UNIVERSITI PUTRA MALAYSIA

EFFECTS OF BOLT SIZES AND INTERLOCKING KEY JOINT PRECAST SLAB SHEAR CONNECTORS ON THE PERFORMANCE OF STEEL-CONCRETE COMPOSITE BEAM

NADIAH BINTI LOQMAN

FK 2021 5

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By

NADIAH BINTI LOQMAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Master of Science

July 2020

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Abstract of thesis presented to the Senate of University Putra Malaysia in fulfilment of the requirement for the degree of Master of Science.

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Chair : **Nor Azizi binti Safiee, PhD**
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Conventional composite steel-concrete beams have been recognized to exhibit stronger structural characteristics, in terms of strength and stiffness, when compared to pure steel or reinforced concrete beams. However, currently, most of the steel beam is fully attached to the concrete slab; this means that the shear connectors are welded through the steel decking on to the steel beam and cast into the concrete slab to fulfil the necessary shear connection. In order to achieve a sustainable structural system, bolted shear connectors are used to connect the precast concrete slabs and steel beam in the composite beam. An interlocking tongue and groove joints between the precast concrete slabs are also introduced into the composite system. Thus, the main objective of this study is to measure the structural behaviour of a composite beam using an interlocking precast concrete slab and bolted shear connector under flexural static load. The structural behaviour of the composite beam that is examined is the stiffness, strength, ductility, end slip between steel-concrete interface and failure mode. For this purpose, an experimental test was conducted on six number of full-scale composite beams. The variables are the effect of an interlocking joint and the size of bolt. This work also incorporates Finite Element (FE) modelling to provide a comparison with the existing experimental test result. The test results demonstrated that the composite beams having a precast concrete slab with interlocking tongue and groove joint have better initial stiffness, ultimate load and deflection by 12.3%, 1.9% and 10.6%, respectively when compared to the precast concrete slab without the interlocking joint which proved that the interlocking joint is an effective mechanism to transfer the applied load and improve the strength and stiffness of the composite beam. The behaviour of composite beams with higher size of bolt also showed a higher ultimate load and deflection by 10.8% and 18.8%, respectively than the composite beam with a lower size of bolt under flexural load. This demonstrated that a bigger diameter of the bolt has a higher load capacity and ductility that can hold both of

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the concrete slab and steel beam together more effectively. The end slip of the composite beams with bolted shear connectors does not show any significant slip between the steel-concrete interface with only 2 mm of slip which is the summation of the bolt clearance hole. The comparison made from FE modelling showed a good agreement at the post-elastic range (non-linear part) between the experimental test result and the Finite Element (FE) result.

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Abstrak tesis ini dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

KESAN UKUR LILIT BOLT DAN KUNCI SAMBUNGAN ANTARA LIDAH DAN SENDI ALUR DI DALAM PAPAK KONKRIT PRATUANG TERHADAP PRESTASI STRUKTUR RASUK KELULI-KONKRIT KOMPOSIT

Oleh

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Rasuk konkrit keluli konvensional telah diperakui menunjukkan ciri struktur yang lebih kuat, dari segi kekuatan dan kekakuan, jika dibandingkan dengan keluli tulen atau konkrit bertetulang. Walau bagaimanapun, pada masa ini, sebahagian besar rasuk keluli dipasang sepenuhnya pada papak konkrit; ini bermaksud bahawa penyambung ricih telah dikimpal pada rasuk keluli dan disambung ke papak konkrit untuk memenuhi sambungan ricih yang diperlukan. Untuk mencapai sistem struktur yang mampan, penyambung ricih bolt digunakan untuk menghubungkan papak konkrit pratuang dengan rasuk keluli di dalam rasuk komposit. Sambungan lidah dan sendi alur yang saling berkait antara papak konkrit pratuang juga dimasukkan ke dalam sistem komposit. Oleh itu, objektif utama kajian ini adalah untuk mengesan tingkah laku struktur rasuk komposit menggunakan papak konkrit pratuang dan penyambung ricih bolt di bawah beban statik lenturan. Tingkah laku struktur rasuk komposit yang diperiksa adalah kekakuan, kekuatan, lenturan, slip antara muka konkrit dan keluli dan mod kegagalan. Untuk tujuan ini, ujian eksperimental dilakukan pada enam bilangan rasuk komposit berskala penuh. Pemboleh ubah adalah kesan sambungan lidah dan sendi alur dan ukur lilit penyambung ricih bolt. Kerja ini juga menggabungkan Finite Element (FE) model untuk memberikan perbandingan dengan hasil ujian eksperimental. Hasil ujian yang telah dilakukan menunjukkan bahawa rasuk komposit yang mempunyai papak konkrit pratuang dengan lidah dan sendi alur yang saling bersambung mempunyai kekakuan awal, kekuatan dan kelenturan yang lebih baik dengan purata peratus masing-masing sebanyak 12.3%, 1.9% dan 10.6% jika dibandingkan dengan papak konkrit pratuang tanpa sambungan lidah dan sendi alur. Ini membuktikan bahawa sambungan lidah dan sendi alur adalah mekanisme yang berkesan untuk memindahkan beban yang dikenakan dan meningkatkan kekuatan dan kekakuan rasuk komposit. Tingkah laku rasuk komposit dengan ukuran bolt yang lebih tinggi juga menunjukkan kekuatan dan kelenturan yang lebih tinggi dengan purata

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peratus masing-masing sebanyak 10.8% dan 18.8% daripada rasuk komposit dengan ukuran bolt yang lebih rendah. Ini menunjukkan bahawa ukur lilit bolt yang lebih besar mempunyai kapasiti kekuatan dan kelenturan yang lebih tinggi yang dapat menahan kedua-dua papak konkrit dan balok keluli bersama dengan lebih berkesan. Slip di dalam rasuk komposit dengan penyambung ricih bolt tidak menunjukkan sebarang slip yang ketara antara muka konkrit dan keluli dengan slip hanya 2 mm yang merupakan penjumlahan ukuran lubang bolt. Perbandingan yang dibuat dari FE model menunjukkan kesepakatan yang baik pada julat pasca elastik (bahagian tidak linear) antara hasil ujian eksperimen dan hasil Finite Element (FE).

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
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LIST OF ABBREVIATIONS

3D	three-dimension
ASTM	American Society for Testing and Materials
BS	British Standard
C3D8R	three-dimensional eight-node continuum element
CB	composite beam
CDP	Concrete Damage Plasticity
DBLNB	double-nut bolt
FEM	Finite Element Modelling
GPC	geopolymer concrete
HASAA	adhesive anchor bolt
HSFGB	high-strength friction grip bolt
HTFGB	high-tension friction-grip bolt
LVDT	linear variable displacement transducer
T3D2	two-node three-dimensional truss element
UB	universal beam
φ	degree of interaction
σ	flexural strength
η	degree of shear connection
b_{eff}	effective width of concrete slab
f_{ck}	compressive strength of concrete
f_y	yield strength of steel beam
h	overall depth of composite beam
h_a	depth of structural steel beam
h_p	overall depth of the profiled steel sheeting
I	moment of inertia
I_a	second moment of steel beam
M_c	bending moment of the composite beam
N_a	actual number of shear connection

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N_p	full shear connection
Q_p	capacity of shear connector
R_{cf}	resistance of concrete flange
R_s	resistance of steel section
R_{sx}	resistance of steel flange above the neutral axis
R_v	resistance of clear web depth
R_w	resistance of overall web depth
t_f	thickness of steel flange
t_w	thickness of steel web
$\bar{x}$	distance to the centroid of a section
y	distance from neutral axis

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CHAPTER 1

INTRODUCTION

1.1 Background

Composite construction has been used in bridges and buildings since the 1930s. It involves connecting one or more components of a structure in such a way that the components act as one unit. The most common type of composite element in bridges applications is composite steel-concrete beams. Composite steel-concrete beam consists of a concrete slab and steel beam that is connected by a shear connector to resist the load.

The flexural strength of the composite beams is greatly influenced by the strength and ductility of the shear connectors between the structural steel beam and the concrete slab. Kwon (2008) stated that compares to non-composite beam where two structural components act separately in flexure, the load-carrying capacity of the composite beams are higher by more than 50% when connecting using shear connectors. Thus, due to higher load-carrying capacity, a high strength composite beam can be achieved in comparison to non-composite beam with an assumption that it is in an infinite state that prevents any slip between two construction elements by shear connectors as shown in Figure 1.1.

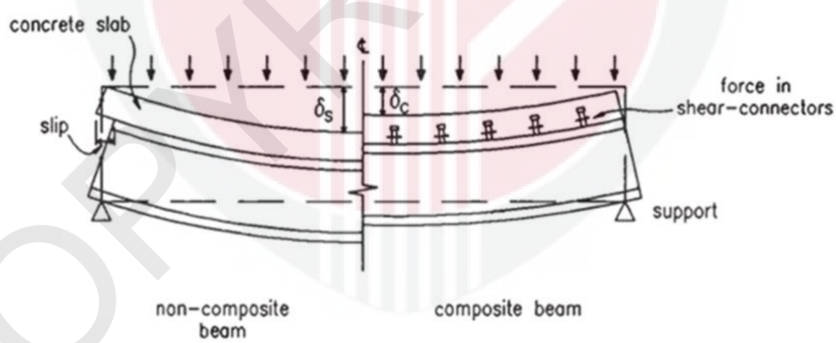

Figure 1.1: Non-composite and composite beam behaviour (Cuthill: 2002)

There are various types of shear connector but the most commonly used is the headed stud shear connector in a conventional cast in-situ concrete slab composite beam and bolted shear connector with a precast concrete slab composite beam. These mechanical shear connectors are generally used to provide the essential shear transfer at the steel-concrete interface by connecting the concrete slab and the steel beam to ensure effective composite action.

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The composite action was mainly based on two types of shear connection which is fully shear connection and partial shear connection. A fully shear connection was designed to achieve a zero slip between the concrete slab and steel beam which result in a large number of shear connections. While a partial shear connection was designed to achieve a sufficient degree of interaction in order to provide the required strength with a lower number of shear connections. Figure 1.2 shows the comparison of end slip between a fully shear connection (complete interaction), partial shear connection (partial interaction) and no shear connection (no interaction).

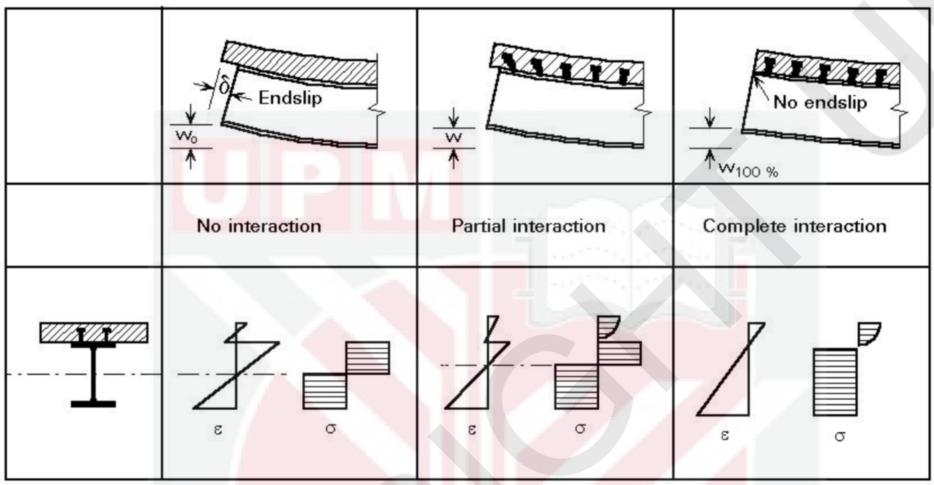

Figure 1.2: Composite beam interaction (Samhal: 2005)

Until now, composite beams are continuously gaining its popularity. The reasons are due to their excellent structural performance in terms of stiffness and strength. They are relatively ease in construction and gives significant economic benefits. The favourable compressive strength of the concrete slab and the high tensile strength of the steel beam is a symbiotic configuration to produce a composite beam which has higher stiffness and strength, less deflection and higher span to depth ratio than traditional bare steel or concrete beam (Ataei et al., 2015).

The precast concrete also has gain popularity in construction because the elements are manufactured in a control casting environment and thus quality can be controlled and maintained easily compared to cast-in-situ concrete. However, there is a lack of research about the connecting joint between the precast concrete panels which could lead to a discontinuity of load distribution throughout the slab. Thus, an interlocking joint is implemented in a precast concrete panel of a composite beam with bolted shear connector as a new innovative idea. The joint consists of a tongue and groove shape to gain a better connection at the joint. The structural performance in terms of the load distribution can also be improved by integrating the interlocking key joint in precast concrete slab.

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1.2 Problem statement

Currently, the conventional headed shear stud connector is most commonly used mechanical shear connector in the composite steel-concrete beam due to its reliability and ease of installation. However, the conventional headed stud shear connectors have to be welded to the flange of the steel beam section and the concrete slab need to be cast on top of the steel beam to achieve the necessary shear connection, producing a permanent bond between both bolt and concrete. This type of connection cannot be deconstructed easily and their elements are not recyclable since the concrete slab cast with the stud needs to be demolished. The demolition is wasteful, energy-intensive and environmentally-intrusive, with the reuse of the components being almost impossible (Ataei et al., 2015). Besides, the conventional composite beam which is cast in-situ concrete often requires temporary supports and formwork which leads to a longer construction time. Problems may arise if replacement of concrete slabs is required either for structural (maintenance) or technical reasons (end of the lifetime). Therefore, the idea of using a bolted shear connector with precast concrete slab considered as an alternative to a headed stud shear connector.

The use of bolted shear connector and precast concrete slab can be a perfect combination due to its constructability and de-constructability which is the ease of assembling and disassembling in composite construction. However, the risk of such concrete cracking is often seen to be a greater imperative in the design and detailing of precast concrete slabs, than in cast in-situ concrete slabs. This is likely due to the segmental nature of precast construction and the associated inherent lack of structural continuity at joint locations. Thus, in order to consider and mitigate this issue, an interlocking tongue and groove joint are implemented in the precast concrete slab to improve the continuity of the load transfer between the concrete panels. The size of the shear connector that is commonly used is 16 mm but the use of a higher size of bolted shear connectors with the presents of an interlocking joint is still unknown. Thus, this study is to investigate the effect of using an interlocking precast concrete slab with different sizes of bolt in the structural behaviour of composite beam under flexural load.

1.3 Objectives

This research aims to study the structural behaviour of a composite beam having an interlocking precast concrete slab and steel beam incorporated with bolted shear connectors under flexural load. In order to achieve the aim of the research, the following objectives are:

a. To study the effects of interlocking key joint in a precast concrete slab on the behaviour of composite beam under flexural load using an experimental approach.

b. To examine the effects of different sizes of bolt on the behaviour of composite beam under flexural load using an experimental approach.

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c. To conduct a comparative study between the experimental data of the composite beam with the Finite Element (FE) analysis.

1.4 Scope and limitations

There is various type of components to be used in composite beam but this study focused on the scope of steel-concrete composite beam having an interlocking precast concrete slab with bolted shear connectors. The type of concrete slab applied in this study is the Ordinary Portland Cement (OPC) reinforced concrete slab. The main focus is to study the behaviour at the interlocking joint of the precast concrete slab and compare to those without the interlocking joint. There is also various type of bolted shear connector to be used in the composite beam with precast concrete slab such as the anchor bolt, single-nut embedded nut and bolt with double embedded nut but only the high-strength friction grip bolted shear connector is used in this study. The steel beam used is the hot-rolled steel I-beam. The method to study the composite beam is by experiment and compared the result with Finite Element Modelling (FEM) by Abaqus. The composite beam will be tested under a static flexural test to obtained the ultimate load, initial stiffness, deflection, end slip and flexural strength of the beam. Figure 1.3 shows a summary of the scope and limitations of this study.

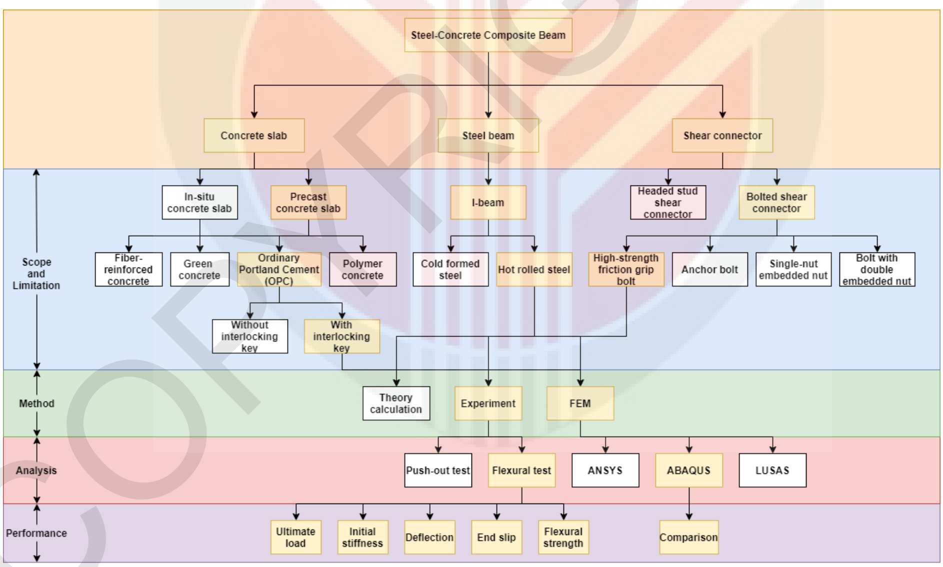

Figure 1.3: Scope and limitations of the study

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1.5 Organization of thesis

The outline of the thesis is divided into five main chapters. Each of the chapters has an introduction to outline the contents and a summary to conclude the findings of the chapter.

Chapter 1 presented a brief introduction of composite steel-concrete beam construction. It provides the problem and solution behind the thesis topic and explains the present situation regarding the progress of the research for composite steel-concrete beams being subjected to flexure. It also identifies the grey areas in the research field and the deficiencies of the past and present research work. The scope of the study has been outlined in this chapter.

Chapter 2 described a detailed literature review on the past and present research work which has been carried out by the other researches regarding the thesis topic. This chapter includes the behaviour of composite beams, the flexural behaviour of composite beams, the conventional shear connector in composite beams, type of bolted shear connectors, factors that affect the composite steel-concrete beam with bolted shear connector and interlocking precast concrete slab. Lastly, the Finite Element (FE) analysis on a composite beam.

Chapter 3 presented the experimental testing procedure of the thesis. This chapter provides the test specimen geometrical and mechanical details, fabrication process, assembling of the composite steel-concrete beam, instrumentation used, test setup and loading procedure of the experimental tests. Material tests were also conducted to determine the material properties of the beam specimens using compression and flexural tests. This chapter also outlined the method of using the Finite Element (FE) analysis to simulate the response under static flexural test for composite steel-concrete beams. The FE method is incorporated into three major phases. They include pre-processing, solution and post-processing. In this chapter, the pre-processing and solution will be explained in detail. The pre-processing, in which the author develops a finite element mesh to divide the subject geometry into subdomains for mathematical analysis, and apply material properties and boundary conditions.

Chapter 4 discussed the experimental results obtained from static flexure beam tests. The test observation and data collected during the experiment are presented and discussed in detail. The discussion includes crack pattern and failure mode, deflection shape, strength in terms of load-deflection of the beams, longitudinal interface slips between the concrete slab and the top steel flange at each end supports of the composite beams and also the effect of interlocking joint and size of bolt. The study on the flexural strength of the composite beam is also discussed in this chapter. Moreover, the results from the three-dimensional (3D) finite element modelling are also discussed and the comparisons are made between the results from FE analysis and the experimental results. The results from the FE models have been compared by the experimental test results in terms of load-deflection response subjected to the static flexural load.

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Chapter 5 provided the conclusions and significant findings of this research project. Moreover, recommendations are made in this chapter for future research to further knowledge of the behaviour of bolted shear connectors in the composite steel-concrete beam.

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