear capacity of angle connectors in HSC either are conservative or overestimate.

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ABSTRACT

An experimental study was performed to investigate the behaviour of angle shear connectors embedded in high strength concrete (HSC) slab. Eight push-out specimens were tested covering various geometries of angle shear connector. On top of the experimental study, the accuracy of the available equations to estimate the load capacities of angle connectors is also evaluated for the angles embedded in HSC. The results show inadequate ductility behaviour for the angle shear connectors embedded in HSC. Nonetheless, the angle connectors exhibited good behaviour in the case of strength degradation under cyclic loading. All specimens experienced the angle fracture type of failure and showed a very low strength degradation (0.1%–1.4%) when they were subjected to low cyclic fatigue loading. This study also concludes that the current available equations estimated the shear capacity of angle connectors embedded in HSC either are conservative or overestimate the ultimate capacity.

1. Introduction

Due to the limitations in the performance of headed studs and Perfobond shear connectors, the use of C-shaped shear connectors as an alternative has been recommended mainly in developing countries. Those limitations include a number of constraints on the fatigue behaviour of studs. For instance, due to welds and the need to have specific welding equipment with high power generations on site, the occurrences of fatigue crack under cyclic loading have been reported [1,2]. The problem with Perfobond shear connectors is the difficulties in positioning the slab for lower reinforcement as the steel bars need to cross the connector openings [3] and this requires drilling of holes. Thus production takes longer time and higher costs. Furthermore, manufacturing of the C-shaped shear connectors is easier compared to the other connectors since in most steel shops, commercial standard sizes for hot rolled steel profiles of C-shaped shear connectors are available. Moreover, by simply cutting in their long steel profiles, these types of connectors can be easily prepared. In comparison with the headed stud and Perfobond connectors, the manufacturing cost and time for C-shaped connectors are significantly lower. With regard to load carrying capacity, C-shaped connectors show higher capacity and with the use of the conventional reliable welding system, it could be welded easily to steel beam [4]. While stud connectors may require some inspections (e.g. bending test), C-shaped connectors do not need this inspection. Also, the use of C-shaped connectors eases the positioning of slab for lower reinforcement which is considered as an obstacle in the application of Profobond shear connectors [3]. The restraints and difficulties faced when using the headed studs and Profobond shear connectors in composite beams can be overcome with the use of C-shaped

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connectors. The C-shaped shear connectors can be easily produced with angle and channel profiles. The angle connectors (Fig. 1), as compared to channel connectors, could be cheaper and more economical due to the absence of bottom flange which ultimately saves more steel. To date, a number of researches have been conducted on the behaviour of different C-shaped shear connectors under various loading conditions [5–11]. Meanwhile, the former researches conducted by the authors of this research were mainly aimed at comparing the connection shear resistance, ductility and failure modes of channel and angle shear connectors embedded in normal strength concrete.

The application of high strength concrete (HSC) has become a common development in modern construction [12]. Using this type of concrete brings more slender structures, upturns their load carrying capacity [13], changes the ratio between maximum slip requirement and connection deformation capacity and demands direct connection ductility checking [14]. In addition, it produces more cost-effective products and offers a feasible technical solution or a combination of both. Meanwhile, it should be noted that the application of HSC can be limited due to its low ductility. For the composite beams made by HSC, the ductility behaviour and its load carrying capacities are of particular interest as well as its fatigue behaviour. The use of HSC along with common types of shear connectors in composite beams has widely increased over the past few years. Since the angle shear connector could be of efficient use in composite beams and because there has been no published study addressing the behaviour of this connector under fully reversed cyclic loading while it is embedded in high strength concrete, the current research is carried out to examine the behaviour of the angle shear connector. In addition, this study evaluates the accuracy of the current available equations for load capacities of angle shear connectors while these connectors are embedded in HSC in order to verify whether the current equations are suitable for estimating the capacity of angle connectors in high strength concrete.

This study involved eight push-out tests conducted under monotonic and fully reversed cyclic loading and separated into two groups. Each group contains four samples and each group's sample was exposed to monotonic loading and fully reversed cyclic loading, respectively. The outcomes of the monotonic tests were then compared to the results obtained from standard tests under fully reversed cyclic loading. The results of the current study offer useful information on the shape of the load–slip curves as well as the damage accumulation at the end of each cycle.

The aim of this paper is to investigate the behaviour and effects of angle shear connectors with different geometry embedded in HSC under monotonic and low cycle fatigue loading. Ultimately, the shear capacities obtained from the experiment were compared with the shear strength suggested by the available equations used for the estimation of shear capacity for angle shear connectors [4,11].

Fig. 1. Typical angle shear connectors.

2. Test program

2.1. Specimen details and test setup

Based on the strength of concrete and the size of the angle shear connector embedded in concrete slabs, eight push-out specimens were designed in two groups. The four specimens in each group were subjected to the monotonic loading and fully reversed low cycle fatigue loading correspondingly. The push-out specimens comprised of a steel I beam and each beam flange was attached with two slabs. One angle was connected by welding to each beam flange and for all slabs; four 10 mm diameter steel bar hoops were applied in two layers, in two perpendicular directions. The details of the push-out specimens were in accordance with those of Maleki and Bagheri [1] and Maleki and Mahoutian [15]. Four different types of angles were used including angles with 75 and 100 mm in height, and 30 and 50 mm in length. The angles with 75 mm height had a web and flange thickness of 7.5 mm and 5.0 mm respectively, while the thickness of the web and flange for the 100 mm high angles were 8.5 mm and 6.0 mm correspondingly. Table 1 illustrated the geometric properties of angle for both monotonic and cyclic tests.

In this study, concrete with compressive strength of 80 MPa was used which complies with the strength defined in the high strength concrete. Silica sand with a maximum nominal size of 4.75 mm and crushed granite with a maximum nominal size of 10 mm were used as fine and coarse aggregates respectively. The particle size analysis of the fine aggregates is given in Table 2 [16,17]. Super plasticizer (SP) was added to the fresh mix at 1% of the cement weight to achieve the acceptable workability. The SP used in this investigation is Rheobuild 1100. The specific gravity of the SP is approximately 1.195, and is dark brown in color with a pH within the range of 6.0–9.0 [18]. The cement used in all mixes was Ordinary Portland Cement (OPC) type II corresponds to ASTM C150 [19] with chemical properties shown in Table 3 [20,21] was used in all mixes as the binding materials. The mix properties of HSC materials are presented in Table 4. Angles with short length were used due to limitations in the size of the concrete slab. In accordance with the laboratory conditions, all push-out specimens were cast in a horizontal position. For both sides of the specimen slabs, reliable quality of the concrete was assumed. All specimens were cured in water for 28 days before the push-out test was executed.

Standard cylinders, 150 mm in diameter and 300 mm in length, and cubes with 100 mm side length were simultaneously cast with the push-out specimens in order to determine the compressive strength. Similar to the push-out specimens, all concrete cubes and cylinders were cured in water. The compressive strength of concrete was measured in accordance with ASTM C39 [22] and the reported results are the average of the strength of the cube and cylindrical samples.

The first letter of the specimens ID denotes the type of connector (A as angle), the second letter signifies the concrete type (H as high strength); the first two/three digits represent the height of the angle shear connector embedded in the concrete slabs while its length is indicated by the last two digits. Monotonic and cyclic loading are represented by the letters M and C respectively. For instance, AH10050-M shows an angle shear connector with the height of 100 mm and the length of 50 mm embedded in high strength concrete that was subjected to monotonic loading. The details of a typical specimen are illustrated in Fig. 2.