# FINITE ELEMENT FORMULATION FOR SEMI-RIGID BEAM-TO-COLUMN CONNECTIONS USING POTENTIAL ENERGY APPROACH

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# FINITE ELEMENT FORMULATION FOR SEMI-RIGID BEAM-TO-COLUMN CONNECTIONS USING POTENTIAL ENERGY APPROACH

MOHD HAIRIL BIN MOHD

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Engineering (Structure)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

APRIL 2011

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# DEDICATION

**Dedicated to my beloved mother, father, families, supervisor, lecturers, STC members and fellow friends.**

## ACKNOWLEDGEMENTS

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## ABSTRACT

This thesis presents the behaviour of semi-rigid connection in the analysis of structural steel frame by utilizing the total potential energy principle. A computer program based on the finite element method was developed using software called MATLAB to simulate the behaviour of semi-rigid connection of a steel frame using total potential energy principle of spring strain energy. Both linear and non-linear moment rotation curves were used to acquire the required solutions for a steel frame under the elastic condition. The results obtained in this study were comparable to the previous findings using the similar finite element method that are available in the literatures. The results of the study were also compared with the experimental results from the literatures where good agreements were observed with not more than 30% differences when adopting the linear moment-rotation curve and not more than 15% differences when adopting the non-linear moment-rotation curve. Therefore, it can be concluded that the behaviour of semi-rigid connection in the analysis of structural steel frame can be well predicted using the finite element method based on the total potential energy approach with the non-linear moment-rotation curve.

# ABSTRAK

Tesis ini membincangkan tentang kelakuan sambungan separa tegar dalam analisis struktur rangka keluli dengan menggunakan prinsip jumlah tenaga keupayaan. Satu program komputer berasaskan kepada kaedah unsur terhingga telah dibangunkan dengan menggunakan satu perisian yang dikenali sebagai MATLAB untuk simulasi kelakuan sambungan separa tegar rangka keluli menggunakan prinsip jumlah tenaga keupayaan tenaga regangan spring. Kedua- dua lengkung momen-putaran lelurus dan tidak lelurus digunakan untuk memperolehi keputusan yang dikehendaki bagi kerangka keluli di bawah keadaan elastik. Keputusan yang diperolehi adalah setanding dengan keputusan lain yang menggunakan kaedah unsur terhingga yang terdapat dalam literatur. Keputusan kajian juga telah dibandingkan dengan keputusan eksperimen dari literatur, di mana keputusan adalah selari dengan rujukan. Keputusan menunjukkan keselarian yang tidak melebihi 30% perbezaan apabila mengaplikasikan lengkung momen-putaran lelurus, dan tidak melebihi 15% perbezaan apabila mengaplikasikan lengkung momen-putaran tidak lelurus. Oleh itu, dapat disimpulkan bahawa kelakuan sambungan separa tegar dalam analisis struktur rangka keluli boleh diramal dengan baik dengan menggunakan kaedah unsur terhingga berdasarkan pendekatan jumlah tenaga keupayaan dengan momen putaran tidak lelurus.

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**SYMBOLS:**

| | | |
|---|---|---|
| $M$ | - | Applied moment |
| $\phi$ | - | Rotation of a connection |
| $\varepsilon$ | - | Strain or constant in classification of a section |
| $E$ | - | Young's modulus |
| $I_b$ | - | Moment of inertia of a beam |
| $I_c$ | - | Moment of inertia of a column |
| $L_b$ | - | Length of beam |
| $L_c$ | - | Length of column |
| $M_R$ , $M_{Rd}$ | - | Moment resistance or moment capacity of a connection |
| $M_u$ | - | Moment ultimate |
| $M_{j.R}$ | - | Moment resistance of the joint |
| $M_{b.pl}$ | - | plastic moment resistance of beam |
| $M_{c.pl}$ | - | plastic moment resistance of column |
| $P$ | - | Concentrated load |
| $S_j$ | - | Rotation stiffness of a connection |
| $S_{j\ ,\ ini}$ | - | initial rotational stiffness of a connection |
| $w$ | - | Distributed load |
| $Z$ | - | Section modulus |

## ABBREVIATION:

| | | |
|---|---|---|
| EC3 | - | Eurocode 3 |
| EC4 | - | Eurocode 4 |
| EEP | - | Extended end plate |
| FEP | - | Flush end plate |
| BS 5950 | - | British Standard 5950 |
| MATLAB | - | Matrix laboratory (programming language for technical computing). |
| SCI | - | Steel Construction Institution |
| BCSA | - | British Constructional Steel Association |
| LRFD | - | Load and Resistance Factor Design |
| ASD | - | Allowable Stress Design Specification |
| FEA | - | Finite Element Analysis |
| PDE | - | Partial Differential Equations |

# CHAPTER 1

# INTRODUCTION

## 1.0 Research Background

Properties and behaviour of semi-rigid connection as well as the need to understand more on semi-rigid connection has created a great interest in the semi-rigid connection analysis and modelling. In Eurocode 3, semi-rigid joint is introduced to enhance the semi-continuous construction in steel frame. Traditionally, the steel portal frame design assumes that beam-to-column connections are rigid or pinned. Rigid connections, where no relative rotations occur between the connected members, transfer not only a significant amount of bending moments, but also shear and axial forces. On the other extreme, pinned connections are characterized by almost free rotation movement between the connected elements that prevent the bending moment transmission. Despite these facts, it is largely recognized that great majority of joints do not exhibit such idealized behaviour. These connections are called semi-rigid, and their design should be performed according to their actual structural behaviour.

Properties or behaviors of connection are presented as moment and connection relative rotation ($M$-$\phi$) relationship as shown in Figure 1.1.

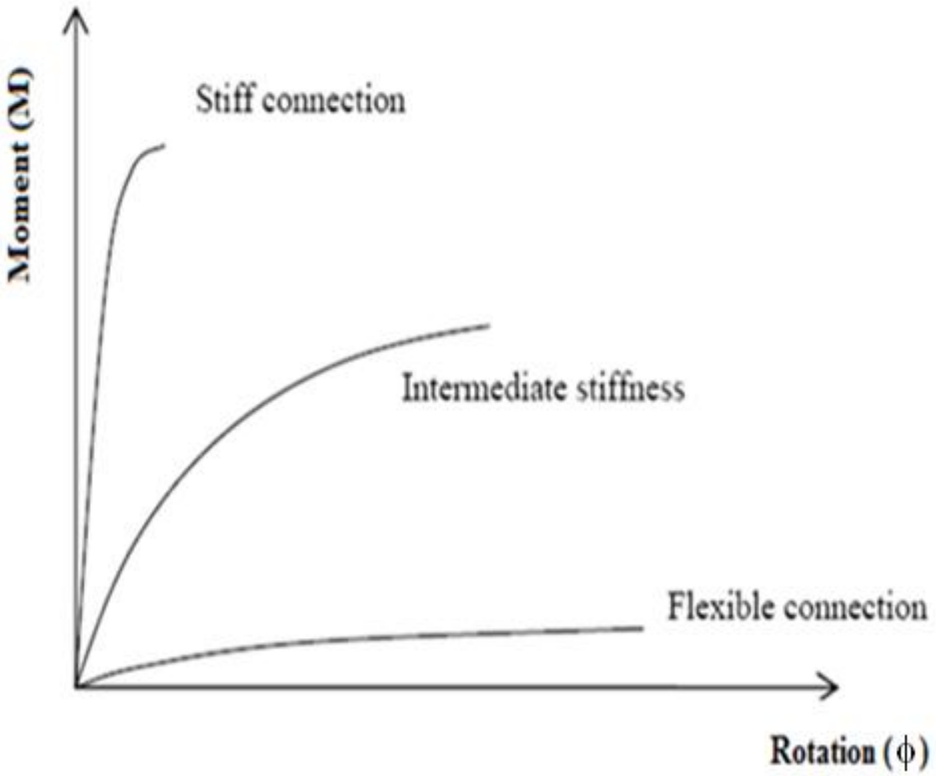


**Figure 1.1:** Moment and rotation (M-ϕ) relationship (Faella et al., 2000).

There are many advantages in semi-rigid joints as compared to rigid or pinned joints however, they are not commonly used because of the difficulties to analyze and model. The advantages are listed as providing sufficient lateral bracing for wind loads in low rise building, making bracing element unnecessary; optimizing the bending moment due to connection’s restrain and minimizing steel weight and overall cost saving (Md Tahir, 1997).

## 1.1 Background of the problem

Steel framework is the most commonly used structural systems in modern construction. Conventional or traditional analysis and design of steel framework basically based on assumption that the connections are either fully rigid or ideally pinned (simple connections). By doing this, calculations and analysis of connections become simpler, but the structural model is not able to reflect the actual structural response. Fully rigid assumption makes it clear that no relative rotation of the connection occurs and the end moment of the beam is completely transfer to the adjacent column. On the other hand, pinned connection implies that no restraint for connection exists and the end moment at the connection is assumed zero (Chen et al., 1996). However, the actual behaviour of the connections used in current practice posseses some stiffness that fall between the two extreme cases of fully rigid and ideally pinned.

Full scale testing on semi-rigid connection tends to be very expensive and time consuming. Therefore, one of the approaches to overcome the cost and time problem are by using connection model.

The use of semi-rigid connection in frame structures is still low as compared to rigid and pinned connections. Therefore, there is a need to encourage builders and designers to implement this concept in order to speed up the construction time, reduced material usage in terms of material weight and also guarantee the quality of the construction.

## 1.2 Problem statement

Most common approach to model the connections in structural analysis is by means of springs attached to the end of the beams at both sides of the joints. These models accurately represent the characteristic of the joint, but they do not take into account the effect of internal and external rotations which are important for analysis under static conditions due to their influence on overall frame behaviour (Krawinkler, 1978). Therefore, an analysis on finite element formulation of semi-rigid beam-to-column connection is conducted by considering the effect of internal and external rotation of beam-to-column connections. Potential energy approach is used to enhance the proposed model.

## 1.3 Purpose and Objective of study

The main purpose of this study is to develop finite element formulation of semi-rigid beam-to-column connections based on potential energy approach. The objectives of this study are as follows:

i. To study the behaviour of connection’s stiffness and moment capacity of semi-rigid connections.
ii. To utilize the potential energy approach in the behaviour of semi-rigid connections.
iii. To validate the formulation of the proposed finite element analysis with the experimental work by Shek (2009).

## 1.4 Research Scope

The behaviour of frame structures is highly influenced by the connections. The analysis of such frames, whether elastic or inelastic, can only be performed with accuracy if the correct joint behaviour is incorporated in the analysis. A computer program (MATLAB) was developed to analyze steel frames by taking into account the effect of internal and external rotations of the connection based on the stiffness method analysis.

Analysis of frame was conducted by using the finite element method based on the potential energy approach. The stiffness matrix used was based on beam–column stiffness matrix by adding the extra element of rotations. This study was limited to the use of linear analysis and tri-linear moment rotation curves by considering different stiffnesses in each stage of analysis. The structural performance was focused on the values moment and deflection at failure. The proposed semi-rigid connections used were focused on extended end-plate and flush end-plate connections. Finite element analysis results were validated by comparing with the available experimental results (in the literature) and work done by other researchers.

## 1.5 Significance of Research

Typically, the behaviour of semi-rigid connections relates to the performance on sub-assemblage frame of beam-to-column connection. In semi-continuous construction design, semi-rigid connection developed an end restrain leading to reduction on beam moment which resulted to lighter beam in many cases (Md Tahir, 1997). The amount of restrain developed from the semi-rigid connections depends on the stiffness of the connection. The term stiffness in each connection nodes can be either modeled as pinned, rigid or semi-rigid case. This leads to the simplicity and effectiveness of the structural analysis. For example, if the stiffness of the connection is equal to zero, the analysis is modeled as pinned joint. However, if the connection stiffness is too stiff and approaches infinity, the connection can be modeled as rigid connection.

The use of semi-rigid connections in building construction has reduced material usage leading to more effective and quicker construction (Hadianfard and Razani, 2003). Studies conducted on semi-rigid connections have proven the savings in material usage while achieving required strength. By utilizing semi-rigid concept, faster construction time could be achieved. Based on these advantages, the structural behaviour of semi-rigid connections could be fully utilized in semi-continuous constructions.

The use of semi-rigid connections also makes available the knowledge of semi-rigid in real situation. Hence, real situation design is applied in the field of construction. Therefore, the semi-rigid concept will avoid over estimation or less estimation of frame structure design and this leads to efficiency in the construction field.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 General

In structural steelwork, the connections between members play an important role. From economic point of view, the costs of design and fabrication have contributed significantly to the total construction cost. However, from structural point of view, the properties of the connections fundamentally influenced the response of the structure to actions. Early study on steel beam-to-column connections was conducted by Wilson and Moore (1917) on the rotational stiffness of steel beam-to-column connections. Although the study of steel beam-to-column connections date back nearly ninety years ago, the interest in semi-rigid action seems to have become more intense during the past twenty years. Researchers traditionally rely exclusively on expensive laboratory tests to understand the behaviour of connection. These tests not only time consuming, but also expensive. In recent years, many researchers have employed the finite element technique to analyze the semi-rigid connections. Besides, a number of powerful finite element software packages are available such as LUSAS, ABAQUS and ANSYS. All of these softwares enable a wide range of engineering problems to be efficiently modeled and accurately analyzed. This chapter briefly explains research work related to analysis and modeling of such connection with finite element method. The classification of steel connection in accordance with the American and European design codes is also discussed. Besides the discussion on finite element analysis and related codes, review on mechanical model to idealize semi-rigid behaviour is also discussed. Connections modeling and finite element semi-rigid connections presented by other researchers are also discussed and highlighted.

Connections, whether welded connections or bolted connections, possess certain degrees of resistance against moments and stiffness and also ductility against rotation, even though, in practice, connections are usually being designed as pinned or rigid. Steel building, on the other hand, are typically categorize into two types of frames. One is braced frames and the other is unbraced frames or moment-resisting frames where the performance of both frames are related to the types the connections used.

To date, emphasis is more on obtaining a balance between the traditionally pinned jointed and rigidly jointed frames either in the aspect of serviceability or the economy. For a pinned jointed frame, beams are assumed as simply supported whilst columns are assumed to sustain axial and nominal moment only. Though the connection is simple, the size of beam obtained from this approach is heavy and deep. On the other extreme, rigidly jointed frame results in heavier columns due to end moments transmitted through the connections. Hence, it leads to a more complicated fabrication of the connections. One approach, which creates a balance between the two extreme approaches, has been introduced. This approach, termed as partial strength connections and used by Eurocode 3 (EC3, 1993) to associate with semi- continuous construction, is referred as connection with moment capacity less than the moment capacity of the connected beam

## 2.2 Steel connection

A steel structure is essentially a collection of individual members that are attached to each other to form stable and safe structure. Steel structural members are attached to each other through a variety of connecting elements, such as angles and plates. Mechanical fasteners or fusion joining process such as welding and bolting are normally used in steel connections. In order to design the connection, the characteristic of the elements and fastening devices must be fully understood. Thus, understanding of the basic behaviour of the connection is essential to engineers (Tarpy and Cardinal 1981). There are three major types of steel connection method; bolt, welded and riveted connection. Bolted connections and welded connections are the two major methods used for steel connections. Bolted connections use mechanical fasteners while welded connections are done by fusion joining process. Riveted connections are almost extinct although riveting was the accepted method used for connecting the members of steel structures for quite a few decades.

## 2.3 Types of connections

Conventionally, in designing multi-storey steel frames, the connection used is either pinned or rigid joint. Ironically, both connections do not represent the actual behavior of the joint where it falls somewhere between these two “ideal” connection. The behavior of joints can be clearly seen by referring to the moment versus rotation curve where the y-axis represents the fully pinned condition. However, in actual situation, the moment-rotation curves for most commonly used connections (refer to Table 2.1 on pages 15 and 16 and Figure 2.7 on page 17) lies between these two conditions. Hence, this type of connections is termed as semi-rigid connections.

EC3 specifies the connections based on the values of the moment resistance they possessed. A full-strength connection refers to the connection that has a moment resistance equal to or greater than the moment capacity of the connecting beam and generally, it is not ductile. A partial strength connection, on the other hand, is the connection that has a moment of resistance less than the moment capacity of the connecting beam and generally, it is ductile. Therefore, adopting the terms used by EC3, the simple, rigid and semi-rigid connections are referred to as pinned, full-strength and partial strength connections respectively. Furthermore, the types of construction of steel frames are termed as simple, continuous, and semi-continuous if pinned, full-strength, and partial strength connections are used respectively. Some of the typical types of connections that fall under the categories of pinned, full-strength, and partial strength connections are shown in Figure 2.1 where it shows the difference between the effects of connection types to the force distribution in a portal frame structure.

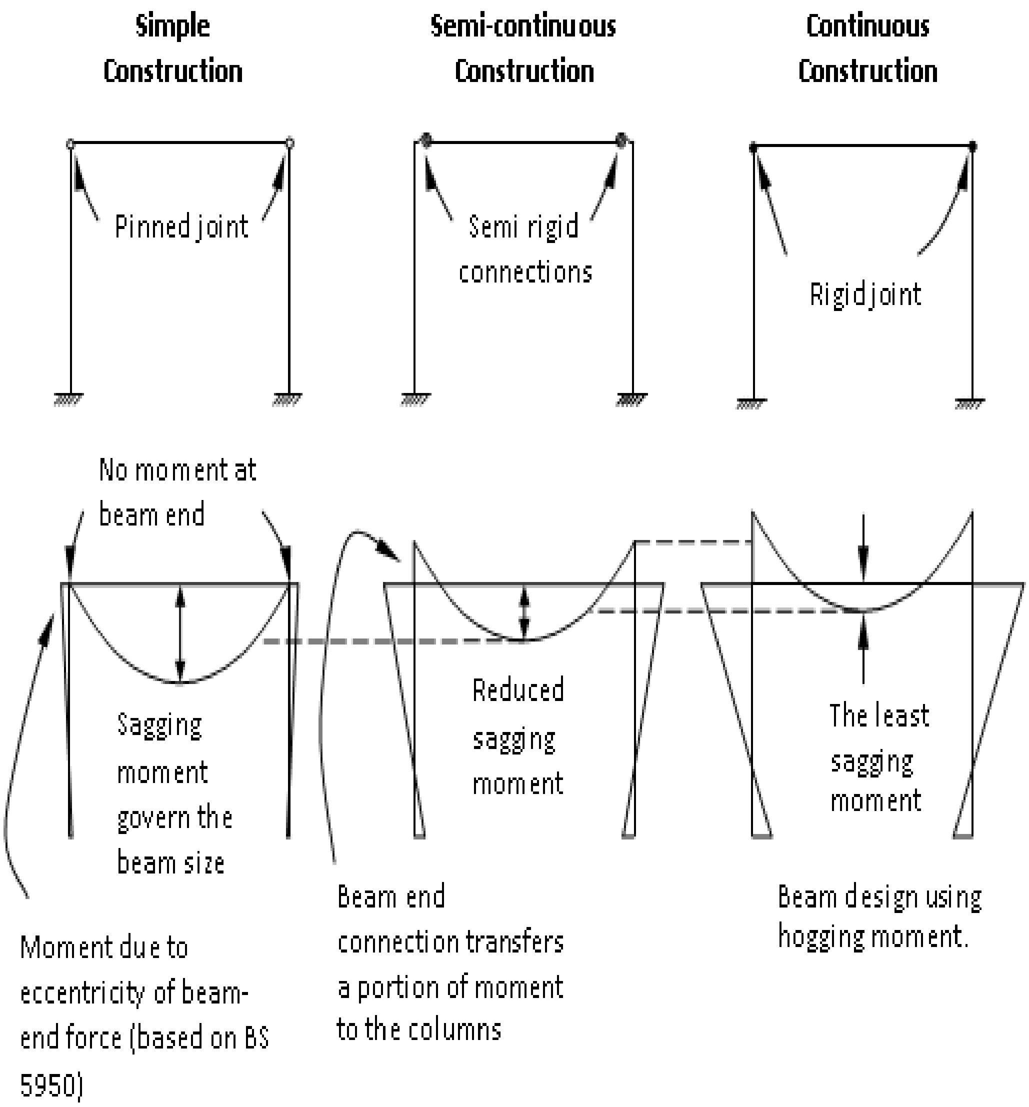


**Figure 2.1:** Moment distribution in various types of connections (Chen et al.,1996).

### 2.3.1 Pinned connections

Pinned connections are the connections that transmit an end shear only resulted from the end reaction of a connecting beam. Also known as flexible connections, they possess sufficiently low stiffness and thus are incapable of transmitting moments an ultimate limit state. In the United Kingdom, the connections are assumed to transmit some nominal moments resulting from the 'eccentricities' of the beam reactions to the columns, but as described in BS 5950-1:2000, the effects of these moments are somewhat offset by using the column buckling length less than the true length. As a result of assuming pin-ended, the design is a bit conservative thus increasing the beam size. A column, in contrast, designed only for axial load, and 'eccentricities' moments has resulted to smaller section. Under pinned connections, there are three common types of the connections that are frequently used:

a) Web Angle Cleat

This type of connection usually comprises of two angle cleats bolted at the web of a beam though single angle cleat is also used normally for small connections or due to limited access around the connections area. Figure 2.2 shows typical double web angle cleats for a beam connected to the major and minor axis of a column.

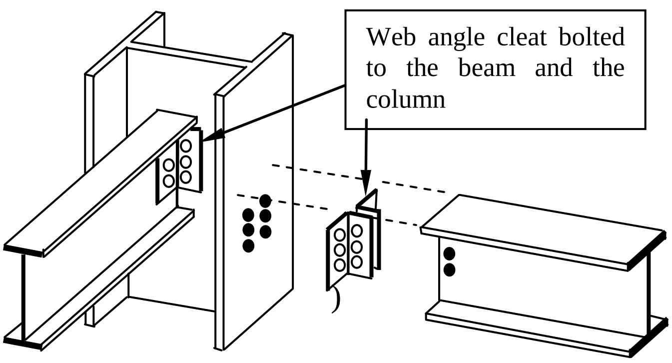


**Figure 2.2:** Web angle cleat connection (Sulaiman, 2007)