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STRUCTURAL ASSESSMENT OF A PROPOSED PRECAST WALL CONNECTION UNDER COMBINED LOADING

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATION

This thesis is dedicated to my parents.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

STRUCTURAL ASSESSMENT OF A PROPOSED PRECAST WALL CONNECTION UNDER COMBINED LOADING

By

RAMIN VAGHEI

January 2016

Chairman : Farzad Hejazi, Senior Lecturer, PhD
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The industrialized building system (IBS) is defined as a construction technique in which the system components are manufactured in a controlled environment on-site or off-site, transported, positioned, and assembled into a structure with minimal additional site work. The connection of precast components in IBS structures is an important factor that play important role in integrity of building and provides stability to buildings subjected to various loads. However, the stability of the building type constructed using IBS is a challenging issue against dynamic loads. And there is a lack of knowledge when the connections of IBS are prepared particularly when those connections subjected to dynamic load caused by earthquakes. Also, based on extensive review of literature, there is no proper analytical and numerical model that can cater for connections and joints of IBS particularly in wall to wall connection.
Hence, this study proposes a new connection for precast concrete wall-to-wall joints subjected to static and dynamic loads. The proposed system is designed to resist multidirectional imposed loads and reduces vibration effects.

The proposed connection is comprised of male and female steel channels and rubber positioned between of male and female connection to dissipate the vibration energy induced by dynamic load.

In order to evaluate performance of proposed connection during imposed load, analytical model for the IBS structure was developed. For this purpose, constitutive law and mathematical model for the IBS members, including: walls and connections are formulated and finite element algorithm is developed. In order to develop finite element formulation for proposed connection is required to determine stiffness of connection in all 6 degree of freedoms (DOFs). For this purpose, six samples of fabricated wall to wall joint equipped by proposed connection are subjected to pushover test in all 6 DOFs, and six more specimens of wall to wall joint equipped by common connection are fabricated besides in order to compare the performance of U-shaped steel channel connection (i.e. proposed connection) and loop connection

(i.e. common connection). The stiffness values which determined through experimental test for each DOF are placed in the stiffness matrix derived from analytical model for the connection. The developed analytical model is codified and implemented in finite element program in order to perform static and dynamic analysis for IBS structure equipped with proposed wall to wall connection.

Beside the physical model and analytical model of the proposed connection, development of this connection has also been performed through finite element simulation in all degree of freedoms include of translations and rotations. Accordingly, the developed finite element model for the precast wall equipped with proposed connection is subjected to progressive monotonic, cyclic and earthquake loads to evaluate the performance of the proposed connection under static and dynamic excitation and compare with the conventional IBS wall connection in terms of capacity, energy dissipation, stress, deformation, and concrete damages in plastic range.

In general, the results indicated that the capacity and energy dissipation of proposed precast wall connection subjected to monotonic and cyclic load respectively is more than that in the counterpart in all six degree of freedoms (DOFs). Dynamic responses of aforementioned connections show that using proposed wall-wall connection can effectively diminish earthquake effects in buildings and reduce seismic responses. It is concluded that the proposed wall to wall connection can be used successfully in IBS structures subjected to static and dynamic load and able to successfully dissipate vibration effect on IBS structure.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENILAIAN STRUKTUR BAGI SAMBUNGAN SENDI UNTUK DINDING PRATUANG DI BAWAH KENAAN BEBAN GABUNGAN

Oleh

RAMIN VAGHEI

Januari 2016

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Sistem pembinaan berindustri ditakrifkan sebagai satu teknik pembinaan di mana komponen komponen sistem yang dihasilkan adalah dalam persekitaran yang terkawal:- di tapak bina atau luar tapak bina, diangkut, diletakkan dan dipasang ke dalam satu struktur dengan sokongan minimal tambahan kerja-kerja di tapak. Penyambung komponen pratuang dalam struktur IBS adalah satu faktor penting yang memainkan peranan penting dalam integriti bangunan dan menyediakan kestabilan kepada bangunan-bangunan yang tertakluk kepada beban yang pelbagai. Walau bagaimanapun, kestabilan bangunan yang dibina menggunakan sistem IBS, adalah isu yang mencabar terutama dari segi kenaan beban dinamik. Tambahan juga, masih ada kekurangan pengetahuan, tentang sambungan sesuai untuk struktur IBS terutamanya apabila tertakluk kepada beban dinamik disebabkan oleh gempa bumi, kenderaan dan jentera dan berdasarkan tinjauan literatur yang luas, terdapat tiada model analisis dan berangka yang sesuai untuk struktur IBS, terutamanya untuk sambungan dan sendi.

Oleh itu, kajian ini mencadangkan penyambung baru untuk sendi dinding ke dinding konkrit pratuang tertakluk kepada beban statik dan dinamik. Sistem yang dicadang di rekabentuk untuk menanggong beban kenaan perbagai arah dan dapat menurunkan kesan kenaan gegaran. Peyambung yang dicadang terdiri daripada salur keluli "jantan" dan salur keluli "betina" dan lapik getah antara keduanya bagi me-nyah tenaga gegaran dari aruhan kenaan beban dinamik.

Untuk menilai prestasi sambungan yang dicadangkan, semasa dikenakan beban, model analisis struktur IBS telah dibangunkan. Untuk usul ini, undang-undang konstitutif dan model matematik untuk unsur-unsur IBS termasuk dinding dan sambungan adalah dirumuskan dan algoritma unsur terhingga dibangunkan.

Untuk membangunkan formulasi unsur terhingga bagi sambungan yang dicadangkan, adalah perlu menentukan kekejangan sambungan dalam semua 6 darjah kebebasan. Bagi tujuan ini, enam sampel dinding-dinding yang dilengkapi bersama dengan

sambungan yang dicadangkan, direka dan ujian "pushover" dilakukan dalam semua 6 darjah kebebasan dan akhirnya nilaian kekejangan sistem dikenakan. Juga enam spesimen lain direka untuk bersama dinding-dinding yang dilengkapi dengan sambungan yang sama untuk membandingkan prestasi sambungan saluran keluli berbentuk U (iaitu cadangan sambungan) dan sambungan "loop" (iaitu biasa sambungan). Nilai-nilai kekejangan yang ditentukan melalui ujian percubaan untuk setiap darjah kebebasan digunakan dalam analisis model untuk sambungan. Model analitikal yang dibangunkan dilaksanakan dalam program unsur terhingga untuk melaksanakan analisis dinamik tidak boleh berubah untuk struktur IBS dengan cadangan sambungan dinding ke dinding. Model unsur terhingga maju untuk dinding pratuang dengan sambungan yang dicadangkan adalah tertakluk kepada beban monotonic, kitaran dan dinamik untuk menilai prestasi sambungan cadangan semasa excitation dinamik dan bandingkan dengan sambungan struktur IBS konvensional dari segi keupayaan, tenaga dissipation, tekanan, kecacatan dan kerosakan konkrit dalam julat plastik.

Selain model fizikal dan analisis model sambungan cadangan, pembangunan ini juga telah dijalankan melalui simulasi elemen terhad, di semua tahap kebebasan termasuk anjakan translasi dan putaran. Oleh itu, model unsur terhingga maju untuk dinding pratuang yang dilengkapi dengan sambungan yang dicadangkan adalah tertakluk kepada progresif monotonic, kitaran dan beban gempa bumi untuk menilai prestasi sambungan cadangan di bawah excitation statik dan dinamik dan bandingkan dengan sambungan dinding IBS konvensional dari segi keupayaan, tenaga dissipation, tekanan, kecacatan dan kerosakan konkrit dalam julat plastik.

Secara amnya, keputusan menunjukkan bahawa kapasiti dan dissipasi tenaga sambungan dinding pratuang, tertakluk kepada beban monotonic dan beban kitaran, masing-masing adalah lebih tinggi berbanding peranti seumpamanya dalam semua enam darjah kebebasan (DOFs). Maklum-balas dinamik sambungan tersebut di atas, menunjukkan, bahawa penggunaan cadangan sambungan dinding-dinding adalah berkesan mengurangkan kesan gempa bumi di bangunan dan mengurangkan kesan seismik. Dapat disimpulkan bahawa sambungan dinding-dinding yang dicadangkan boleh digunakan dengan jaya dalam struktur IBS yang tertakluk kepada beban statik dan dinamik dan mampu memberi kejayaan menghilang kesan getaran ke atas struktur IBS.

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I certify that a Thesis Examination Committee has met on 19 January 2016 to conduct the final examination of Ramin Vaghei on his thesis entitled "Structural Assessment of a Proposed Precast Wall Connection under Combined Loading" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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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 Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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Declaration by graduate student

I hereby confirm that:

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision; Guide to Thesis Preparation
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CHAPTER 1

INTRODUCTION

1.1 Overview

Precast concrete offers a distinct advantage from the viewpoint of lower costs of construction. The importance of precast construction approaches, also called modern methods of construction (MMC) or particularly addressed in Malaysia as industrialized building system (IBS), has increased since the mid-1990s. The industrialized building system is defined as a construction technique in which components are manufactured in a controlled environment on-site or off-site, transported, positioned, and assembled into a structure with minimal additional site work. The components of IBS structure are floors, walls, columns, beams, and roofs. They are then assembled and erected on the site properly joined to form the final units. IBS utilizes techniques, products, components, or building systems which involve prefabricated components and on-site installation. Figure 1.1 shows different common types of IBS.

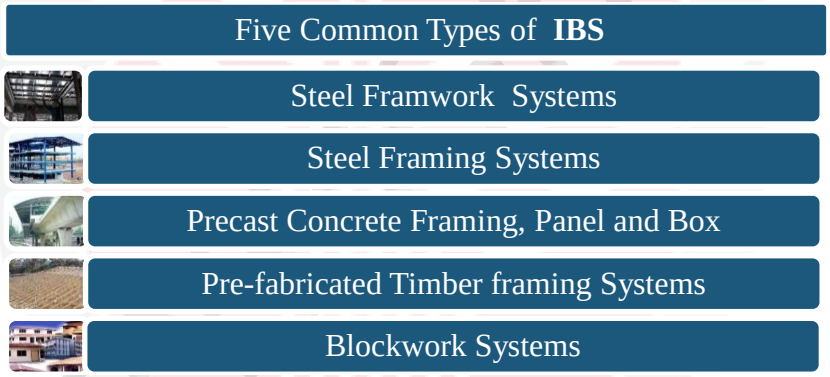

Figure 1.1. Five common types of IBS (CIDB, 2003)

Figure 1.2 illustrates the benefits of industrialized building system as well. A significant contribution in the progress of precast concrete technology is the development of connection details and devices that enhance the simplicity and convenience of erecting and joining together the various precast elements to form a reliable, structurally sound integrated building frame. Joints in IBS buildings are key components to ensure structural integrity of building performance subjected to imposing loads.

Since precast panels are joined together at the connections, the overall performance of the building depends to a great extent on the performance of the connections. It is recognized that distribution of loading to the individual panels depends by a great deal on the behaviour of the connections. Such behaviour is influenced by the deformations in each connection. Depending on the type of loading, the resulting deformations in a connection can change the distribution of forces at the adjoining panel, drastically. Thus, the design and resistance of the precast panels are not the governing factor; rather the connections constitute the weak points in this type of

construction.

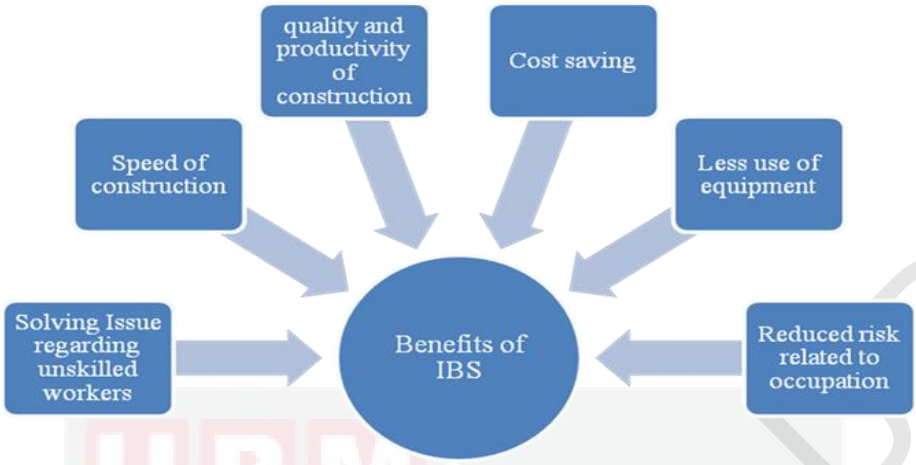

Figure 1.2. Benefits of IBS (CIDB, 2003)

The main structural issue in precast construction is related to the behavior of the connections particularly wall connections among all types of connections and even more crucial when the structure is exposed to seismic actions. Based on the literature which was studied extensively, it can be said that there is shortage of knowledge about the analytical model of IBS structures and connections and there is no numerical fundamental in order to use for modelling and simulation of IBS structures and design under the applying load. Especially there is no proper connection for precast walls subjected to dynamic excitation.
The main hypotheses of this research on the connections must satisfy the following conditions:

(1) The structure must be strong and safe. The proper application of the fundamental principles of analysis, the laws of equilibrium and the consideration of the mechanical properties of the component materials should result in a sufficient margin of safety against collapse under accidental overloads.
(2) The structure must be economical. Materials must be used efficiently, since the difference in unit cost between concrete and steel is relatively large.

In this research an attempt will be made to propose a special precast concrete wall-to-wall connection system for dynamic loads. Furthermore, formulate the constitutive law and numerical model for IBS members and proposed connections. Also, the special finite element model and algorithm will derive in order to elastic and inelastic analysis of IBS structures under imposing loads. Then performance of propose connection for IBS structures is evaluated by conducting experimental test under dynamic loads and severe vibration will design.

1.2 Statements of the problem

From the extensive review of literature it is observed that there is no comprehensive

research on the behaviour of different types of precast concrete connections between the walls under static and dynamic loads. Consequently, there are crucial unresolved gaps in the understanding and assessment of IBS connections including,

- There is no proper IBS wall connection which be able to resist against multidirectional static and dynamic loads.
- Most of the available literature on the behavior of wall-wall joints was dedicated to testing membrane action of the wall connection. However, most studies lacked the accuracy of representing the actual structure's realistic conditions, including the effect of out-of-plane loading. Thus, there is no proper wall connection element addresses all degrees of freedoms in order to develop a robust analytical finite element and constitutive models to simulate a wall joint behavior in reinforced concrete structures.
- Until today, few research efforts were directed to develop computer program code or software for analysis of IBS structures equipped with connections under static and dynamic loads in compliance with the finite element model and constitutive law formulation.

1.3 Aims and Objectives

The current study aims to fill vital gaps in the development and assessment of precast wall connections in Industrialized Building Systems (IBS) subjected to static and dynamic loads. As such, the following objectives are targeted:

- To develop a new connection for precast walls subjected to static and dynamic loading.
- To formulate the proper constitutive model and analytical model and subsequently develop finite element model and algorithm for proposed wall-wall connection in order to perform elastic and inelastic analysis of precast walls' connection and finally implement developed model in finite element program.
- To conduct experimental test and evaluate the capacity of new connection and verify developed constitutive model.

1.4 Scope and limitation

The emphasis in the present study is placed on the wall-wall connection. It should be kept in mind that such connections have, in general, the greatest influence on the overall behavior of precast concrete structures. In order to achieve the above objectives, the present study has been carried out in the following steps:

- In this study , a new developed wall to wall connection designed for six degree of freedom in space. A developed wall to wall connection in IBS structure is extendable for other joint of IBS structure members.
- Analytical model, mathematical model and constitutive model are developed for wall-wall connection subjected to static and dynamic load.
- Finite element technique is implemented for numerical simulation.
- Experimental test have been done for two types of precast wall to wall connections.

Limitations of the present study include:

- Due to complexity of various type of connection in precast structures, only precast walls' connection is investigated in this study and this study cannot be generalized to the whole Industrialized Building system (IBS).
- Tight budgets result in giving up to conduct an experiment test on full-frame building equipped with a connection.
- Conventional concrete, normal steel and natural rubber have been utilized for theoretical and experimental study; however, high strength concrete like UHPC, malleable steel and artificial rubber or rubber like materials might improve the performance of the connection.
- Although drilling effect which occurs due to inplane moment doesn`t have significant effect on overall performance of walls; the last degree of freedom should be derived for wall element and then implemented in its connection.
- Displacement measurement accuracy requirements can approach accuracy requirements similar to those for force or strain measurements, so that the calibration of LVDTs are evitable in order to avoid transducer glitches.

1.5 Organization

The thesis has been divided into 5 chapters and the brief description about each chapter is described as below:

The importance and the definition of the problem chosen for the present investigation have been highlighted in Chapter 1 along with the objectives and scope of the study.

Chapter 2, covers the review of work related to the precast structures, industrialized building system, precast concrete connection, analytical model, inelastic analysis of precast concrete connection.

The methodology of present study is presented in Chapter 3. Development of 3D nonlinear precast wall connection, development of finite element procedure for nonlinear analysis of reinforce frame structures with precast wall connection are also presented in this chapter.

In Chapter 4, three methods have been used to verify and complement one an other. These three approaches are analytical procedure and computer programming, finite element simulation and experimental tests.

Firstly, the incremental iterative procedures for computation of nonlinear response of RC frame with precast wall connection are illustrated through step by step procedure. Then the development special computer code based on the computational scheme has been presented.

Secondly, the developed finite element model for precast wall connection has been reported through analysis of proposed precast wall connection subjected to various loading types including monotonic, cyclic and time history in six different degrees of freedom. The comparisons of results with common precast wall connection are also presented in this chapter.

Thirdly, the test results and discussion of the current experimental investigation are presented in current chapter. The test results are represented by various performance measures of precast wall connection subjected to monotonic loading that are defined in this chapter. The last but not the least one, the verification and parametric study of developed program by comparing the results with FE program was presented in this chapter.

Chapter 5 deals with the major conclusions drawn from the study carried out in the thesis together with the suggestions for further research in this area.

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