THERMAL PERFORMANCE OF AXIALLY RESTRAINED STEEL BEAMS WITH SLANT END-PLATE CONNECTIONS

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To my beloved mother, wife and lovely son,

your courage and compassion have taught me humility.

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ABSTRACT

Steel beams restrained at their ends exhibit lower structural performance when subjected to thermally induce axial expansion. In this regard, the design of the connection plays an utmost essential role in restrained beams in order to dissipate the thermal force. Most existing studies on the thermal behaviour of connections have so far focused only on conventionally vertical end-plate type. This research describes mechanical behaviour of axially restrained steel beams with slant end-plate connection under thermal increase and gravity loads (symmetric and non-symmetric). The analytical, numerical and experimental approaches were used in this study. The analytical method was designed to simplify and simulate the proposed slant end-plate connections based on force equilibrium at the connection. The numerical approach was employed to expand the analytical simplified models by direct stiffness method and 3D finite element computer program (ABAQUS). As a verification, three specimens with different sizes and slanting angles were tested in the laboratory as well as studied using analytical and finite element models. The results of the analytical and numerical approaches as well as experimental tests proved that the slant end-plate connection can successfully reduce the extra thermal axial forces through small upward sliding at the end of the beam on the inclined end-plates. The results demonstrated that the steel beam with slant end-plate connections can reduce the thermal axial stress from 80% to 90% in comparison to the vertical end-plate connections. For the influence of pattern of loading it was concluded that the axial load-bearing of a steel beam under symmetric gravity load is higher than similar case under non-symmetric load at room temperature but, these values are the same at elevated temperature conditions. Based on the good agreement between theoretical and experimental methods, a series of design curves were developed as a safe-practical range for the slant end-plate connections which depends on the geometrical and mechanical conditions of the connection.

ABSTRAK

Rasuk keluli yang dihalang pada hujungnya mempamerkan prestasi struktur yang lebih rendah apabila dikenakan kenaikan haba menyebabkan pengembangan paksi. Dalam hal ini, reka bentuk sambungan memainkan peranan penting dalam rasuk dihalang di dalam menyerap daya disebabkan kenaikan suhu. Kebanyakan kajian ke atas kelakunan sambungan setakat ini hanya memberi tumpuan kepada plat hujung jenis tegak. Kajian ini menerangkan kelakunan mekanikal rasuk keluli dihalang paksi dengan sambungan plat hujung jenis condong dibawah kenaikan suhu dan beban graviti (simetri dan tidak simetri). Pendekatan analisis telah direkabentuk untuk memudahkan dan membuat simulasi keatas cadangan plat hujung condong berasaskan konsep keseimbangon daya pada sambungan. Pendekatan kaedah berangka telah digunakan untuk mengembangkan model analisis mudah dengan kaedah kekukuhan terus dan unsur terhingga 3D didalam program komputer (ABAQUS). Sebagai pengesahan tiga spesimen yang berbeza dari segi skala dan sudut condong telah diuji didalam makmal serta dikaji menggunakan analisis dan kaedah unsur terhingga. Keputusan dari kaedah analisis berangka serta ujikaji membuktikan bahawa sambungan plat hujung condong berjaya mengurangkan daya paksi disebabkan haba melalui gelongsor hujung rasuk pada plat hujung condong tersebut. Keputusan yang diperolehi menunjukkan bahawa rasuk keluli dengan sambungan plat hujung condong boleh mengurangkan daya paksi haba dari 80% hingga 90% jika dibandingkan dengan sambungan plat hujung tegak. Untuk kesan corak pembebanan, dapat disimpulkan bahawa daya paksi bagi rasuk keluli di bawah beban graviti simetri adalah lebih tinggi berbanding dengan beban tidak simetri pada suhu bilik tetapi bernilai sama pada keadaan suhu tinggi. Berdarsarkan kepada perbandingan yang baik diantara teori dan ujikaji, satu siri keluk reka bentuk telah dihasilkan yang memberikan julat selamat yang praktikal untuk sambungan plat hujung condong yang bergantung kepada keadaan geometri dan mekanikal sambungan itu.

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A	-	Cross section of beam
E	-	Young’s modulus
F_f	-	Friction force
I	-	Moment of inertia
K_g	-	Stiffness of simulated spring due to gravity load
K_t	-	Stiffness of simulated spring due to elevated temperature
L	-	Length of beam
M	-	Bending moment
M_p	-	Plastic Bending moment
V	-	Shear force
N	-	Normal reaction of support
P_b	-	Total force of tightening in friction bolts
P_{cr}	-	Critical compressive axial load
P	-	Axial force
P_i	-	Compressive axial load
P_t	-	($P_t = \alpha AE\Delta T$) Axial force due to increase in temperature
P_{tm}	-	Movement axial load due to increase in temperature
P_y	-	Yielding compressive axial load
R	-	Reaction of support based on the friction force
W	-	Distributed load (gravity load)
ΔT	-	Temperature change
ΔT_{cr}	-	Critical temperature change
ΔT_{m}	-	Movement initiation temperature
α	-	Coefficient of thermal expansion
μ_{s}	-	Friction factor
φ	-	Friction angle
θ	-	Slanting angle

λ	-	Slenderness ratio
r	-	Radius of gyration
ΔL	-	Length change in member
η	-	Load level
K_{bt}	-	Stiffness of beam
K	-	Stiffness
ε_{th}	-	Thermal strain
ε_{t}	-	Total strain
ε_{mec}	-	Mechanical strain
N^{*}_{T}	-	Thermal axial compression force
L_b	-	Length of beam
F_a	-	Capacity of axial stress in steel member
f_a	-	Induced axial stress in steel member
F_b	-	Capacity of bending moment stress in steel member
f_b	-	Induced bending moment stress in steel member
F_s	-	Safety factor
F_y	-	Yielding stress
S	-	Section modulus
Q	-	Resultant vector of induced gravity load (total gravity load)
K_g	-	Stiffness of spring due to gravity load
K_t	-	Stiffness of spring due to elevated temperature

CHAPTER 1

INTRODUCTION

1.1 General

1.1.1 Overview of thermal effect hazard

Thermal effects can be one of the most harmful conditions that any steel structures should expect throughout its service life. If not correctly considered, it may result in destruction of the structures, followed by of repair cost and even injury or deaths. With the developing large cities and limitation in occupied field by buildings, it is inevitable to grow up structures to height. Therefore the risk of thermal effects hazard becomes higher. During a fire in a steel structure, temperature increase. It can induce a huge thermal axial force in the structural members before primary material melting. This phenomenon is the main cause of fast structural collapse during fire. For many years the ability of highly redundant steel framed structures to resist the effects of increase in temperature has been undervalued and largely misunderstood. This was first realized when, after a number of real fires in multi-storey composite steel structures structural failure did not occur. Before 1990, research on the thermal resistance of steel structures was mainly focused on isolated members, such as girders, columns and floor slabs, etc. In 1990, a fire occurred in a partly completed 14-storey office block at the Broadgate development in London (Engineering, 1991). From the investigation after the fire attack, it was found that the behaviour of the beams was strongly influenced by restraint provided by the surrounding structural components.

The most remarkable specified weakness of steel structures is reduction in its compressive strength during temperature increase. It is well established that the thermal behaviour has a key influence on steel structural behaviours. The search for an economical resistance method to improve the performance of steel structures due to elevated temperature remains a challenging task that captures the interest of structural engineers. Study on steel structures with confining of axial expansion in fixed beams has been quite intensive in the past decade. Commonly employed existing engineering solutions to address temperature related concerns are in the forms of increasing section area, provision of lateral supports (Usmani et al., 2001), cooling action by air-conditioning and watering (Bailey et al., 1996), and thermal break (Larson and Van Geem, 1987).

1.1.2 Overview of conventional vertical end-plate connections in steel structures

Steel connections play key role in structural behaviour of a steel structure. They provide strong links between the other principal structural components. These connections enable members to work together to guarantee building stability. End-plates are categorized as 'semi-rigid' connections with the end-plate welded to the beam web. End-plate connections are generally used in the construction of multi-storey steel structures because of simplicity in fabrication and assembling and speed of installation. Figure 1.1 shows the typical conventional (vertical) end-plate connections. The end-plate, which may be partial depth or full depth, is welded to the supported beam in the workshop. The beam is then bolted to the supporting beam or column on site. In this kind of connection, beam members need to be fabricated within tight limits. End plates are the most popular of the beam connections at present in use in the world. They can be utilized with slanted beams and be able to tolerate moderate offsets in beam to column joints.

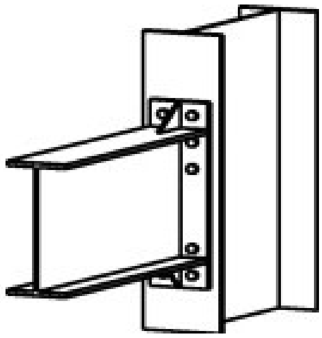

Figure 1.1 Conventional (vertical) bolted end-plate connection (Dessouki et al., 2013)

1.1.3 Overview of thermal behaviour of vertical and proposed (slant end-plate) connections

A steel beam with axially restrained supports tends to have an thermal expansion when it is subjected to temperature increase. Therefore, if the restraints resist against this expansion, the end-supports' reactions will apply extra axial forces in the beam. Figure 1.2 shows the thermal behaviour of conventional end-plate connections at room and elevated temperatures conditions based on the end-supports' reactions. As shown in Figure 1.2, after an increase in temperature, the steel beam tends to buckle due to increase in axial force (P_{cr}), because vertical end-plate connections resist against thermal expansion. The stages of thermal behaviour of the axially restrained steel beam with vertical end-plate connections are : a) beam connections before increase in temperature, b) beam connection after increase in temperature (contact two plates together) and c) beam connection after increase in temperature (buckling or yielding and decrease Young's modules).

On the other hand, when it is used proposed slant end-plate connections (Figure 1.3) instead of conventional connections the generated thermal axial force is reduced. After an increase in temperature, the supports reactions apply axial force to the beam through member expansion. The slant surfaces allow the beam to dissipate the generated axial force and expansion by linear crawling on the slant surface. Most of the times, the elongation of members in elastic range of material is very small although, the induced axial force is significantly large. However, the slant end-plate connection can reduce this huge axial force.

It is noted that in the conventional end-plate connections, bolts with standard or oversize holes are generally used. In the proposed slant end-plate connections, it has been considered oval (slot) shape holes instead of circular to lubricate sliding movement. However, the magnitude of thermal expansion in a steel beam usually is too small and this elongation is measured a half of the overall expansion at each support. Hence, if we use oversized circular holes according to the standard (AISC, 2013), the clearance between bolt and oversized hole is greater than the sliding displacements. Figure 1.4 shows the oval holes that used in the present study for various slant end-plate connections.

The stages of thermal behaviour of the axially restrained steel beam with slant end-plate connections are: a) beam behaviour before increase in temperature, b) beam behaviour after increase in temperature (two plates are in contact), c) beam behaviour after increase in temperature (two plates contact together and in movement) and d) beam behaviour after increase in temperature (buckling or yielding and decrease in Young’s modulus).

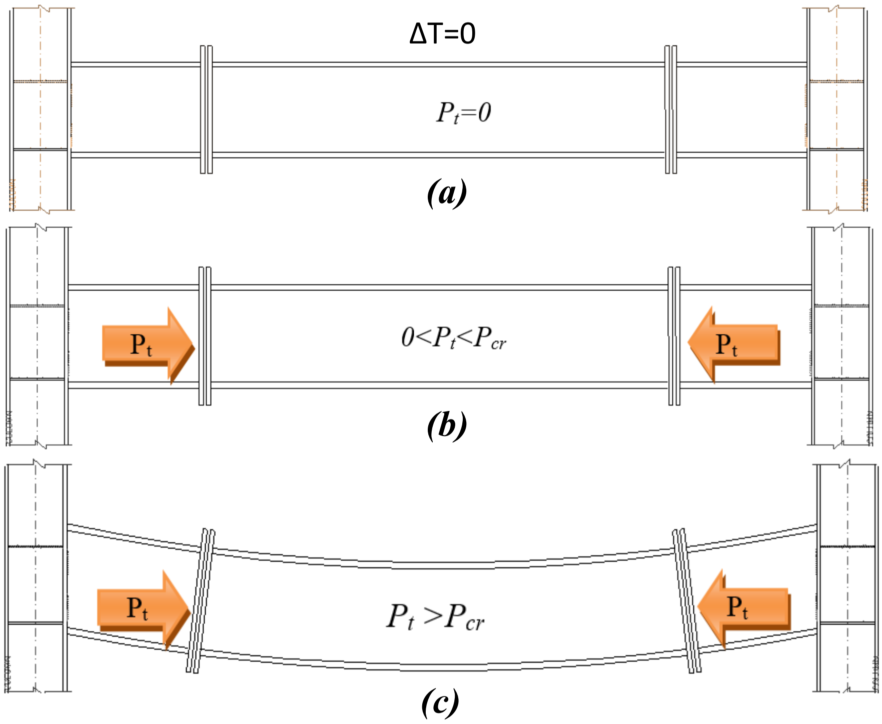

Figure 1.2 Beam with vertical bolted end-plate connection subjected to temperature increase. a) Stage1, b) Stage2 and c) Stage3

Although there is a clearance gap at the bolt hole in vertical end-plate connections, it is unable to absorb the expansion of two ends of the beam in horizontal direction. This is because the direction of expansion is perpendicular to the direction of moving surface. In the slant end-plate connection, there is a slanting tolerance between the surfaces such that it can absorb the expansion of two ends of the beam using crawling mechanism over the slanting faces, because the direction of horizontal expansion can be projected to the slanting plane of connection.

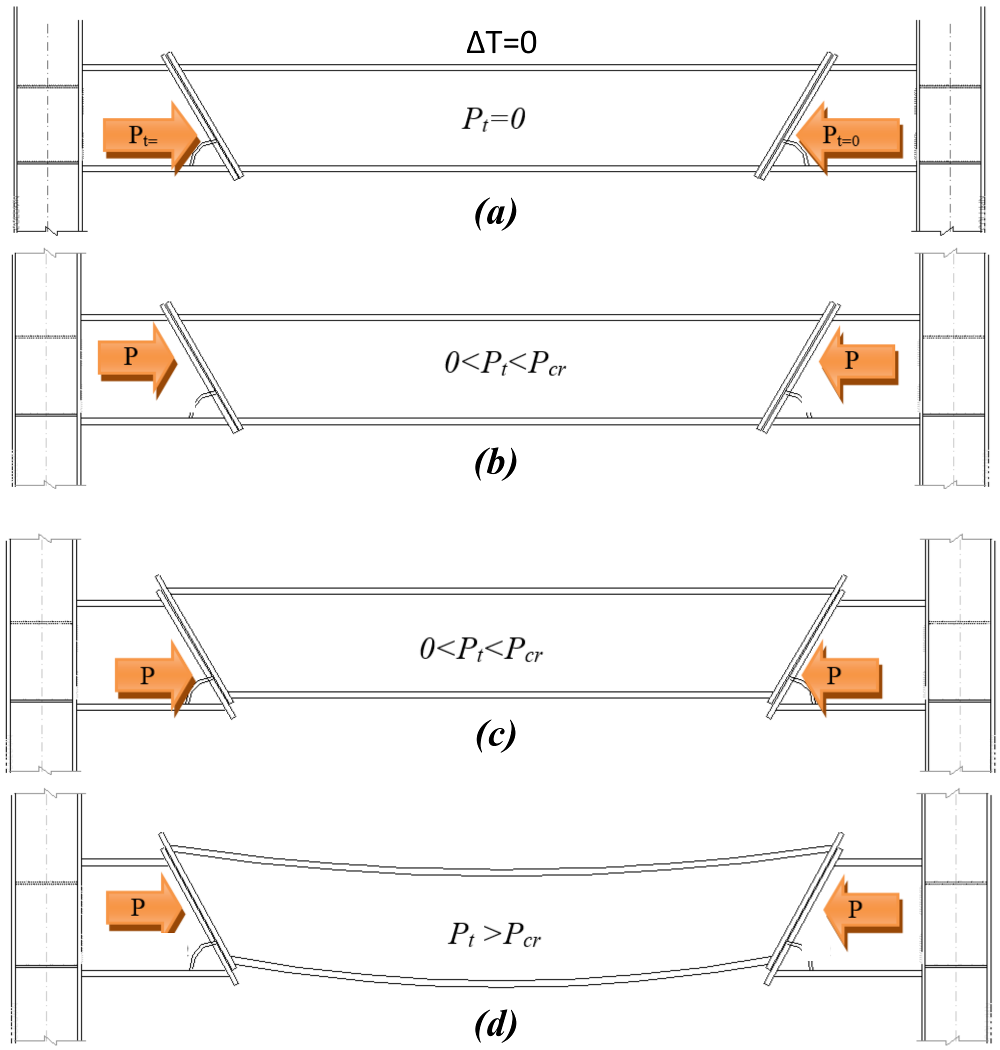

Figure 1.3 Beam with slant bolted end-plate connection subjected to temperature increase. a) Stage 1 , b) Stage 2, c) Stage 3 and d) Stage 4

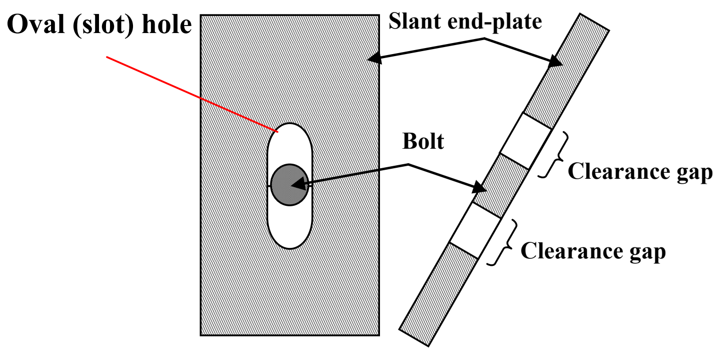

Figure 1.4 Oval (slot) holes detail in a slant end-plate connection

1.2 Background of Problem

In the presence of a real thermal effects on steel structures and an experimental study on the main members due to temperature increase (Bradford, 2006; Heidarpour and Bradford, 2009), it was found that the axial thermal failure behaviour of members occurs in two principal steps: elastic and inelastic. In many cases, the first step is due to the initiation of failure that passes the tangential elastic modulus (Figure 1.5). Mourão and E Silva (2007) found that the expansion of beams due to uniform heating is one of the primary causes of elastic failure. Wong (2005) explored the influence of this expansion by investigating the axially restrained beams under elevated temperature by an analytical method. This analytical study showed that supports’ reaction and failure of a beam when subjected to temperature increase almost depends on the section area, boundary conditions, span, properties of material, and the amount of elevated temperature.

Figure 1.5 Axially restrained beam subjected to elevated temperature (Armer and Moore, 1994)

Thermal expansions of the materials are a vital behaviour that should be considered through the analysis of the heated beam. The steel beam is a structural member that is expected to carry gravity loads. For the beam which is completely or partially restrained axially, the expansion due to elevated temperature can cause a huge axial force, because it is restrained from elongation (ΔL) due to thermal increase. This force can be a demerit for the structural performance. The axial force (P_t) in a restrained heated beam with length L is given by Equation 1 to Equation 3:

$$\Delta L = \left(\frac{PL}{AE}\right) \tag{1}$$

$$\Delta L = \alpha \, L \, \Delta T \tag{2}$$

$$P_t = \alpha A \, E \, \Delta T \tag{3}$$

where *ΔT* is the elevated temperature, *A* is cross section area, *E* is Young's modulus and *α* is coefficient of thermal expansion. From Equations 1 and 2, the axial load due to increase in temperature can be obtained as given in Equation 3. From Equation 3, a heated steel beam with a fully axially restrained supports must have enough strength against the additional axial force. In designing a non heated beam, increase in the section area has direct influence on the amount of member's strength. However, in a heated beam, increase in the section area only, cannot increase strength of beam (i.e. beam member) against the axial load. In such condition, axial force should satisfy by two equations where the first equation presents the stress in pure axial load and the second equation shows the axial load due to elevated temperature (Equation 3). Hence increase in section area has direct relation with strength of the steel beam. However it is just inversely for decreasing of thermal axial force (by increasing of section area, the thermal axial force will increase).

In thermal conditions and after increase in temperature, the thermal behaviour of members' connections can play vital role in failure or vice versa save a steel structure. So far the various steel connections subjected to elevated temperature were studied by many researchers. Simões da Silva et al. (2001) could find an analytical solution for behaviour of steel connection at elevated temperature. Heidarpour and Bradford (2009) improved this study by new 2-D analytical simulation. Saedi Daryan and Bahrampoor (2009) and Qian et al. (2008) validated the theoretical behaviour of steel connections by experimental method. Most of the times, finite element methods can cover various cases of studies in comparison to experimental method. Yang and

Tan (2012) and Díaz et al. (2011b) simulated various steel connections when they are in thermal effects by numerically method.

The results of these studies show that, detail of connections can play an important role in carrying or damping thermal expansion of an axially restrained beam in steel structures. The use of a simplified model for a connection that is described using all effective components has attracted researchers to simulate with maximum efficiency the complicated thermal behaviour of joints. Thus far, most of the researches have focused on the strength and stiffness of moment connections within the elastic regime. Although extensive works have been carried out on the thermal behaviour of steel structures, limited information on the behaviour of slant end-plate connections has been revealed.

1.3 Problem statement

A beam with any type of supports tends to expand when subjected to temperature increase. Therefore when the supports do not allow the beam to have enough elongation, the supports' reaction will induce extra axial force in the beam. In designing steel structures, engineers have to think about ways against thermal effects. Nowadays, the following engineering solutions are common: increasing section area, provision of lateral supports, cooling system by air-conditioning and water, system covering by concrete or isolation and thermal break. These methods are however expensive and uneconomical. In some situations, especially under strong thermal effect due to increase in temperature, these effects can cause the structural damage or even collapse of structure. For the structures that have damping methods the likelihood of damage will be decreased. However, for structures subjected to thermal effects, the natural damping in the structure is not sufficient to decrease the structural response but by damping behaviour of some members such as beams and connections can control and dissipate elongation energy by friction and movement.

From the discussion in problem background, it can be summarised that, many elements should have enough strength against additional axial forces that often induced by elevated temperature. In normal case study on the beam-columns (without thermal effects), based on the basic stress equation, it can be estimated the optimum requirement of section area for designing against axial load. However in thermal case study on the beam-columns, from investigation of relation between axial load and elevated temperature, it is not linear estimation to find optimum section. For example, increasing the section area could not just increase the strength of beam-column against axial load due to increase in temperature, because relations should conform to both, static load stress equation and thermal stress equation. Although extensive works have been carried out on the thermal behaviour of steel structures, limited information on the behaviour of inclined end-plate connections has been revealed. In conjunction, there exists no research on the behaviour of slant end-plate connections subjected to elevated temperature.

The results of this research will be useful for safety considerations on the thermal resistance system in steel structures. Therefore three main questions need to be answered from outcomes as follows:

i) How to reduce the induced thermal axial force by use of a proposed connection (slant end-plate connection) in comparison with conventional connections?

ii) How to protect an axially restrained steel beam from yielding due to elevated temperature under various gravity loads?

iii) How to predict the thermal behaviour of an axially restrained steel beam with slant end-plate connections based on the equilibrium equations and virtual simulations?

Although the number of economical structural solutions for a thermal resistance system are limited in building industry, it is believed that in future, finding a thermal damping system have good potential to reduce manufacturing cost of steel structures against thermal hazard.

1.4 Objectives of study

The purpose of this study is to investigate the performance of vertical and slant bolted end-plate connections subjected to temperature increase by experimental study on the behaviour of these connections in various cases study to compare and verify analytical and numerical methods. The objectives of study are:

i) To determine the thermal performance of steel beams with slant end-plate connections under symmetric and non-symmetric gravity load by analytical method.

ii) To determine thermal performance of steel beams with slant end-plate connections under symmetric and non-symmetric gravity load by numerical methods.

ii) To validate the obtained results from analytical and numerical models by experimental method.

1-5 Scope and range of study

This study focuses on the behaviour of the axially restrained steel beams under various boundary conditions. The boundary conditions consist of gravity loads, temperature, various supports and connection’s bolts. The scopes of study for each case are:

i) Temperature: in the thermal conditions the temperature is considered symmetric-uniform and the value of elevated temperature is limited from 0 °C to 100 °C (elastic range of steel material).

ii) Gravity loads: two types of gravity loads are considered in this study first, symmetric gravity load and second, non-symmetric gravity load. The values of gravity loads in all illustrations and tests are considered based on the allowable range of elastic deflection and Euler Bernoulli beam theory. Therefore, it was ignored from large deflection in the beams.

iii) Bolts: in this research the effects of two types of bolts on the performance of proposed connection is investigated first, normal bolt and second, friction bolt.

iv) Clearance of holes in connection: according to primary assumptions the end-plates' holes at connections are considered slot and oversize for free sliding on inclined plane.

v) Study methods: in this thesis three methods are used to verify primary assumption. First, analytical and finite element approaches are employed to simulate and analyse the performance of proposed connection for various cases and boundary conditions. Second, by the use of obtained results from experimental tests, the determined outcomes from analytical and numerical analysis are validated.

1.6 Significance of Study

The most important benefits of this research that would be gained from the results of study include the following:

i) Slant end-plate connection is a type of connection in steel moment frame structures that with compare as conventional (vertical) types of ones, it has enough ability to dissipate high axial force when a steel beam is subjected to increase in temperature. This ability can protect steel beams and also structures against primary failure in elastic field.

ii) A series of design curves that concluded from obtained results can employ as an application output for designing steel beams with slant end-plate connections in a safe-practical range.

iii) Thermal resistance connection (slant end-plate) can reduce the size of beams' section and also weight of structure to decrease total construction costing with thermal safety when a steel moment frame structure must be design against thermal effects.

These advantages can be obtained just with changing connections' detail by using slant end-plate connection replacing that of vertical. In this study it is shown how this induced high thermal axial force can be damped by friction sliding and movement on the slope surface of end-plate. It will be obtained the optimum design that has enough ability to absorb the huge axial force induced due to temperature increase before any yielding can occur in the beam.

1.7. Thesis Organization

This thesis contains eight chapters which are arranged according to the sequence of the main objectives and illustrative of the study. A brief description on the structure of chapters is provided following:

In chapter 1, it is described a brief background of influence of elevated temperature on steel structures, a reviewing of famous equations of thermal stress on members, definition of vertical and slant end-plate connection in frame and finally main hypotheses of thermal crawling damping behaviour of connections. The end of this chapter includes objective and scope of study and significance of research.

In chapter 2, it is tried to find similar studies about influence of elevated temperature on members of a steel structure and also several methods of study and modelling of connections and latest solutions for thermal and fire resistance systems.

In chapter 3, it is focused on the research methodology and at first it is described about analytical and numerical methods with concentrate on equations and results before any experimental test because it seems to be necessary to estimate experimental results before real test to provide requirement measurement instruments.

In chapters 4 to 6 it is described about three methods with three separate categories. In these three chapters, it is tried to mention details of deriving equations and solve an illustration in analytical methods next used finite element model for numerical method and finally make experimental sample like as illustration model of two previous methods.

In chapter 7, it will be focused on comparison of three methods and verifying results by experimentally methods. In the end of this chapter will be mentioned to advantages and disadvantages of vertical and slant end-plate connections according to previous chapters and comparison.

Finally, chapter 8 will be concluded the outcome of this study and highlights areas where further research can be carried out.

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