ANALYTICAL AND NUMERICAL MODELING OF FLUSH END-PLATE CONNECTION SYSTEM WITH BUILT-UP HYBRID BEAM

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To God,

To my beloved

mother and father

My son Mohamed

My sisters and my brothers

My faithful friends and research mates

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ABSTRAK

Tesis ini membentangkan kajian analitikal dan berangka perilaku lenturan sambungan plat-hujung rata dengan rasuk hibrid terbina yang disambung dengan kimpalan separa. Pertama, perisian unsur terhingga (FE) ABAQUS telah digunakan untuk memodel kelakuan tiga dimensi (3D) sambungan rasuk kepada tiang di dalam persekitaran geometri tidak linear untuk empat konfigurasi struktur yang berbeza. Kedua, satu persamaan baru telah dicadangkan untuk menghasilkan hubungan momen-putaran (M-θ) bagi sambungan dengan menggunakan pendekatan penyelarasan parameter-parameter bertaburan linear untuk huraian terma momen maksimum, yang mengambilkira juga terma kekukuhan putaran yang ditakrifkan dengan menggunakan kaedah komponen. Keputusan kaedah FE, persamaan dan eksperimen telah dibandingkan di mana persetujuan dalam hubungan M-θ dan mod kegagalan adalah sangat jelas. Untuk demonstrasi aplikasi persamaan yang dicadangkan, beberapa konfigurasi geometri *European steel i-beams* (IPE) telah dipilih daripada EN10034:1993 yang mana hubungan M-θ yang dihasilkan adalah sepadan dengan model FE. Selain itu, butiran kontur taburan tegasan telah diplot melalui kaedah FE, dan dibincangkan bagi semua model, di mana taraf kritikaliti tegasan bagi semua bahagian telah ditentukan. Kajian ini mendapati bahawa kelakuan putaran sambungan yang dikaji adalah dikuasai oleh bahagian tegangan dan lengkukan web rasuk, yang mana bahagian yang paling kritikal adalah pada bolt dan bahagian berlubang, dengan tegasan bolt berjumlah dua kali ganda berbanding bahagian-bahagian lain. Sumbangan utama kajian ini adalah dalam bentuk pengenalan teknik persamaan novel yang telah disahkan dengan bantuan pemodelan FE tiga dimensi dalam menerangkan kelakuan lenturan sistem rasuk kepada tiang dari segi pembinaan hubungan M-θ yang bukan sahaja murah dari segi komputeran, tetapi juga sangat bermanfaat untuk kajian parametrik.

ABSTRACT

This thesis presents the analytical and numerical investigations of the flexural behavior of flush end-plate connections with built-up hybrid beam connected in a partially welded manner. Firstly, the ABAQUS finite element (FE) software was used to model the three-dimensional (3D) beam to column connection behaviors in a geometrically nonlinear environment, for four different structural configurations. Secondly, a new equation had been proposed to produce the moment-rotation (M–θ) relationship of connections using a linearly distributed multi-parameter fitting approach for the maximum moment term description, taking into account also the rotational stiffness term, which is defined by the component method. The results of FE, equation, and the experimental approaches were compared, from which agreements in the M–θ relationship and the failure mode were strongly evident. For demonstration of applicability of the proposed equation, several geometric configurations of European steel i-beams (IPE) were chosen from EN10034:1993 where the produced M-θ relationship corresponded excellently with those of FE models. In addition, details of stress distribution contours had been plotted by FE, and discussed for all models, from which the ranking of stress criticality of all parts had been determined. It was found that the rotational behavior of the studied connection is dominated by the tension side and beam web buckling, the most critical parts of which are bolts and holed areas, with the stress in the former doubles those in other areas. The main contribution of current study comes in the form of the introduction of a verified novel equation technique validated with the aid of 3D FE modeling for describing the flexural behavior of beam to column system in terms of computationally cheap production of M-θ relationship, greatly beneficial for parametric study.

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LIST OF SYMBOLS

A_s	-	The tensile stress area of the bolt or of the anchor bolt
A_{vc}	-	The shear area of the column
b	-	beam width
$b_{eff,t,wc}$	-	the effective width of the column web in tension
d_b	-	clear distance between beam flanges
d_c	-	the clear depth of the column web
e	-	the distance from the center to center of the radius of a bolt hole
E	-	elastic modulus of steel
$f_{y,i}$	-	the yield strength of member *i*
$f_{y,b}$	-	bolt capacity
$f_{y,wb}$	-	material yield stress of beam web
$f_{y,fb}$	-	material yield stress of beam flange
$f_{y,ep}$	-	material yield stress of end plate
$f_{y,wc}$	-	material yield stress of column web
$f_{y,fc}$	-	material yield stress of column flange
g	-	gage distance
h	-	beam depth
h_{ep}	-	end-plate depth

k_i	-	stiffness coefficient for basic joint component *i*
k_1	-	stiffness coefficient of column web panel shear
k_2	-	stiffness coefficient of column web in compression
k_3	-	stiffness coefficient of column web in tension
k_4	-	stiffness coefficient of column flange in bending
k_5	-	stiffness coefficient of end-plate in bending
k_{10}	-	stiffness coefficient of bolts in tension
L_{eff}	-	the effective length of the T-stub flange
ℓ_w	-	weld length
M	-	moment of the connection
M_p	-	the plastic moment capacity of the connection
M_c	-	moment capicity of the connection
M_{max}, M_u	-	maximum moment of connection
M_y	-	characteristic moment
m_1	-	distance from bolt center to 20% distance into column root or end plate weld with beam web
m_2	-	distance from bolt center to 20% distance into end plate weld with beam flange
$S_{j,ini}$	-	the initial rotational stiffness of the joint
t_{fb}	-	thickness of the beam flange
t_{wb}	-	thickness of the beam web
t_{ep}	-	thickness of end plate
t_{wc}	-	thickness of the column web
t_{fc}	-	thickness of the column flange
W	-	beam section weight
Z	-	the lever arm

μ	-	the stiffness ratio
ß	-	coefficient depending on the thickness ratio of the connected plates
θ	-	rotation of the connection
ν	-	Poisson's ratio
σ	-	stress
ε	-	strain
ξ	-	power parameter

CHAPTER 1

INTRODUCTION

1.1 General

The chief aim of analyzing steel connection is to carry out the theoretical determination of its load-deformation behavior which commonly includes also the ultimate moment resistance. Model formulation and analysis are widely used for steel connection study due to its considerable saving of computational cost and time. Thus far, there are many computational software programs such as ABAQUS, ANSYS and LUSAS and analytical formulation approaches for studying the steel structures. The purpose of using numerical software and analytical formulation is to promote an economic use or rather, if possible, a reduction of experimental work since it is well known that the cost of experimental testing is very high compared with software simulation and analytical model formulation. So far, there are many researches on steel connection carried out to fine-tune the steel structural behavior prediction equation along with the use of software for validation, and hence promote an efficient use in the load-deformation studies. Also, the ultimate moment capacity of connection is of ultimate importance in steel connection studies. Hence, this research focuses on establishing a new methodology to offer analytical equation that works complimentarily with numerical simulation to predict the moment-rotation behavior of connection that involves a beam to column system with a hybrid beam connected to the flush end-plate in a partial welding manner.

1.2 Background

Connection of structural parts has been known since the beginning of the existence of human being on earth. Connection between similar or dissimilar material has been the spine for the creation of useful tools, such as the manufacturing of products and the erection of structures. Even though the points or areas in concern are possibly weak in the formed structural system, its existence is necessary in terms of function, manufacturability, cost reduction and aesthetic (Messler, 2004). Figure 1.1 shows the significance of using steel connection especially the flush end-plate type in an existing structure.

Figure 1.1: Sample of flush end-plate connection (global innovative campus, 2010)

Beam to column connections, which consist of end-plate whether flush or extended, are used widely in the field of steel structures (Owens and Cheal, 1989 and Tahir *et al*., 2009). It is well established that the behaviors of beam are directly influenced by the connection between the column and beam, using the end-plate as the linking component (Maggi *et al*., 2005; El-Rimawi *et al*., 1997 and Fabbrocino *et al*., 1999). Comparatively, as the axial and shearing deformations are small with respect to the deformation due to moment, the moment-rotation deformation can principally be the main characteristic consideration in the description of the behaviors of connection (Tahir *et al*., 2008 and Shi *et al*., 2008). This connection type has been commonly denoted as the semi rigid connection whose actual behavior is expressed using the finite stiffness of the joints (Diaz *et al.*, 2011a).

For the past few decades, the research attention has been centralized on the semi rigid connection since in reality connection can be neither simple nor totally rigid. Most of the studies concern about fulfilling the purpose of gaining better knowledge about the response of semi rigid connection. However, the study on joints using a hybrid beam that is partially welded to the end-plate has not been fully explored. Thus, this study is focusing on the analytical formulation for such a structural system, proposed using a newly developed methodology.

1.3 Problem Statement

The study of beam to column connection which consists of hybrid beam is aimed in the current thesis due to some advantages, such as beam cost reduction, light weight and easy to be custom-made which allows freedom of choice of different designs. It is well accepted that from the experimental study, the actual behavior of beam to column connection can be obtained and therefore leading to a better understanding of the whole structural behavior. However, it is also generally established that the experimental work is unable to cover all important parameters required for characterizing detailed behavior of structures. The main short-comings of experiments are constraint of cost and time (Shi *et al*. 2008). It is not efficient to validate all available connections using experimental test due to cost constraint. Furthermore, experimental test normally needs a complete set of equipment and the cost of fabrication is usually very high. For example, Abidelah *et al*. (2012), Shi *et al*. (2007), and De Lima *et al.* (2004) had studied experimentally beam to column connections using eight, five, and seven specimens, respectively, simply to justify one particular behavior. Moreover, one set of specimen only represents one type of the connection and this is not sufficient for comprehensive understanding of the whole structural behavior. In other words, the change in the connection details requires additionally more tests for exact behavior description. However, change in the connection details can be modeled reasonably accurate using nowadays well established numerical approach, such as finite element method without performing experimental work in a massive manner. Finite element method can be used to validate the experimental result and the cost involved is relatively much cheaper. Moreover, the moment-rotation relationship can be wide ranging, depending on the configuration of components used. Multiple structural configurations can be modeled using a set of well-defined equations. Such technique had been demonstrated in the works of Abolmaali *et al*. (2005) and Khodaie *et al*. (2012) who conducted analytically a full scale study of beam to column connection. Since every new configuration of connection demands conventionally a new set of experimental studies, the current study aims to propose an analytical procedure to circumvent highly laborious nature of both experimental and numerical methods. Therefore, a simple analytical approach can be constructed on the basis of observations made from experimental and numerical outcomes in such a way that the load-deformation relationship of structures with various geometric and material descriptions can be produced in a general fashion.

In particular, the current study selects investigation on hybrid beams with flanges and web that are formed using different material properties, couples with a connection to column that is constructed using a partially welded flush end-plate to show the efficiency of the currently proposed analytical methodology, which did not modeled by Shek *et al*. (2012) in terms of numerical and analytical approaches.

1.4 Objectives of Study

The aim of this research is to produce a simplified analytical model and a numerical modeling methodology for beam to column connection system that uses flush end-plate hybrid beam, which consist the following objectives:

1. To numerically model the beam to column connection with a flush end-plate incorporating hybrid beam using ABAQUS, and validate it with existing experimental results
2. To formulate simple equation that represents the moment-rotation relation for such a connection with the characteristics that conform to the numerical models and experiments
3. To perform geometrical variation study for different connection configurations using the formulated equation
4. To study the stress distribution of the beam to column system, detail of which is exhibited using the finite element model

1.5 Scope of Study

The scope of this research involves the modeling of the moment-rotation relationship for the flush end-plate connection with a built-up hybrid beam using the component method of Eurocode 3 (EC3, 2005) and ABAQUS standard version 6.9 (ABAQUS, 2009), a commercial software package. Only one and two rows of tension bolt set are considered based on the experimental geometry configuration. Table 1.1 shows the types and details of test specimens similarly used in the in the present study.

Table 1.1: Types and details of test specimens

Specimen	Build-up hybrid beam size	Column size	No of bolts (tension bolts-shear bolts)	End-plate size	Bolt size
N1	400×140×41.13/12/5	305×305× 118 UC	4 (2-2)	450×200 ×12	20
N2	500×180×63.59/16/5				
N3	450×160×46.86/16/6		8 (4-4)		
N4	600×200×85.91/16/6				

- Build-up hybrid beam size (beam depth × flange width × self-weight / flange thickness / web thickness)
- Note all dimensions in mm

Also, the investigated connection is of partially welded. The moment-rotation curves obtained from finite element and experiment data of four test specimens are to be investigated and they are used to form the basis for the proposed analytical technique. The proposed analytical equation is established through behaviors exhibited by the type of connection currently explored. Different connection configurations in terms of the number of bolts, and beam geometries are also considered. The details of this research cover the following considerations:

1) Finite element (FE) models are investigated for four specimens using ABAQUS 6.9 which are then compared to existing test results. Each specimen has different geometries. They are two specimens constructed with one bolt row whereas another two are formed with two rows of bolts. Both tri-linear material properties and non-linear geometric analysis are considered in the FE modeling.

2) Simple equation is developed using the same connection configurations of finite element (FE) model and test. In the development of the equation, there are many parameters considered, such as:

   a) All geometrical parameters of connection that include beam depth (h), beam width (b), thickness of the beam flange (t_{fb}), thickness of the beam web (t_{wb}), end-plate depth (h_{ep}), bolt capacity ($f_{y,b}$), the lever arm (z), and the material yield stress parameters of beam web ($f_{y,wb}$), beam flange ($f_{y,fb}$), end-plate ($f_{y,ep}$), column web ($f_{y,wc}$), column flange ($f_{y,fc}$) and welding length (ℓ_w).

   b) Material properties are constant for all specimens.

c) Additional geometry parameters which are in accordance with the Eurocode 3 such as distance from bolt center to 20% distance into column root or end plate weld with beam web (m_1), distance from bolt center to 20% distance into end plate weld with beam flange (m_2), the distance from the centre to centre of the radius of a bolt hole (e) and gage distance (g).

3) Seven sizes of IPE beam (IPE, 1993) are chosen for demonstrating the efficiency of the developed analytical equation. Table 1.2 shows all considered IPE beam geometric parameters where r is the root radius of IPE beam section.

Table 1.2: IPE beam geometric parameters (all dimensions in mm)

Designation	h	b	t_{fb}	t_{wb}	r
One bolt row					
IPE220	220	110	9.2	5.9	12
IPE360	360	170	12.7	8	18
IPE550	550	210	17.2	11.1	24
IPE600	600	220	19	12	24
Two bolt rows					
IPE400	400	180	13.5	8.6	21
IPE500	500	200	16	10.2	21
IPE600	600	220	19	12	24

1.6 Significance of Study

It is envisaged that this research produces a reliable and effective finite element model which can be used for predicting the behavior of the connection of flush end-plate with build-up hybrid beam as such the need for expensive time-taking laboratory tests can be reduced down to some considerable extent. Also, different behaviors from several structural configurations (moment-rotation relationship) can be plotted from the numerical model. Furthermore, the mode of failure that is conformed to experimental observations can be predicted. Subsequently, the validation of both finite element result and experimental existing result can be done. In addition, these results can be compared with theoretical results such as the well-practiced component methods which have been proposed by the Steel Construction Institute (SCI) (1995). The model may be used for both educational and practical applications.

In addition, the currently formulated equation established through a well-defined procedure gives an alternative to structure analysts in modeling the beam to column or rather the moment-rotation characteristic of any steel-based connection. The analytical model aids in circumventing laborious process of both experimental work and numerical model set-up especially when dealing with 3D configuration. A continuous M-θ relation can be formed using only minimized set of numerical / experimental results for verification before generally utilized for wide-ranging use.

1.7 Thesis Organization

The current study aims to produce analytical and numerical methodologies for the moment-rotation behavior of flush end-plate beam to column connection that adopts a hybrid build-up beam. Flush end-plate beam to column connection that uses hybrid beam section with different steel properties are not widely used, since they are more difficult to be designed and analyzed than commonly used standard beam sections. In this study, flush end-plate beam to column connections are investigated using the finite element (FE) simulation and newly proposed equation. Of particular concern is the flush end-plate beam to column connection that employs hybrid beam, which is partially welded between end-plate and beam web.

After introductory chapter, Chapter 2 presents a literature review of the semi-rigid beam to column connection, beginning with Section 2.1 that deals with an overview of the semi-rigid steel connection and following with a brief history of experimental testing and data banking. Exploration of the trends in connection usage until the modern flush end-plate design is presented, giving context to the current study of semi-rigid steel connections, in Section 2.2. Section 2.3 examines some of the connection's types, providing their moment transferring concepts. Section 2.4 considers some literature that describes three main methods currently used, i.e., experimental, numerical modeling and analytical modeling. Section 2.5 is devoted to the partially strength and composite connections, from which some advantages of using hybrid beam in steel structure's connections are shown. Section 2.6 describes the results from major studies of the connection behavior, which give emphasis on the investigation of the moment-rotation relationship.

Chapter 3 begins with the general information about the finite element analysis (FEA) and analytical methods chosen in the current research (Section 3.1). Section 3.2 introduces the experimental setup used to test four specimens of flush end-plate connections using hybrid beam and partially welding, including geometry of connections, which are used in the development of both analytical and numerical works. Section 3.3 describes the full procedure of FE ABAQUS software modeling for all connection's components. The description includes: Material properties including stress-strain curves, assembly of connection's parts, contact interactions, boundary condition, loading and analysis steps, and element type and meshing. Section 3.4 describes the application of Eurocode 3 (components method) for analyzing studied connection. Section 3.5 explains the general proposed analytical equation used in the research. Section 3.6 describes the development of moment equation that integrates with proposed equation. The implementation of parameters considered for proposed maximum moment equation including the fitting procedure is demonstrated. Section 3.7 describes FE, analytical and test results comparison. Section 3.8 explains the additional variation in the connection configuration using IPE beam sections for further exploration of the proposed equation. Section 3.9 is devoted to additional results of stress distribution obtained from the finite element analysis.

Chapter 4 describes the results of FE model and developed equation compared with experimental results from Shek *et al.* (2012). The described comparison include: Comparison of FE and formulae using Eurocode 3 and an improve method with test results in terms of moment-rotation relationship, and comparison between FE and equation approaches employing IPE beam section for both one bolt row and two bolt rows configurations available in IPE 1993. Section 4.2 explains the comparison of failure modes of all test specimens with FE models. The failure modes of structures that use IPE beam sections are also presented. Section 4.3 presents the stress distribution study for both the test and IPE specimens.

Chapter 5 offers the conclusion of the present research as well as some recommendations for future study.

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