EVALUATION OF EFFECT OF GEOMETRIC AND MATERIAL PARAMETERS OVER THE PERFORMANCE OF STEEL-CONCRETE-STEEL SANDWICH (SCSS) STRUCTURES WITH J-HOOK CONNECTORS

PROJECT REPORT

Submitted by,

AKHILESH A R

REG. NO.: TKM20CESC03

ROLL NO.: M20CESC02

Department of Civil Engineering

T.K.M. College of Engineering, Kollam- 691005

A. P. J. ABDUL KALAM TECHNOLOGICAL UNIVERSITY

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DECLARATION

I undersigned hereby declare that the project report “Evaluation of effect of geometric and material parameters over the performance of steel-concrete-steel sandwich (SCSS) structures with j-hook connectors”, submitted for partial fulfillment of the requirements for the award of degree of Master of Technology of the APJ Abdul Kalam Technological University, Kerala, is a bonafide work done by me under supervision of Prof. Asif Basheer, Assistant Professor, Department of civil engineering, TKM College of Engineering. This submission represents my ideas in my own words and where ideas or words of others have been included, I have adequately and accurately cited and referenced the original sources. I also declare that I have adhered to ethics of academic honesty and integrity and have not misrepresented or fabricated any data or idea or fact or source in my submission. I understand that any violation of the above will be a cause for disciplinary action by the institute and/or the University and can also evoke penal action from the sources which have thus not been properly cited or from whom proper permission has not been obtained. This report has not been previously formed the basis for the award of any degree, diploma or similar title of any other University.

Kollam Akhilesh A R

07/06/2022

DEPARTMENT OF CIVIL ENGINEERING

T.K.M. COLLEGE OF ENGINEERING, KOLLAM

CERTIFICATE

This is to certify that the report entitled **'EVALUATION OF EFFECT OF GEOMETRIC AND MATERIAL PARAMETERS OVER THE PERFORMANCE OF STEEL-CONCRETE-STEEL SANDWICH (SCSS) STRUCTURES WITH J-HOOK CONNECTORS'** submitted by **AKHILESH A R**, to the APJ Abdul Kalam Technological University in partial fulfillment of the requirements for the award of the Degree of Master of Technology in Structural Engineering & Construction Management is a bonafide record of the project work carried out by him under our guidance and supervision. This report in any form has not been submitted to any other University or Institute for any purpose.

Guide	Coordinator	Head of the Dept.
Prof. Asif Basheer	**Dr. Ramaswamy K. P.**	**Dr. Sajeeb R.**
Assistant Professor,	Assistant Professor,	Professor,
Dept. of Civil Engg.	Dept. of Civil Engg.	Dept. of Civil Engg.
TKMCE, Kollam	TKMCE, Kollam	TKMCE, Kollam

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Akhilesh A R

ABSTRACT

Steel-concrete-steel sandwich (SCSS) structure is a type of composite structure in which a concrete core is sandwiched in between two steel plates. SCSS structures can offer a greater amount of moment of resistance and stiffness compared to that of steel plates with same amount of steel consumption. Among the different components of an SCSS structure, shear connectors can be referred as the most crucial component contributing to the composite action. J-hook connectors are a type of novel shear connectors which can overcome the limitations faced by other shear connectors like headed studs and bi-steel connectors.

In this particular study various factors affecting the load-slip behaviour and ultimate strength behaviour of SCSS structures were reviewed and tests such as mid-point bending test of SCSS beam and pushout test of SCSS pushout test specimen were numerically simulated using ANSYS software. From the results, influence of variation of different parameters such as grade of concrete and steel, diameter of shear connector, core thickness, plate thickness, and spacing of shear connectors over the behaviour of SCSS structures under quasi-static loading conditions were analysed. Based on the obtained results an empirical relation for the force-slip model of SCSS structures was suggested while incorporating the important parameters.

Keywords: Steel-concrete-steel sandwich, shear connector, J-hook connector, headed stud, bi-steel connector, bond slip

CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOTATIONS AND ABBREVIATIONS

d	: Diameter
h_c	: Core thickness
f_{cu}	: Ultimate cube strength of concrete
f_{yb}	: Yield strength of shear connector
f_{ub}	: Ultimate strength of shear connector
f_{yp}	: Yield strength of plate
f_{up}	: Ultimate strength of plate
L	: Span of beam
SCSS	: Steel-Concrete-Steel Sandwich
s_x	: Longitudinal spacing of shear connectors
t_c	: Thickness of bottom plate
t_t	: Thickness of top plate
ULCC	: Ultra Lightweight Cement Composite
ρ_v	: Shear reinforcement ratio

CHAPTER 1

INTRODUCTION

Construction industry is one of the age old and ever developing areas which demands significant research attention. Advancements in construction practices had been implemented over centuries by considering its different dimensions. Among such various advancements an important milestone can be considered as the use of different materials together in order to overcome one's weakness. Reinforced cement concrete (RCC) structures can be considered as a classic example for a composite system. Concrete is very strong in compression but weak in tension. But this weakness can be overruled by providing reinforcements which are strong in bearing tensile forces.

Even though RCC structures are very common and have wide range of applications it is insufficient to meet all the emerging requirements in a modern construction sector. Steel structures are considered as a well-accepted alternative to RCC structures when situations are much more demanding as in the case of high-rise structures, long span bridges etc. Instead of using steel or concrete alone, these materials can be used together such that they function as a single component. Materials are combined like this for achieving better functionality than they had while being used separately. Composite structures have various advantages over steel structures like higher strength and stiffness, reduced steel usage, higher resistance to seismic and cyclic loading (Yan et al. 2019), and smaller member size. Apart from that, systematic incorporation of composite construction can bring better economy and also faster construction than traditional practices. Among the various types of composite structures Steel-Concrete-Steel Sandwich (SCSS) structures are one of the most relevant in terms of its performance under large loads.

1.1 SCSS COMPOSITE STRUCTURES

Weakness of concrete under tensile forces and proneness to buckling of steel under compressive forces can be overcame by effectively combining them. Through the composite action of steel and concrete, enhancement of overall performance of the structure can be achieved rather than optimizing it. One such way of effectively combining steel and concrete is by aligning the layers in a sandwiched fashion. An

SCSS composite structure is one in which a concrete core is sandwiched in between two steel plates (Figure 1.1). These layers are designed and connected in such a way that the structure has to behave as an integral unit when an external load is applied over it.

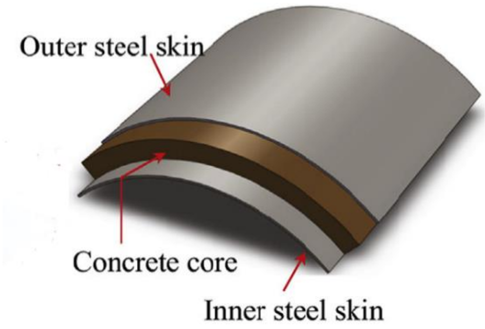


Figure 1.1 SCSS structure (Liew et al., 2017)

1.2 RESEARCH SIGNIFICANCE

Most important aspect of a composite structure is regarding the connection of its constituent materials. For ensuring sufficient composite action it is necessary to design the connecting elements as per the requirement. Different methods are being adopted for connecting the layers in an SCSS structure. These methods can be broadly classified into two, ie. by using cohesive materials and shear connectors. Shear connectors enjoy some advantages over cohesive materials due to its more reliable performance. A lot of studies had been conducted for providing the most effective solution for connecting the layers, since the integrity of the structure and effectiveness of composite action is solely relied upon it.

A novel type of connector used nowadays are J-hook connectors. It has some advantages over other mechanical shear connectors due to its practicality and performance. But its applications are limited due to lack of studies conducted for understanding its behaviour. So, study on the utility of J-hook connectors need significant research attention for enhancing the applicability of SCSS structures.

1.3 OBJECTIVES

Objectives of this particular project includes,

1. Develop finite element models of SCSS beam and pushout test specimen using J-hook connector
2. Conduct parametric study on behaviour of FE models of SCS sandwich structure by varying parameters; connector diameter, steel plate thickness, spacing of shear connectors, core thickness, and grade of steel and concrete
3. Find out the relationship between spacing of shear connectors and the degree of composite action of the SCSS structure
4. Propose an empirical formulation for preparing load-slip model

1.4 METHODOLOGY IN BRIEF

For satisfying the objectives stated above a methodology was formulated as follows. First step in the methodology was to conduct an extensive literature survey and collect the data required for conducting this particular study. It included the data regarding material properties of steel and concrete under consideration, behaviour of steel and concrete at the interaction surface, data regarding load-slip behaviour of SCSS structures from experimental observations, and also the data regarding observed ultimate strengths from previous experiments. Once these were explored, assumptions as per the scope of the study was formulated and according to that finite element modelling was done. Important steps in the process of finite element modelling were to define the material properties of constituent materials like concrete core, steel plate, and shear studs, geometric modelling of the structure and setting up of interaction between different surfaces. Once the modelling was done, it had to be validated based on previously conducted researches. After satisfactory completion of validation, parametric study of SCSS structures was done using developed models. During this phase, influence of various parameters like connector diameter, steel plate thickness, spacing of shear connectors, core thickness, and grade of steel and concrete over the properties of sandwich structures were evaluated. From the results obtained an empirical relationship was derived for the load-slip model. After formulating the empirical model, it was validated by comparing with the experimental results.

1.5 SCOPE

This study was based on the numerical analysis using ANSYS 2022R1. The scope of the study was limited to SCSS composite structures with J-hook type of shear connectors. This particular study analysed the behaviour of SCSS beams and pushout test specimens under static or very slow loading conditions only.

1.6 ORGANIZATION OF THE REPORT

The thesis is structured into seven main chapters. Chapter one describes the background of the study, problem statement, significance of the research, objectives of the study, a brief description of the adopted methodology and the scope and limitations of the study.

Chapter two reviews about the studies conducted on SCSS structures in the past. It focuses on the literatures about different methods of compositing adopted in SCSS structures, important influencing parameters for load slip behaviour and load-displacement behaviour of SCSS structures and available empirical relations formulated for these behaviours.

Detailed reporting of the methodology adopted for the study is done in chapter three. Description on finite element modelling test setups and parametric study done using ANSYS software is given in this chapter.

Chapter four describes about software validation of ANSYS. It details about the comparison of results obtained through reference journal and the results obtained through the numerical analysis of simulated model.

Chapter five presents the results of numerical studies and the inferences obtained from them. It mainly includes the force-displacement relations for SCSS beams and the force-slip behaviour observed while carrying out simulated pushout tests with varying parameters. It also includes the study about the influence of spacing of shear connectors over the degree of composite action in an SCSS structure.

Development of empirical relations for the force-slip behaviour of SCSS structures is detailed in chapter six.

Chapter seven reports the major findings and conclusions derived from the study, along with identified future scope for further studies in this particular research area.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

SCSS composite structures improve bearing capacity, ductility, impact resistance, and leakage by combining the advantages of reinforced concrete (RC) systems and steel plates. (Liew and Wang 2011). Additionally, they make prefabrication and installation easier, which can cut down on the cost of fabrication and speed up construction. Another benefit of having two face plates at the top and bottom of a SCSS structure is that it removes the need for extra formwork by serving as a permanent formwork throughout construction. SCSS composite structures outperform traditional engineered structures in applications requiring high resistance, high ductility, and high energy absorption capabilities (Zhang et al. 2020), which gives them great potential to be used in submerged tunnels, shear walls, building core, basement of multistorey building, nuclear power plant structures, protective structures, ship hulls, and offshore structures (Liew and Sohel 2009).

2.2 STEEL STRUCTURES VS SCSS STRUCTURES

Thin steel plates that are supported in one direction by stiffeners are often used for plating of ship decks and hulls, components of offshore structures, box girder bridges, bridge decks, and other structures where a high strength-to-weight ratio is crucial (Grondin et al. 1999). However, SCSS structures have some benefits over stiffened steel plates, including the elimination of the need for secondary beams, a reduction in welding and an increase in work productivity, a reduction in the surface area of the steel and a consequent decrease in the cost of corrosion protection, an increase in acoustic and thermal insulation, the ability to create a straightforward structural form that can be easily fabricated, and an improvement in structural performance against impact, blast, and fatigue loads. Table 1 compares the amount of steel used, the weight of the total structure, the moment resistance, and the stiffness of steel plate structures and SCSS plates. As shown in the table among a steel plate and SCSS plate made with equal steel consumption, the sandwich plate is observed to have a moment resistance and stiffness of 12 times and 200 times respectively, compared to that of steel plates (Liew et al. 2017). It is also to be noted that for an SCSS structure with equal moment of resistance as that of steel plate steel consumption and overall weight can be reduced by 33% and 56% respectively, without compromising the stiffness of the structure (Liew et al. 2017).

Table 1.1 Comparison of SCSS plates V/s Steel plate (Liew et al. 2017)

Comparison	Steel plate structure	SCS sandwich plate	
	t	$0.5t$, $15t$, $0.5t$	$t/3$, $5/3t$, $t/3$
Steel consumption	1.0	1.0	0.67
Overall weight	1.0	1.92	0.44
Moment resistance	1.0	12	1.0
Stiffness	1.0	200	1.03

2.3 METHODS OF COMPOSITING

2.3.1 Cohesive Materials

The SCSS composite structures can be made of cohesive materials like epoxy. Due to the bonding material's imperfection, brittle bond failure at the steel-concrete interface can be occurred when compared to the mechanical shear connectors, endangering the structural integrity of the SCSS structure. These sandwich beams behaved similarly to beams made of reinforced concrete without shear reinforcement (Solomon et al. 1976).

Jurkiewiez et al. (2011) observed that, steel-concrete composite beam with a bonding connection and normal strength concrete can exhibit similar behaviour with that of a composite beam with mechanical connectors like studs. However, the author cautions that, the behaviour of the flexural member show sufficient ductility without shear failure only if the bonding joint is appropriately designed.

2.3.2 Mechanical shear connectors

They provide the necessary shear connection for composite action between steel plates and concrete core. Designing shear connectors is an essential factor in making composite beams. Experimental studies have been conducted extensively to determine how different shear connectors behave. Different types of shear connector that can be found in composite structures are given as follows.

2.3.2.1 Headed studs

To resist horizontal shear and vertical uplift forces in composite steel-concrete structures, the most commonly used type of shear connector is the headed stud (Figure 2). It is also called as Nelson stud. Much study has been done on headed stud shear connectors and numerous formulae have been proposed to determine the strength of studs. The head of the stud is designed to prevent slab lifting while the root is designed to transmit the horizontal shear stress acting at the steel-concrete interface. The shear strength of a stud connector is directly proportional to its cross-sectional area, and the compressive strength and elastic modulus of the concrete have a significant impact on the connector's shear strength. When the headed studs are used, resistance of individual layers against tensile separation will be dependent on the pull out resistance of headed studs (Liew and Sohel 2009). Previous studies have found that a number of factors affecting the strength of stud connectors. The stud's shank diameter, height, and tensile strength, as well as the concrete's compressive strength, elastic modulus, and casting orientation, are some of the most crucial factors. (Ali Shariati 2012).

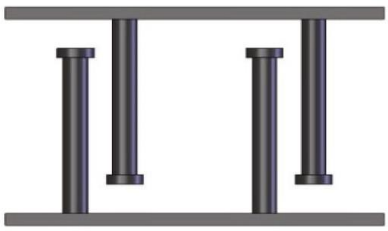


Figure 2.1 Overlapping headed studs (Liew et al. 2017)

Headed stud connectors has the advantages as follows: fast welding, good anchor in concrete, easy arrangement of reinforcement through the slab, and easy large scale production. The standard dimensioned head acts as a resistance factor for slab uplift. Major disadvantage of headed studs is that, it loses its pull-out resistance when concrete core is cracked. Studies conducted by Hanswille et al. (2007) shown that when stud connecters are subjected to fatigue loads it drastically reduces the static strength.

2.3.2.2 Bi-steel connectors

Friction welding the two steel face plates to the straight steel bar connectors as shown in Figure is an innovative approach to increase the structural integrity of SCSS structures. These connectors can effectively prevent tensile separation and local buckling in the structures (Bowerman and Chapman 2002). However, the friction weld apparatus used for the connector installation restricts the thickness of SCSS structures to a range between 200 and 700 mm (Liew et al. 2017).

Figure 2.2 Bi-steel structure (Liew et al., 2015)

2.3.2.3 J-hook connectors

Another type of SCSS composite structure is with double J-hook connectors (Figure). These J-hook connectors worked in pairs that interlocked each other and were attached to two face plates to transfer interfacial shear forces, resist tensile separation and prevent local buckling of face plates. This proposed composite structure performed well under static (Sohel and Liew 2011), impact and fatigue loading, and has wide range of uses as offshore platforms, tunnels, bridge deck, building cores, and protective structures. Moreover, the SCSS composite structure using J-hook connectors can be produced in slim deck with minimum thickness of even 50 mm (Liew and Sohel 2009). It was found that the J-hook worked well in transferring both vertical and interface shear. (Sohel and Liew 2011).

J-hook connectors can be made by either forging or bending reinforcing bar. To meet the requirements for strength and deck height, they can be made in a variety of diameters and heights. The J-hook connector's diameter is constrained for slim decking with thin core by its bending radius. A shear stud arc welding equipment that is readily accessible in the marketplace can be used to weld the J-hook connectors to the face plate (Sohel et al. 2012).

Figure 2.3 J-hook connectors (Liew et al., 2017)

2.3.2.4 Comparison of structural performance

Load-slip behaviour of J-hook connectors compared with headed studs and bi-steel connectors are given in Figure and Figure . From the figures it can see that that the load-slip behaviour of J-hook connectors are comparable to that of headed studs and bi-steel connectors. J-hooks, on the other hand, can offer some residual shear and pull-out resistance in the case of concrete cracking that headed studs are unable to supply.

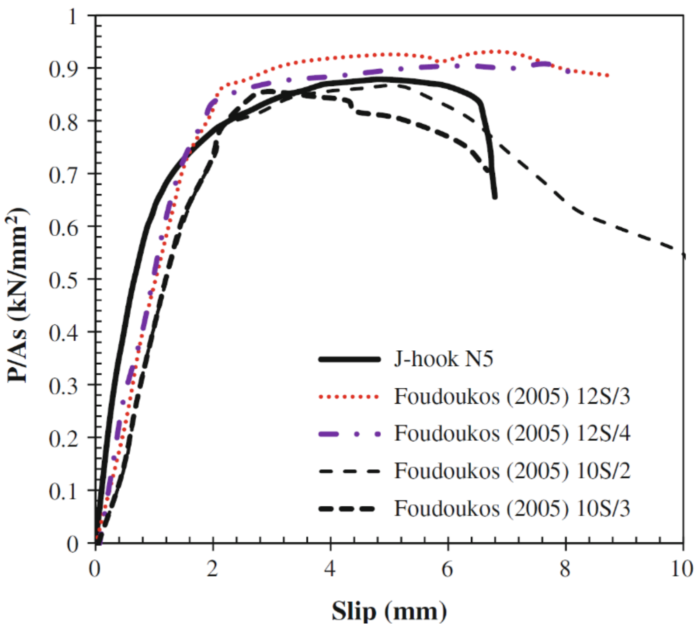


Figure 2.4 Comparison between J-hook and Bi-steel connector (Yan et al. 2014)

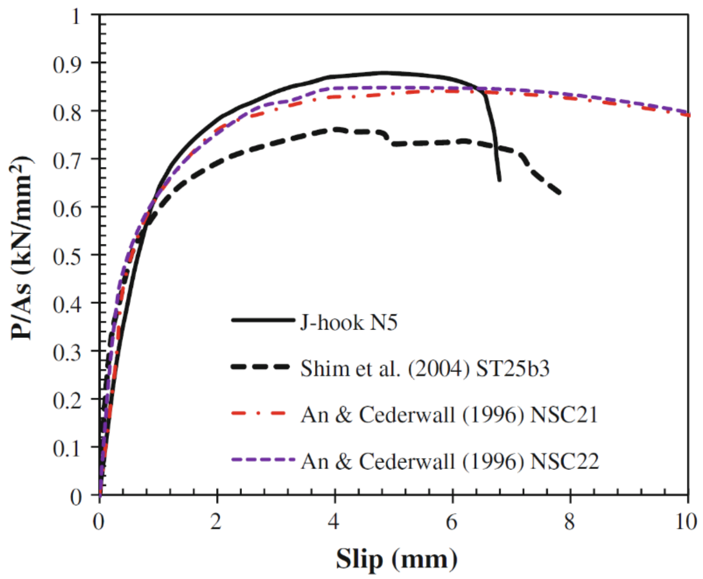


Figure 2.5 Comparison between J-hook and headed stud (Yan et al. 2014)

2.4 BEHAVIOUR OF SCSS STRUCTURES UNDER LOADING

2.4.1 Load-slip behaviour

Load-slip behaviour of a sandwich structures represents the amount of slipping between individual layers upon the application of an interfacial shear force. During a push out test, loading is provided to the concrete core in such a way that, it pushes the core concrete out from the steel plates. Load-slip curves obtained from push out tests can provide an understanding about the bond strength between connected layers and degree of composite action of the structure. A schematic representation of loading mechanism during a push out test is shown in figure.

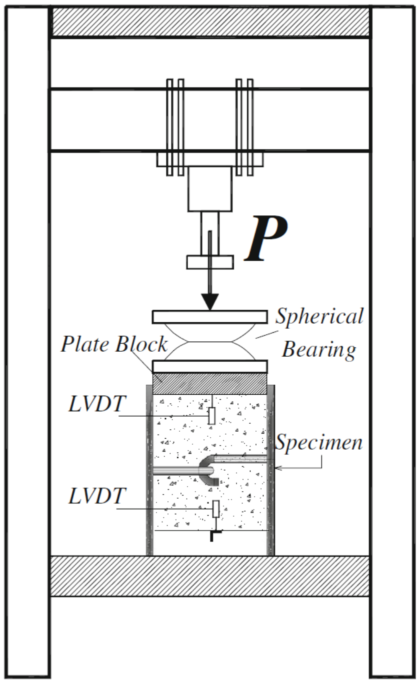


Figure 2.6 Pushout test experimental setup (Yan et al. 2014)

2.4.2 Failure Mechanisms of SCSS Structures

Failure mechanism of SCSS structure mainly depends upon the amount of shear connectors provided. The bond-slip between steel plate and concrete can be effectively reduced by arranging sufficient shear connectors. However, adding more shear connectors in practical engineering applications makes construction more difficult and is economically inefficient. There mainly three types of failure modes associated with SCSS structures are described below.

2.4.2.1 Shear failure without bond slip

When there is sufficient shear connectors provided, failure mechanism usually followed is concrete crushed failure without bond slip (Leng and Song 2016).

2.4.2.2 Shear failure with bond slip

This failure pattern occurs when beam is with insufficient shear connectors. The bottom steel plate is affected by the critical diagonal crack, and there is evidence of bond-slip between the steel plate and concrete. But the top steel plate's bottom surface is not affected by the critical diagonal crack, and the concrete in the shear-compression zone is not crushed.

2.4.2.3 Bond slip failure

Here, Failure features show obvious bond slip between the steel plate and concrete, which limits the ultimate strength and shows that the steel plate is not working to its maximum capacity. SCSS beams exhibit out-of-plane shear failure and interfacial shear failure. If shear connectors are very few, it can result into premature and brittle failure of the structure (Qin et al. 2016).

There is no web-shear crack for bond slip failure. A web-shear fracture develops around the middle of the beam in the shear span for the failure modes of partial bond-slip failure and concrete crushed without bond slip, and the two ends of the crack extend to the support and loading points.

When there is an occurrence of bond slip it results into weakening of composite action, increase in the angle of the critical diagonal cracking (CDC) in concrete and relieving of loading on the bottom steel plate.

2.4.3 Important Parameters

2.4.3.1 Embedment Depth to Diameter Ratio

Yan et al. (2014) observed that the maximum applied load on the connector increased with the increment of h_c/d ratio. When h_c/d ratio increased it was also found that the failure modes of some specimens were shifted from core cracking to shank shear failure. This implies that h_c/d ratio greatly influences the maximum applied load as well as failure mode.

2.4.3.2 Connector Diameter

Previous research had demonstrated that increasing the connector's diameter increases the maximum applied load of the connectors. This is due to the fact that greater connector diameters have greater cross sections and bearing areas on the concrete, both of which enhance the connector's maximum shear resistance. However, the yield strength of the connector and the mechanical characteristics of the concrete core (compressive strength, shear strength, and Young's modulus) also have an impact on the maximum applied load of the connector. The failure was controlled by concrete bearing failure when the connector's diameter was large (i.e., greater than 12 mm), and it was observed that the strength of the concrete core affected the connector's maximum resistance. When the connector's diameter was under 10 mm, shank shear was the major control factor for failure rather than the strength or type of concrete.(Yan et al. 2014).

2.4.3.3 Concrete Strength and Concrete Type

Literatures suggest that concrete strength and concrete type has an influence on the maximum shear strength of the J-hook connector. Authors claim that higher concrete strength provides stronger anchorage to the shear connectors and thus improves the maximum shear strength of the connector. For the connectors failed by concrete cracking, increase of concrete strength was found to increase the shear strength of the connector.

When compared to specimens with LWC, the impact of concrete strength on the shear strength of the J-hook was less pronounced for specimens with ULCC. The maximum shear strength of J-hook for specimens with ULCC and LWC increased by 33 and 56 percent, respectively, as f_c rose from around 20 to 60 MPa. However, it was found that specimens with ULCC had a greater impact from f_c on the shear strength of J-hook than specimens with NWC. For specimens with ULCC and NWC, when f_c was raised from 30 to 60 MPa, the maximum shear strength of J-hook rose by roughly 12 and 1%, respectively (Yan et al. 2014).

Instead of the strength and type of core concrete addition of fibres was also found to be effective in improving the ultimate strength of SCSS structures. It was observed that the ultimate strength of the structure had improved by 27% and 31% on addition of 0.5% and 1% of steel fibres by volume fraction respectively when subjected to concentrated loads (Yan et al. 2016).

2.4.3.4 Steel Plate Ratio

Steel plate ratio is defined as the ratio of combined thickness of top and bottom plates to that of the total thickness of the beam. The finite element simulation results by Lin et al. (2019) shows that the bond-slip between the steel plate and concrete varies slightly with increasing steel plate ratio for SCSS beams with various steel plate ratios. The steel plates did not yield when bond-slip failure occurred, and the ultimate strength rose nearly linearly with increasing the steel plate ratio. The bottom steel plate yielded, and the ultimate strength improved noticeably with increasing steel plate ratio when the failure modes of partial bond-slip failure and concrete crush failure without bond-slip appeared.

2.4.3.5 Shear Reinforcement Ratio

Lin et al. (2019) found that ρ_v has a slight effect on the bond-slip of SCSS beams. Authors also observed an increase in the ultimate strength by 5.6%, 19.1% and 21.8% when the ρ_v increased by 0.039, 0.104 and 0.187, respectively. Authors claim that the longitudinal and transverse shear forces between the steel plate and concrete are resisted by cross ties. As a result, adding more cross ties makes the beam stiffer and improves the composite action of the steel plate and concrete.

However, they have also observed that ρ_v reaches a particular value, the additional shear reinforcement slightly improves the ultimate strength of SCSS beams. The ultimate strength of SCSS beams hence cannot be further increased by increasing ρ_v over this level.

2.4.3.6 Spacing of Shear Connectors

The failure mode and ultimate strength of SCSS beams are significantly influenced by the spacing of shear connectors. According to experimental research, as shear stud spacing is reduced, ultimate strength rises and there is less bond-slip between the steel plate and concrete. This outcome was seen as a result of the increased composite action and improved binding behaviour between the steel plate and concrete caused by the addition of extra shear studs. It improves the yielding of the steel plate and the steel plate's contribution to ultimate strength, which can raise the ultimate strength of SCSS beams. But, when the spacing of shear studs decreased beyond a certain value, the ultimate strength of SCSS beams increases only by small amount. This outcome comes as a result of the steel plate's full advantage contributing to the shear behaviour and the composite action between the steel plate and concrete reaching a high bound. In conclusion, the structural behaviour of SCSS beams is significantly influenced by the design of shear connectors.

2.4.4 Shear strength of SCSS structures

Shear strength of SCSS structures is contributed by core concrete, steel plates and shear connectors. Shear strength contributed by different connectors like headed studs, J-hook connectors are also different.

2.4.4.2 Shear Strength of J-Hook Connectors

The loads that could be imparted to a pair of interlocking J-hook connectors include longitudinal shear, tensile, and most likely combined shear and tension forces (Yan et al. 2015). Design guides are not available for calculating shear strength of J-hook connectors. But, some preliminary observations on the relationship between the shear resistance of J-hook connector, P_J, and the primary parameters such as f_{ck}, E_c and h_s/d are reported by Yan et al. (2014).

$$P_J/A_s = \alpha f_{ck}^{x} E_c^{y} \left(\frac{h_s}{d}\right)^{z}$$

The four coefficients α, x, y, and z were taken into account by Yan et al. (2014) in various combinations, and ultimately = 1.0, x = 0.265, y = 0.469, and z = 0.154 were found for the model that provided predictions with a 95 percent confidence level. A partial safety factor of = 0.855 was advised for design purposes in order to decrease the number of risky predictions and take interaction between steel and concrete into consideration.

2.4.5 Load-slip Model

Load- slip behaviour is an important aspect of sandwich structures as it represents the loss of integrity of the structure due to interfacial slip upon the application of loading.

2.4.5.1 Load-Slip Behaviour of Headed Studs

Xue et al. (2008) has conducted 30 push-out tests of headed studs and based on the results, an expression for load-slip model was proposed as follows.

$$\frac{P}{P_u} = \frac{\delta}{0.5 + 0.97\delta}$$

Where, P is the applied shear force, P_u is the shear resistance of the connector, and δ is the slip in mm due to applied load P.

An and Cederwall (1996) proposed two expressions based on their test results using nonlinear regression analysis to predict the load–slip response of headed stud connectors in NWC and high-performance concrete subjected to cyclic loading.

$$\frac{P}{P_u} = \frac{2.24(\delta - 0.058)}{1 + 1.98(\delta - 0.058)} \quad \text{for NWC}$$

$$\frac{P}{P_u} = \frac{4.44(\delta - 0.031)}{1 + 4.24(\delta - 0.031)} \quad \text{for HPC.}$$

An alternate empirical relationship for load-slip model of headed studs was suggested by Gattesco and Giuriani (1996) as given below.

$$\frac{P}{P_u} = \alpha\sqrt{1 - e^{-\beta\delta/\alpha}} + \gamma\delta$$

2.4.5.2 Load-Slip Behaviour of J-hook Connectors

Yan et al. (2014) proposed the load-slip models for J-hook connectors in NWC, LWC, and ULCC based on the results of push out test as follows.

$$\frac{P}{P_u} = \frac{2\delta}{1 + 1.85\delta} \quad \text{for NWC,}$$

$$\frac{P}{P_u} = \frac{2.5\delta}{1 + 2.5\delta} \quad \text{for LWC,}$$

$$\frac{P}{P_u} = \frac{3\delta}{1 + 3\delta} \quad \text{for ULCC.}$$

2.5 SUMMARY OF LITERATURE REVIEW

An extensive literature survey was done for understanding the behaviour of SCSS structures based on previous studies. From the literatures it was found that SCSS structures are highly effective in various fields of applications and also performs better when compared to steel structures. Ensuring the bond between steel plates and concrete core is the most important aspect of an SCSS structure. One novel way of doing that is by the use of J-hook connectors.

From reviewing the behaviour of SCSS structures under loading, different types of associated failure mechanisms and important parameters influencing the behaviour were identified. Major influencing parameters identified from the literatures include embedment depth to diameter ratio, diameter of shear connectors, concrete strength and concrete type, steel plate ratio, shear reinforcement ratio and spacing of shear connectors. Based on these, some fundamental influencing parameters were identified for conducting the parametric study such as follows

- Diameter of shear connectors
- Core thickness
- Grade of concrete and steel
- Thickness of steel plate
- Spacing of shear connectors

From the literatures some preliminary expressions for the shear strength and load slip behaviour were also reviewed and it was found that much research attention is needed for the more accurate mathematical formulation of behaviour of SCSS structures under loading.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 INTRODUCTION

An SCSS structure is highly complex for an accurate analytical representation since it involves large number of individual components which are interacting and collectively taking part in the load bearing mechanism. So, this study was conducted by means of numerical methods. This particular study on SCSS structures was primarily done through finite element analysis using ANSYS software. Detailed analysis procedure for the study is given as follows.

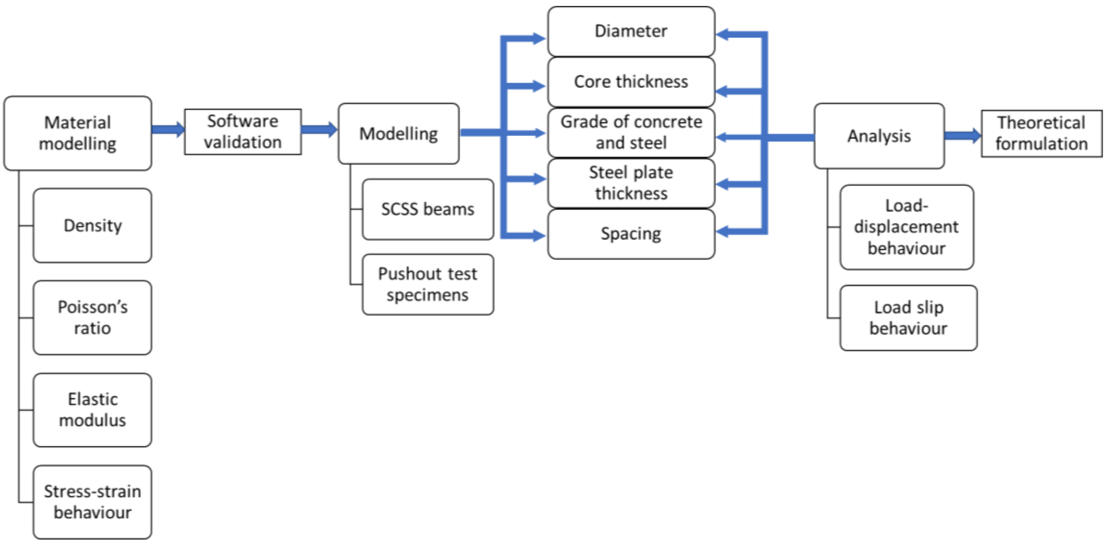


Figure 3.1 Schematic representation of methodology

3.2 MATERIAL MODELLING

Data regarding material properties for steel and concrete, and their interaction in a composite structure was collected for the purpose of material modelling.

3.2.1 Concrete material model

Elasto-plastic behaviour of concrete upon loading is modelled as per the stress strain behaviour obtained from Xiao et al. (2017). Stress-strain model used for concrete is given in figure 9.

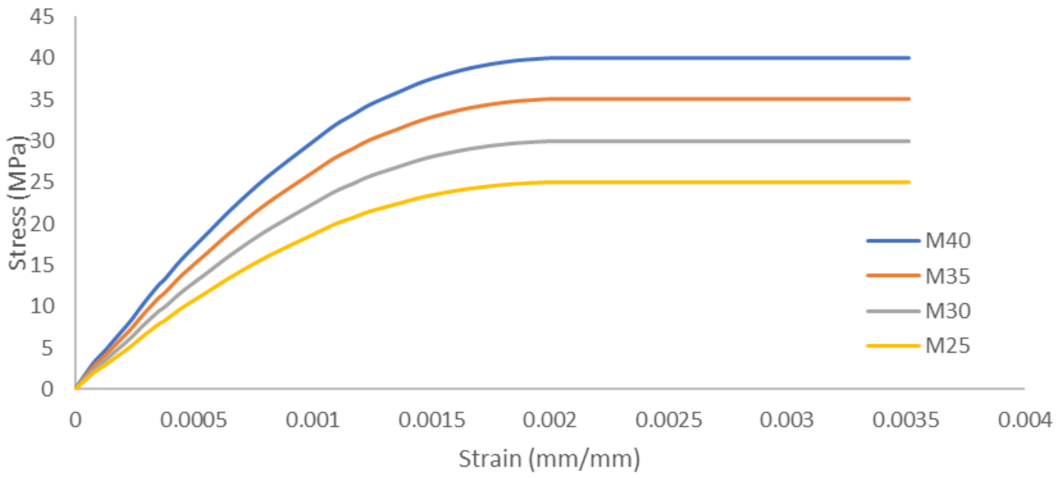


Figure 3.2 Stress-Strain curve for concrete

3.2.2 Structural steel material model

Structural steel sections including steel plates and shear connectors were modelled as elasto-plastic materials with strain hardening behaviour. 2 types of steels used in this study including ASTM A36 and ASTM A572. Stress-strain behaviour of steel is approximated to a bilinear isotropic hardening model as shown in figure 10.

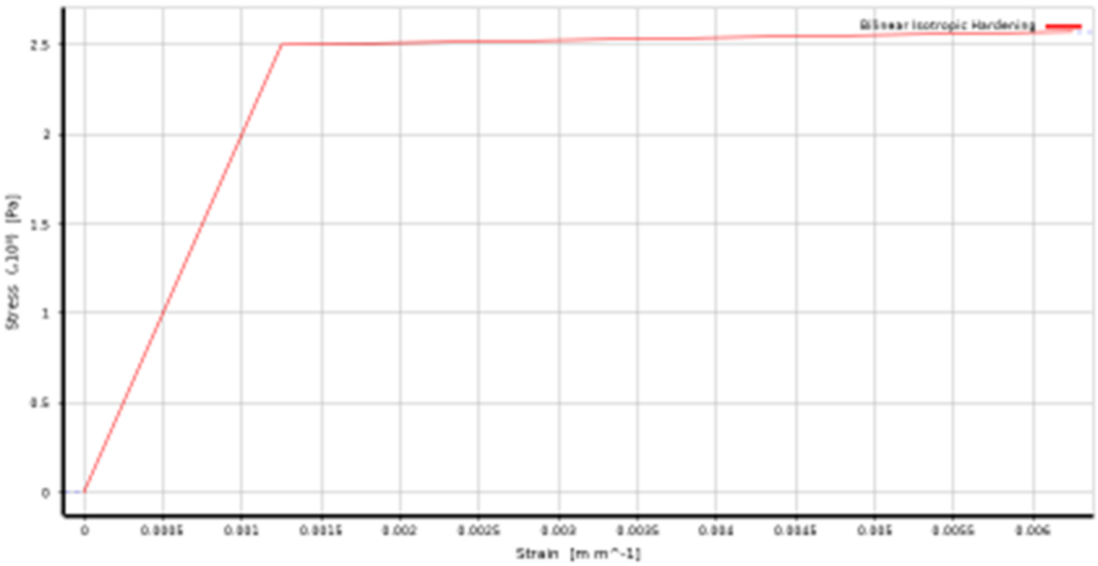


Figure 3.3 Stress-Strain curve for ASTM A36 steel

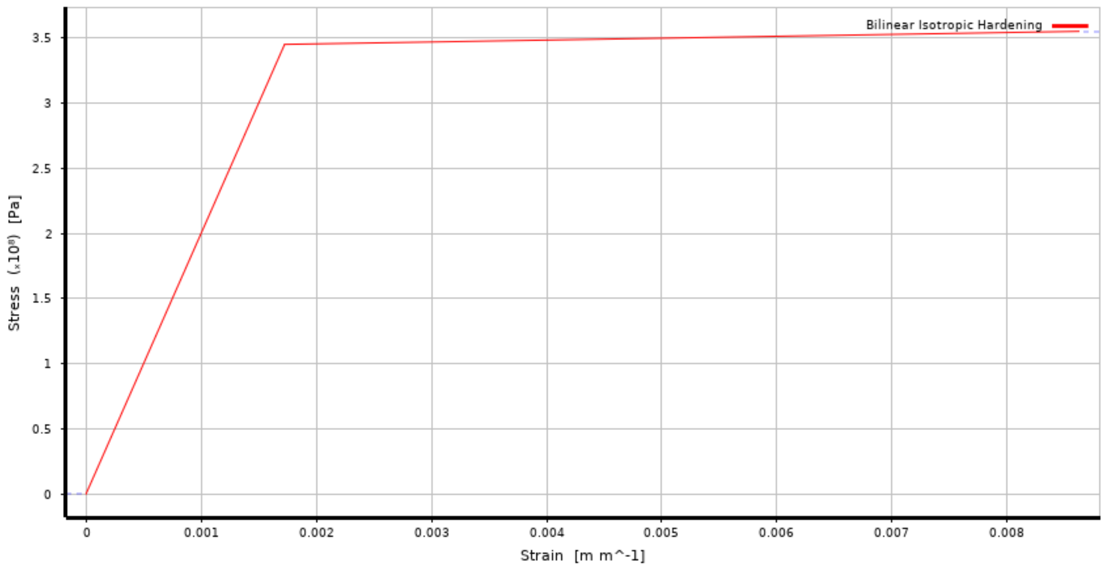


Figure 3.4 Stress-Strain curve for ASTM A572 steel

3.3 CONTACT SURFACE MODELLING

3.3.1 Shear Connectors and Concrete core

Contacts between shear connectors and concrete core were assumed as bonded in nature. It is almost true in the real scenario since the presence of interconnected hooks make the slip between core and connectors impossible.

3.3.2 Steel Plates and Concrete core

From experimental studies it was observed that the coefficient of friction between steel plate and concrete generally lies in between 0.6 and 0.7 (Rabbat and Russell 1985). In this study interface between steel plate and concrete was provided with a frictional contact having a coefficient of friction of 0.65.

3.3.3 Shear Connectors and Steel Plate

It was assumed that the connector was welded to the steel plate, and a bonded connection is established between steel plate and the shear connectors.

3.4 MODELLING OF GEOMETRY

3.4.1 J-hook Beam

SCSS beam using J-hook connectors was modelled as shown in figure 12. A total of 15 models were considered for the analysis purpose while varying different parameters such as connector diameter, steel plate thickness, spacing of shear connectors, core thickness, and strength of concrete and steel. Different combinations of values adopted for different parameters for each beam model is provided in table 2.

Table 3.1 Combinations for beam study

Model	**Connector diameter (mm)**	**Steel plate thickness (mm)**	**Spacing of shear connectors (mm)**	**core thickness (mm)**	**fc (MPa)**	**fy (MPa)**
BS1	10	5	300	300	40	250
BS2	10	5	300	300	35	250
BS3	10	5	300	300	30	250
BS4	10	5	300	300	25	250
BS5	10	3	300	300	40	250
BS6	10	8	300	300	40	250
BS7	10	10	300	300	40	250
BS8	10	5	300	250	40	250
BS9	10	5	300	350	40	250
BS10	10	5	300	400	40	250
BS11	10	5	300	500	40	250
BS12	10	5	200	300	40	250
BS13	10	5	350	300	40	250
BS14	10	5	400	300	40	250
BS15	10	5	500	300	40	250

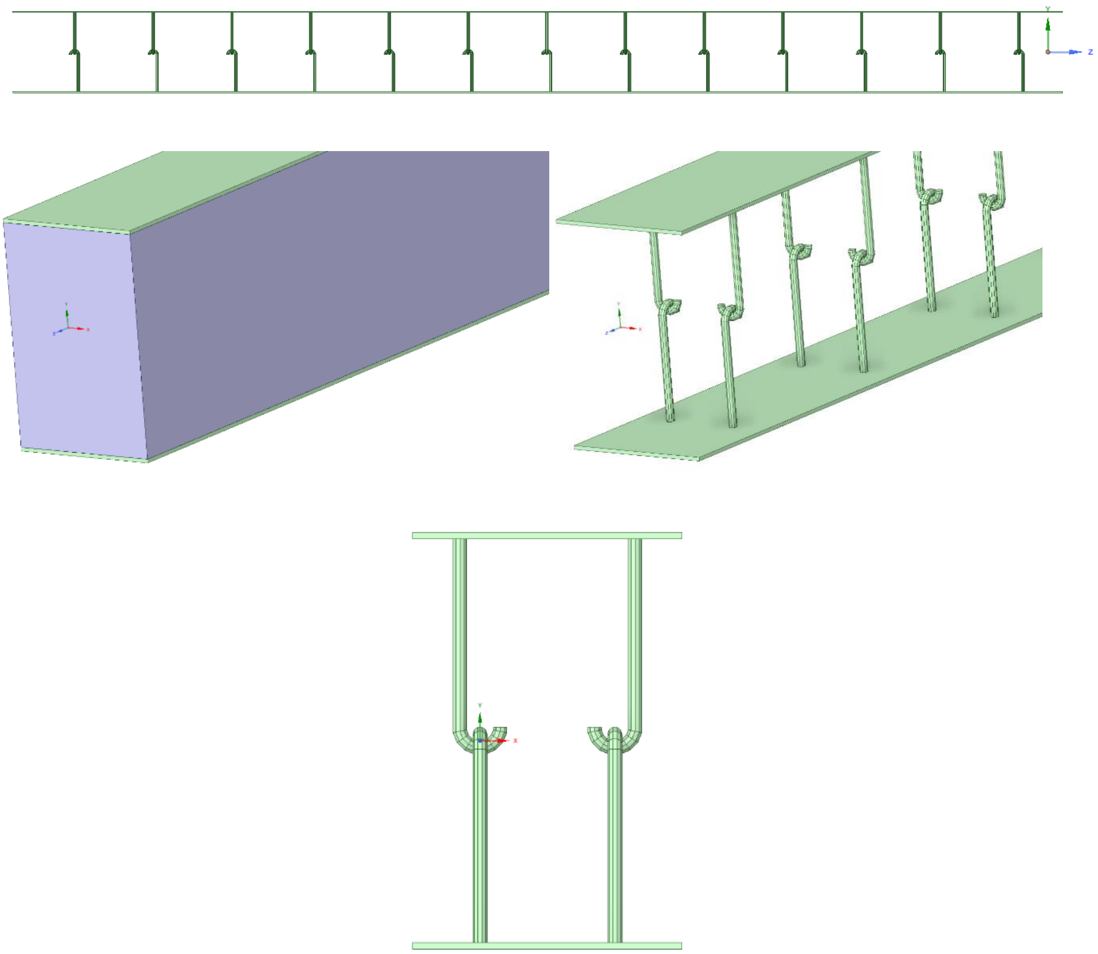


Figure 3.5 SCS beam modelled in Ansys

3.4.2 Modelling of Push-out Test

Specimen for push-out test was modelled as shown in figure 13. A total of 18 models were considered for the analysis purpose while varying different parameters such as connector diameter, steel plate thickness, core thickness, and strength of concrete and steel. Different combinations of values adopted for different parameters for each beam model is provided in table 3.

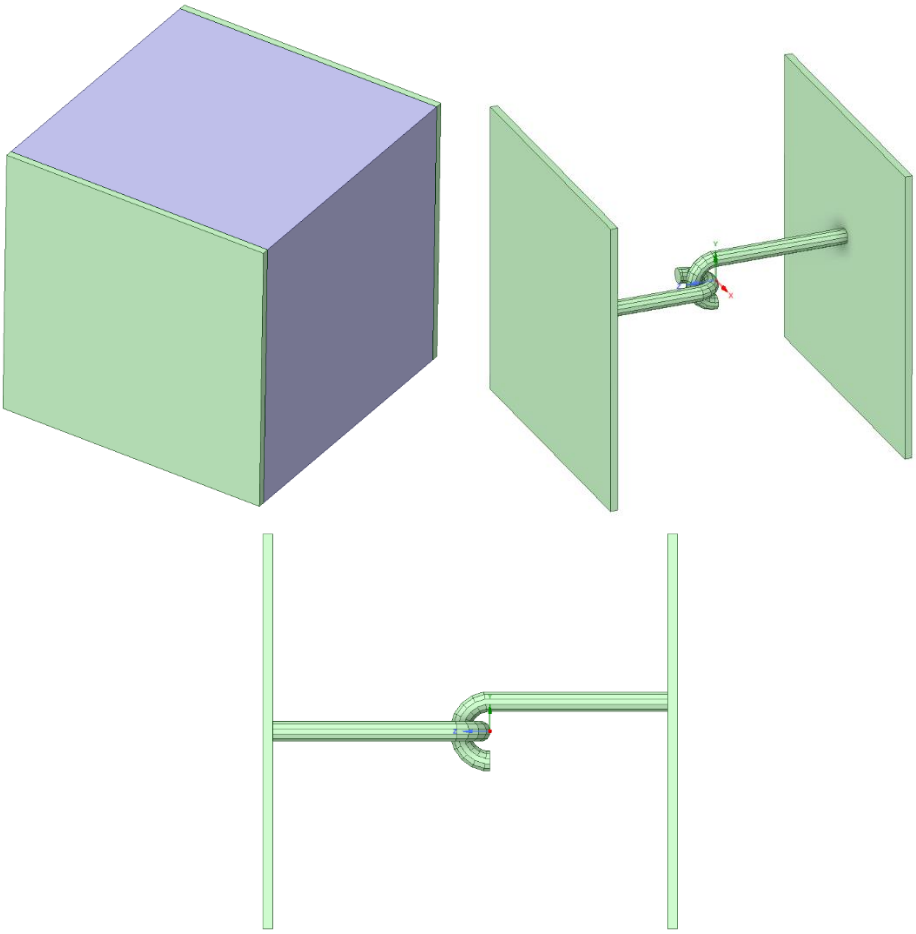


Figure 3.6 Pushout out test specimen modelled in Ansys

Table 3.2 Combinations for pushout test simulation

Model	Connectors diameter (mm)	Steel plate thickness (mm)	core thickness (mm)	fc (MPa)	fy (MPa)
PS1	6	5	200	40	250
PS2	8	5	200	40	250
PS3	10	5	200	40	250
PS4	12	5	200	40	250
PS5	10	5	200	35	250
PS6	10	5	200	30	250

PS7	10	5	200	25	250
PS8	10	3	200	40	250
PS9	10	8	200	40	250
PS10	10	10	200	40	250
PS11	10	5	150	40	250
PS12	10	5	250	40	250
PS13	10	5	300	40	250
PS14	10	5	400	40	250
PS15	10	3	200	40	350
PS16	10	5	200	40	350
PS17	10	8	200	40	350
PS18	10	10	200	40	350

3.5 PARAMETRIC STUDY USING FINITE ELEMENT ANALYSIS

Geometric models developed as per table 3 were meshed and boundary conditions are applied for simulating the test conditions.

3.5.1 J-hook Beam

A generalized representation of simulation of beam bending test by midpoint loading done using ANSYS software is given in figure 14.

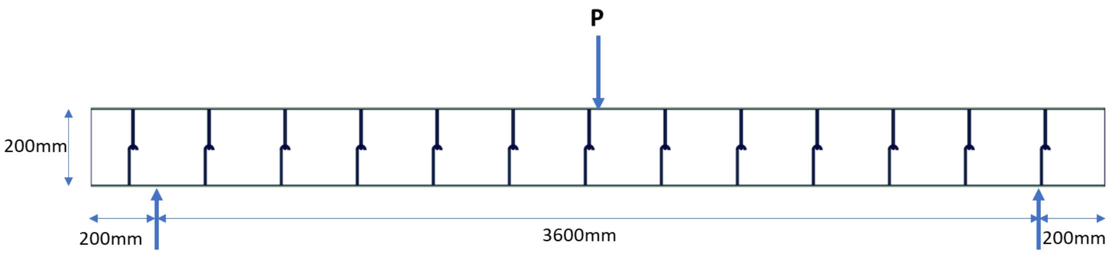


Figure 3.7 Diagram for mid-point beam bending test

3.5.2 Push-out Test

A generalized representation of push-out test simulation done using ANSYS software is given in figure 15.

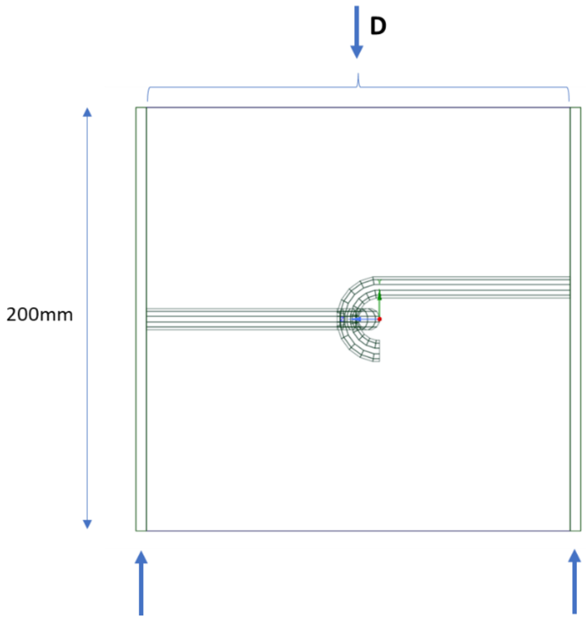


Figure 3.8 Diagram for push out test

CHAPTER 4

SOFTWARE VALIDATION

For the validation of software an experimental study conducted by Xie et al. (2007) was simulated using ANSYS software and results were compared. Xie et al. (2007) conducted static tests on SCSS beams with bi-steel connectors. Details of the beam specimen is given as follows.

t_c = 11.93 mm	f_{yp} = 384 N/mm^2
t_t = 6.2 mm	f_{up} = 507 N/mm^2
h_c = 200 mm	f_{yb} = 541 N/mm^2
s_x =300 mm	f_{ub} = 566 N/mm^2
L = 1800 mm	f_{cu} = 58 N/mm^2

Test setup was simulated in ANSYS software as shown in figure 16. One end is provided with roller support and the other end is provided with hinged support, same as that in the experimental setup. Figure 18 shows the comparison of force displacement relations corresponds to the deflection at mid-point from the finite element analysis to that from the experimental results obtained by Xie et al. (2007). Deflected shape of the beam after loading is given in figure 17.

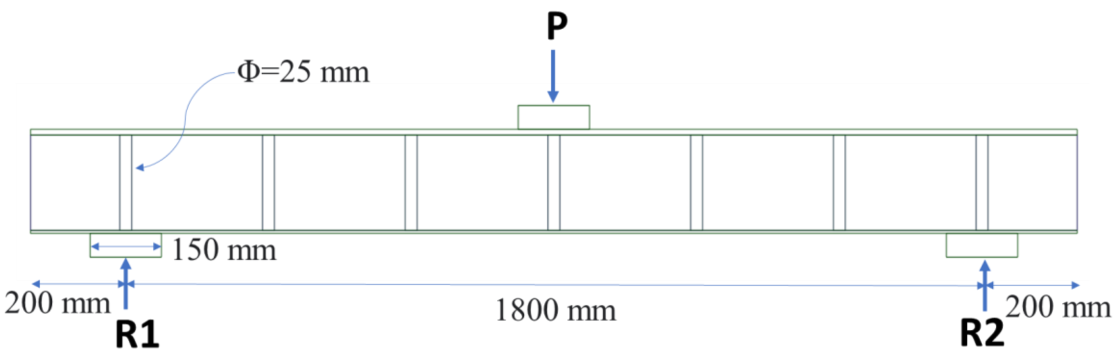


Figure 4.1 Testing of SCSS beam as per Xie et al. (2007)

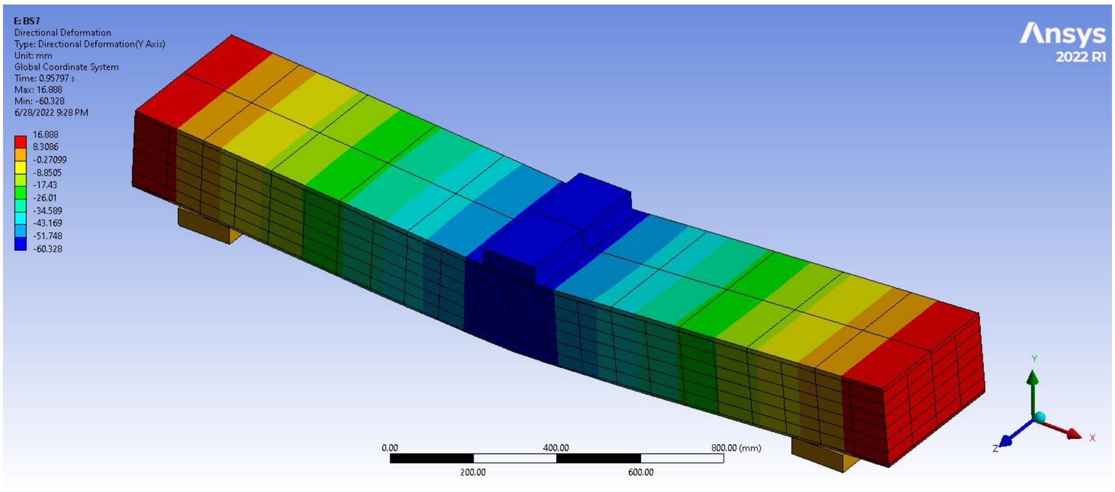


Figure 4.2 Deflection as per numerical simulation

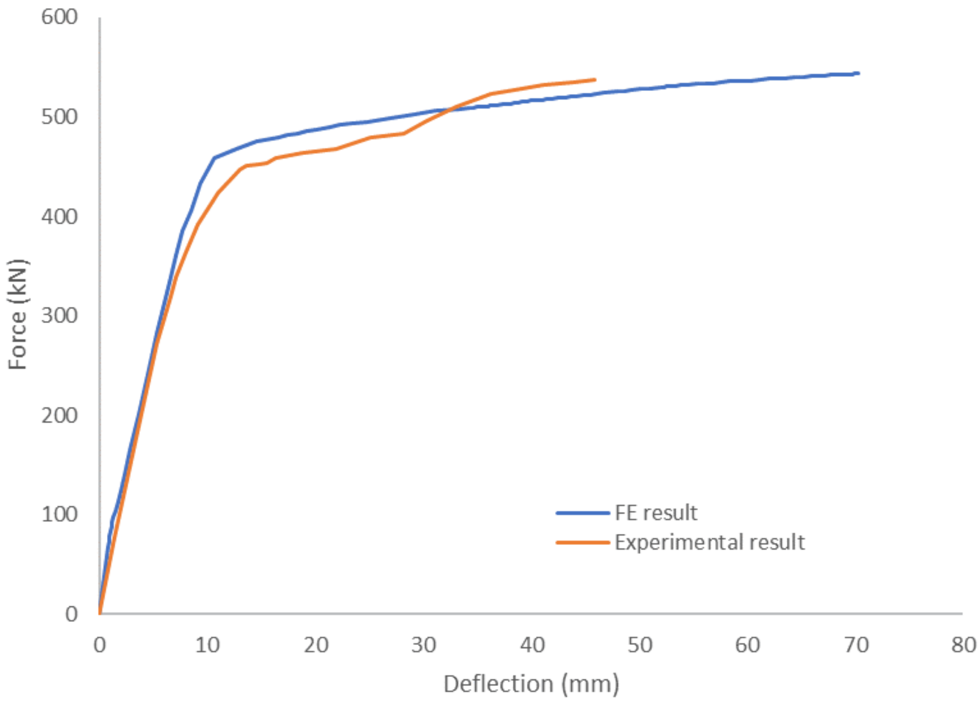


Figure 4.3 Comparison of force-deflection curves of SCSS beams

Difference incurred while comparing the FE results with experimental results were numerically calculated by comparing the areas under the curves upto the failure point on experimental results.

Area under the graph obtained by experimental analysis = 18870 units

Area under the graph obtained by FE analysis = 20433 units

Percentage difference = 8.28 %

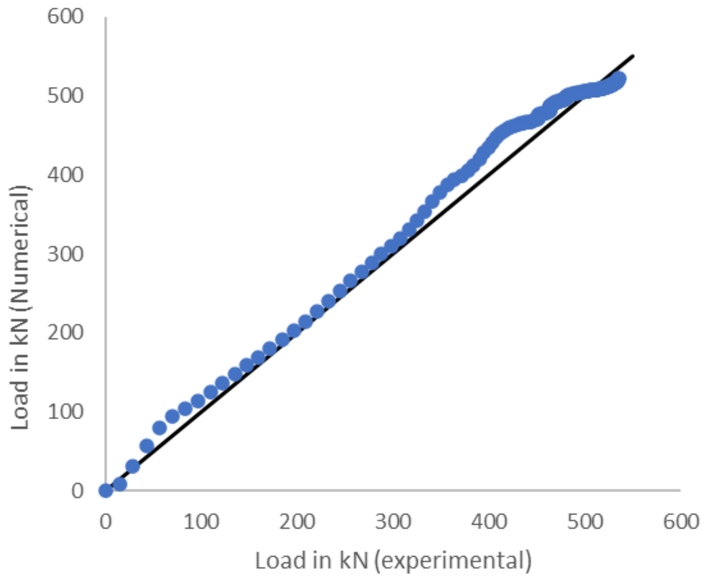


Figure 4.4 Parity curve of load values from experimental and numerical analysis

Comparison of force reactions observed through experimental study and numerical study are represented through a parity curve in figure 19. While comparing with the experimental results, it was found that FE results were within the acceptable limits. Hence, software was considered as validated.

CHAPTER 5

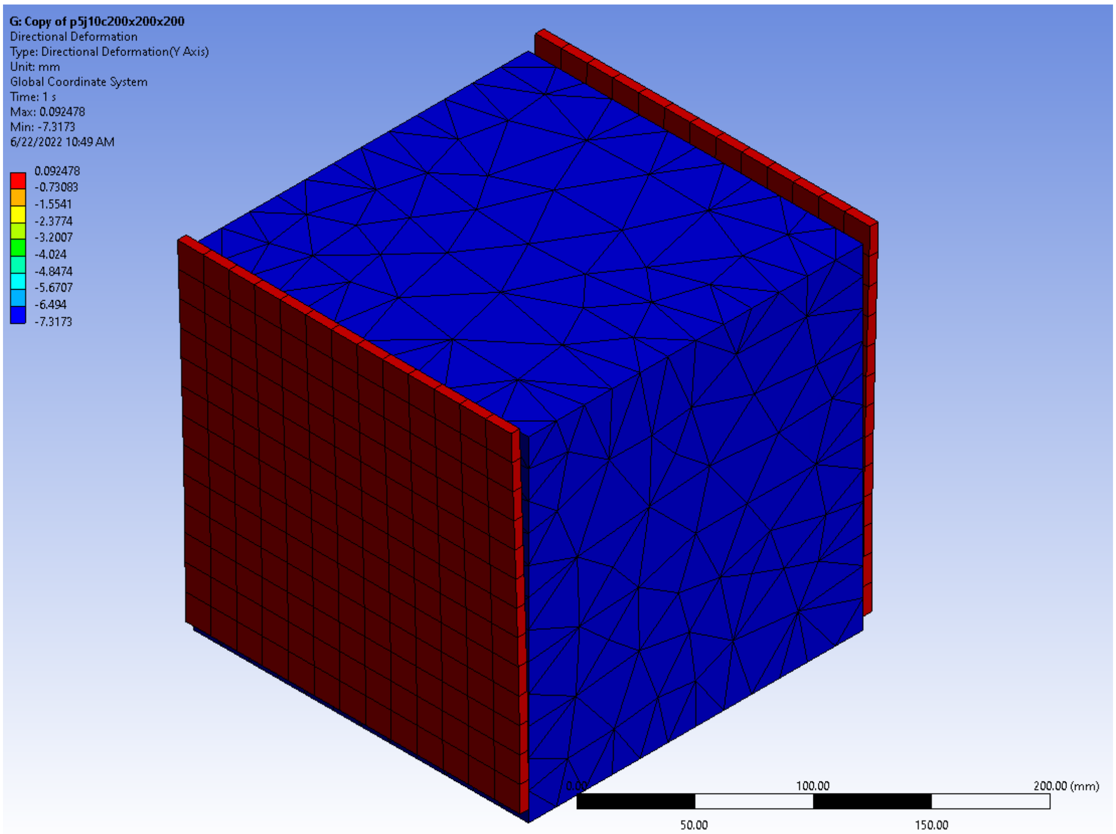
RESULTS AND DISCUSSIONS

5.1 INTRODUCTION

Analysis of finite element models of SCSS beams and push-out test could primarily yield the force- displacement behaviour of SCSS beams and force slip behaviour of the interface while subjected to push-out test. Results obtained through this study and their subsequent inferences are discussed below.

5.2 PUSH-OUT TEST

Force-slip behaviour of the steel plate-concrete core interface is the primary result of a pushout test. Pushout test was simulated as explained in section 3.5.2. deflected view of PS3 after loading is shown in figure 20.



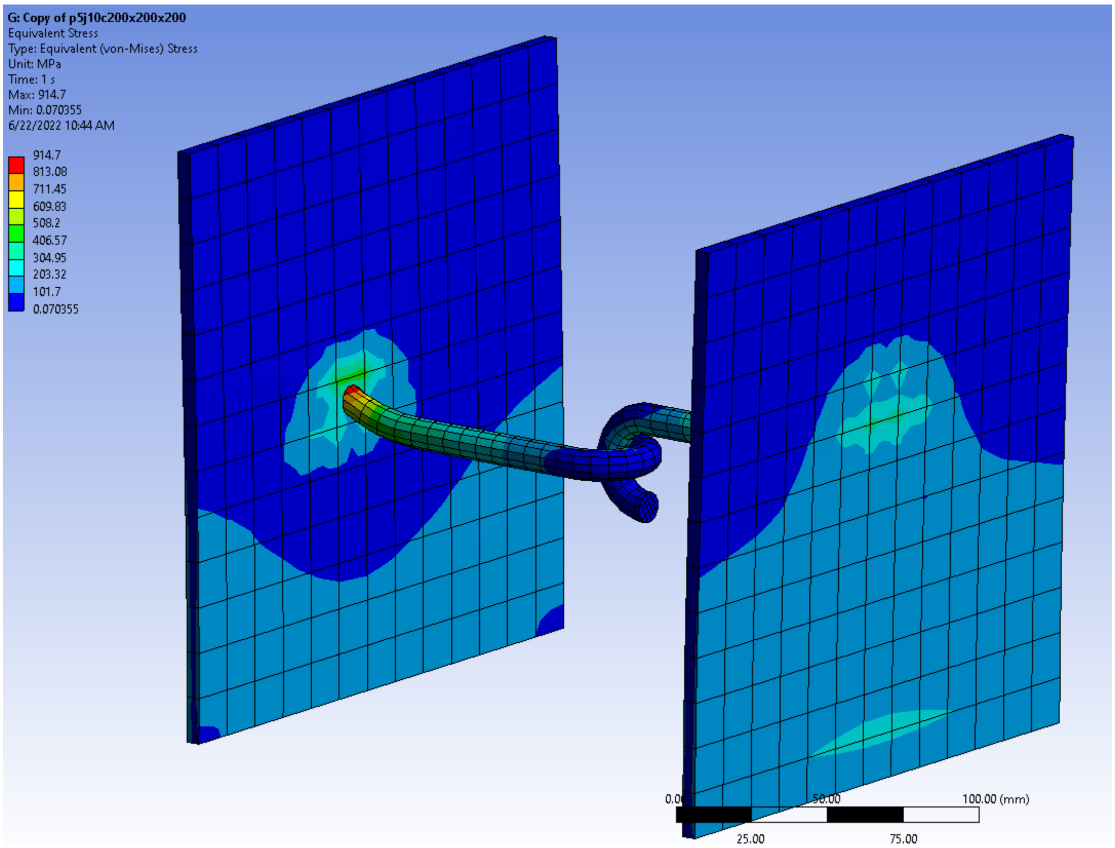


Figure 5.1 Model after Pushout test

From figure 20 it was observed that, while the load was applied, contact region between plates and connectors experiences maximum stress. It is due to the large shear force acting at the interface upon pushing out the core from the plates. Results obtained from the parametric studies is given as follows.

5.2.1 Effect of Plate Thickness

When the steel plate thickness is increased from 3mm to 10mm, a slight decrease in bond slip was observed. This behaviour can be attributed to the improved stiffness of the steel plate upon thickening. It was also observed that the bond slip could be reduced by improving the grade of steel.

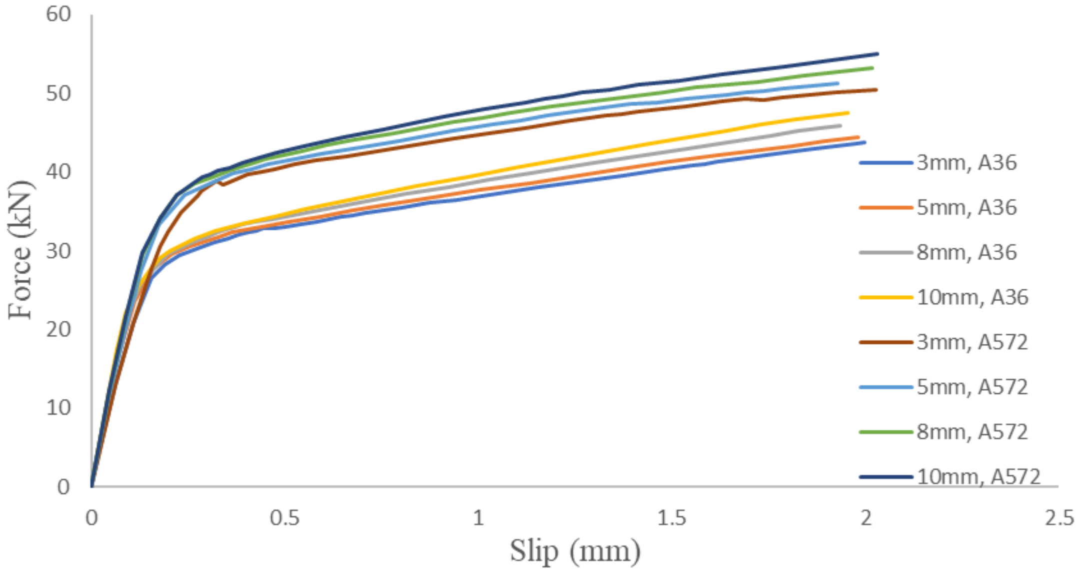


Figure 5.2 Load-slip behaviour of SCSS structures with J-hook connectors while varying plate thickness

5.2.2 Effect of diameter of J-hook connectors

Bond-slip between the plates and core were observed to be highly dependent on the diameter of the connector. While varying the diameters clearly distinguishable yield plateaus were generated as shown in figure 22 It could mainly attributed to two factors including increase in contact area, and improved strength of connector. When the diameter of connector was increased, it could avail more contact area with the plate and concrete for bonding. Similiarly, increase in diameter was also resulted in increased cross-sectional area of the connector, and thereby increased its shear strength. It was also observed that the improvement in load carrying capacity was almost linear with increase in diameter as shown in figure 23.

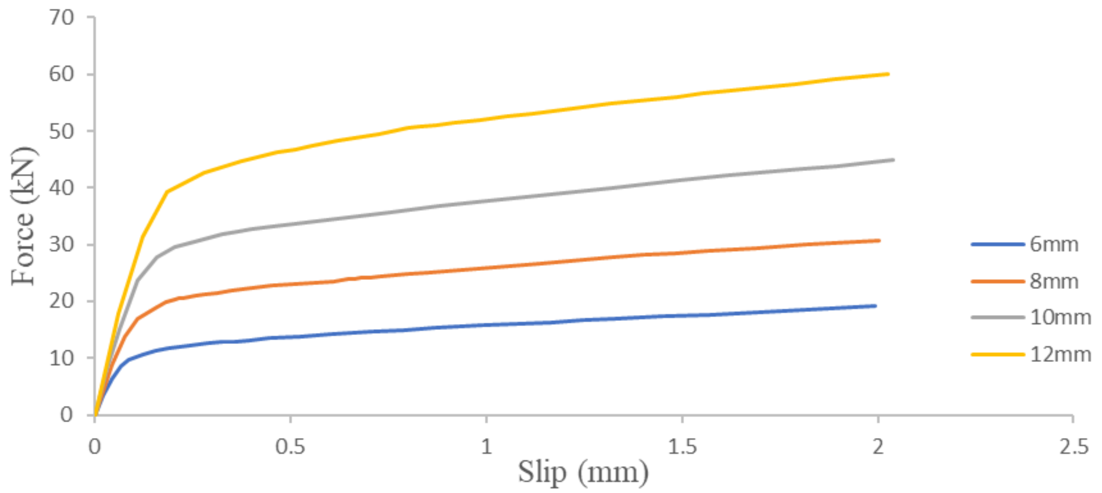


Figure 5.3 Load-slip behaviour of SCSS structures with J-hook connectors while varying diameter

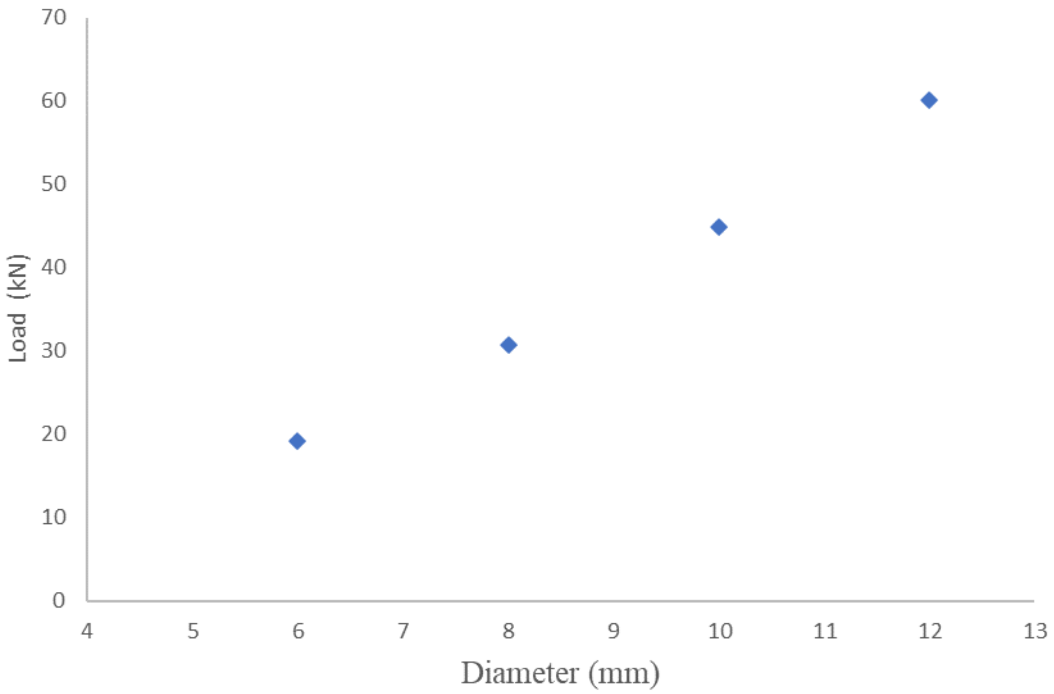


Figure 5.4 Effect of diameter over the load-carrying capacity

5.2.3 Effect of core thickness

Figure 24 shows that the core thickness did not have much influence over the bond slip while conducting pushout test. It was attributed to the assumption that the connectors and core are perfectly bonded together. Since there was no separation between them, despite the value of core thickness, all the forces applied over the core were transferred to the interface directly. This behaviour was also attributed to the fact that, the test was conducted in a strain-controlled manner. Since it was strain controlled over the face of the core, the slip had occurred to the core as a whole instead of allowing any bending of the core.

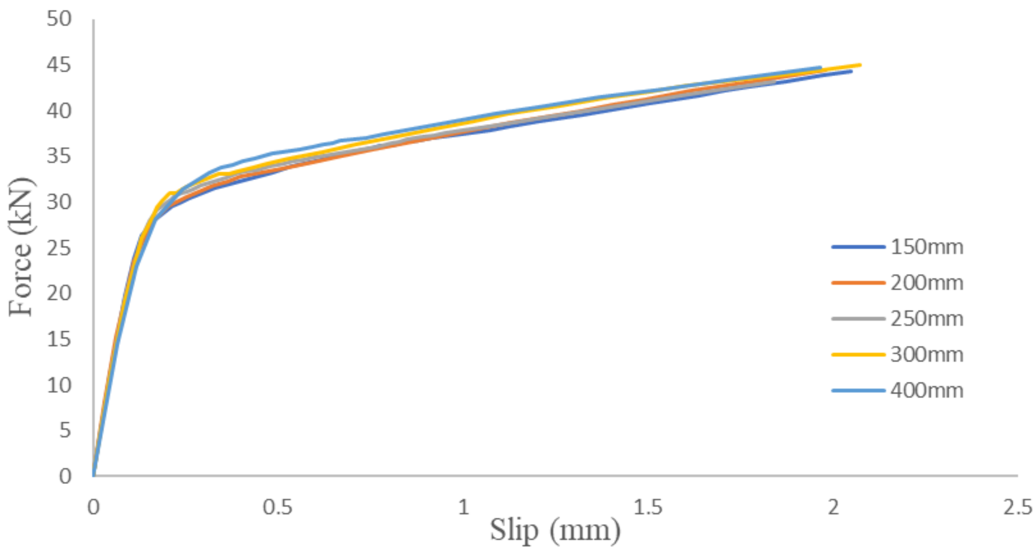


Figure 5.5 Load-slip behaviour of SCSS structures with J-hook connectors while varying core thickness

5.2.4 Effect of concrete strength

Effect of concrete strength over the bond-slip is shown in figure 25 from the figure it was evident that the bond-slip behaviour was clearly dependent over the strength of concrete. When the concrete strength was improved from 25MPa to 40MPa corresponding to a slip of 0.5mm, the resistance was found to be increasing by about 25%. It was due to the fact that when higher grades of concrete were used it could provide more anchorage and support to the shear connectors against shear deformation.

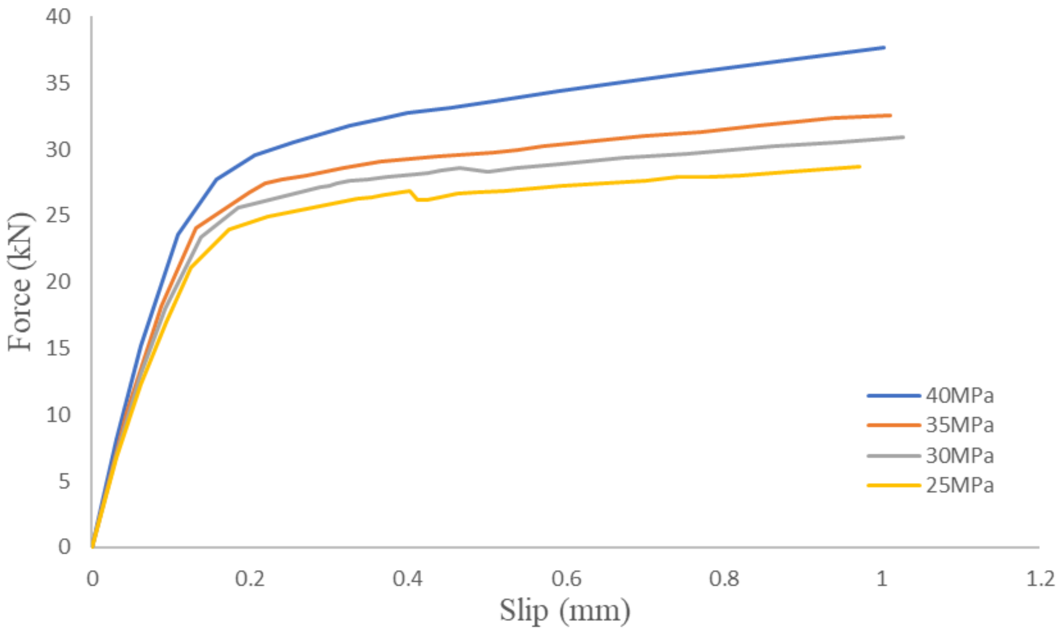


Figure 5.6 Load-slip behaviour of SCSS structures with J-hook connectors while varying concrete strength

5.3 MID-POINT LOADING OF SCSS BEAM

Beam specimens detailed in table 2 were analysed as described in section 3.4.1. Deflected view of the beam models is given in figure 26.

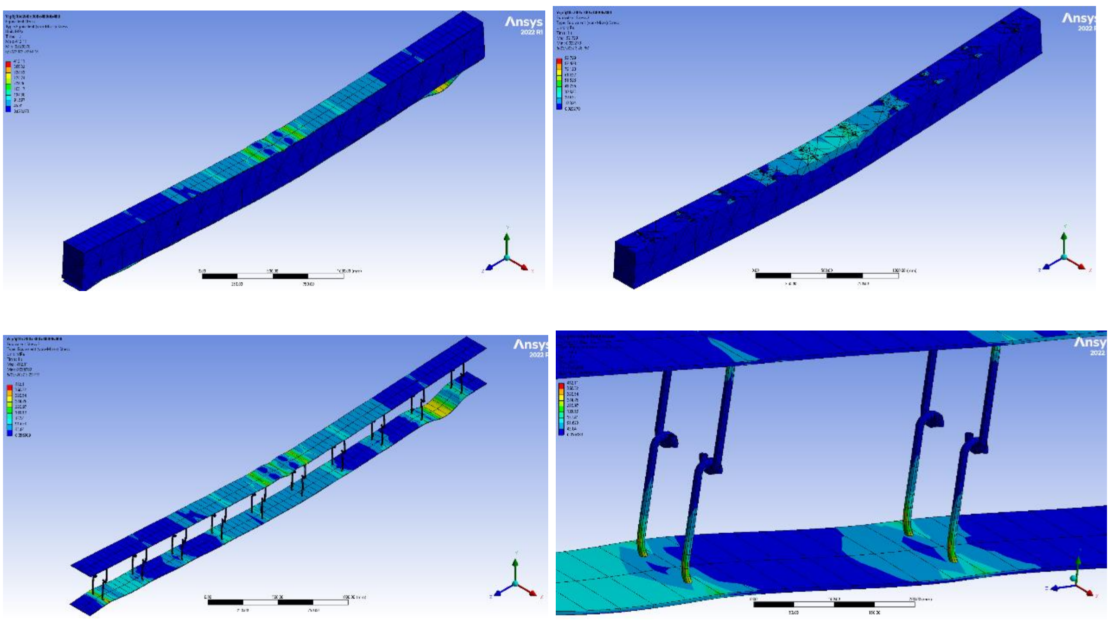


Figure 5.7 SCSS beam after bending

Results obtained from the analysis primarily includes the force-displacement relations. Results obtained through this study and their subsequent inferences are discussed below.

5.3.1 Comparison with steel plate

Performance of SCSS beam was compared with steel plates of different thicknesses as shown in Figure 27. It was found that stiffness of BS12 is much more than that of the steel plate alone. So, it could imply that the insertion of a concrete core could enhance the serviceability criteria also by undergoing lesser deformation while carrying the loads.

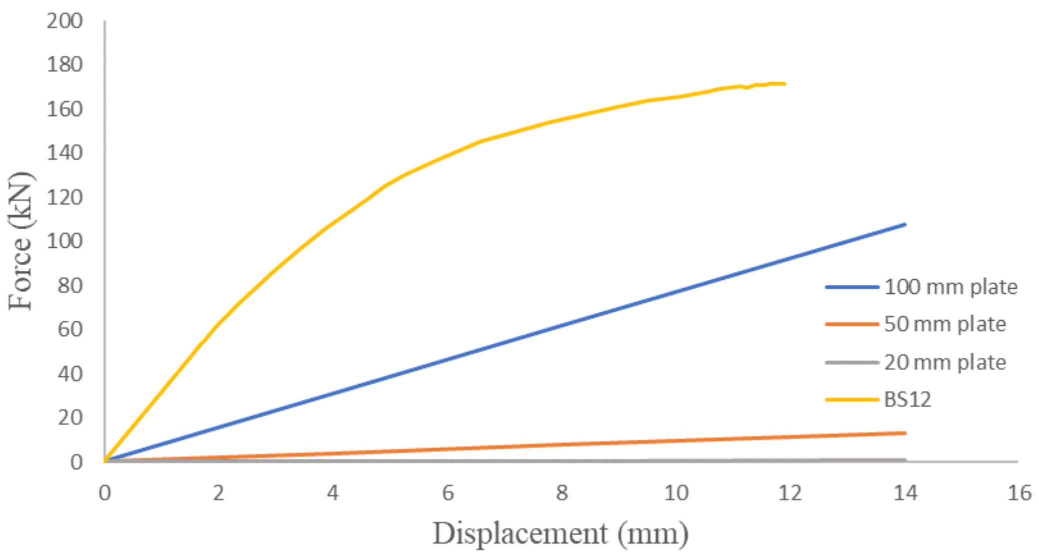


Figure 5.8 Force-displacement behaviour of SCSS beams Vs Steel plates

Overall stiffness value of the SCSS beam was compared with that of steel plates when subjected to 10mm deformation at mid-point is shown in figure 28. It was found that the beam model BS12, which is having a total steel plate thickness of 10mm could provide a stiffness of 260 times that of the 20mm thick steel plate. Even after the steel plate thickness was increased to 50mm and 100 mm, stiffness of the BS12 model was observed to be higher by a factor of 18 times and 2 times respectively.

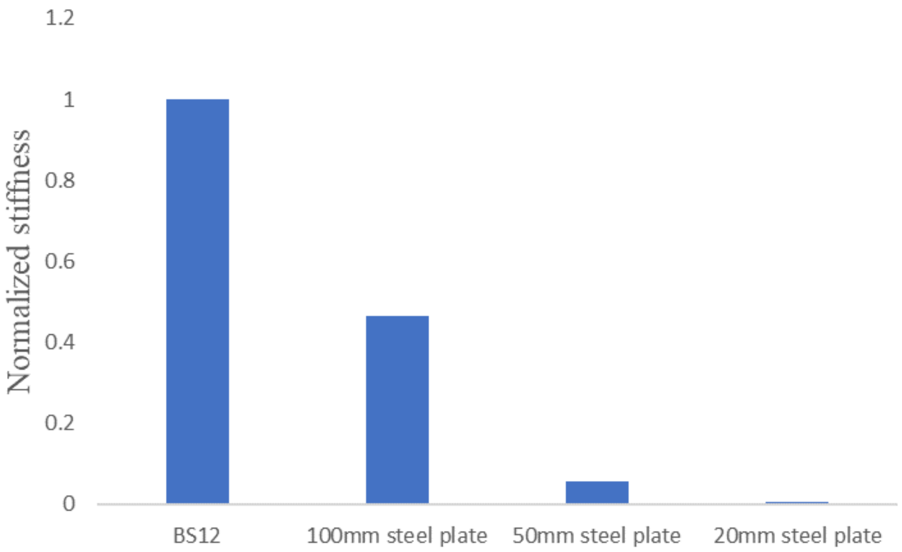


Figure 5.9 Effective stiffness at 10mm deflection for SCSS beams and Steel plates

5.3.2 Effect of plate thickness

Figure 29 shows the force displacement relationship for beams with varying plate thicknesses. It was observed that, when the plate thickness was increased it improved the force-displacement behaviour (and ultimate strength also) of the beam as it increased the overall stiffness of the structure. When the plate thickness was increased from 3mm to 10mm it was found that the strength was improved by more than 3 times.

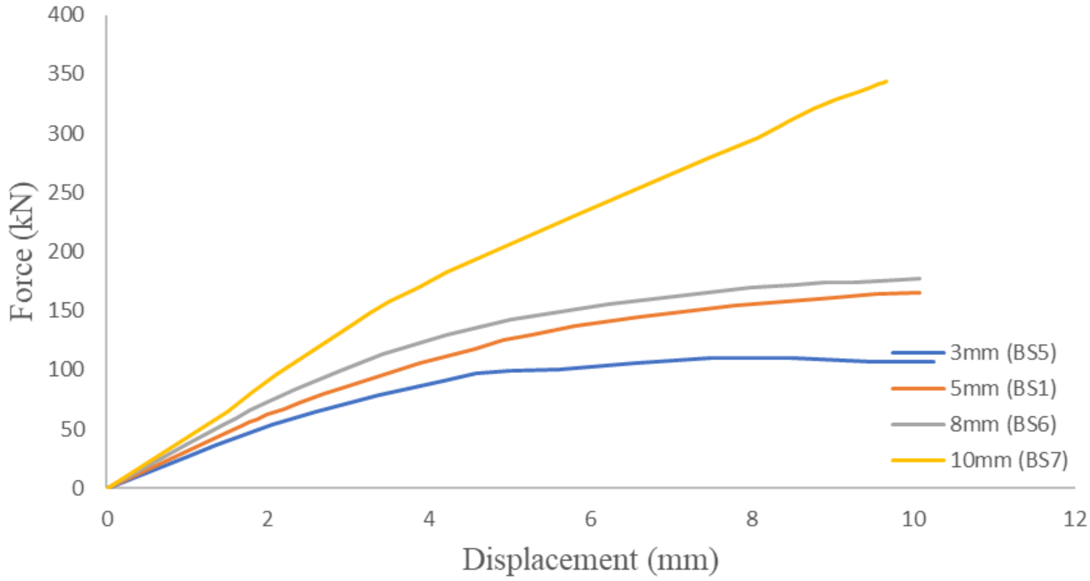


Figure 5.10 Force-displacement behaviour of SCSS structures with J-hook connectors while varying spacing of connectors

5.3.3 Effect of spacing of connectors

Understanding about the spacing of shear connectors to be provided in the beam demands sufficient importance as it affects the overall performance of the structure. Particularly, the extent of compositing happening between the plates and the core is highly dependent over the spacing of shear connectors. When spacing is increased from 200 mm to 500mm the ultimate strength of the beam was found to be reduced to half. It was also observed that when the spacing was reduced to half (ie. From 400mm to 200mm) ultimate strength of the beam had improved by over 70%. Closer spacing made the beam behave in a more monolithic manner and thereby improved the composite action between the individual components. Effect spacing over the ultimate strength of SCSS beam is shown in figure 30.

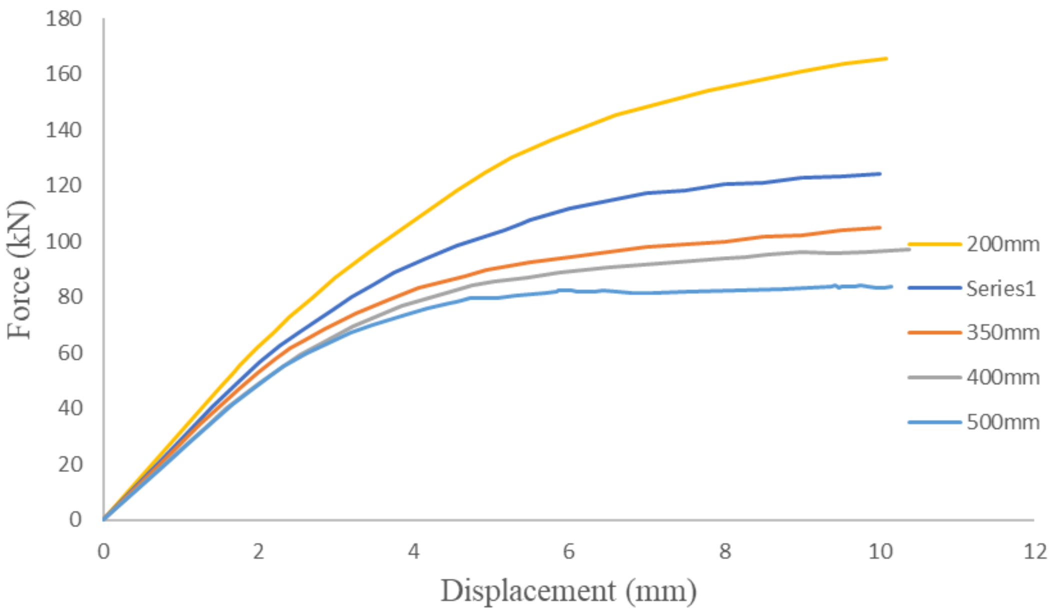


Figure 5.11 Force-displacement behaviour of SCSS structures with J-hook connectors while varying spacing of connectors

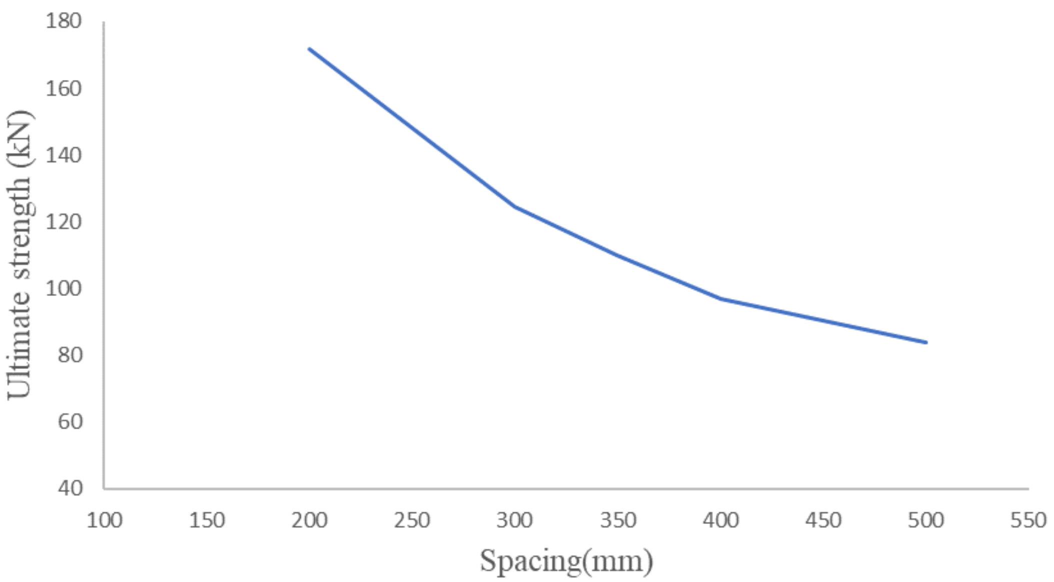


Figure 5.12 Ultimate strength Vs spacing

Figure 31 shows the plot between spacing of shear connectors and degree of composite action realized in the structure based on the obtained force displacement relations. From the graph it was clearly observed that the effectiveness of the composite structure is highly dependent over the spacing of the shear connectors. When spacing was increased from 200mm to 400 mm and 500mm, degree of composite action was reduced by14% and 20% respectively.

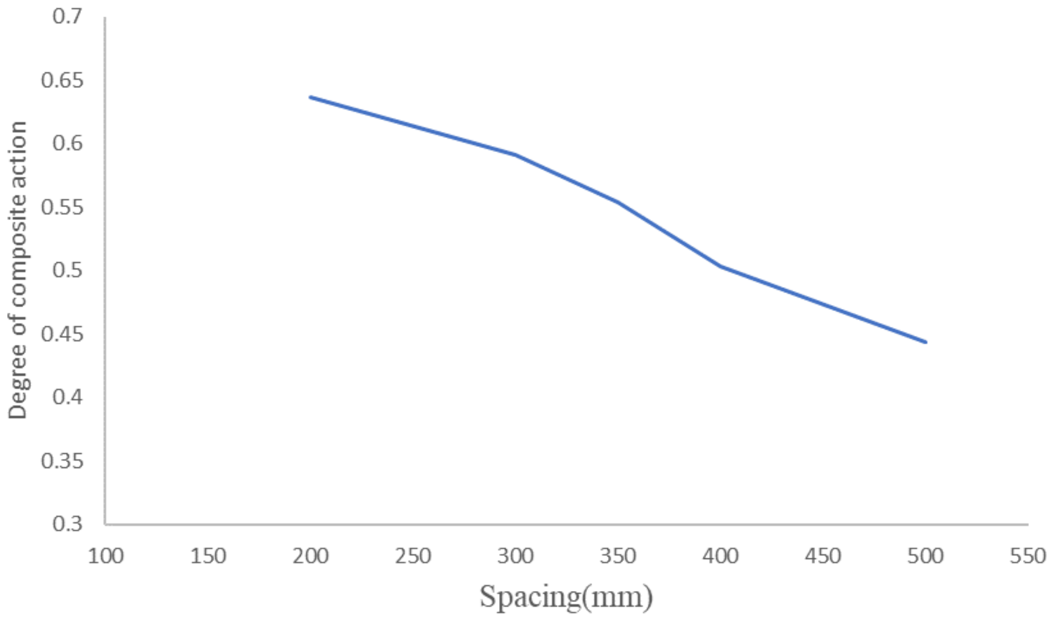


Figure 5.13 Degree of composite action Vs spacing

5.3.4 Effect of concrete strength

Figure 33 shows the effect of concrete strength over the performance of SCSS beams subjected to mid-point loading. From the analysis it was observed that for each 5MPa rise in concrete strength, about 5% rise in overall strength was observed. It implies that, compared to that of RCC beams, the effect of concrete strength over the overall strength of beam is lesser. So, for an SCSS beam concrete core is more important in terms of providing anchorage to connectors and filling the portion between the plates rather than contributing to the strength of the beam.

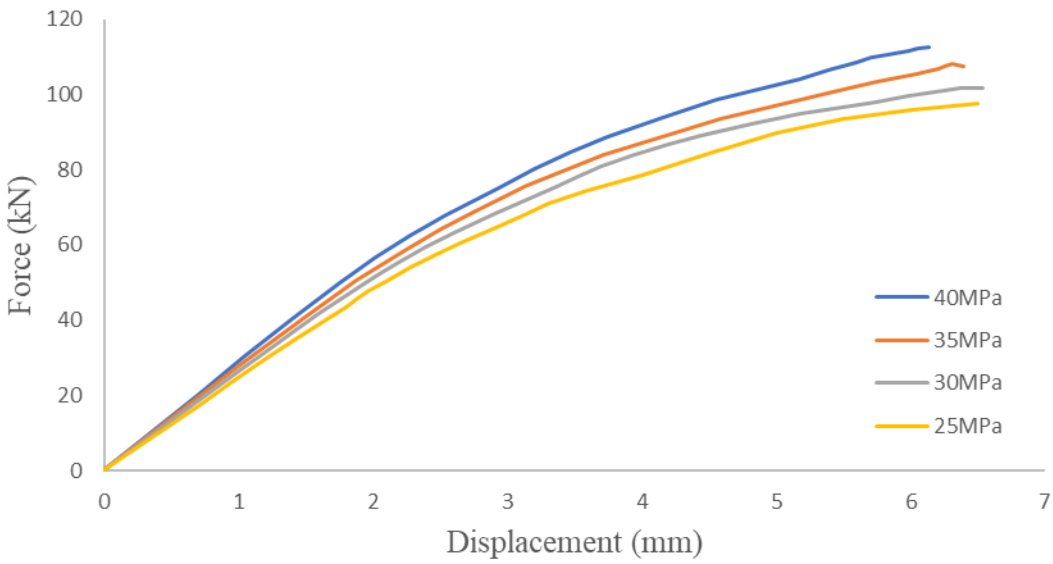


Figure 5.14 Force-displacement behaviour of SCSS structures with J-hook connectors while varying concrete strength

5.3.5 Effect of core thickness

Figure 34 shows the influence of core thickness over the strength of SCSS beams. From the analysis it was observed that increase in core thickness improves the strength of beam drastically.

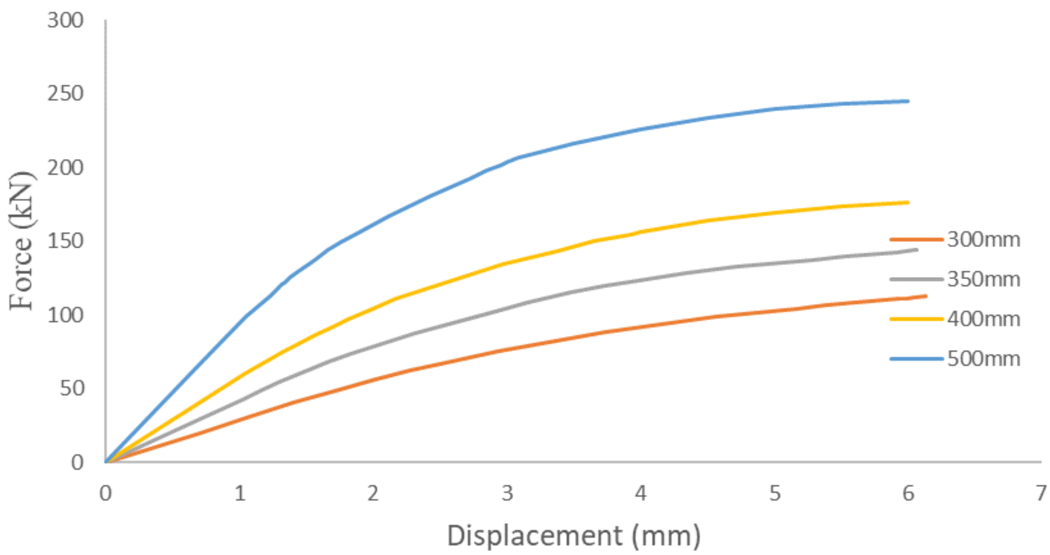


Figure 5.15 Force-displacement behaviour of SCSS structures with J-hook connectors while varying core thickness

5.4 SUMMARY

From the analysis it was found that, spacing of shear connectors was the most important parameter to be considered while designing an SCSS beam. Degree of composite action and ultimate strength of SCSS beam was found to be highly dependent over the spacing of shear connectors. Another important parameter identified was the thickness of steel plate. While analysing the beam it was found that increase in plate thickness improved the load carrying capacity of the structure. But this trend was almost absent while analysing the pushout test results. It indicated that the increased plate thickness improves the strength without improving interfacial slip resistance.

Diameter of shear connector was found to improve the bond slip behaviour effectively, since connectors with higher diameters could increase the shear resistance. Another important parameter that improved the strength of beam was the grade of concrete. Increased strength of concrete could improve the overall load carrying capacity of beam and also improved the slip resistance.

CHAPTER 6

EMPIRICAL FORMULATION

6.1 INTRODUCTION

Load-slip behaviour of SCSS structures were obtained through numerical simulation of pushout tests. Based on the results, an empirical formulation for the load-slip model was derived as follows.

6.2 FORCE-SLIP BEHAVIOUR

From the literatures, it was found that the force-slip behaviour of SCSS structures were approximated to a rectangular hyperbola. Results of this particular study also shown that the force-slip behaviour of SCSS structures follow a rectangular hyperbolic path. For defining the relationship, a modified equation for rectangular hyperbola is used as given in eqn (1).

$$P = \frac{a\delta}{1+b\delta} \qquad \text{............Eqn.(1)}$$

Load-slip curves obtained for different models were fitted through non-linear least square fitting by the help of Sigma Plot 14.5. Values of coefficients ‘a’ and ‘b’ were both linearly and non-linearly related to different parameters.

6.2.1 Derivation of Linear Relationship of Parameters

Linear relationship of different parameters with the coefficients of rectangular hyperbolic model was derived based on the general linear equation given in eqn (2) & (3).

$$a = mx + p \qquad \text{............Eqn.(2)}$$

$$b = nx + q \qquad \text{............Eqn.(3)}$$

Where, ‘x’ is the value of parameters in units specified in table 4. Estimated values for the coefficients ‘m’, ‘n’, ‘c’, and ‘d’ are given in table 4.

Table 6.1 Derivation of Linear Relationship of Parameters

Parameter	a		b	
	m	p	n	q
d (mm)	48.963	-36.83	-1.014	21.639
t (mm)	11.691	382.045	0.229	9.729
f_{ck} (MPa)	2.495	370.26	-0.132	17.322
f_y (MPa)	-0.057	443.04	-0.027	18.098

From the estimated coefficients, a generalized linear empirical relation for ‘a’ and ‘b’ incorporating the parameters ‘d’, ‘t’, ‘f_{ck}’, and ‘f_y’ were derived as given in eqn (4) & (5).

$$a = 2.495\ f_{ck} + 48.963\ d + 11.691\ t - 0.057\ f_y - 178.472 \qquad \text{.............Eqn.(4)}$$

$$b = -\ 0.132\ f_{ck} - 1.014\ d + 0.229\ t - 0.027\ f_y + 32.466 \qquad \text{.............Eqn.(5)}$$

6.2.2 Derivation of Non-linear Relationship of Parameters

Non-linear relationship between the parameters and the coefficient of rectangular hyperbolic model were derived based on eqn (6) & (7).

$$a = \alpha\ x^s \qquad \text{.............Eqn.(6)}$$

$$b = \beta\ x^t \qquad \text{.............Eqn.(7)}$$

Eqn (6) & (7) were modified to logarithmic terms as in eqn (8) & (9).

$$\ln a = \ln \alpha + s \ln x \qquad \text{.............Eqn.(8)}$$

$$\ln b = \ln \beta + t \ln x \qquad \text{.............Eqn.(9)}$$

Estimated values for the coefficients ‘s’, ‘ln α’, ‘t’, and ‘ln β’ are given in table 5.

Table 6.2 Derivation of Non-linear Relationship of Parameters

Parameter	a		b	
	s	ln α	t	ln β
d (mm)	1.14	2.672	-0.704	1.082
t (mm)	0.159	2.657	0.130	1.048
fck (MPa)	0.184	2.649	0.324	1.040
fy (MPa)	-0.037	2.66	-0.781	1.055

From the estimated coefficients, a generalized non-linear empirical relation for ‘a’ and ‘b’ incorporating the parameters ‘d’, ‘t’, ‘f_{ck}’, and ‘f_y’ were derived as given in eqn (10) &(11)

$$a = 15.952\,\frac{fck^{0.184}\ d^{1.14}\ t^{0.159}}{fy^{0.037}} \qquad \text{............Eqn.(10)}$$

$$b = 1119.058\,\frac{fck^{0.324}\ \ t^{0.13}}{d^{0.704}\ fy^{0.781}} \qquad \text{............Eqn.(11)}$$

Load-slip behaviour of pushout specimen PS3 was compared with the empirical models developed and shown in figure 35 From the comparison it was concluded that both the suggested empirical relations give satisfactory results.

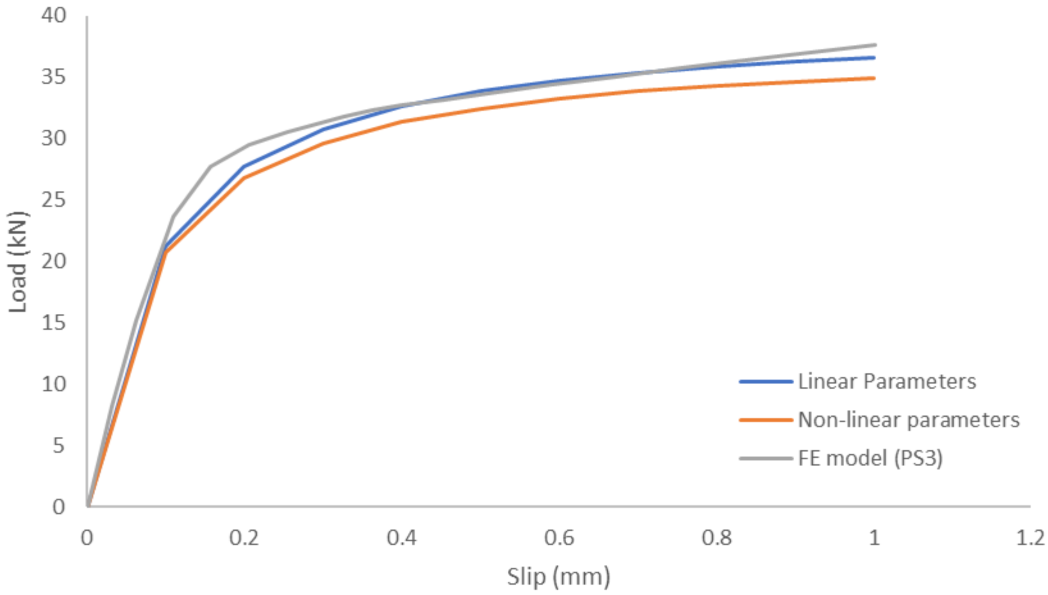


Figure 6.1 Comparison of load-slip behaviours from numeric analysis and empirical relations

6.3 SUMMARY

Based on the finite element model, two empirical formulae for load-slip model of SCSS structures including the linear relationship between the parameters of SCSS structures and the coefficients of rectangular hyperbolic model, and the non-linear relation between them were suggested. When compared those with the finite element results it was found that both of the relations as satisfactorily accurate.

CHAPTER 7

CONCLUSIONS

7.1 INTRODUCTION

SCSS structures are very effective in carrying large loads without undergoing much deformation when compared to the steel structures. In this study a numerical analysis of models of SCSS structures while varying important parameters were carried out and an empirical model for force slip behaviour was proposed. This chapter describes the major findings from the study and scope for future studies in this area.

7.2 MAJOR FINDINGS

From the studies conducted following conclusions were derived

- J-hooks can provide some residual shear and pull-out resistance upon concrete cracking, which cannot be achieved with headed studs.
- Failure due to bond slip can occur in the structure if sufficient shear connectors are not provided.
- Important parameters to be considered while analysing the behaviour of SCSS structures while loading include diameter of shear connectors, core thickness, grade of concrete and steel, thickness of steel plate, and spacing of shear connectors.
- While conducting pushout test, core thickness has no effect in bond-slip while plate thickness has only a slight positive effect over the bond-slip.
- Resistance to bond-slip increases by about 25% When the concrete strength improves from 25MPa to 40MPa.
- When the plate thickness increases from 3 mm to 10 mm ultimate strength of SCSS beam improves by more than 3 times.
- When the spacing was reduces to half (from 400mm to 200mm) ultimate strength of the beam had improves by over 70% and when spacing increases from 200mm to 400 mm and 500mm, degree of composite action reduces by14% and 20% respectively.
- For each 5MPa rise in concrete strength, overall strength of SCSS beam rises by about 5%.

7.3 SCOPE FOR FUTURE STUDY

This particular study was limited in few aspects, which can be addressed in future studies. Future scope for expanding the work can be identified on the following aspects:

- Studies can be expanded to other type of shear connectors.
- Empirical formulation for ultimate strength calculation can also be done.
- This study was done on SCSS beams only. It can be extended to columns, slabs and joints of different elements.

REFERENCE

1. Ali Shariati. 2012. "Various types of shear connectors in composite structures: A review." Int. J. Phys. Sci., 7 (22): 2876–2890
2. An, L., and K. Cederwall. 1996. "Push-out Tests on Studs in High Strength and Normal Strength Concrete." J. Constr. Steel Res., 36 (1): 15–29
3. Bowerman, H., and J. C. Chapman. 2002. "BI-STEEL TM STEEL-CONCRETE-STEEL SANDWICH CONSTRUCTION." Compos. Constr. Steel Concr., 4: 656–667
4. Eurocode 4 (2004) Design of composite steel and concrete structures—Part 1.1: general rules and rules for buildings. BS EN 1994-1-1:2004
5. Gattesco, N., and E. Giuriani. 1996. "Experimental Study on stud shear connectors subjected to cyclic loading." J. Constr. Steel Res., 38 (1): 1–21
6. Grondin, G. Y., A. E. Elwi, and J. J. R. Cheng. 1999. "Buckling of stiffened steel plates - A parametric study." J. Constr. Steel Res., 50 (2): 151–175
7. Hanswille, G., M. Porsch, and C. Ustundag. 2007. "Resistance of headed studs subjected to fatigue loading. Part I: Experimental study." J. Constr. Steel Res., 63 (4): 475–484
8. Jeong, Y. J., H. Y. Kim, H. B. Koo, and S. T. Kim. 2005. "Steel-concrete interface behavior and analysis for push-out." KSCE J. Civ. Eng., 9 (2): 119–124
9. Jurkiewiez, B., C. Meaud, and L. Michel. 2011. "Non linear behaviour of steelconcrete epoxy bonded composite beams." J. Constr. Steel Res., 67 (3): 389–397
10. Leng, Y. B., and X. B. Song. 2016. "Experimental study on shear performance of steel-concrete-steel sandwich beams." J. Constr. Steel Res., 120: 52–61
11. Liew, J. Y. R., and K. M. A. Sohel. 2009. "Lightweight steel-concrete-steel sandwich system with J-hook connectors." Eng. Struct., 31 (5): 1166–1178
12. Liew, J. Y. R., J. B. Yan, and Z. Y. Huang. 2017. "Steel-concrete-steel sandwich composite structures-recent innovations." J. Constr. Steel Res., 130: 202–221

13. Liew, J. Y., and T. Y. Wang. 2011. “Novel steel-concrete-steel sandwich composite plates subject to impact and blast load.” Adv. Struct. Eng., 14 (4): 673–688
14. Lin, Y., J. Yan, Y. Wang, F. Fan, and C. Zou. 2019. “Shear failure mechanisms of SCS sandwich beams considering bond-slip between steel plates and concrete.” Eng. Struct., 181 (July 2018): 458–475
15. McKinley, B., and L. F. Boswell. 2002. “Behaviour of double skin composite construction.” J. Constr. Steel Res., 58 (10): 1347–1359
16. Qin, F., S. Tan, J. Yan, M. Li, Y. L. Mo, and F. Fan. 2016. “Minimum shear reinforcement ratio of steel plate concrete beams.” Mater. Struct. Constr., 49 (9): 3927–3944
17. Rabbat, B. G., and H. G. Russell. 1985. “Friction Coefficient of Steel on Concrete or Grout.” J. Struct. Eng., 111 (3): 505–515
18. Roberts, T. M., D. N. Edwards, and R. Narayanan. 1996. “Testing and analysis of steel-concrete-steel sandwich beams.” J. Constr. Steel Res., 38 (3): 257–279
19. Shanmugam, N. E., G. Kumar, and V. Thevendran. 2002. “Finite element modelling of double skin composite slabs.” Finite Elem. Anal. Des., 38 (7): 579–599
20. Sohel, K. M. A., and J. Y. R. Liew. 2011. “Steel-Concrete-Steel sandwich slabs with lightweight core - Static performance.” Eng. Struct., 33 (3): 981–992
21. Sohel, K. M. A., J. Y. Richard Liew, J. B. Yan, M. H. Zhang, and K. S. Chia. 2012. “Behavior of Steel-Concrete-Steel sandwich structures with lightweight cement composite and novel shear connectors.” Compos. Struct., 94 (12): 3500–3509
22. Solomon, S. K., D. W. Smith, and A. R. Cusens. 1976. “Flexural Tests of Steel-Concrete-Steel Sandwiches.” Mag. Concr. Res., 28 (94): 13–20
23. Xiao, Y., Z. Chen, J. Zhou, Y. Leng, and R. Xia. 2017. “Concrete plastic-damage factor for finite element analysis: Concept, simulation, and experiment.” Adv. Mech. Eng., 9 (9): 1–10
24. Xie, M., N. Foundoukos, and J. C. Chapman. 2007. “Static tests on steel-concrete-steel sandwich beams.” J. Constr. Steel Res., 63 (6): 735–750
25. Xue, W., M. Ding, H. Wang, and Z. Luo. 2008. “Static Behavior and Theoretical Model of Stud Shear Connectors.” J. Bridg. Eng., 13 (6): 623–634

26. Yan, J. B., J. Y. Richard Liew, K. M. A. Sohel, and M. H. Zhang. 2014. "Push-out tests on J-hook connectors in steel-concrete-steel sandwich structure." Mater. Struct. Constr., 47 (10): 1693–1714
27. Yan, J. B., J. Y. Richard Liew, and M. H. Zhang. 2015. "Shear-tension interaction strength of j-hook connectors in steel-concrete-steel sandwich structure." Adv. Steel Constr., 11 (1): 73–94.
28. Yan, J. B., J. Y. Wang, J. Y. R. Liew, X. Qian, and L. Zong. 2016. "Ultimate strength behaviour of steel-concrete-steel sandwich plate under concentrated loads." Ocean Eng., 118: 41–57
29. Yan, J. B., Y. Y. Yan, T. Wang, and Z. X. Li. 2019. "Seismic behaviours of SCS sandwich shear walls using J-hook connectors." Thin-Walled Struct., 144 (January): 106308
30. Zhang, K., A. H. Varma, S. R. Malushte, and S. Gallocher. 2014. "Effect of shear connectors on local buckling and composite action in steel concrete composite walls." Nucl. Eng. Des., 269: 231–239
31. Zhang, W., Z. Huang, Z. Fu, X. Qian, Y. Zhou, and L. Sui. 2020. "Shear resistance behavior of partially composite Steel-Concrete-Steel sandwich beams considering bond-slip effect." Eng. Struct., 210 (November 2019)