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Tensile resistance of J-hook connectors used in Steel-Concrete-Steel sandwich structure

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ABSTRACT

Steel-Concrete-Steel (SCS) sandwich panel with ultra-lightweight cement composite core has been proposed to produce slim decking for bridge and building construction. One special feature of this lightweight sandwich panel is the use of J-hook connectors to improve the structural performance against combined actions of vertical shear and bending moment on the section. The proposed J-hook connectors provide effective bond between the steel and concrete, prevent local buckling and separation of the steel face plate, and enhance the transverse shear resistance to the structure. This paper investigates the tensile resistance of this new form of J-hook connectors by performing tensile tests on 79 sandwich specimens with various types of core materials including normal weight concrete, lightweight concrete, and ultra-lightweight cement composite. Their ultimate tensile resistances were obtained and corresponding failure modes were reported. The main parameters that influenced the tensile resistance of J-hook connectors were discussed and analyzed. Theoretical methods were developed to predict the tensile resistance of the J-hook connectors and their accuracy was verified against test results. Finally, recommended methods were proposed for design purposes.

1. Introduction

In Steel-Concrete-Steel (SCS) sandwich composite structures, shear connectors are usually used to achieve composite action transferring longitudinal shear forces at the steel and concrete interface and resisting transverse shear forces applied on the structures. Different types of shear connectors have been developed for SCS sandwich structures in the past three decades including headed studs [1,2], Bi-Steel connectors [3], angle connectors [4], through bolt connector [5], and bi-directional corrugated strip connector [6]. To produce slim depth and lightweight sandwich structures to withstand impact and blast loads, J-hook connectors were proposed by the main author [7]. Sandwich beams and plates with J-hook connectors showed promising performances subject to static and impact loads in author's recent research [7–10]. As shown in Fig. 1, the J-hook connectors work in pairs and interlock the central concrete core in SCS sandwich structures. By this interlocking system, the steel face plates are prevented from up-lifting as well as local buckling.

In SCS sandwich composite structures with J-hook connectors, transverse shear force is resisted by concrete core and J-hook connectors. The J-hook connectors act as shear links to resist diagonal shear cracks in the concrete core as shown in Fig. 2. From this point of view, tensile resistance of the J-hook connectors contributes certain transverse shear resistance to the structure. Another scenario of the working condition of J-hook connector is that tensile resistance can be provided to resist local buckling of the steel face plates and prevent separation between the steel face plates and concrete core. Local buckling of the steel face plates can occur when the flat sandwich member is subjected to compression (Fig. 3a), or in the compression zone of the steel plate subject to flexural loading (Fig. 3b). When a sandwich wall is subject to lateral impact or blast loading [7], severe debonding and cracking of concrete core may lead to separation between the steel plate and concrete core, and the J-hook connectors can interlock the two face plates and prevent tensile separation and maintain the overall structural integrity, as illustrated in Fig. 3c. In summary, the tensile resistance of J-hook connectors is an important parameter that will affect the structural performance of SCS sandwich structure. This provides the motivation to the present research to investigate the tensile resistance of this new form of connectors.

Extensive experimental studies were carried out on tensile resistance of headed studs. From these studies, it was found that the tensile resistance of the headed studs embedded in the concrete was closely related to their failure modes [11]. The observed failure modes of the stud connector subjected to tension were steel failure of connector, pullout failure, concrete breakout failure, side-face blowout, and concrete splitting, as shown in Fig. 4 [11]. Therefore, the tensile resistance was determined by the lowest value of the strengths corresponding to these failure modes. Research was carried out to investigate the strengths of headed studs for different failure modes. The concrete breakout strength was widely investigated and theoretical models were developed for prediction purposes [12–18]. The influence of the cracks and

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Notation

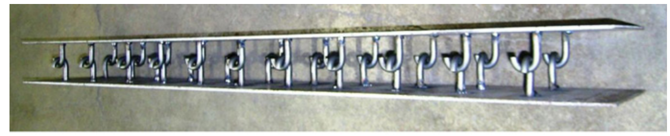
A_{brg}	Local bearing area of the head of stud or anchor bolt
A_v	Shear interaction area
D	Inner diameter of the hook
E_c	Elastic Young's modulus of the concrete material
E_s	Elastic Young's modulus of the steel material
P	General tension force acted on the connector
P_T	Tensile resistance of a pair of J-hook connectors in concrete
P_{TD}	Design tensile capacity
P_{Tc}	Concrete breakout for tension
P_{Ts}	Tensile fracture strength of the connector
P_{Th}	Pullout strength of J-hook connectors in concrete
P'_{Th}	Hook straightening strength of pure J-hook connectors
P_{TV}	Punching shear strength of the steel face plate
a	Length of equivalent square section to the circular section of the J-hook
d	Diameter of the J-hook shear connectors
d_H	Diameter of the headed shear stud connectors
e_h	Projection length of the anchoring length of the L-shape of hook shape connectors
h_s	Height of the shear connectors
h_{ef}	Effective height of the headed shear stud connectors
f_{ck}	Compressive strength of concrete cylinders
f_{cu}	Compressive strength of concrete cubes
f_{ut}	Ultimate tensile strength of the stud steel material
f_y	Yield strength
w	Density of the concrete
x	Distance from the upper compression region to the neutral axis in the section
α	Safety factor

Abbreviations

CC	Concrete breakout failure
COV	Coefficient of variance
HS	Hook straightening
Mean	Average value of the ratios
PO	Pullout failure
PS	Punching shear failure of the steel face plate
STF	Steel bar tension failure
STDEV	Standard deviation

fibers in concrete were reported in Refs. [19] and [20], respectively, and the research findings were incorporated into design codes (ACI 349 [11], ACI 318 [21]). The strengths for other failure modes were also specified in these codes. Little information is available to predict the shear and tensile resistance of a pair of interlocked connectors, such as J-hook connectors and overlapped headed shear studs, to be used in the SCS sandwich structures. In the design guide published by SCI [22] on SCS sandwich composite structures, only the ultimate tensile fracture strength of the connectors was used to calculate the transverse shear resistance of the structures. This may significantly overestimate the transverse shear resistance of the structures.

The authors had proposed a new form of J-hook connectors to be used with ultra lightweight cement composite (ULCC) [23] to produce slim and lightweight SCS sandwich deck. In this paper, tensile tests are carried on 79 sandwich specimens with interlocked J-hook connectors embedded in different kinds of concrete and lightweight cement composite core. Parameters influencing the tensile resistance of J-hook connectors are analyzed and discussed. Theoretical models are developed to predict the tensile resistances for different failure modes and their accuracy is verified against the test results. Finally, a step-by-step design



a) SCS sandwich beam with J-hook shear connectors (before casting)

b) SCS sandwich beam with J-hook shear connectors (after casting)

c) SCS sandwich shell with the J-hook shear connector(before casting)

d) SCS sandwich shell with the J-hook shear connector (after casting)

Fig. 1. SCS sandwich composite structure with J-hook shear connectors.

procedure is proposed to calculate the tensile resistance of the interlocked J-hook connectors in the SCS sandwich structures. The tensile resistance of the connectors is needed to quantify the transverse shear resistance of the SCS sandwich composite to be used in beams, slab, and shell structures.

2. Experimental program

The tensile resistance of a pair of J-hook connector embedded in concrete may be obtained directly from tensile tests. Two tests methods are available in the literature: one method (herein named as method A) was recommended for straight bar connectors in Bi-steel structure proposed by Xie and Chapman [24]. Another method (called method B) was developed initially by Sohel and Liew [8] for direct tensile test. In this research, both methods A and B were used and the experimental results obtained were compared for the recommendation of the proper test method for J-hook connectors.

2.1. Test setup, loading procedure, and measurements

All the specimens were tested under a universal testing machine with a load carrying capacity of 300 kN. A displacement controlled loading with a velocity of 0.05 mm/min was used until failure of the specimens. Once the J-hook connectors were straightened or pulled out,