# PERFORMANCE OF STRUCTURAL COMPOSITE SLAB WITH PARTIAL AND FULL INTERACTION

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# DEDICATION

My humble effort I dedicate to:

Iraq army that defence our belong country and provide us peaceful life, and I dedicate to my sweet and loving, father and mother whose affection, love, encouragement and prays of day and night make me able to get such success, and also to my dear sisters and brothers.

اهدي هذا الجهد البسيط:

الى الحبيب المسجون خلف قضبان الحقد والتعسف العراق الغالي

الى الدرع البشري الذي يموت كل يوم شيء فيه لكي ينام ابنائه بسلام جيشنا الفذ وحشدنا الشعبي

الى ذلك الرجل الذي تحكي كل شيبة فيه قصة طويلة من التعب لكي نصل الى بر الامان والعلم ابي الرائع

الى تلك المخلوقة النادرة التي حازت شيئا من سمو السماء وبراءة الملائكة امي الحبيبة

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# ABSTRACT

Composite concrete slab with steel decking profile as permanent formwork is gaining wide acceptance in structural construction of large scale buildings. The strength and behaviour of composite slabs are governed by the shear interaction between the concrete and the steel deck. The loss of interaction between the two materials is the main reason of the failure of composite slabs before reaching the maximum bending capacity. Technical information to strengthen the bonding and interaction in composite slab is still lacking. This study presents a new method for strengthening composite slab by an innovative U-bolts shear connectors and conventional headed studs shear connectors (HSSC). The study comprises of three components; experimental, theoretical and numerical works. The experimental work consists of eight full-scale composite slab specimens. The first specimen was made without any shear connection. The second specimen was constructed with one line of shear studs welded to the support beam while the third, fourth and fifth specimen was constructed with two lines of shear studs. The sixth specimen was constructed with U-bolts shear connectors that were fixed through the steel sheets profile. The seventh specimen was constructed with one line of shear studs with the U-bolts shear connectors. The eighth specimen was constructed with two lines of shear studs and the U-bolts shear connectors. The theoretical work consists of modifying existing stiffness method to analyse the composite slab with the U-bolts shear connectors and end anchorages. A calculation procedure was also developed to study the shear bond stress versus end slip relationships (shear bond property) from four-point bending test. Finally, three-dimensional finite element software, ANSYS, was used to determine the accuracy of the elastic stiffness method. Experimental results of composite slab tests show that the shear connectors had more efficiency for increasing the stiffness and strength of the composite slab compared with composite slab without shear connectors. Also, it was observed that the U-bolts shear connectors are strong and ductile enough to provide full composite action between the profile steel plate and concrete slab. Composite slabs with the U-bolts shear connectors show that the best performance is achieved compared to composite slab with HSSC shear connectors. The bending resistance of the proposed composite slab was improved up to 500% compared to conventional composite slab. The theoretical results show that the modified elastic stiffness method is successful to analyse partial and full composite slab. The theoretical values show a good agreement compared to the results of full-scale slab test. Good agreement was recorded between the results from finite element modelling, experimental and the modified stiffness method at linear elastic stage. It is concluded that the proposed composite slab is strong enough to be used in large scale structure.

## ABSTRAK

Papak konkrit rencam dengan profil keluli geladak sebagai acuan tetap semakin meluas digunakan dalam pembinaan struktur bangunan berskala besar. Kekuatan dan kelakan papak rencam adalah disebabkan oleh interaksi ricih antara konkrit dan geladak keluli. Kehilangan interaksi antara kedua-dua bahan ini adalah sebab utama kegagalan papak rencam sebelum mencapai keupayaan lenturan maksimum. Maklumat teknikal mengenai pengukuhan ikatan dan interaksi dalam papak rencam adalah sangat terhad untuk diperolehi. Kajian ini membentangkan mengenai kelakuan papak rencam kukuh dengan kancing berkepala konvensional penyambung ricih (HSSC) dan dengan penyambung ricih inovatif atau yang baru diperkenalkan (U-bolts). Kajian ini terdiri daripada tiga komponen - kerja ujikaji, teori dan kaedah berangka. Kerja-kerja eksperimen terdiri daripada lapan skala penuh spesimen rencam papak. Spesimen pertama dibuat tanpa sambungan ricih. Spesimen kedua terdiri daripada satu baris kancing ricih dikimpal kepada sokongan rasuk manakala spesimen yang ketiga, keempat dan kelima terdiri daripada dua baris kancing ricih. Spesimen keenam terdiri daripada penyambung ricih jenis U-bolts yang dicadangkan dan digerudi melalui kepingan keluli profil. Spesimen ketujuh terdiri daripada satu baris kancing ricih dengan penyambung ricih U-bolts. Spesimen kelapan terdiri daripada dua baris kancing ricih dan penyambung ricih yang dicadangkan. Kerja-kerja teori terdiri daripada pengubahsuaian kaedah kekukuhan sedia ada untuk memberikan kesesuaian menganalisis papak rencam dengan penyambung ricih U-bolts dengan tambatan hujung. Prosedur kiraan telah dibangunkan untuk mengkaji hubungan tegasan ikatan ricih berbanding slip hujung (sifat ikatan ricih) berdasarkan ujian lenturan empat titik. Perisian unsur terhingga tiga dimensi, ANSYS telah digunakan untuk menentukan ketepatan kaedah kekukuhan anjal. Keputusan eksperimen ujian papak rencam menunjukkan bahawa penyambung ricih mempunyai kecekapan yang tinggi untuk meningkatkan kekukuhan dan kekuatan papak rencam berbanding dengan papak rencam tanpa penyambung ricih. Selain itu, didapati bahawa penyambung ricih yang dicadangkan adalah cukup kuat dan mulur untuk menghasilkan tindakan rencam penuh antara plat profil keluli dan papak konkrit. Papak rencam dengan penyambung ricih U-bolts menghasilkan prestasi yang terbaik berbanding papak rencam dengan penyambung ricih HSSC sahaja. Rintangan lenturan papak rencam dengan U-bolts telah meningkat sehingga 500% berbanding dengan papak rencam konvensional. Keputusan teori menunjukkan bahawa kaedah kekukuhan anjal berjaya digunakan untuk menganalisis papak rencam separa dan penuh. Nilai teori menunjukkan keputusan yang baik berbanding dengan keputusan ujian papak berskala penuh. Keputusan yang baik dicapai antara pemodelan unsur terhingga, eksperimen dan analisis menggunakan kaedah kekukuhan diubahsuai pada tahap anjal lelurus. Kesimpulannya, papak rencam yang dicadangkan dalam kajian in adalah cukup kuat untuk digunakan dalam struktur berskala besar.

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# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AISI | - | American Iron and Steel Institute |
| ASCE | - | American Society of Civil Engineers |
| BS | - | British Standard |
| CGI | - | Corrugated Galvanized Iron |
| CRC | - | Crumb Rubber Concrete |
| EC4 | - | Eurocode 4 |
| FEM | - | Finite Element Modelling |
| FS | - | Full-Scale Specimen |
| HSSC | - | Headed Studs Shear Connector |
| LVDT | - | Linear Variable Displacement Transducer |
| LRFD | - | Load and Resistance Factor Design |
| POCC | - | Palm Oil Clinker Concrete |
| PSC | - | Partial Shear Connection |
| SDP | - | Steel Deck Profile |
| SLS | - | Serviceability Limit State |
| UBSC | - | U-bolts Shear Connector |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $A_p$ | - | Cross section area of profile corrugated plate |
| $A_c$ | - | Area of concrete |
| $A_s$ | - | Steel deck area |
| $b$ | - | Slab width |
| $b_o$ | - | Width of the profile steel haunch |
| C | - | Internal axial compression in concrete |
| $D$ | - | Thicknesses of the concrete in composite slab |
| $d$ | - | Height of the corrugated steel sheet in composite slab |
| $d_p$ | - | Effective depth of composite slab |
| e | - | Centroid axis of profile steel sheeting |
| $E_c$ | - | Modulus of elasticity of concrete element |
| $E_s$ | - | Modulus of elasticity of steel element |
| $(EI)^0_{\mathrm{comp}}$ | - | Bending stiffness of the composite slab without composite action |
| $(EI)^\infty_{comp}$ | - | Bending stiffness of the composite slab with full composite action |
| $f_c$ or $f_{ck}$ | - | Concrete cylinder compressive strength |
| $f_{ctm}$ | - | Concrete mean tensile strength |
| $f_c'$ or $f_{cn}$ | - | Concrete cube compressive strength |
| $F$ | - | External force |
| $f_{yp}$ | - | Yield strength of corrugated steel plate |
| $f_y$ | - | Yield tensile strength of steel material |
| $f_u$ | - | Ultimate tensile strength of bolt |

| | | |
|---|---|---|
| $h_p$ | - | Depth of the profile steel haunch |
| $h_{sc}$ | - | Height of the headed stud |
| $h$ | - | Depth of beam section |
| $h_t$ | - | Total thickness of composite slab |
| $h_c$ | - | Height of concrete slab above profile steel sheeting |
| $h_p$ | - | The height of profile steel sheeting |
| $I_c$ | - | Moments of inertia of concrete |
| $I_s$ | - | Moments of inertia of steel |
| $I_n$ | - | Effective second moment of profile steel area |
| $k$ | - | ordinate intercept of reduced experimental shear-bond line |
| $k$ | - | Curvature of the common deflection |
| $K$ | - | Shear stiffness of U-bolts |
| K | - | Stiffness matrix for the beam element |
| $\mathrm{k_c}$ | - | Elastic stiffness matrix of the element |
| L | - | Length of composite slab |
| $L_s$ | - | Shear span length |
| $M$ | - | Resisting moment |
| $m$ | - | Slope of reduced experimental shear-bond line |
| $M_c$ | - | Moment in concrete element |
| $M_c$ | - | Moment in steel element |
| $M_R$ | - | Design moment resistance |
| $M_U$ | - | Ultimate bending moment |
| $m$ | - | Shear modulus of the steel–concrete interface |
| $n$ | - | Distance from the central axis of the concrete to that of the corrugated steel sheet |
| $P_{RK}$ | - | Shear connector design resistance |
| $Pu$ | - | Ultimate load |
| $Q$ | - | External deformation |

| | | |
|---|---|---|
| s | - | Slip at concrete-steel interface |
| $S_p$ | - | Effective compression section modulus of profile steel plate |
| $S_n$ | - | Effective section modulus tension of profile steel plate |
| $T$ | - | Axial tension in steel |
| V | - | Maximum shear at failure due to full scale tests |
| $V$ | - | Shear force of U-bolts |
| $v$ | - | shear density transferred by single U-bolt on the interface |
| W | - | Distributed load |
| $W_t$ | - | Maximum load |
| $W_{0.1}$ | - | Load cause slip 0.1 mm |
| $Z_c$ and $Z_s$ | - | Distances from the neutral axes of concrete and steel components to their top surfaces respectively |
| $Z_\infty$ | - | Height of the neutral axial of the total section of composite slab |
| $\rho$ | - | Concrete density |
| $\delta$ | - | Vertical deflection |
| $\delta_u$ | - | Slip at ultimate load |
| $\delta_{uk}$ | - | Characteristic slip capacity |
| $\gamma_v$ | - | Partial factor of safety |
| $\tau_u$ | - | Mean ultimate shear stress |
| $\tau_{u,Rd}$ | - | Design value of shear stress |
| $\alpha$ and $\varphi$ | - | Parameters relevant to material properties and section dimensions in composite slab |
| $\sigma$ | - | Bending stress |
| $\varepsilon_c$ | - | Concrete strain |
| $\varepsilon_s$ | - | Steel strain |
| $\varepsilon_{slip}$ | - | Slip strain |
| $\mu$ | - | Coefficient of friction |

# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

Concrete is one of the most important materials in the construction that promises a lot of advantages. The obvious advantages of concrete are that it can be cast into any shape, its excellent resistant to water and high temperatures and it requires less maintenance because of its high durability. Concrete is also known as an economical material which can reduce the overall project cost. Concrete alone is not applicable for construction due to its low tensile strength. Concrete can be strengthen by acting compositely with steel. This is due to the fact that steel materials have advantage that is not available for concrete (Al Nageim and MacGinley, 2005; Lui, 1999) such as:

1. High strength/weight ratio: Hence, the dead weight of steel constructions is relatively small. This property makes the steel a very attractive structural material for long-span bridges, high-rise buildings and structures located in seismic areas.

2. High ductility: steel can undergo great plastic deformation before failure, so providing high reserve strength. This property is referred to as ductility. A ductile structure has energy-absorbing capacity and will not incur rapid failure. It shows large visible deformation before collapse.

3. Predictable material properties: Properties of steel can be expected with a high degree of certainty. Steel indeed shows elastic behaviour up to a relatively high and well-defined stress level.

4. Speed of erection: Steel constructions can be erected rather rapidly.

5. Quality of construction: Steel structures can be built with narrow tolerances and high-quality workmanship.

6. Ease of repair and adaptation of prefabrication to repetitive use.

7. Expanding existing structures: Steel buildings can be easily expanded by adding new bays or wings.

8. Steel structures have relatively good fatigue strength.

Therefore, in order to take advantage of both concrete and steel, they can combine to form composite structure. The composite structure that combine steel and concrete is composite slab which is more durable, stiffer and strong that using the materials alone. Composite structure can benefit from both the advantages of concrete and the advantages of steel together. The ability of composite slab to carry the loads depends on the degree of connection between the concrete and the steel. Therefore, whenever the interaction between these two materials is increased, the capacity and stiffness of composite slab increased.

There are many types of composite slab but the most widely used type of composite slab is shown in Figure 1.1. The corrugated steel profile sheeting acts as the tensile reinforcement for the slab and normally the steel sheeting contains embossments to reduce the relative movements between the steel and concrete. Light mesh reinforcement is placed in the concrete to resist the cracking and shrinkage. Shear connectors are used to develop and increase composite action between the slab and the beam.

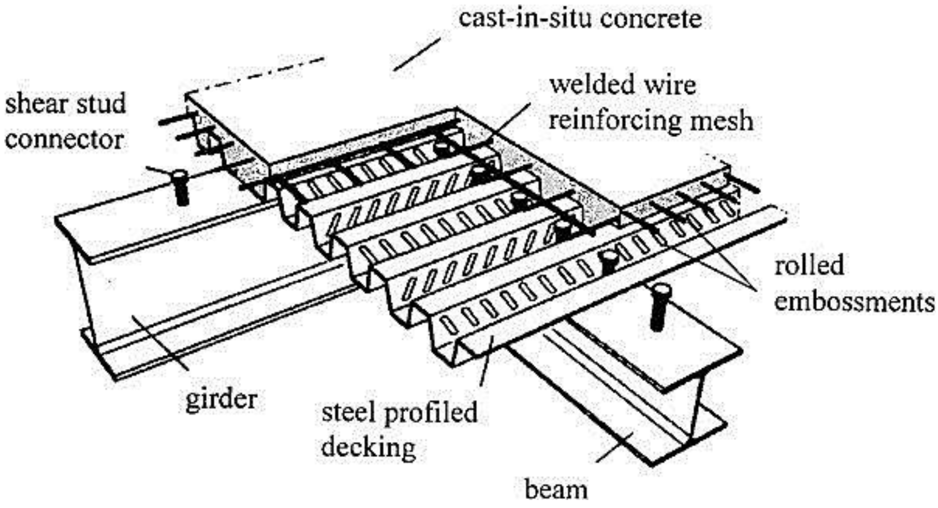


**Figure 1.1:** Typical steel and concrete composite constructions (adopted from Crisinel and Marimon, 2004)

Steel is a material that works very well in tension. Figure 1.2 shows the plastic stress distribution in the composite slab. The proportions of the concrete slab and steel section refer to that the plastic neutral axis usually lies within the concrete slab. Therefore, all steel is in tension. Concrete material works well in compression but has insignificant resistance in tension. Hence for construction purposes, it conventionally depend on profiled steel deck to carry the tensile forces (this is the role played by the steel deck part of the composite cross section, which is efficient external reinforcement).

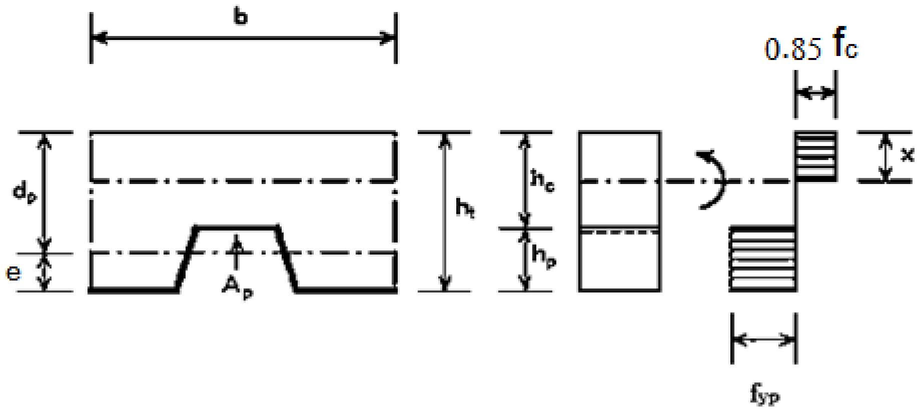


**Figure 1.2:** Plastic stresses distribution of typical composite slab under positive bending

Where;

$d_{p}$: Effective depth of composite slab

e: Centroid axis of sheeting

$A_p$: Cross section area of profile corrugated steel plate

$f_c$: Concrete cylinder compressive strength

$f_{yp}$: Yield strength of corrugated steel plate

$h_t$: Total thickness of composite slab

$h_c$ The height of concrete slab above profile steel sheeting

$h_p$ The height of profile steel sheeting

The steel part of a cross section undergoes the tension, and the concrete part (within the effective width) undergoes the compression force. The two materials should be structurally tied together using different types of shear connectors that are attached to the upper flange of the steel beam support. This type of shear connector is considered as end anchorage for composite slab. The profiled steel decking is sandwiched between the top flange and the base of the stud, and the welding process links all the three together.

The overall construction system has many significant advantages to offer when compared to the conventional systems. Composite slabs are the ideal solution for any type of construction project requiring both maximum technical and mechanical performance. Additional implicit advantage of this system is that it is lighter, it has a better quality control, and it reduces site time - fast track construction and less material handling at site. Furthermore, it has a better ductility and hence superior lateral load behaviour, better earthquake resistance and the overall construction depth is reduced because of the relatively short spans used (Altenbach *et al.*, 2004; Ault and Kelly, 1976). In addition, the choice of this technology corresponds to certain inevitable requirements found in modern buildings, such as the composite slab is allowed for using false ceilings and improving planning of the various stages of execution.

Composite slabs have conventionally found their highest application in steel framed office buildings, but they are also suitable for the following categories of building (Figure 1.3):

1. Hospitals and schools
2. Commercial buildings
3. Leisure buildings, cinemas and stadia
4. Industrial buildings and warehouses
5. Refurbishment projects.
6. Housing; both individual houses and residential buildings


**Figure 1.3:** Applications of composite slab construction

## 1.2 Problem Statements

The problem statements for this study can be given as follow:

1. A composite member is designed to act monolithically. The monolithic behaviour is possible only if the horizontal shear at the interface between the two components can be resisted. Traditionally, full composite action can be achieved by neglecting the interface slip movement between the two components in the composite member (Ariffin, 2010).

2. The shear bond failure of the composite slab is a big challenge facing by the designers and researchers. Introducing composite action between the corrugated steel plate and concrete slab should be based on their strength and ductility requirements. The improvement of the composite action will be studied in this research.

3. The headed studs shear connectors (HSSC) is the most famous type of shear connection device. The shear studs acts with composite slab as end anchorage. However, the efficiency of using such structural members with concrete to form composite slab members has not been properly investigated.

4. According to European standards code Eurocode 4 (EN 1994-1-1, 2004), the method of analysis and design of the composite slab is semi-empirical. Modifying the existing stiffness method for analysis of every new type of composite slab will pose a problem.

5. In the literature, the theoretical and numerical analysis for full and partial composite slab with shear connection along the shear span distance is very limited and have drawbacks.

## 1.3 Aim and Objectives

The aim of this study is to develop an efficient composite slab system with fully composite behaviour through experimental work, analytical and numerical analysis.

Four specific objectives are considered in this study:

1. To develop a new type of shear connectors in which more efficient and able to obtain composite slab full connection capacity.

2. To study the performance of composite slab with cold formed corrugated steel and using welded shear studs connectors (HSSC). Also to compare the difference of the strength between the conventional composite slab, composite slab with the proposed shear connectors and composite slab with HSSC shear connectors.

3. To modify the existing elastic stiffness matrix analysis method for predicting the behaviour of the composite slab with the proposed shears connectors and to simplify the analysis of composite slab with end anchorage (headed studs shear connectors)

4. To validate the performance of the proposed composite slab by comparing empirical result and theoretical predictions with finite element analysis using ANSYS software.

## 1.4 Scope of Study

A new type of composite slab system comprising of corrugated steel plate sections as permeant formwork and concrete as slab is studied. A new type of shear connectors (U-bolts) is used. This study focuses on the behaviour of full and partial composite slab structural system. The study covers two areas of research; the first research area is related to the performance of the proposed shear connectors by experimental work. The second research area is related to the analysis of partial and full composite slab action by modifying existing stiffness method analysis. The scopes of the study are as follows:

1. Laboratory test program of composite slab, comprising of eight samples of composite slab utilizing profile trapezoidal deck type (SDP51-10) that is commonly available in Malaysian market. Full-scale 2.0 m length simply supported is tested using four-point load system. These specimens are built using one type steel deck and concrete grade 35 N/mm$^2$.

2. The first composite slab specimen was made without any shear connection. The second specimen was constructed with one line shear studs welded to the support beam while the third, fourth and five specimen were constructed with two lines of shear studs welded to the support beam. The sixth specimen was constructed with U-bolts shear connector that was fixed through the profiled steel sheets. The seventh specimen was constructed with one line of shear studs with a U-bolts shear connector and finally the eighth specimen was constructed with two lines of shear studs and a U-bolts shear connector.

3. In experimental work, the composite slab behaviour was investigated by measuring:
   a. Load-deflection behaviour
   b. End-slip interface between the concrete and corrugated steel plate
   c. Strain distribution at steel and concrete
   d. Mode of failure
   e. The plasticity of the composite slab based on EN code
   f. Stiffness of slab

4. Simplified headed studs shear connectors (HSSC) as rotation spring to analyse the composite slab with end anchorage was presented. In addition, derivation

a stiffness equation for the analysis of the proposed composite slab with U-bolts shear connector was conducted.

5. A comparison between experimental, theoretical and 3D finite element analysis results was conducted.

## 1.5 Significance of the Research

Composite slab are extensively used in construction industry due to their efficiency in strength, stiffness and material savings (Degtyarev, 2014b). To date, headed stud shear connectors are commonly used to perform the composite action between steel beam and concrete slab (Lawson *et al.*, 2001). However, it was found in many research that headed stud shear connectors is not enough to achieved full composite slab action. For this reason, a new shear connectors needed to be developed in an economical manner and easy construction.

The new type of shear connectors that is developed in this study, namely U-bolt shear connectors (UBSC) is able to reduce the longitudinal shear stress and to increase the resistance of shear bond at the interface between the steel deck and concrete. As a result the strength and capacity of composite slab is increased. The U-bolt shear connectors could also reduce the rotation between the composite slab and the support beam due to the increment of the composite slab stiffness. On the other hand, the analysis method for composite slab needs to be modified to be equivalent with the new shear connectors and with the headed studs shear connectors (HSSC). The findings from this research may eventually lead to the development or improvement of the existing system to reduce the longitudinal shear failure of composite slab. Therefore, using U-bolt shear connectors with composite slab could significantly increase the strength and stiffness capacities required and achieved full composite action. It is potentially useful in the construction of longer composite slab.

## 1.6 Thesis Layout

**Chapter one** presents the general introduction, background of the study, problem statement, aims and objectives, scope of this research. Significance of the study and thesis layout are also described in this chapter.

**Chapter two** details a comprehensive literature review on the area of study and all published works related to the current study.

**Chapter three** provides detailed description on the methodology of experimental work. The fabrication of new shear connectors and their configurations are presented. Push test specimen configuration, fabrication, instrumentation and test procedure are described. Also, detailed description on the full–scale composite slab test i.e. fabrication of the specimen, test setup and procedure are outlined.

**Chapter four** describes and analysis the experimental results for full-scale flexural test of composite slabs. Load-deflection curves and load-slip curves of all specimens and their strength capacity and ductility as well as failure modes are discussed.

**Chapter five** presents the theoretical analysis of composite slab using stiffness analysis method. Also, is the derivation of the modification stiffness matrixes for composite slab containing the proposed shear connectors which are fixed along the shear spans distance.

**Chapter six** expounds the modelling validations of theoretical and experimental work using three dimension finite element software ANSYS.

**Chapter Seven** presents the summary of this research, conclusions, and recommendations for future work development.

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