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Push-out tests on steel composite sections with engineered cementitious composite

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ABSTRACT

This paper investigates the shear strength and failure modes of steel-concrete-steel (SCS) sandwich composite member with Engineered Cementitious Concrete (ECC) and explores the influences of various shear connectors such as headed stud and bolt on shear behavior of SCS sandwich composite member by carrying out push-out testing program. Based on the test results in this study, the failure modes and the load-slip behavior of the specimens are investigated. In addition, the experimental results on the shear resistance of the headed stud connector with various connector spacing and numbers of connector is compared and explored.

1. Introduction

A steel-concrete-steel1(SCS) sandwich1composite structure consists of a concrete core sandwiched between two steel faceplates and attached to the concrete core by shear connectors such that all behaves monolithically. Due to its excellent performances, this type of structural system has a wide range of possible applications in building and offshore construction structures due to the ease of manufacture and its high strength characteristics (Soundararajan & Shanmugasundaram, 2008; Liew & Sohel, 2009). In a SCS sandwich composite, two steel-concrete interfaces are connected by shear connectors, as shown in Fig. 1. There have been several studies conducted on SCS composite sections with various materials and shear connectors (Yousefi & Ghalehnovi, 2017; Yan et al., 2015; Yan et al., 2021; Gad et al., 2021).

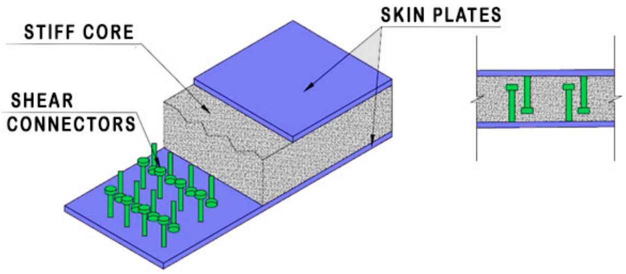

Fig. 1. Steel-Concrete-Steel (SCS) sandwich structure with shear headed stud connectors

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The ultimate strength of the SCS sandwich composite members with headed stud connectors is governed by three possible failure modes which are flexural, horizontal slip and vertical shear failures (Liew& Sohel, 2010; Yan et al., 2013). The slippage between concrete and steel plate in a SCS sandwich structural member may cause the composite action to be decreased and significantly affect their load-bearing capacity. The composite interaction between concrete and steel in SCS sandwich composite structures is critical to ensure the superior performance of SCS sandwich composite structures.

In recent years, a new generation of high-performance concrete known as bendable concrete or engineered cementitious concrete (ECC) has been increasingly used in construction technology. ECC features high ductility, crack control and enhanced mechanical properties (Nikbakht et al., 2021; Alraeeini & Nikbakht, 2022; Nikbakht et al., 2019; Bandelt & Billington, 2016). To date, there is very limited research conducted on the incorporation of ECC as a core in sandwich composite SCS sections. Therefore, this research investigates the composite action between ECC, steel plates and connectors. Moreover, various shear connectors such as stud head and bolts are compared, and the shear behaviour of the specimens are explored.

2. Experimental program

There are numerous parameters that affect the shear resistance of SCS sections such as thickness of steel plate, type of connectors, size of the connector, roughness of steel surface, concrete age, concrete strength, and concrete mixture. In this paper, the key parameters such as type and spacing of connectors are studied by carrying out push-out tests. All specimens have the same dimensions and thickness. The steel plates are welded with shear connectors. Engineered cementitious concrete (ECC) with the compressive strength of 50 MPa is used. The mixture design of the concrete used in this study can be found in Table 1.

Table 1. Mix design for ECC

Materials	Mixture/m^3
Cement	600 kg
Fly Ash	726 kg
Coarse aggregate	-
Fine aggregate	483 kg
Water	330 L
Super-plasticizer	6 L
Polyvinyl Alcohol (PVA) Fiber	26 kg

After inserting the steel plates into the formwork, the concrete was poured in between them. Both specimens were given a 30 mm gap from the bottom to provide space to allow slippage between the sandwiched concrete core and steel plates. A total of 7 SCS sandwich specimens were designed and prepared. The specimens' specific details and labeling of all specimens can be found in Table 2.

Fig. 2 and Fig. 3 show the test setup and schematic setup for the push-out test. To examine the interaction of the interfaces between steel plate and sandwiched concrete, a steel block was put on top of the sandwiched concrete surface, to ensure the load is only applied to the sandwiched concrete core. Fig. 4 shows the geometry and three types of shear connectors (SC) arrangement used in this study. A Universal Testing Machine (UTM) is used with the loading speed of 0.5 mm/min for all push-out tests.

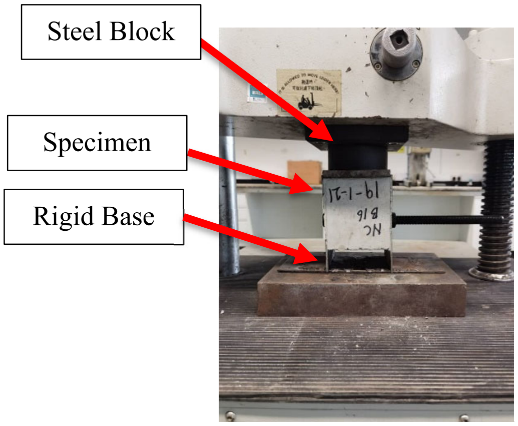
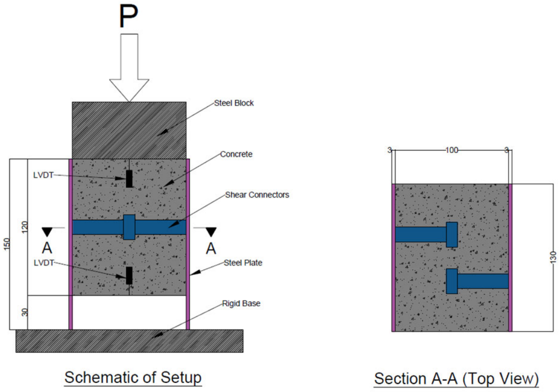


Fig. 2. Test setup



Schematic of Setup

Section A-A (Top View)

Fig. 3. Schematic of Setup and Section A-A (Top View)

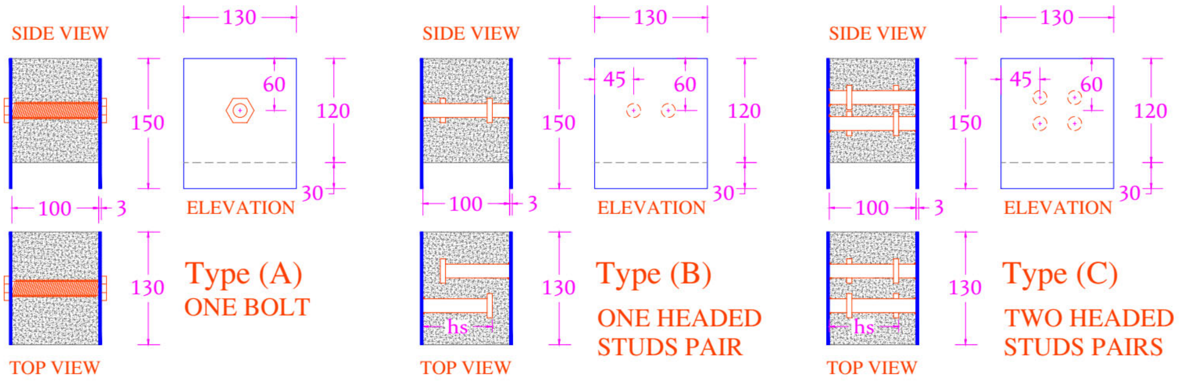


Fig. 4. Geometry and type of shear connectors (SC)

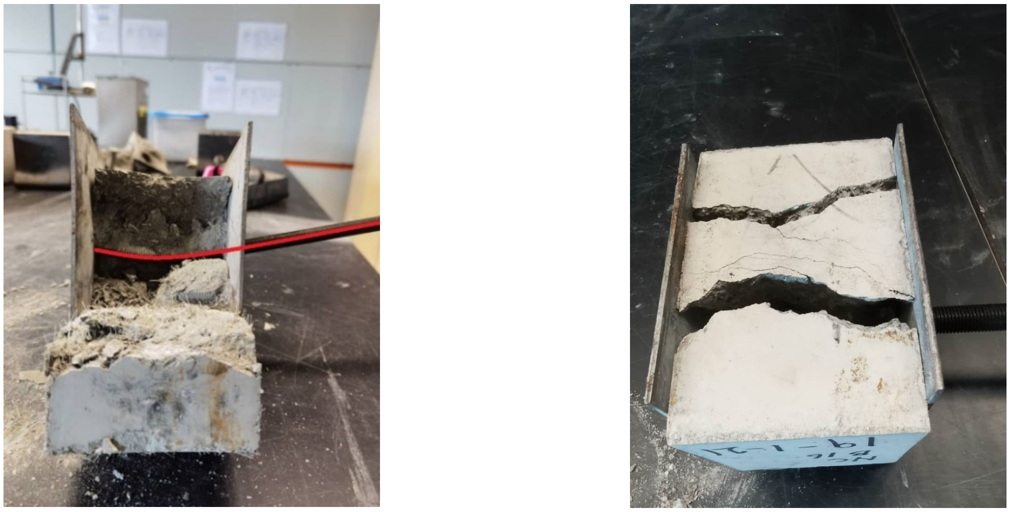
Table 2. Shear connector types and labeling

No.	ID	Material	Type	Diameter (mm)	SC Length (mm)
1	ECC-B12*	ECC	A	12	100
2	ECC-B16*	ECC	A	16	100
3	ECC-13/55	ECC	B	13	55
4	ECC-13/80	ECC	B	13	80
5	ECC 2×13/80	ECC	C	13	80
6	ECC-16/80	ECC	B	16	80
7	ECC 2×16/80	ECC	C	16	80

* B12 and B16 stands for bolt connector with diameter of 12mm and 16mm.

3. Results and discussions

Different types of failure modes were identified during the push-out experiments. The first type of failure was steel plates buckling. This type of failure occurred due to the steel compression bearing capacity. Besides, shear connector failure was observed as the second type of failure mode as displayed in Fig. 4(a). The third type of failure was concrete bearing failure as shown in Fig. 4(b). The specimen's failure mode can be categorized based on the relative strengths of the shear connector, steel plate, and concrete core. Shear connector failure or steel plate buckling would occur if the concrete core were strong enough to withstand the interfacial shear force. Otherwise, the concrete core will fail first without failure of the shear connector. The load–slip curves from the push-out tests are compared in Fig. 5.



(a) (b)

Fig. 4. (a) Bolt bending. (b) Concrete crushing and cracking.

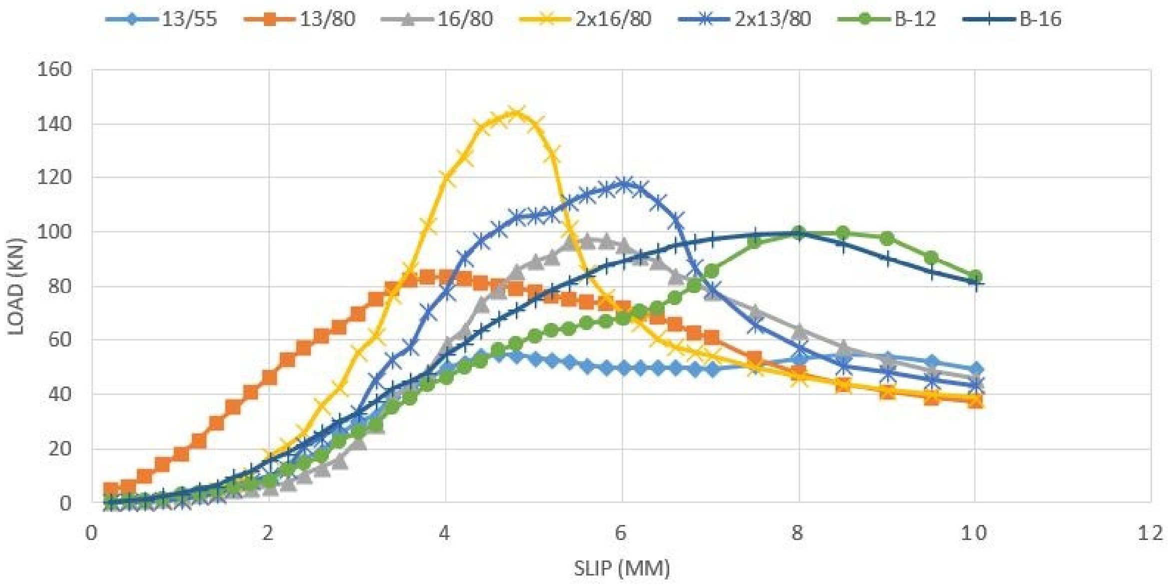


Fig. 5. Load-Slip Curve (ECC).

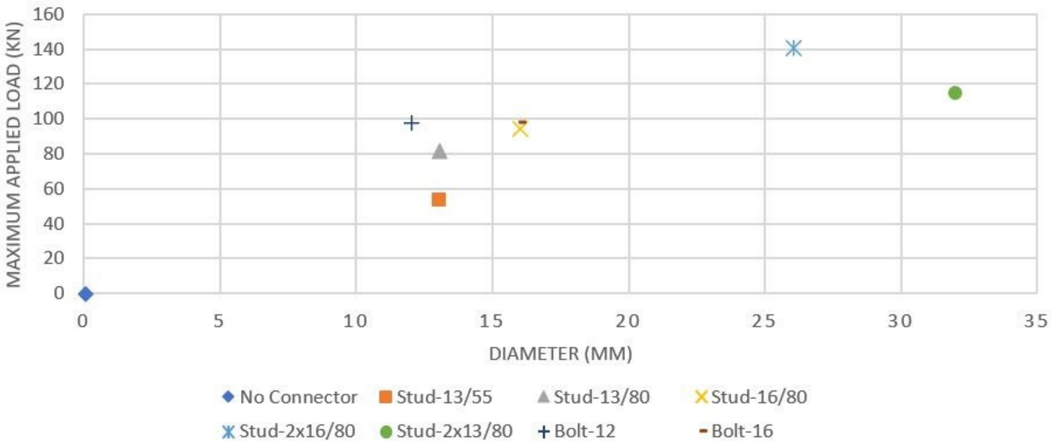


Fig. 6. The effect of connector's diameter and type on maximum applied load

As can be seen from Fig. 5, the relationship between load and slip in ECC specimens is increasing proportionally at the initial stage of loading. However, the load-slip curve exhibits a gradual decrease after reaching the ultimate load. This is due to the high tensile strain and ductility associated with ECC between the steel plates.

Shear connector fails when the concrete core's tensile resistance is strong enough to resist the induced stresses. On the other hand, failure due to the concrete crush indicates a rather brittle behavior. Among all specimens, only the specimen with bolt size of 12mm exhibited shear connector failure while other specimens in this study failed due to concrete bearing or steel plate failure. Moreover, as the load-displacement results indicate that specimens with bolt-12mm connectors have a lower stiffness compared to other specimens. On the other hand, the failure mode of the specimen with bolt-16mm connector was due to steel plate buckling with minor concrete crack. This is due to the lower bearing capacity of the steel plates compared to the concrete core and shear connectors in this specimen. Consequently, steel plates buckle prior to the concrete crush and connectors failure.

Fig. 6 illustrates how the diameter and type of connector affect the maximum applied load. As shown in the figure, the greater the diameter of the connector, the higher the overall applied load resisted by the connectors. This is because the larger diameter connector has a larger cross-sectional area and a larger total surface area where the concrete interacts with the connector. As can be observed from Fig. 6, the bolt connector exhibited stronger shear resistance than the corresponding headed stud connector with similar diameter, however, the headed stud connector attained a stronger shear resistance compared to the bolt connector specimens when two headed stud connectors are used. Moreover, as the results show when the connector's diameter is small, the failure is controlled mainly by shear connector failure, whereas the strengths and types of concrete have little impact.

4. Comparison with the theoretical shear resistance of connectors

In this section, the shear resistance of the headed stud connector with various connector spacing and numbers of connector is compared to the existing theoretical shear resistance of connectors. Ollgaard et al. (1971) developed a formula for load-slip model for shear studs as follow:

$$P = P_u(1 - e^{-18S})^{0.4} \tag{1}$$

where P = Shear resistance of headed stud connector (kip/in), P_u = Ultimate applied load (kip), and S = Slip (in).

Eq. (1) had been modified by Lorenc and Kubica (2006) by carrying out experimental studies with various stud connector and welding directions such as straight and draped and proposed the following relation.

$$P = P_u(1 - e^{-0.55S})^{0.3} \tag{2}$$

where *P* = Shear resistance of headed stud connector (N/mm), P_u = Ultimate applied load (kN), and *S* = Slip (mm).

Furthermore, a new formula for load-slip relation for shear headed studs was presented according to the results obtained from push-out test and considering the parameters such as connector diameter, height and type of concrete which was proposed by Xue et al. (2008) as shown in Eq. (3).

$$\mathrm{P} = P_u \frac{\mathrm{S}}{0.5 + 0.97\mathrm{S}} \tag{3}$$

where *P* = Shear resistance of headed stud connector (N/mm), P_u = Ultimate applied load (kN), and *S* = Slip (mm). However, based on Eurocode 4 (2004), the design strength of shear headed stud connector are specified as the following equation.

$$P = \frac{0.8 f_u \pi \mathbf{d}^2}{4\gamma_V} \tag{4}$$

where P = Shear resistance of headed stud connector (N/mm), f_u = tensile strength of headed stud connector (N/mm^2), *d* = diameter of connector shank (mm), and γ_V= 1.25. Table 3 compares the shear resistances of connectors obtained from the experimental results in this study and the results calculated by the Equations 1-4. The accuracy and reliability of the various design approaches are evaluated from the P_{Test}/P_{Theo} ratio. As can be observed from Table 3, the Eq. (1), (2) and (3) all show good agreement with the experimental results with the ratio between 1.0 to 1.05. However, Eq. (4) overestimates the experimental results with the ratio up to 2.6.

Table 3. Shear Resistance of Connector Comparison

Type of Concrete	ECC					
Type of Shear Connector	13/80	16/80	2×13/80	2×16/80	B12	B16
Number of Studs	1	1	2	2	1	1
Shank Diameter,d (mm)	13	16	13	16	12	16
Ultimate applied load, P_u (kN)	82.04	95.19	141.16	115.44	97.73	97.76
Slip (mm)	4.06	5.7	4.55	6	14.1	7.8
Tensile Strength of Studs, f_u	415	415	415	415	415	415
Comparison between Experimental/Theoretical Ratio						
Eq. (1)	1.03	1.01	1.02	1.01	1	1.01
Eq. (2)	1.04	1.02	1.03	1.02	1.01	1.01
Eq. (3)	1.1	1.06	1.08	1.06	1.01	1.04
Eq. (4)	1.87	1.43	1.61	0.87	2.61	1.47

5. Conclusions

In this study, push-out testing was used to determine the shear resistance of the composite SCS members with ECC core and shear connectors. Two types of shear connectors including stud head connectors and bolts were investigated. During the laboratory experiments, the failure modes of the specimens were examined. The following conclusions can be drawn based on the experimental results in this study.

1) The push-out tests showed four different types of failure: bonding failure, steel plates buckling, shear connector

failure and concrete crushing.

2) From the load-slip curves, the specimens with ECC exhibited a relative ductile behavior.
3) Eq. (1), $P = P_u(1 - e^{-18S})^{0.4}$, showed better agreement with the experimental results in this study.
4) Larger diameter of the shear connector increases the shear interaction area and thus increases its shear resistance. The bolt connector exhibited stronger shear resistance compared to the headed stud connector with similar diameter. However, by increasing the number of headed stud connectors to two, the shear resistance of the specimen was stronger due to the larger interaction area.

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