Push-Out Test on SCS sandwich composite members with various concrete cores and shear connectors.

by

Chang Jia Wei
24509

Dissertation submitted in partial fulfilment of
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CERTIFICATION OF APPROVAL

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Approved by,

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TRONOH, PERAK

January 2021

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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CHANG JIA WEI

ABSTRACT

The development of Steel-Concrete-Steel (SCS) sandwich composite construction has accelerated in recent decades. SCS members have been used as lightweight key components in buildings, bridges, and other structures in civil engineering applications because of its features and advantages. Slippage in SCS sandwich composite member could happen in between concrete and steel plates under compressive loading or in a column under axial load. As a result, the composite action could be reduced and thus decreasing the load-bearing capacity. This research is to explore the failure modes of the SCS specimens and to study the influences of various parameters such as concrete type and shear connector type on the interface behavior in SCS sandwich composite column by carrying out a series of push-out tests. A total number of 16 specimens were prepared and had been tested on their shear resistance between steel plate and concrete core in SCS sandwich composite member. There were two type of shear connectors that had been used for this study which were headed stud connectors with diameter of 13mm & 16mm and bolt connectors with diameter of 12mm and 16mm. Besides, two type of concrete core were used such as normal concrete and engineered cementitious concrete with capacity of 50 Mpa. The load was applied to all specimens with a loading speed of 0.5mm/min by using Universal Testing Machine (UTM). As a result, there were four type of failure modes from the push-out test were observed such as bonding failure, steel plate buckling, shear connector failure and concrete bearing failure. Load-slip behavior was compared with failure mode and observed that ECC specimens exhibited a relative ductile characteristic compared to NC specimens. The connector's diameter and type have significant impact on the shear resistance which the larger the diameter, the stronger the shear resistance while the bolt connector has stronger shear resistance than headed stud connector with similar diameter. Lastly, the ECC specimens have stronger shear resistance than NC specimens because of the mix design. In conclusion, the objectives of this research have been achieved. SCS sandwich composite structures are worthy to be investigated. There are numerous of parameters that could be studied on the steel-concrete behavior in SCS sandwich composite member in the future works.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

A steel-concrete-steel (SCS) sandwich composite structure consists of a concrete core sandwiched between two steel face plates and attached to the concrete core by shear connectors such that the concrete behaves monolithically. Due to its excellent cost-strength performances, this type of structural system has a wide range of possible applications in building and offshore construction structures such as building floors, cores, offshore decks, underwater tunnels, and oil containment.

Because of the bond between the two materials, concrete and steel will generally work well together. In a SCS sandwich composite, two steel-concrete interfaces are connected by shear connectors, as shown in **Figure 1.1**. **Figure 1.1** shows one of the examples of SCS sandwich composite with shear headed stud connectors. Since their load-bearing capacity is affected by the performance of both interfaces, the performance of the SCS structure system is significant.

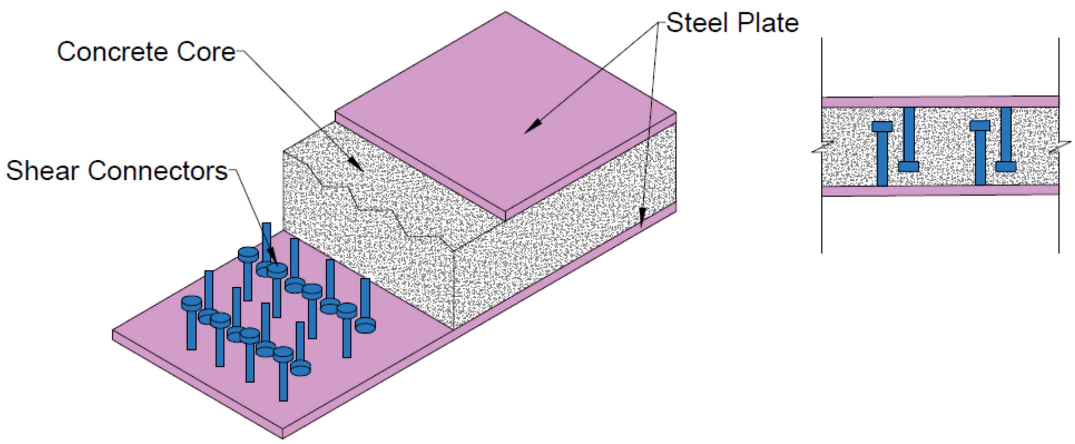

Figure 1.1: Steel-Concrete-Steel (SCS) sandwich structure with shear headed stud connectors.

Furthermore, it could be more effective in withstanding greater various loads such as axial compression or stress, bending moment, shear, and torsion by combining the steel plate members with concrete. This is because both the infilled concrete and the steel plate's structure help to overcome each other's weaknesses.

Moreover, steel-concrete-steel sandwich composite structures have the advantage of being cost-effective and easy to build, allowing for the pre-fabrication of large structures in the manufactory and quick installation into the main structure, as well as the two steel plates serving as permanent formwork, minimizing fabrication costs and time. The structural performance of the SCS sandwich composite structure, which has been investigated and found to have higher bending stiffness, ductility, strength, and cyclic performance even lowering the overall self-weight, has demonstrated its supremacy over most conventional engineering structure applications.

1.2 Problem Statement

The development of the Steel-Concrete-Steel (SCS) sandwich composite construction has accelerated in recent decades. SCS members have been used as lightweight key components in buildings, bridges, and other structures in civil engineering applications because of its features and advantages. For example, immersed tube tunnel application under Conwy River.

Furthermore, the slippage between concrete and steel plate could occur in a SCS sandwich structural member under bending moment or a slab which is subjected to lateral load. This may cause the composite action to be decreased and thus their load-bearing capacity are affected. When a load was applied on the SCS sandwich composite structure, the load applied would be transferred between steel plates and concrete core which they would work together to exhibit superior performance. If the bonding strength between concrete core and steel plate is not strong enough, the load transfer would fail and finally affect the structural performance. The composite interaction between concrete and steel in SCS sandwich composite structures is critical to make sure the superior performance of SCS sandwich composite structures. Furthermore, there are inadequate research that have been done on the behavior of steel plate to concrete interfaces with various concrete core and shear connector in SCS sandwich composite structure.

Therefore, further research is required to study the composite interactions between concrete and steel in SCS sandwich composite structures, as well as the behavior of concrete-steel interfaces in SCS sandwich composite structures, using various concrete cores, such as normal concrete and engineered cementitious concrete, and shear connectors, such as shear headed studs and bolt connectors.

1.3 Objectives

i. To explore the failure modes by carrying out a series of pushout tests on SCS sandwich composite structure.
ii. To study the influences of various parameters such as concrete type and shear connector type on the shear resistance capacity in SCS sandwich composite structure.

1.4 Scope of Study

The scope of the research work was controlled by the following factors in order to meet the objectives within the limited time and resources.

i. Thickness and dimension of steel plates are 3 mm and 130 mm × 150 mm.
ii. Steel formworks have been fabricated.
iii. Overlapping headed stud connectors with 13, 16 mm shaft diameter and 22, 32 head diameter with total length 55 mm and 80 mm, respectively.
iv. Bolt connectors with 12 mm & 16mm.
v. 2 type of Grade M50 of concrete which are engineered cementitious concrete and normal concrete have been used for filling in between steel plates.

CHAPTER 2

LITERATURE REVIEW

2.1 Strengthening of Structural Elements Using Concrete Infilled

Nowadays, reinforced concrete is substituted with the steel-concrete composite in the small to medium sized of construction projects. The steel-concrete composite consists of structural elements which are comprising hollow steel elements with concrete infilled (Soundararajan & Shanmugasundaram, 2008). The application of this composite is widely used in the construction industry due to the ease of manufacture and its high strength characteristic and more significantly advantage is being more economical (Gho & Liu, 2003). In this combination, the steel and concrete can work together thus can counter the weaknesses on of another. For example, the concrete will be in compression and the steel will withstand the tension. This in turn will make the structural elements more stiffer and lower the risk of failure of the composite members.

The strength and ductility of the composite is improved by the steel hollow section as the steel constrained the volume increase in the core concrete caused by the cracks. High-strength stee hollow sections provide better strength and ductility performance while high-strength concrete contributes larger stiffness to the structural system (Gho & Liu, 2003).

2.2 Structural Performance of Steel-Concrete-Steel (SCS) Sandwich Composite Structures

2.2.1 Sandwich Composite without Shear Connectors

A form of Steel-Concrete-Steel (SCS) sandwich beam comprises concrete core which is bonded in between two steel plates by means of epoxy resin adhesive. The behavior of these sandwich beams was similar to reinforced concrete beams without shear reinforcement (Liew and Sohel, 2010). The failure of the beams happened in a shear-tension mode and the ultimate shear resistance of the beam may be calculated as:

$$V_a = \mathrm{b}h_c(0.14\sqrt{f_{cu}} + 17.2\frac{\rho h_c}{a_v}) \qquad (1)$$

where, $\rho = A_s / bh_c$

A_s = cross-sectional area of tensile steel plate;

b = width of the beam;

h_c = depth of the concrete core;

a_v = shear span of the beam.

2.2.2 Sandwich Composite with Shear Connectors

The Steel-Concrete-Steel (SCS) sandwich system required mechanical shear connector to counter the weakness in shear. Therefore, improvement was made by providing shear connectors in order to achieve better performance of the system. There are several types of shear connector such as overlapping headed stud, Bi-steel sandwich, J-hook, C-channel, bi-directional and one end welded corrugated-strip connectors. The main purpose of shear connector is to facilitate shear transfer between steel plates and concrete core, as well as to avoid vertical separation of the face plate from the concrete core which arise from the buckling of the compression plate. There is numerous research on SCS sandwich structure have been carried out by several researchers which can be concluded as follow:

Overlapping Headed Stud Shear Connectors

Numerous tests and analysis have been reported on SCS sandwich structures with overlapping headed stud connectors. From the result obtained, the ultimate strength performance of the SCS sandwich composite beams with headed stud connectors is governed by 3 possible failure modes which are flexural, horizontal slip and vertical shear failures (Liew and Sohel, 2010). These failure modes may or may not be preceded by local buckling of compression plate. It was found that the shear connection should be designed as 55% in the tension zone and 80% in the compression zone to its ultimate strength due to the complex interaction of shear, axial and bending stresses on the connectors. **Figure 2.1** below has shown the SCS sandwich with overlapping headed stud shear connectors.

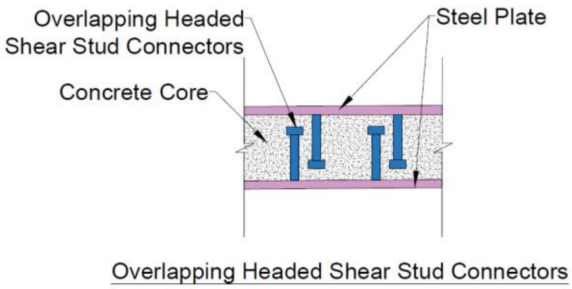

Figure 2.1: SCS sandwich with overlapping headed stud shear connectors.

Bi-Steel Sandwich Structure

Bi-Steel Sandwich Structure consisted of two steel face plates which are fixed at their relative positions by welding an array transverse bars connectors at each end to the steel face plate which are arranged in a closely spaced regular pattern. **Figure 2.2** below has shown the SCS sandwich with Bi-Steel shear connectors.

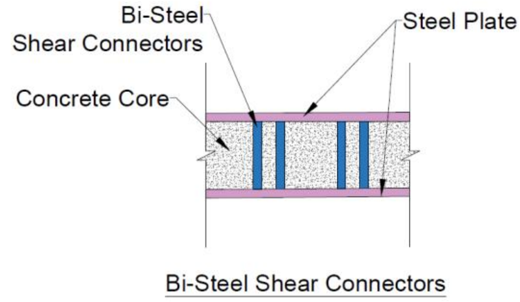

Figure 2.2: SCS sandwich with Bi-Steel shear connectors.

An analysis has been carried out by several researchers which is proposing a truss model to determine the moment capacity of bi-steel beams. An inherent characteristic of this model is that the plates are connected to the concrete only at the nodal points which means there is no bond between steel and concrete as in reality (Xie and Chapman, 2006). From the truss analysis, the member forces can be calculated as:

$$F_c = \frac{\mathrm{F}}{2\sin\theta} = \frac{\mathrm{F}\sqrt{h^2 - s_s^2}}{2h} \; and \; F_t = \frac{\mathrm{F}}{2\tan\theta} = \frac{\mathrm{F}s_s}{2h} \qquad (2)$$

Where,

$$h = \frac{nt_c(2h_c + t_c + t_t) + (y_m - t_c)[h_c - \frac{y_m - t_c}{3} + \frac{t_t}{2}]}{2nt_c + y_m - t_c}$$

Where,

$$y_m = -n(t_c + t_t) - t_c + [n^2(t_c + t_t)^2 - n(t_c^2 - 2t_c h_c - t_t^2)]^{1/2}$$

J-Hook Connectors

The pull-out strength of overlapping headed stud is not sufficient to avoid tensile separation of the steel plates from the concrete core. Bi-steel connectors are connected and welded to each end to the steel face plate, but the core thickness required a more thicker which must be minimum 200 mm for the placement of the bar connectors. Therefore, a special J-hook connected has been developed which are capable to resist the tension and shear as well as not being restricted by the thickness of the core (Liew and Sohel, 2009). The J-hook connectors are welded to the two face plates which are then interlocked and the gap between the face plates is filled by concrete. **Figure 2.3** below has shown the SCS sandwich with J-Hook shear connectors.

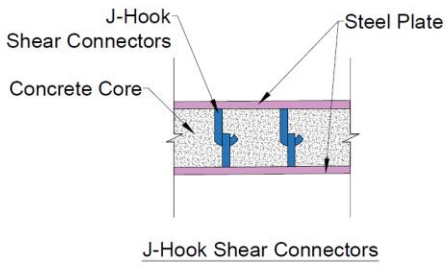

Figure 2.3: SCS sandwich with J-Hook shear connectors.

Vertical tension will be supported by the J-hook connectors, and the inclined compressive force is resisted by the virtual concrete strut in strut and tie model. When an impact force is applied on a SCS sandwich plate from the top, the bottom steel face will be pushed out from the concrete core by the impact shock wave. Therefore, it is necessary to bond both two plates by using shear connectors to avoid tensile separation of the plates.

C-Channel Connectors

The SCS steel plates will be fabricated which the holes are reserved for the externally connected bolts on the top and bottom steel face plates. C-channel connectors will be connected to the steel plates in regularly space with bolt and nut.

C-Channel Connector has been developed and connected to the steel face plates which the connector acted as shear connector in SCS sandwich structure which is especially suitable for slim decking and shear walls with limited spacing between two steel face plates in SCS sandwich (Yan, Hu and Wang, 2020). Moreover, the SCS sandwich structure with C-channel connectors has enough stiffness to overcome pressure of wet concrete during the casting and no additional formworks will be required. **Figure 2.4** below has shown the SCS sandwich with C-Channel shear connectors.

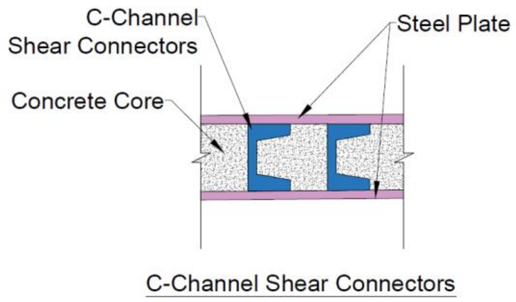

Figure 2.4: SCS sandwich with C-Channel shear connectors.

One End Welded Corrugated-Strip Connectors

One end welded corrugated-strip connectors are modified from the bi-directional corrugated-strip connectors system. The corrugated-strip connector is connected one end to the steel face plate. It is expected that the system is able to resist against the interlayer slip under applied load. **Figure 2.5** below has shown the SCS sandwich with One End Welded Corrugated-Strip shear connectors.

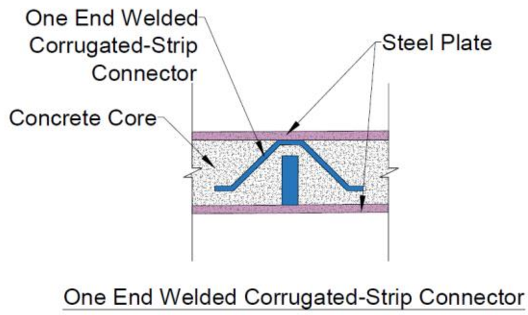

Figure 2.5: SCS sandwich with One End Welded Corrugated-Strip shear connectors.

2.3 Previous studies on the pushout test on SCS sandwich structure with various shear connectors.

Numerous investigations have been carried out on the bond behavior between steel face plate and concrete for steel-concrete-steel sandwich composite previously. Pushout tests were usually adopted to estimate the interaction of the steel-concrete interface in SCS sandwich composite.

The average ultimate shear resistance was obtained by dividing the ultimate strength with the area of interface. The shear resistance of steel-concrete interface in SCS sandwich composite consisted of chemical adhesion, micro-interlocking or friction and macro-interlocking, which was accepted and adopted by several researchers. The chemical adhesion mainly came from intermolecular forces and was governed by the mixture. The micro-interlocking, or friction was caused by the local unevenness of the steel surface. The macro-interlocking, from a holistic perspective, came from the irregularities of the steel plate, such as the tolerance of diameter along the longitudinal direction. The local buckling of the steel tube would aggravate this function.

Various parameters such as type of shear connector and concrete core that might affect shear resistance were focused and explored experimentally in previous investigations, which are summarized as follows:

2.3.1 Pushout test on SCS sandwich composite with J-Hook connectors.

There are numerous critical parameters which would influence the shear strength of the J-hook connectors such as the embedding depth of J-hook connector, tensile strength and elastic modulus of J-hook connectors and the properties of concrete core.

A research has been carried out by Yan and Liew about pushout test on SCS with J-hook connectors. The test specimen comprises two steel plates with dimension 250 mm × 300 mm and thickness with 6 mm and 10 mm, J-hook connectors with normal steel bar (f_y = 310 MPa) and high strength steel bar (f_y = 435 MPa) and three type of concretes such as normal concrete (NC), lightweight concrete (LWC) and ultra-lightweight (ULWC) concrete which grades C30, C45 and C60 are used.

From the pushout test result, there are three type of failure modes were observed such as shank shear failure, welding toe failure and crushing &cracking of the cementitious core material (Yan and Liew, 2013). Shank shear failure is the J-hook connector was sheared off near the weld toe of the connector. Besides, welding toe failure is occurred in sudden and is considered to be brittle and should be prevented by ensuring the weld quality during installation of connectors.

The influence of the diameter of the J-hook connector on the shear strength has been observed. The result obtained from the pushout test is the larger the diameter, the higher the shear strength which can be explained that the larger diameter of connector increases the shear interaction area as well as concrete bearing area thus enhances its shear resistance.

The effect of concrete strength and concrete type on the maximum shear strength of the J-hook connector. The concrete strength has great influence on the shear strength of the connectors which the higher the concrete strength, the stronger the anchorage to the shear connector. The influence of the concrete type on shear strength of J-hook connectors for specimen with NC, LWC and ULWC has been observed. When the concrete strength increased from 30 to 60 MPa, the LWC has more significant influence on the shear strength than ULWC which is increased by 33% for ULWC and 56% for LWC. However, the ULWC has more significant influence on the shear strength of J-hook connectors than NC which increases by about 12% for ULWC and 1% for NC (Yan and Liew, 2013).

The shear resistance of the J-hook shear connectors is controlled either by the shank shear strength or concrete bearing strength. The formula below can be used to determine the shear resistance of inter-locked J-hook connectors used in the sandwich composite structures with various concrete core such as normal concrete, lightweight concrete and ultra-lightweight:

$$P_J/A_s = \min\{0.855 f_{ck}^{0.265} E_c^{0.469} (\frac{h_c}{\mathrm{d}})^{0.154}, 0.8 f_u \qquad (3)$$

Load-slip curves for interconnected J-hook connectors can be expressed as below:

$$P/P_u = 2\delta/(\ 1 + 1.85\delta) \text{ for normal concrete} \qquad (4)$$

$$P/P_u = 2.5\delta/(\ 1 + 2.5\delta) \text{ for lightweight concrete} \qquad (5)$$

$$P/P_u = 3\delta/(\ 1 + 3\delta) \text{ for ultra} - \text{lightweight concrete} \qquad (6)$$

Where, P, Pu and δ are load, shear resistance and slip (mm) respectively.

2.3.2 Pushout test on SCS sandwich composite with C-Channel connectors.

Numerous parameters such as web-width of C-channel, height of the C-channel, installation direction of C-channel and concrete strength have been studied by Yan, Hu and Wang. To study the influence of web-width of C-channel on shear strength, C-channel connectors are design with different width of 30 mm, 50 mm and 70mm for the web-width and different height of 100 mm, 120 mm and 140 mm for the connector height. C-channel connectors were installed horizontally and vertically on the steel face plate in order to study the influence of the installation direction of connector on shear strength. There are 3 grades of concrete such as C 40, C50 and C60 were prepared for observing the influence of the concrete core on shear strength.

Model failure has been exhibited successive subjected to interfacial shear force. The externally connected bolts firstly failed in shear fracture, and then the shear fracture occurred to the C-channel connectors. The concrete core remains contact during these tests except for the specimens with wide web. From the test result obtained, the C-channel with 70 mm web-width, splitting failure mode occurred to the concrete core (Yan, Hu and Wang, 2020).

The width of the web and height of the C-channel connector are having significant influence on the shear strength. The wider the width of the web, it provides higher shear strength as well as the higher the height of the connector, the higher the shear strength. Furthermore, the C-channel connectors which were installed horizontally exhibit better shear strength which is 22% higher than the connector with vertically installed. From the data obtained, the ultimate shear strength and initial stiffness of C-channel increases linearly with the increasing strength of concrete core. However, the slip capacity of C-channel connector decreases when the compressive strength of concrete core increased (Yan, Hu and Wang, 2020).

2.3.3 Pushout test on SCS sandwich composite with one end welded corrugated-strip connectors.

Various parameters have been investigated such as thickness of steel plates & concrete core, the width of connector and the angle of the connector sides to the plates. To study the influence of thickness of steel plate and concrete core on shear strength, steel plates with 6 mm, 8 mm, 10 mm & 12 mm and concrete core with 50 mm, 60 mm, 70 mm, 85mm, 100mm and 186 mm were prepared. Width of connectors with 20 mm, 70 mm, 140 mm, and 200 mm were used to study the influence of width of connector on shear strength. Besides, there are three angles which were adopted to study the influence of angle of connector side to steel plate such as 45^o, 60^o and 90^o.

There are several model failures were observed from the study which investigated by Yousefi and Ghalehnovi such as shear failure of the left-strip connector, flexural failure of the right-strip connectors, buckling of the steel face, concrete wedge shear in the direction of connectors' sides, concrete crushing, and concrete shear crack. However, welding failure did not occur in the study.

From the pushout test result obtained, the thicker the steel plate, the higher the shear strength, but the shear strength will converge to a constant value at certain thickness of steel plate. The wider of the connector also gave a greater influence on the shear strength because the total surface area of the interaction between the connector and concrete has been increased. Furthermore, the angle 45^{o} of connector sides to steel plate is more ductile compared to the others and the highest ultimate shear strength has been obtained from the connector with angle 60^{o} (Yousefi and Ghalehnovi, 2017). From the work, load-slip curves are defined as below:

$$P/P_u = 100\delta/(\ 1 + 100\delta) - 0.005\delta \text{ when steel faces buckles} \quad (7)$$

$$P/P_u = 100\delta/(\ 1 + 100\delta) - 0.02\delta \text{ when steel faces do not buckles} \quad (8)$$

CHAPTER 3

METHODOLOGY

3.1 Introduction

Steel-concrete-steel (SCS) sandwich composite are having great potential that being used in various structural construction field such as building, bridge and offshore structures but the shear resistance between steel plate and concrete might affect the load bearing capacity as a structural construction member. The necessary retrofit means is strengthening the steel member with infilled concrete. There are numerous parameters that might be affecting the shear resistance 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 study, few parameters such as type of connectors and concretes that might be affecting the shear resistance are studied by carrying out pushout test. The methodology of the study is explained as below.

3.2 Materials

Material used in this project are as follows:

1. 8 units of shear headed stud connectors with 22 mm of head diameter and 13 mm diameter of shaft diameter which 2 of them are 55 mm and others are 80 mm of total length.
2. 4 units of bolt connectors which 2 of them are 12 mm and others are 16 mm diameter with 250 mm of total length.
3. 32 units of steel plates with dimension of 130 mm × 150 mm × 3 mm.
4. Normal concrete with capacity of 50Mpa.
5. Engineered cementitious concrete with capacity of 40Mpa.

3.3 Test Methodology and Procedures

Laboratory experiments would be conducted to explore the model failure of SCS sandwich composite and to study various parameters such various concrete core and shear connectors that might influence the shear resistance between steel plate and concrete. The shear resistance capacity of the shear connector and the model failure will be observed after the test. There are few main steps needed and are summarized as following:

3.3.1 Preparation of Steel Plates with connectors and Formwork

In this project, one of the objectives is to determine the influence of parameter such as shear connectors connected on steel plate on the shear resistance between concrete and steel tube under axial load. All specimens will have the same dimensions and thickness. However, the steel plates are required to be welded with shear connectors. Besides, steel formwork has been fabricated as shown in **Figure 3.1** below. Therefore, these are the factors to be considered when purchasing and preparing the samples.

Figure 3.1: Steel formwork for specimen preparation.

3.3.2 Concrete Preparation

There are 2 types of concrete that are going to be used in this study which are normal concrete (NC) and engineered cementitious concrete (ECC) with minimum compressive strength of 50 Mpa. The mix design for 1 m3 of concrete for normal concrete and engineered cementitious concrete as listed in **Table 1.1** below.

Materials	Concrete type	
	Normal Concrete (NC)	Engineered Cementitious Concrete (ECC)
Cement	565 kg	600 kg
Fly Ash	-	726 kg
Coarse aggregate	960 kg	-
Fine aggregate	600 kg	483 kg
Water	180 L	330 L
Super-plasticizer	2.6 L	6 L
Polyvinyl Alcohol (PVA) Fiber	-	26 kg

Table 1.1: Mix design for NC and ECC.

3.3.3 Concrete Casting

Concrete was proportionally mixed and poured into the steel formwork after being thoroughly mixed in the mixer, as per the manual's instructions. Furthermore, the concrete was poured into the mold to form concrete cubes, ensuring that the concrete's compression strength meets the desired value of 50 MPa.

3.3.4 Specimen Preparation

The steel plates were fabricated to the exact dimensions and thickness that were specified. After inserting the steel plates into the formwork, the concrete was poured in between them. Both specimens were given a 30 mm gap to allow slippage to occur between the sandwiched concrete core and steel plates. A total of 16 SCS sandwich specimens were designed and prepared for the investigation of the steel plate's shear resistance capability with various connectors. The specimens' specific details can be found in **Table 1.2**.

No.	Label	Steel Plate Dimension (mm)	Shear Connectors	No. of connectors (Nos)	Shaft Diameter (mm)	Head Diameter (mm)	Total Length of connector (mm)	Concrete Cores
1	NC NC	130 × 150 × 3	No connector	-	-	-	-	NC
2	NC B-12	130 × 150 × 3	Bolt	1	12	-	100	NC
3	NC B-16	130 × 150 × 3	Bolt	1	16	-	100	NC
4	NC-13/55	130 × 150 × 3	Headed Stud	1	13	22	55	NC
5	NC-13/80	130 × 150 × 3	Headed Stud	1	13	22	80	NC
6	NC-2x13/80	130 × 150 × 3	Headed Stud	2	13	22	80	NC
7	NC-16/80	130 × 150 × 3	Headed Stud	1	16	32	80	NC
8	NC-2x16/80	130 × 150 × 3	Headed Stud	2	16	32	80	NC
9	ECC NC	130 × 150 × 3	No connector	-	-	-	-	ECC

10	ECC B-12	130 × 150 × 3	Bolt	1	12	-	100	ECC
11	ECC B-16	130 × 150 × 3	Bolt	1	16	-	100	ECC
12	ECC-13/55	130 × 150 × 3	Headed Stud	1	13	22	55	ECC
13	ECC-13/80	130 × 150 × 3	Headed Stud	1	13	22	80	ECC
14	ECC-2x13/80	130 × 150 × 3	Headed Stud	2	13	22	80	ECC
15	ECC-16/80	130 × 150 × 3	Headed Stud	1	16	32	80	ECC
16	ECC-2x16/80	130 × 150 × 3	Headed Stud	2	16	32	80	ECC

Table 1.2: Information of Specimens

3.3.5 Test Setup and Instrumentations

Figures 3.2 and **3.3** show the test setup and schematic setup for the push-out test. A rigid based was placed at the bottom of the SCS sandwich specimen to let the specimens set vertically during testing. 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, as shown in **Figure 3.2**, to make sure the load was only applied to the sandwiched concrete core. A Universal Testing Machine (UTM) was used in the test to record the slippages. The loading speed of 0.5 mm/min was used for this push-out test. The loading was terminated until the failure occurred.

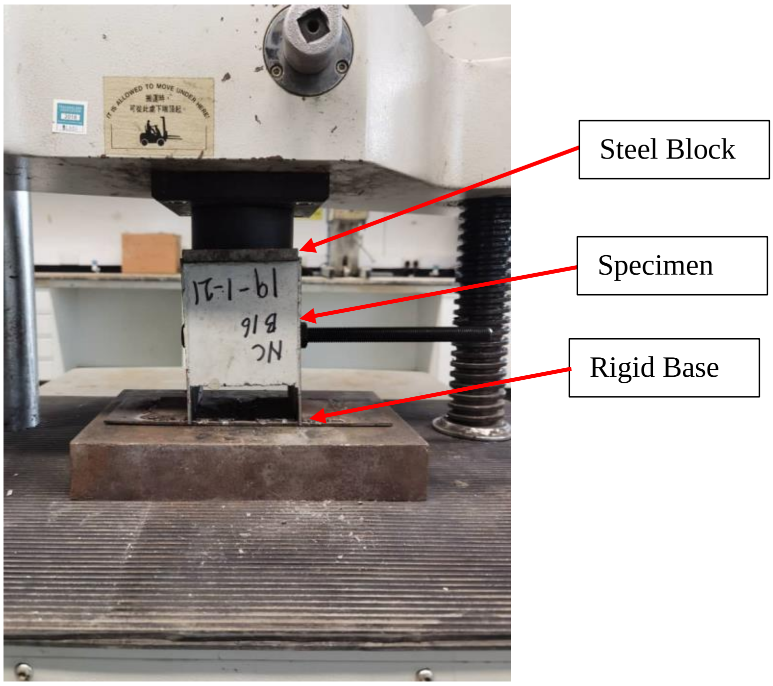

Figure 3.2: Test setup.

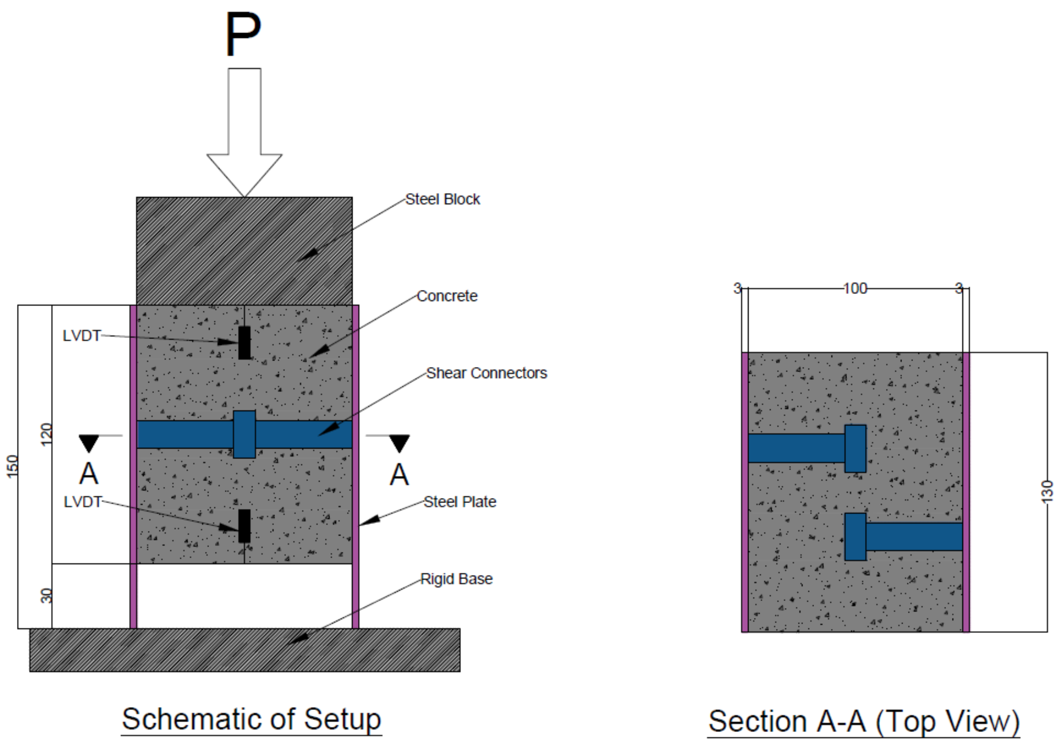

Figure 3.3: Schematic of Setup and Section A-A (Top View).

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Failure Modes

Four types of failure modes were identified during the push-out experiments. The first type of failure modes was bonding failure. The steel plates without any shear connectors were separated from the concrete cores after being casted and removed from the formwork. It had proven that the shear resistance between steel plates and concrete core without shear connectors was very weak. The second type of failure was steel plates buckling. This type of failure occurred due to the steel compression bearing capacity. The **Figure 4.1 (a)** shows the steel plates buckling. Besides, shear connector failure was observed as third type of failure mode. The bolt connector was bended as shown in **Figure 4.1 (b)**. The fourth type of failure was concrete bearing failure as shown in **Figure 4.1 (c).** The concrete was crushed and cracked after the push-out test due to its bearing capacity. 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 bearing will fail first without the shear connector failure. The summary of failure modes for each specimen have been listed in **Table 2.1**.

(a) (b) (c)

Figure 4.1: (a) Steel buckling. (b) Bolt bending. (c) Concrete crushing and cracking.

Concrete Cores	Shear Connectors	Model Failure
Normal Concrete	No Connectors	Steel plates are separated from concrete cores
	Stud – 13mm / 55mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 13mm / 80mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 16mm / 80mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 2 × 13mm / 80mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 2 × 16mm / 80mm	Small crack on concrete + steel plates buckling
	Bolt – 12mm	Concrete crushing due to bearing capacity + steel plates buckling + bolt bending
	Bolt – 16mm	Concrete crushing due to bearing capacity + steel plates buckling
Engineered Cementitious Concrete	No Connectors	Steel plates are separated from concrete cores
	Stud – 13mm / 55mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 13mm / 80mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 16mm / 80mm	Concrete crushing due to bearing capacity + steel plates buckling
	Stud – 2 × 13mm / 80mm	Small crack on concrete + steel plates buckling
	Stud – 2 × 16mm / 80mm	Small crack on concrete + steel plates buckling
	Bolt – 12mm	Concrete crushing due to bearing capacity + steel plates buckling + bolt bending
	Bolt – 16mm	Small crack on concrete + steel plates buckling

Table 2.1: Summary of failure modes for each specimen.

4.2 Load-slip Behaviors

During push-out tests, the relative slips between the concrete core and the steel plate were observed. The load–slip curves for NC and ECC, respectively, are shown in **Figures 4.2** and **4.3**, based on the results of push-out testing. The load– slip behavior was compared with failure modes for discussion purpose.

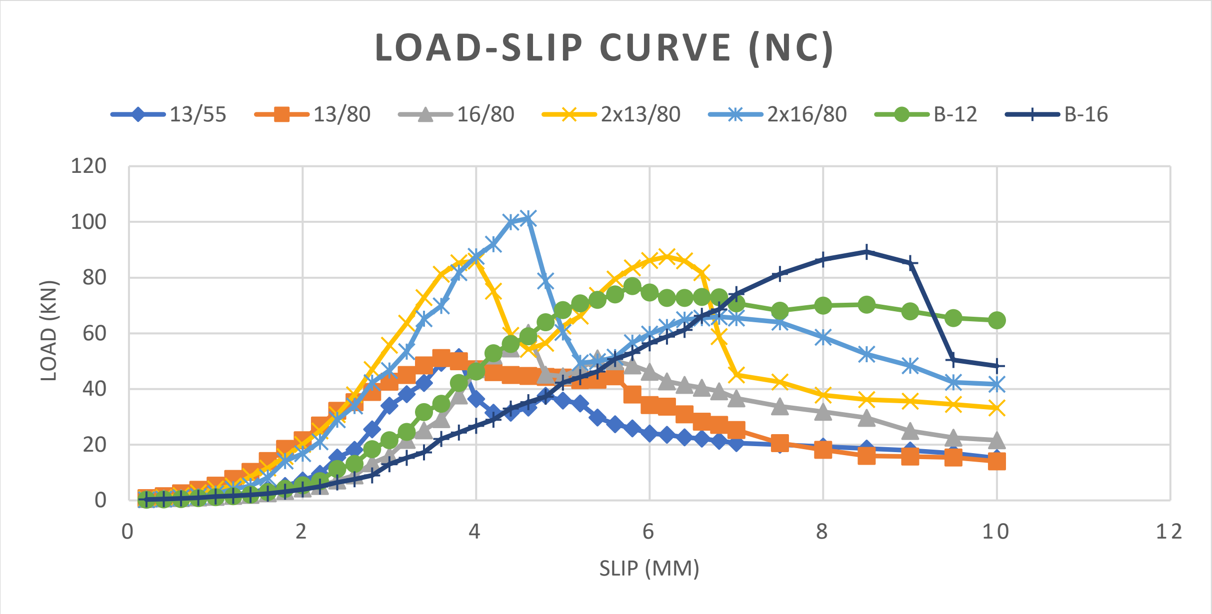

Figure 4.2: Load-Slip Curve (NC).

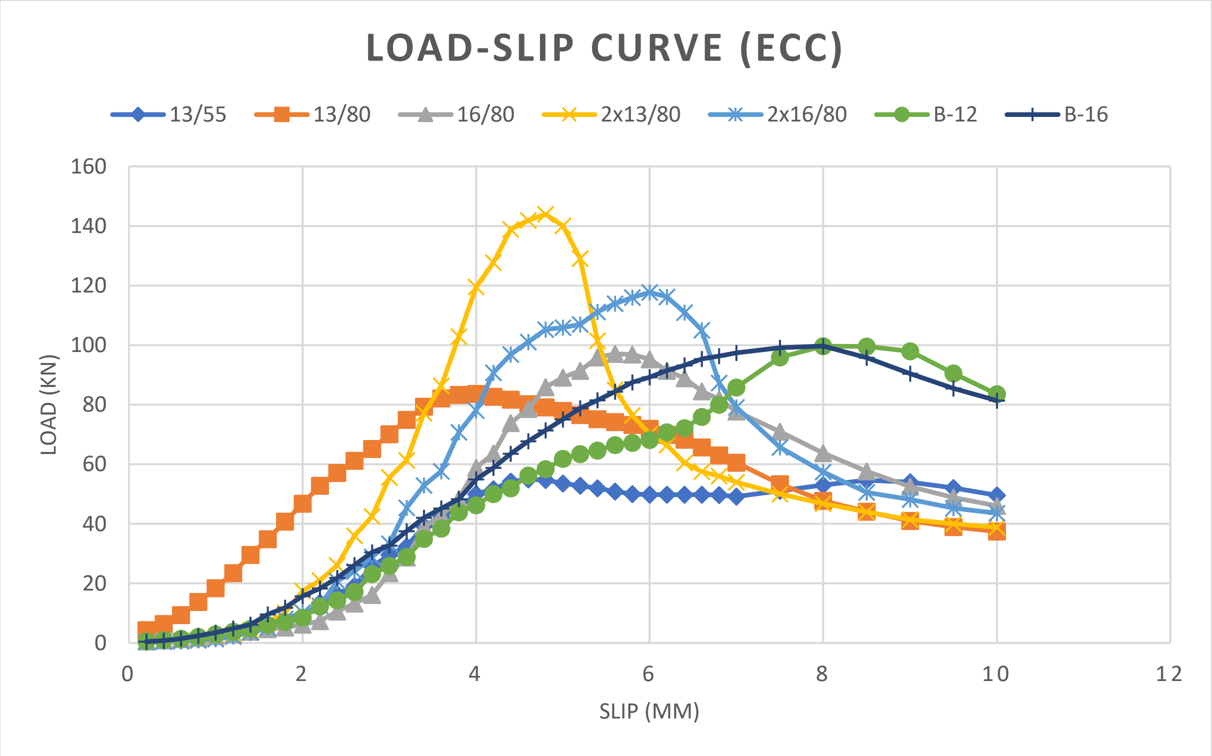

Figure 4.3: Load-Slip Curve (ECC).

Figure 4.2 shows that the relationship between load and slip in NC specimens increased proportionally at the beginning of the loading process. After meeting the maximum load, the load–slip curve showed a rapid drop in behavior. This can be explained by the fact that the NC specimens were relatively brittle. In **Figure 4.3**, the relationship between load and slip in ECC specimens, on the other hand, was also increasing proportionally at the initial stage of loading. However, the load-slip curve exhibited a gradually decreasing instead of a quick drop after reached to the maximum load. This can be explained by the fact that the ECC specimens were more ductile than the NC specimens.

A shear connector failure proved that the tensile force generated during the push-out testing could be resisted by the concrete core if the concrete core's tensile resistance were high enough. Otherwise, the specimen failed in concrete cracking, which showed a more brittle behavior than the specimen that failed in shear connector failure. From the failure mode at the previous section, only the specimen with bolt-12mm connector exhibited shear connector failure while other failures were due to concrete bearing and steel plate failure. This shows that the specimen with bolt-12mm connector was having a relative ductile behavior compared to others. The failure modes for other specimens were concrete bearing and steel plate buckling but not certainly that they were relatively brittle. For example, the failure mode for specimen with bolt-16mm connector was steel plate buckling with minor crack as shown in the following section in **Figure 4.7**. This can be explained by the fact that the bearing capacity of the steel plates was lower than that of the concrete core and shear connector, causing steel plate buckling to occur before concrete bearing and shear connector failure.

The key takeaway from the study is that failure of steel plates due to bearing failure is not ideal, and it does not reflect the true behavior of shear connectors in sandwich plates. Such failure can be prevented by increasing the compressive bearing capacity of the steel plates such as increasing the thickness of the steel plates in order to resist the compressive strength from the push-out testing. As a result, the true behavior of the shear connector in the steel plate can be measured and investigated.

4.3 Shear Resistance of Connector Comparison

In this section, the load-slip relation was assessed, and the shear resistance of the headed stud connector was also calculated. Ollgaard et al. (1971) indicated a formula for load-slip model for shear studs based on the experimental results as follow:

$$P = P_u(1 - e^{-18S})^{0.4} \tag{9}$$

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

The Eq. (9) had been modified by Lorence and Kuica (2006) by carrying out experimental studies and suggested the following relation.

$$P = P_u(1 - e^{-0.55S})^{0.3} \tag{10}$$

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 which was proposed by Xue et al. in 2008. The formula as follow:

$$\mathrm{P} = P_u \frac{\mathrm{S}}{0.5 + 0.97\mathrm{S}} \tag{11}$$

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

Based on Eurocode 4 (EC4), the design strength of shear headed stud connector had been specified as following equation.

$$P = \frac{0.8 f_u \boldsymbol{\pi} \mathbf{d}^2}{4\gamma_V} \tag{12}$$

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 = safety factor = 1.25.

The **Table 2.2** & **Figure 4.4** have shown the comparison between shear resistances of connectors which were calculated by adopting various theoretical formulas. For the purposes of comparison with test results, partial safety factors were assumed to be 1.0 in these formulas. Otherwise, the design guides should be used to assess these partial safety factors. The accuracy and reliability of the various design approaches could be evaluated from the the P_{Test}/P_{Theo} Ratio.

From the **Table 2.2** and **Figure 4.4**, it can be observed that the Eq. (9), (10) & (11) exhibit good result which close to the test result. However, the result from Eq. (9) gives the best fit to the test results. Besides, the Eq. (12) which was proposed by EC4 offers the least accuracy and reliable results because of higher percentage difference up to 87% in this comparison. The Eq. (12) is also not suitable for the prediction of shear resistance of bolt connector which gives a huge percentage difference up to 261%. As a result, the proposed formula Eq. (9) offers a more accurate and reliable predictions and is recommended for use in the design of SCS sandwich composite with headed stud connectors.

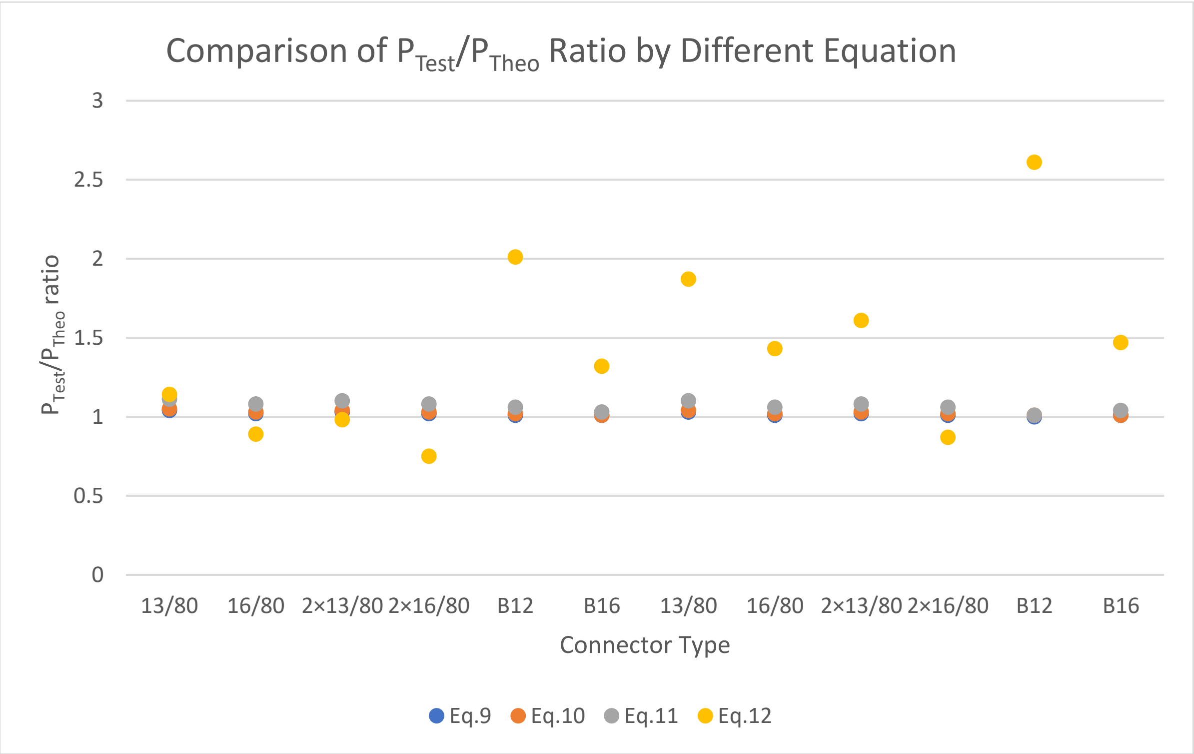

Figure 4.4: Comparison of P_{Test}/P_{Theo} Ratio by Different Equation.

Type of Concrete	NC						ECC					
Type of Shear Connector	13/80	16/80	2×13/80	2×16/80	B12	B16	13/80	16/80	2×13/80	2×16/80	B12	B16
Number of Studs	1	1	2	2	1	1	1	1	2	2	1	1
Shank Diameter,d (mm)	13	16	13	16	12	16	13	16	13	16	12	16
Ultimate applied load, P_u (kN)	50.16	58.98	85.82	99.3	75.42	87.55	82.04	95.19	141.16	115.44	97.73	97.76
Slip (mm)	3.61	4.64	3.86	4.56	5.73	8.85	4.06	5.7	4.55	6	14.1	7.8
Tensile Strength of Studs, f_u (N/mm^2)	415	415	415	415	415	415	415	415	415	415	415	415
Partial Safety Factor, γ_V	1	1	1	1	1	1	1	1	1	1	1	1
Compressive Strength of concrete, f_{cu} (Mpa)	53.8	53.8	53.8	53.8	53.8	53.8	48.51	48.51	48.51	48.51	48.51	48.51
Shear Resistance, P (kN/mm)												
Eq. (9)	48.58	58.1	41.78	48.86	74.9	87.49	80.17	94.52	69.45	57.4	97.73	97.61
Eq. (10)	47.99	57.57	41.31	48.41	74.44	87.35	79.3	93.93	68.8	57.08	97.72	97.36
Eq. (11)	45.26	54.73	39.03	45.99	71.34	85.3	75.05	90	65.36	54.8	97.2	94.54
Eq. (12)	44.08	66.77	44.08	66.77	37.56	66.77	44.08	66.77	44.08	66.77	37.56	66.77
Comparison between Theoretical value and Experimental value, (Experimental/Theoretical Ratio)												
Eq. (9)	1.04	1.02	1.03	1.02	1.01	1.01	1.03	1.01	1.02	1.01	1	1.01
Eq. (10)	1.05	1.03	1.04	1.03	1.02	1.01	1.04	1.02	1.03	1.02	1.01	1.01
Eq. (11)	1.11	1.08	1.1	1.08	1.06	1.03	1.1	1.06	1.08	1.06	1.01	1.04
Eq. (12)	1.14	0.89	0.98	0.75	2.01	1.32	1.87	1.43	1.61	0.87	2.61	1.47

Table 2.2: Shear Resistance of Connector Comparison.

4.4 Effect of Connector's Diameter and Connector Type

Figures 4.5 and **4.6** illustrate how the diameter and type of connector affect the maximum applied load. **Table 2.3** summarizes the overall applied load, compressive strength, and deformation obtained during the push-out test**.** The greater the diameter of the connector, the higher the overall applied load of the connectors, as can be seen in **figures 4.5** and **4.6**. This is because the larger diameter connector has a larger cross-sectional area and a larger total surface area, which is the area where the concrete interacts with the connector, increasing the connection's overall shear resistance. From **Table 2.3**, the bolt connector exhibited stronger shear resistance compared to headed stud connector with similar diameter, but the headed stud connector was having stronger shear resistance compared to bolt connector when the number of headed stud connectors increased to two, this can be explained by the larger the total surface area that interact with concrete core, the stronger the shear resistance.

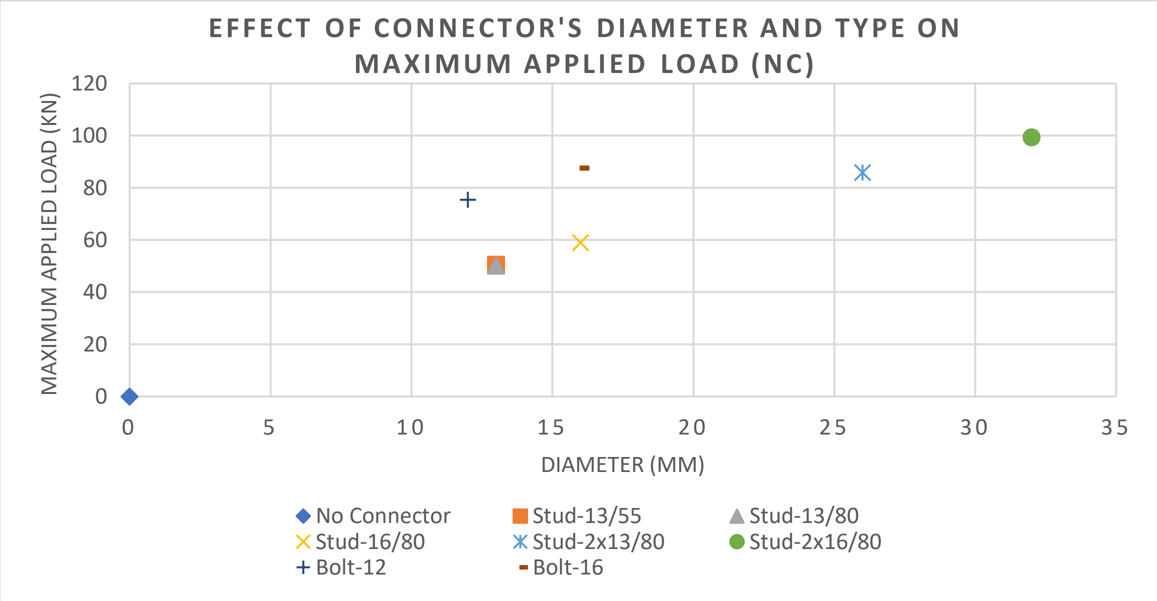

Figure 4.5: The effect of connector's diameter and type on maximum applied load (Normal Concrete).

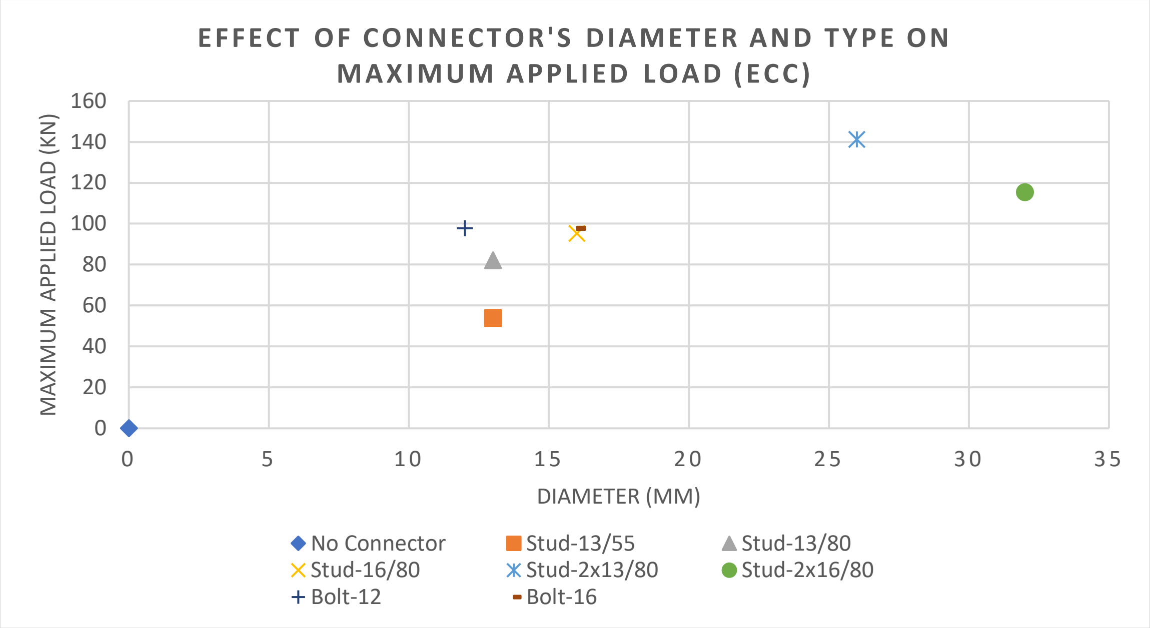

Figure 4.6: The effect of connector's diameter and type on maximum applied load (Engineered Cementitious Concrete).

Concrete Cores	Shear Connectors	Maximum Load (kN)	Compressive Strength (Mpa)	Deformation (mm)
Normal Concrete	No Connectors	0	0	0
	Stud – 13mm / 55mm	50.522	3.886	3.64
	Stud – 13mm / 80mm	50.155	3.858	3.61
	Stud – 16mm / 80mm	58.980	4.537	4.64
	Stud – 2 × 13mm / 80mm	85.821	6.602	3.86
	Stud – 2 × 16mm / 80mm	99.302	7.639	4.56
	Bolt – 12mm	75.415	5.801	5.73
	Bolt – 16mm	87.553	6.735	8.85
Engineered Cementitious Concrete	No Connectors	0	0	0
	Stud – 13mm / 55mm	53.839	4.141	4.60
	Stud – 13mm / 80mm	82.036	6.310	4.06
	Stud – 16mm / 80mm	95.191	7.322	5.70
	Stud – 2 × 13mm / 80mm	141.157	10.858	4.55
	Stud – 2 × 16mm / 80mm	115.444	8.880	6.00
	Bolt – 12mm	97.730	7.518	14.10
	Bolt – 16mm	97.756	7.520	7.80

Table 2.3: Summary data of the maximum applied load, compressive strength, and deformation from the push-out test.

It can be observed that the overall applied load is linearly proportional to the connector diameter for headed stud connectors of different diameters. Besides, the bolt connector has higher shear resistance than the headed stud connector with similar diameter. The yield strength of the connector and steel plate, as well as the compressive strength of the concrete core, influence the overall applied load of the connector. When the connector's diameter is small, the failure is controlled by shear connector failure, and the strengths and types of concrete have little impact. Since the failure is influenced by the concrete bearing failure when the diameter of the diameter is high, the maximum shear resistance of the connector is determined by the strength or type of the concrete core. Furthermore, there is one more outcome which is the steel plate failure prior occurred before the shear connector and concrete bearing failures. The steel plates buckled, but the shear connectors were fine, and the concrete core just had a slight crack, as can be seen in **Figure 4.7**.

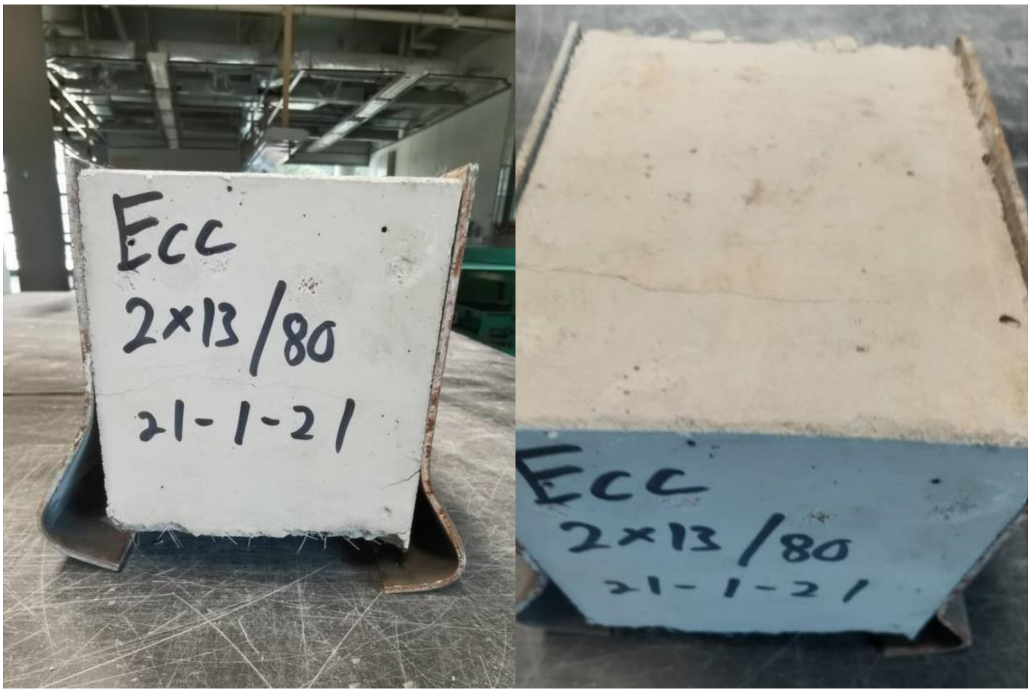

Figure 4.7: Steel plate buckling with minor crack.

However, there was an imperfection from the result obtained such as the maximum applied load for the ECC specimen with headed stud – 2x13/80mm was supposed lower than the maximum applied load for ECC specimen with headed stud – 2x16/80mm. This issue occurred might because of systematic error such as the specimens were not levelled enough which were not perpendicular to the ground base.

4.5 Effect of Concrete Strength and Concrete Type

Table 2.4 shows the maximum applied load differences for various concrete types, while **Figure 4.8** depicts the impact of concrete type on the maximum applied load. As compared to NC specimens of equivalent average compressive strength, the maximum applied load on the ECC specimen increases by 6.60 to 64.48 % as shown in **Table 2.4**. The fact that ECC's mix design offers better anchorage to the shear connector explains this. As a result, it can be concluded that the impact of concrete type on interfacial shear resistance is greater for ECC specimens than for NC specimens.

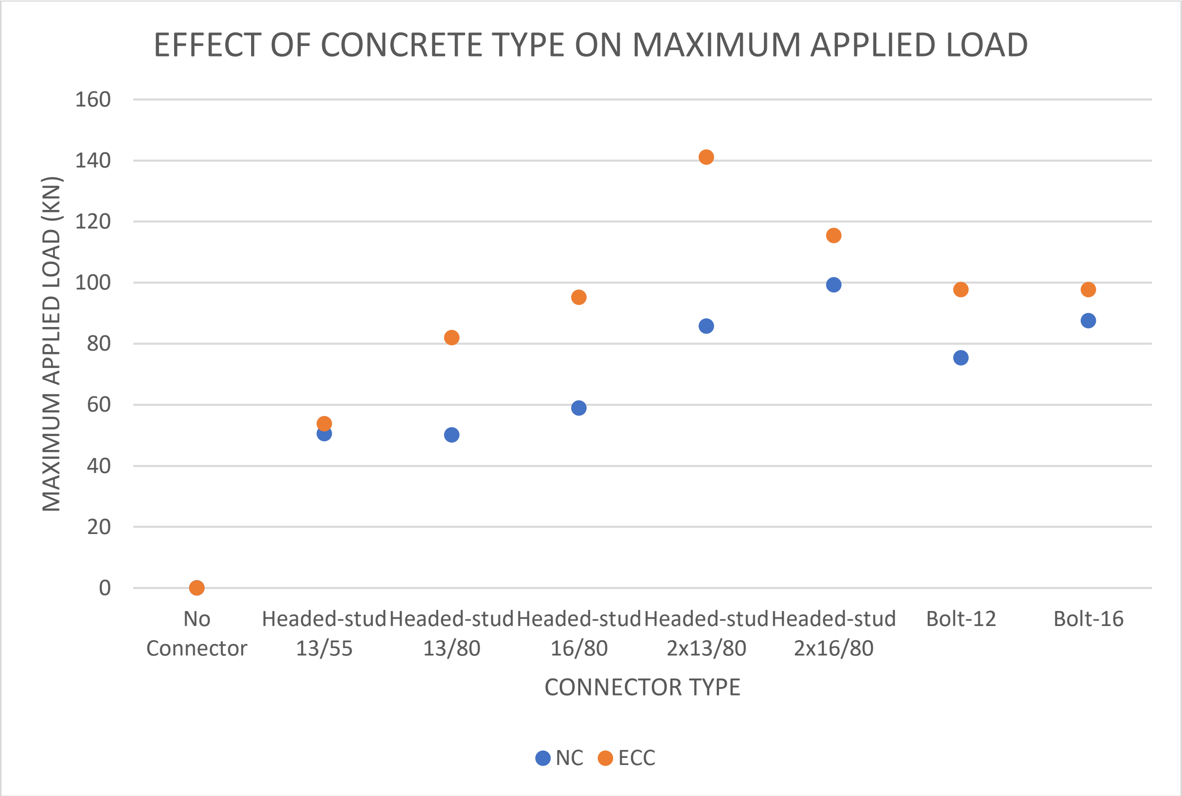

Figure 4.8: Effect of concrete type on maximum applied load.

Concrete type	Casting Date	Concrete weight (kg/0.001m^3)	Concrete Strength for (Mpa)	
			7-day	28-day
Normal Concrete	19/01/2021	2.326	-	55.96
	19/01/2021	2.314	-	50.22
	19/01/2021	2.346	-	50.33
	20/01/2021	2.327	51.00	57.90
	20/01/2021	2.337	42.30	54.60
	Average			53.80
Engineered Cementitious Concrete	20/01/2021	1.956	32.00	48.37
	20/01/2021	1.951	34.50	47.72
	21/01/2021	1.949	35.70	52.34
	21/01/2021	1.983	34.00	51.22
	21/01/2021	1.889	-	46.51
	27/01/2021	1.976	33.30	50.50
	27/01/2021	1.898	32.50	42.90
	Average			48.51

Table 2.4: Compressive strength of concrete for 7-day and 28-day.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

Push-out testing was used to determine the interfacial shear resistance capability of various shear connectors and concrete cores in a Steel-Concrete-Steel sandwich composite member in this study. During the laboratory experiments, the model failures of the specimens were examined and observed. The following conclusion can be drawn based on the test results and discussions in the previous chapter.

1) The push-out tests showed four different types of failure: bonding failure, steel plates buckling, shear connector failure and concrete crushing and cracking due to bearing.
2) From the load-slip curves, the specimens with ECC exhibited a relative ductile behavior compared to NC specimens.
3) The Eq. (9) which was proposed by Ollgaard et al. (1971) $P = P_u(1 - e^{-18S})^{0.4}$ offers more accurate and reliable results compared to others in this research.
4) The steel plate buckling failure may be avoided by increasing thickness of the steel plates in order to investigate and observe the true behavior of shear connector.
5) Larger diameter of shear connector increases the shear interaction area and thus increases its shear resistance. The bolt connector exhibited stronger shear resistance compared to headed stud connector with similar diameter, but if increases the number of headed stud connector to two, the shear resistance of the specimen with two headed stud connectors was stronger due to larger interaction area.
6) Since the mix design of ECC offers better anchorage to the shear connector, specimens with ECC have higher shear resistance than NC.

5.2 Recommendations

Based on the results and discussion, some recommendations for further research into the impact of concrete type and shear connector type on SCS sandwich composite members could be made in the future.

1) To prevent systemic error, specimens used for push-out testing must be carefully checked to ensure they are levelled and perpendicular to the ground base.
2) Since the relationship between the concrete core and the steel plates is complex, the strength of the concrete core used in the study could have an impact on the overall outcome. This involves a change in bonding strength, which could have an effect on the SCS sandwich composite member's interfacial shear resistance. As a result, various types of concrete cores (with varying strengths and mix designs) can be used in future research projects.
3) The steel plates used for the research are not enough to resist the compressive strength during push-out testing. The steel plates failure prior occurred before concrete bearing and shear connector failure which the result obtained does not represent the true behavior of the shear connector. Therefore, the thickness of the steel plates could be increased, or a type of steel plate with a higher compressive bearing capacity could be used.in the future research project.
4) The shear connectors used in the study were limited in terms of type and diameter. Shear connectors come in a different type, and various diameters may be used in future research projects.

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