NONLINEAR BEHAVIOUR OF BEAM-TO-COLUMN CONNECTION IN REINFORCED CONCRETE INDUSTRIALISED BUILDING SYSTEM

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In the name of ALLAH, Most gracious, Most merciful

To my first teacher, my father

my beloved mother

my patient wife

my gracious aunt, Fatemeh

and my family who respects the knowledge and science.

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ABSTRACT

The connection between beam and column affects directly the integrity of the building structure. In precast reinforced concrete Industrialised Building Systems (IBS), complexity often occurred in the implementation of a new type of beam-to-column connection. This is due to the new IBS arrangement and the consequent new interaction between the jointed elements of beam and column. In this study, an innovative new type of semi-rigid beam-to-column connection, called SMART IBS consisting of beam to column steel connectors and reinforced concrete elements cast together were detailed out. Four full scale experimental tests were conducted to achieve the real behaviour of the connection in H-shape and Cruciform sub-frames. The tests were supplemented with conventional monolithic models representing the moment resisting connection for comparison of structural specifications. Moreover, for obtaining more comprehensive behaviour, nonlinear finite element analysis (NLFEA) using ABAQUS software was conducted. Furthermore, the whole behaviour of IBS using this new connection was researched through 3D linear analysis to include gravitational and seismic time-history loads using SAP 2000 software. The response of the connection was investigated through the study of the ultimate loading capacity, ductility ratio, load-displacement, moment-rotation, modes of failure and crack patterns. The results of this research confirmed that the new SMART IBS beam-to-column connection was a semi-rigid connection with extra beneficial ductility in comparison with conventional reinforced concrete connection. The ultimate strength of the SMART IBS beam-to-column connection was equal to the conventional model. Furthermore, the results of NLFEA were matched up to 90% with experimental tests. In terms of seismic performance, a three dimensional building of SMART IBS seismic performance was better than the conventional reinforced concrete frames.

ABSTRAK

Sambungan antara rasuk dan tiang mempengaruhi secara langsung integriti struktur bangunan. Dalam pra-tuang konkrit bertetulang Sistem Bangunan Berindustri (IBS), kerumitan sering berlaku dalam pelaksanaan sambungan rasuk-ke-tiang. Ini terhasil dari susunan jenis baru sistem IBS dan interaksi baru di antara rasuk dan tiang. Dalam kajian ini satu jenis sambungan inovatif separa tegar dikenali sebagai SMART IBS terdiri dari penyambung keluli dan elemen-elemen konkrit dituang telah diperincikan. Empat ujian skala penuh telah dilakukan untuk menghasilkan tingkah laku sebenar sambungan pada kerangka-sub bentuk-H dan salib. Ujian juga ditambah dengan model monolitik konvensional yang mewakili sambungan rintangan momen sebagai perbandingan spesifikasi struktur. Selain itu, untuk memperolehi kelakuan yang lebih komprehensif kajian tingkah laku struktur analisis unsur tak terhingga (NLFEA) dengan perisian ABAQUS juga telah dijalankan. Seterusnya, kelakuan menyeluruh bangunan IBS dengan sambungan jenis baru ini telah diselidiki melalui analisis tiga dimensi lelurus termasuk kesan graviti dan seismik dengan menggunakan perisian SAP 2000. Kelakuan sambungan telah di kaji melalui semakan kapasiti keupayaan beban muktamad, nisbah kemuluran, anjakan beban, putaran, momen-putaran, mod kegagalan dan corak retak. Hasil kajian ini mengesahkan bahawa sambungan SMART IBS rasuk-ke-tiang adalah sambungan separa tegar dengan berkemuluran tambahan yang memberi menfaat berbanding dengan sambungan konkrit konvensional. Kekuatan sambungan SMART IBS rasuk-ke-tiang adalah sama dengan kekuatan model konvensional. Tambahan pula, keputusan NLFEA adalah berketepatan sehingga 90% berbanding ujian makmal. Dari segi prestasi seismik, SMART IBS pada bangunan tiga dimensi adalah lebih baik daripada rangka konkrit bertetulang konvensional.

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LIST OF ABBREVIATIONS

ACI	-	American Concrete Institute
BIM	-	Building Information modelling
BS	-	British Standard
BSI	-	British Standard Institute
CIDB	-	Construction Industry Development Board
EC	-	Euro Code
ERP	-	Enterprise Resource Planning
FEM	-	Finite Element Method
IBS	-	Industrialized Building System
IBC	-	International Building Code
IBS	-	Industrialised Building System
NLFEA	-	Nonlinear Finite Element Analysis
PCI	-	Prestressed/Precast Concrete Institute
TPS	-	Toyota Production System

LIST OF SYMBOLS

E_c	-	concrete modulus elasticity
f'_c		Uniaxial compression strength of concrete
f_{cm}	-	Peak stress of Concrete
f_{cr}	-	Cracking stress of concrete in tension
f_y	-	Yield stress of steel
f_u	-	Ultimate stress of steel
j_{is}	-	Initial rotational stiffness
K_s	-	Nondimensional stiffness
I	-	Second moment of inertia
l	-	Length
M	-	Moment of inertia
T_1	-	Fundamental period of structure
Φ_y	-	Connection rotation at yield load
Φ_u	-	Connection rotation at ultimate load
σ_c	-	Compressive stress of concrete
σ_t	-	Tensile stress of concrete
ε_c	-	Tensile strain of concrete
ε_c	-	Compressive strain of concrete
ε_{c1}	-	Compressive strain in the concrete at the peak stress
ε_{cr}	-	Tensile strain at concrete cracking
ε_{cu}	-	Maximum strain of concrete
ε_y	-	Yield strain of steel

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Industrialised Building System (IBS) is a construction process that utilizes techniques, products, components, or building systems which involves prefabricated components and on-site installation. Industrialisation has demonstrated to reduce the costs, improve the quality and get complex products available at high quality of finishing to vast majority of people (Richard, 2005). Another definition of IBS by Trikha (1999) is a system in which concrete components, prefabricated at site or in factory are assembled to form the structure with minimum in-situ construction.

According to these definitions, the major benefits of IBS are: better quality control, speed of construction, solving the dependency on skilled labour on site and simplified convenient working conditions at lesser variations. On the other hand, the conventional cast in-situ method for reinforced concrete construction has problems like dirty work and difficulties in wet construction, casting in hot or cold weathers and in-doubt quality control such as durability and strength for end-user.

The main difficulty in performance of an Industrialised Building System (IBS) is the connection design and realisation. Furthermore, the integrity of these structures is dependent on efficiency of their connections. Nonetheless if the entire

IBS component prefabricated with the best quality in factory does not join together properly on site, the system will not behave as a monolithic and ductile structure. This phenomenon will be more obvious where the lateral loads (such as wind or seismic loads) becoming the design criteria.

In this study, a new type of semi-rigid ductile prefabricated reinforced concrete beam-to-column connection, patented as SMART IBS, consists of prefabricated precast reinforced concrete beam and column elements with steel end connectors was studied. Four full-scaled specimens consist of H and cruciform subframes using this connection were tested as well as their equivalent conventional monolithic specimens. Furthermore, for obtaining more detailed behaviour, nonlinear finite element analysis (NLFEA) using ABAQUS was conducted. The whole behaviour of reinforced concrete SMART IBS structure is also studied through linear analysis considering gravitational and seismic time-history loads by using SAP 2000. Load-displacement, load-strain, moment-rotation relationships, modes of failure, crack patterns , ultimate strength, ductility, stiffness and energy absorption capacity are the characteristics that made the structural behaviour of the connection comprehensible.

1.2 Statement of the Problem

In Industrialised Building system (IBS) construction, the success in forming a monolithic structure of moment resisting systems, depends on the execution of beam-to-column connections. Difficulties are often found in newly implemented beam-to-column connections and consequent new interaction between the jointed elements of beam and column.

In this study a new hybrid steel-concrete beam-to-column connection for joining precast reinforced concrete IBS beam and column was studied through experimental test and finite element analysis.

The features of this IBS beam-to-column connection are:

1. Easy and fast installation with fastening four bolts for every beam end
2. No wet work, the connection is not needed to any cast in-situ which is time consuming and dirty and also the dependency on foreign workers will be diminished
3. No welding work at site, results in fast and trusted construction
4. Using both benefits of steel and concrete, ductility of steel in connector regions and solidity of concrete in body of elements
5. Beam replacement ability, flexible connection properties allow the replacement and rehabilitation of damaged beams (probably through earthquake or explosion)
6. Compatibility with architecture, no salient object in the finished view
7. Simplicity of the connection, an innovative hybrid of I shape steel profile at beam ends plus cruciform and cloven box at the ends of IBS reinforced concrete columns

Due to previous full-scale tests many of typical beam-column IBS connections behave as semi-rigid connections, providing semi-continuity to the connected IBS components, reducing sagging moments due to gravity load, as well as enhancing the frame action of IBS skeletal structures. As Elliott *et al* (2004) said Codes of Practice (e.g. BS8110, EC2 and ACI 318) do not cater for these types of connections even though the design and analysis of precast structures are significantly affected by their behaviour. Also EC4, the code of design of composite steel and concrete structures, generally addresses EC3 (the code of design of steel structures) for the assessment of moment-rotation behaviour of composite steel and concrete beam-to-column connections. Although the Precast/Prestressed Concrete Institute (PCI) manual (2010) contains descriptions of typical beam-to-column connections fulfilling many functions, the published test results are available for only a few of them. Besides that, each IBS connection has its exclusive arrangement of joints and elements with different materials that makes each connection's behaviour, individual. On the other hand, reliable connection behaviour can only be properly assessed by experimental tests or proven performance (Loo and Yao, 1995).

Furthermore, in most of experimental tests only the joint part of the beam-to-column connection considered by cantilever manner (cruciform subframe) loading in which a concentrated point load is applied on a part of the beam. In conclusion stated by Elliott *et al* (1998): (i) full-scale testing carried out on cruciform shaped specimens has not allowed the redistribution of hogging bending moments at the end of the beam and only hogging moments at the end points of the beams were studied in cruciform specimens and (ii) the ratio of the moment-to-shear force remains constant in cruciform models while in real structure it is not constant. In this study we modelled the whole beam and two end columns in H-shape subframe with two point loading manner enhancing the practical real loads applied on the structure, as well as cruciform one for better investigation of flexural behaviour such as strength, rigidity and ductility of beam-to-column connection.

In addition, a nonlinear finite element analysis was conducted to investigate the behaviour of this new connection subjected to permanent loads. In fact, the inherent complexity of this new hybrid steel-concrete beam-to-column connection and its connected members needs NLFEA to aid the experimental tests for better explanation of the behaviour of the connection. Furthermore, the deformation of each part of a connection will result in a new arrangement in internal forces. The nonlinear finite element analysis considers this internal forces redistribution.

The degree of rigidity of beam-to-column connection greatly affects the behaviour of the global skeletal structures against gravitational and lateral loads. This effect was investigated by performing 3D analysis of the structures by SAP 2000.

1.3 Purpose of the Study

The purpose of this study was to develop an innovative hybrid steel-concrete beam-to-column connection for precast reinforced concrete Industrialised Building System using experimental and nonlinear finite element analyses.

1.4 Objectives of the Study

The objectives of this study are:

i) To establish full- scale experimental laboratory tests of proposed new SMART IBS in H and cruciform subframes and to study the structural behaviour of this new IBS beam-to-column connection.

ii) To compare the behaviour of the SMART IBS with monolithic conventional reinforced concrete beam-to-column connection through similar full-scale H and cruciform subframes experimental tests.

iii) To carry out a nonlinear finite element analysis (NLFEA) of proposed IBS beam-to-column connection and monolithic one, using ABAQUS software application and comparison with experimental results.

iv) To obtain the comparative global behaviour of the 3-Dimensional frames using SMART IBS and conventional reinforced concrete beam-to-column connections.

1.5 Significance of the Study

From this study, a clear understanding on the behaviour and failure mechanism of a new hybrid steel-concrete connection between beam and column in reinforced concrete Industrialised Building System (SMART IBS) is observed. The results of this study will be beneficial in understanding the performance of the connection and its role in the Industrialised Building Systems. Besides that, the strength of the structure after erection can be predicted too. On the other hand, the safety of the structure after erection can be investigated.

1.6 Scope of the Study

In this study, the full-scale experimental tests of the new hybrid steel-concrete IBS beam-to-column connection were carried out with H and cruciform shape cut-out beam and columns (subframes). The size of the beam and column of both subframes was 300 mm x 300 mm. The H-shape subframe had a 3200 mm clear span and 3300 mm columns height. The cruciform subframe had two 1500 mm length beams in two sides of a 3300 mm column.

The static loads for H-shape and cruciform models were applied gradually in a downward vertical direction and in the form of two points load on $\frac{1}{3}$ of beam length until failure. The loading manner consisted of loading gradually until 10 %, at 2.5 % increasing steps, of calculated failure load then releasing the applied load to zero. At second stage of loading, load was applied step by step to 30 %, was at 5 % increment, of expected failure load then released gradually to zero. Finally, the load monotonically increased at 5% of steps to failure. The loads applied on cruciform shape subframe had two reverse directions at the ends of side beams. Besides that, full-scale monolithic models of those H and cruciform shape subframes constructed conventionally with the same dimensions for the purpose of comparison between IBS models and monolithic conventional ones using similar described point loads as above. The experimental procedures and results are described in chapters 3.6 and 4 respectively.

Furthermore, nonlinear finite element analysis (NLFEA) of all four models had been conducted by ABAQUS finite element software for achieving a better understanding of structural behaviour of them. The NLFEA procedures and results are described in chapters 3.7 and 5, respectively.

Two real size IBS buildings (5-bay, 3500 mm span, 6-storeys, 3300 mm height) consisted of type I: moment resisting frame system without earthquake load and type II: improved moment resisting frame with shear wall system considering the earthquake load was analysed by SAP 2000 software. The application of this connection is focused on the typical house in Malaysia except the earthquake loads. Therefore, the non-seismic loads applied on the elements of the models were taken with reference to Eurocode 1 (2005). The lateral force method using static equivalent earthquake load was implemented based on Eurocode 8 (2008). In addition, the seismic time-history analysis was conducted using earthquake spectra of Bam earthquake in Iran and El Centro in US. The whole structures analysis procedures and results are described in chapters 3.8 and 6, respectively.

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