SEISMIC AND PROGRESSIVE COLLAPSE ASSESSMENT OF NEW PROPOSED STEEL CONNECTION

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In memory of my Father;

To my Mother, Wife and Son to whom I owe everything I
have achieved in my life

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Finally, I dedicate this thesis to my mother and memory of my father who passed away during my study. In addition, special thanks go to my wife for her support and patience during the period of my study and to my son, who give me real happiness and blessings in my life. Their presence has encouraged me very much to work on my research and to achieve my goals.

ABSTRACT

The disastrous consequences of the partial collapse of the Ronan Point apartment in 1968 and Northridge earthquake in 1994, exposed the vulnerability of steel moment frames subjected to extreme loading. The reports of these two catastrophic events revealed the significant role of beam to column connection where the damage was mainly formed in this area. In this research, the performance of three different steel beam to column connections known as SidePlate, reduced beam section (RBS) and a new proposed “saddlebag” connection subjected to cyclic and progressive collapse experimentally and numerically were investigated. The main objective of this research was to evaluate the adequacy of the new proposed connection to resist extreme loading compared to SidePlate and RBS. Seismic performance evaluation was focused on the interstory drift angles based on 2010 AISC seismic provisions. In the other hand, investigation of progressive collapse was associated with satisfaction of acceptance criteria by rotational capacities of the connections provided in UFC 4-023-03 guideline. The results indicated that the new proposed connection was capable of achieving adequate rotational capacity of 0.2 radians, two times bigger than acceptance criteria, and developing full inelastic capacity of the connecting beams during the progressive collapse analysis. In addition, an excellent cyclic performance was demonstrated by the proposed connection as plastic hinges only appeared in the connected beams at the interstory drift angle of 0.06 radians, 1.5 times bigger than acceptance criteria. The seismic assessment also revealed that the proposed saddlebag connection possess adequate energy dissipation capacity attained by stable hysteretic behaviour into the inelastic range. The study also concluded that SidePlate provide adequate performance as it develop 0.2 radians of plastic hinge rotation angle and 0.06 radians of interstory drift angle to resist progressive collapse and cyclic loading respectively. However, RBS connection showed vulnerable performance to resist seismic and progressive collapse loading where tensile stress mainly appear at the groove welding.

ABSTRAK

Akibat bencana, keruntuhan sebahagian daripada apartmen Ronan Point pada tahun 1968 dan gempa bumi Northridge pada tahun 1994, mendedahkan kelemahan kerangka keluli di bawah tindakan bebanan melampau. Laporan kedua-dua peristiwa bencana mendedahkan peranan penting sambungan rasuk tiang di mana kerosakan adalah sebahagian besarnya terbentuk di kawasan ini. Dalam kajian ini, prestasi tiga sambungan keluli yang berbeza bagi rasuk ke tiang dikenali sebagai SidePlate, mengurangkan keratan rasuk dikecilkan (reduced beam section-RBS) dan cadangan baru "*saddlebag*" di bawah tindakan keruntuhan kitaran dan progresif secara ujian dan berangka telah disiasat. Objektif utama kajian ini adalah untuk menilai kecukupan sambungan baru yang dicadangkan untuk menahan beban yang melampau berbanding SidePlate dan RBS. Penilaian prestasi seismik telah memberi tumpuan kepada sudut putaran antara tingkat berdasarkan peruntukan garis panduan seismic 2010. Di sudut lain, penyiasatan keruntuhan progresif dikaitkan dengan kriteria penerimaan yang memuaskan oleh keupayaan putaran sambungan yang diperuntukkan dalam garis panduan UFC 4-023-03. Keputusan menunjukkan bahawa sambungan baru yang dicadangkan mampu mencapai kapasiti putaran mencukupi 0.2 radian, dua kali lebih besar daripada kriteria yang boleh diterima, dan memberikan keupayan tak-anjal penuh rasuk sambungan di dalam analisis keruntuhan progresif. Di samping itu, prestasi kitaran yang sangat baik telah ditunjukkan oleh sambungan “s*addlebag*” itu di mana engsel plastik hanya terjadi dalam rasuk yang tersambung pada sudut putaran 0.06 radian, 1.5 kali lebih besar daripada kriteria penerimaan. Penilaian seismik juga mendapati bahawa sambungan “saddlebag” yang dicadangkan mempunyai keupayaan pelesapan tenaga yang mencukupi dicapai oleh kelakunan *hysteretic* yang stabil. Kajian ini juga merumuskan bahawa SidePlate memberikan prestasi yang mencukupi kerana ia memberikan sudut putaran ensel plastik 0.2 radian dan 0.06 radian sudut putaran sambungan untuk merintangi keruntuhan progresif dan beban kitaran masing-masing. Walau bagaimanapun, sambungan RBS menunjukkan prestasi terendah untuk menanggung beban seismik dan progresif runtuh di mana tegasan tegangan terutamanya muncul di kimpalan alur.

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LIST OF ABBREVIATIONS

AISC - American Institute of Steel Construction
APM - Alternate Path Method
ASD - Allowable Strength Design
ASCE - American Society of Civil Engineers
ASTM - American Society for Testing and Materials
BWWF - Bolted Web-Welded Flange
DCR - Demand Capacity Ratio
DoD - Department of Defence
ELR - Enhanced Local Resistance
FEMA - Federal Emergency Management Agency
FEM - Finite Element Method
GMAW - Gas Metal Arc Welding
GSA - General Services Administration
IBC - International Building Code
LRFD - Load and Resistance Factor Design
LVDT - Linear Variable Displacement Transducer
MRF - Moment Resistant Frame
RBS - Reduced Beam Section
SMF - Special Moment Frames
SMRF - Special Moment Resistant Frame
UFC - Unified Facilities Criteria

LIST OF SYMBOLS

F - Force
g - Gravity = 9.81 m/s^2
I - Moment of inersia
m_{pb} - Expected flexural strengths of beams in saddlebag connection
v_g - Shear force from connected beams to saddlebag connection plate
m - Mass
d_1 - Horizontal distance between two connection plates
R'_w - weld strength per unit length
k - Plate buckling coefficient
r_y - Radius of gyration about y-axis
b_{fb} - beam flange width
t_{fb} - beam flange thickness
t_{wb} - beam web thickness
θ - Angle
ρ - Density
d_b - Depth of the beam
d_c - Depth of the column
b_{bf} - Width of beam flange
z_c - The plastic section modulus of the column
F_y - The minimum specified yield strength
z_b - The Plastic section modulus of the beam
$\varnothing_d$ - Resistance factor for ductile limit state
$\varnothing$ - Reduction factor of the allowable stress of the weld
t_{wb} - Thickness of beam web
R_y - Adjustment coefficient for material
c_{pr} - Factor to reflect the peak connection strength

s_h - Distance from face of the column to plastic hinge

M_p - Beam plastic moment according to the anticipated yield stress

D_L - Dead load

L_L - Live load

σ_E - Engineering stress

ε_E - Engineering strain

A_0 - Original cross-sectional area

P - External axial tensile load

L_0 - Original length

L_f - Final length

E - Young's modulus

v - Poisson’s ratio

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Significant damage imposed on beam-to-column connections within steel structures after the Northridge Earthquake in January, 1994 raised great concerns in engineering societies[1]. The post-earthquake reports revealed that beam-to-column joints went through rotation levels way below the intended yield capacity of their framing members which was different from the design philosophy of such frames. The steel moment-resisting frame (SMRF) system lost its credibility among engineers compared to other structural systems due to its premature and brittle modes of failure. The Northridge earthquake of 1994 is known to have cost millions of dollars of damage within the building industry.

The damages and deadly outcomes of progressive collapse events throughout history including the 1968 Ronan Point building catastrophe, the in 1995 along with the September 11 attacks to the World Trade Center have raised global concerns among people[2-4]. Such collapses, along with other unpredicted hazards not taken into account during the design phase, indicate the need to secure the inhabitants of residential buildings in case of extreme events. Hence, the performance of structures in case of progressive collapse has become greatly popular among engineering and scientific communities. Progressive collapse is recognized as a chain failure within structural members initiated by local damage or failure due to abnormal loading conditions which ends up in entire or partial collapse of the building [5]. Such abnormal loading conditions might result from unexpected circumstances, with a very low occurrence possibility, high intensity and short time effect like vehicle impact, gas explosions and softening members due to fire.

This study is aimed at the behaviour of beam-to-column connections in case of extreme loading conditions. This is due to the fact that beam-to-column connections have an important function in resisting such loads within steel structures. The objective is to evaluate two beam-to-column connections known as SidePlate and reduced beam section “RBS” to resist progressive collapse and cyclic loading conditions. Eventually, a new proposed steel beam-to-column connection will be recommended and compared against the SidePlate and RBS connections. In the proposed connection, two parallel beams are used to transfer the loads along the column sides where the beam-to-column connection is provided via a plate that is attached to the column flange. The configuration of the new proposed connection is in a manner to make sure that the entire substantial connection deformation/energy dissipation takes place outside the connection welds, plates and the column. This connection hires shop fillet-welded construction and column tree-link beam erection procedure to obtain enhanced cost efficiencies and quality control. This new solution attempts to avoid brittle fracture for any element in a construction system like plates, welds and column. Also, this strategy guarantees that the frame rotational performance could avoid reliance on column web weak panel zone participation. To sum up, this connection incorporates simplified load paths that are not a function of brittle, unreliable and indeterminate behaviour mechanism.

1.2 Background of the Problem

The beam-column joints as critical parts of any structural system is believed to have control over the extent of catenary action as a result of limited rotation capacity and resistance of the joints. Furthermore, based on the inspections conducted after the earthquakes, it has been observed that a great deal of brittle connection damage was incurred on structures, ranging from negligible cracking to fully served columns or beams. This is an indication of the fact that beam-to-column connections within steel moment frames play a significant role in resisting extreme loading conditions. Generally, adequate resistance must be provided by these connections to develop the full capacity in connected beams. This design philosophy is composed of the so-called “strong-column and weak-beam” scenario along with the preferred elastic behaviour in beam-to-column connections. It has been widely accepted that beam-to-column connections are among one of the weakest members in case of extreme loading conditions. This failure mode type in beams from hinges is known as the most appropriate condition for maintaining proper global energy-dissipation with no serious degradation of capacity within the connections. Hence, understanding the behaviour of steel beam-to-column connections is the first step towards controlling the general performance of a structure.

Widespread research conducted in countries throughout the world has revealed the critical aspects of the behaviour of beam-to-column connections. In non-seismic areas, the buildings are mostly designed to bear gravity loads with less consideration towards the lateral load effects. Despite the fact that these buildings are not situated in seismic regions, long-distance explosions or earthquakes could affect these structures. Therefore, this contradiction to seismic design concept would make the beam-column joints of these buildings very vulnerable in case of extreme loading conditions.

1.3 Problem Statement

An old perception within the civil engineering community that states that structural steel frames designed against earthquake loads i.e. moment and braced frames demonstrate a higher resistance towards progressive collapse[6]. This means that seismic detailing and design would be equal to increased performance in case of progressive collapse. Since no design guidelines regarding progressive collapse issue have been published by any institution, practitioners and scientists tend to support the seismic resistant design in occasions where the design objective includes progressive collapse prevention [7]. No systematic study so far has been performed to highlight the role of seismic detailing and design on structural system behaviour in case of progressive collapse. It is noteworthy to mention that an absolutely different kind of demand will be imposed on a structure by seismic forces compared to those imposed by progressive collapse. For instance, high moment demands will be created within the connection region of many moment frames through seismic forces. Yet, as this will be addressed in Chapter 3 in detail, collapse will be accompanied by big tensile forces that could have an adverse effect on behaviour of seismically designed connections. Nevertheless, it has not been mentioned in the literature what kind of beam-to-column connection entails satisfactory robustness to allow the plastic rotation development at beam ends along with significant tensile forces. Hence, there is no evidence regarding the complete prediction of behaviour of seismically designed structures in case of progressive collapse and therefore, it remains an open issue for further investigations for engineers before being recommended for real projects.

Another important issue need to take into account on design procedure of progressive collapse is the dynamic nature of extreme loading. Although the earthquake is considered as dynamic event, extreme loading events like vehicle impact, gas explosions and terrorist suicide attacks are listed as strong dynamic processes entailing very high strain rates occur in flash of a second. A different response is anticipated for filler metal and welding under high loading rates compared to low or static loading conditions that proves the dependence of stress-strain relationship on strain rates [8]. The following is a summary of the main features of this behavior as shown in Figure. 1.1:

i. The ultimate tensile strength rises slightly with strain rate.

ii. A much higher increase is demonstrated by the yield strength, in comparison.

iii. The ultimate tensile strain is able to reduce with strain rate.

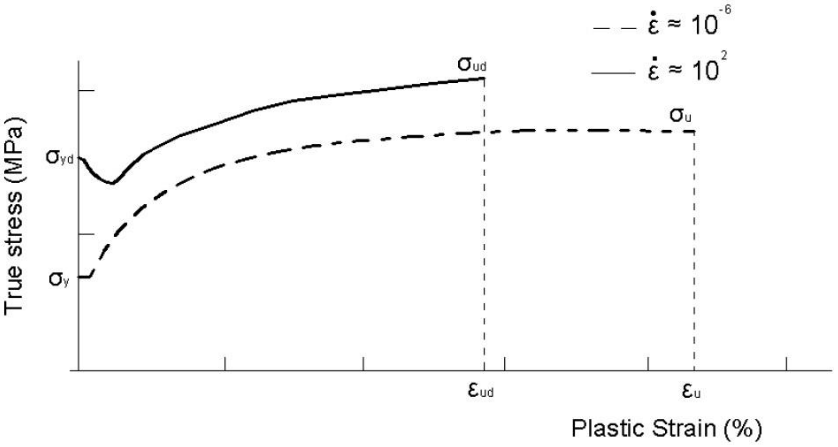

Figure 1-1 Monotonic flow curve for low and high strain rates [9]

Only one steel beam-to-column connection has been introduced so far that fulfils the requirements for both progressive collapse and cyclic loading. This connection is known as the SidePlate moment connection system [11] that was introduced after the disastrous damages of the 1994 Northridge earthquake to secure structures against manmade and natural catastrophes i.e. progressive collapse and bombings. In SidePlate connection, no direct attachment exists between the beam ends and columns; instead, the beams are sandwiched to the column via two resilient full-depth SidePlates. Nevertheless, construction methods and design configurations used by the SidePlate moment connection technology have their own disadvantages in terms of construction. Besides, this connection type entails a field fillet-welded step to connect the cover plates and steel beams which could be hard to control. Thus, incorporation of the innovative feature named the “saddlebag” connection would exclude the drawbacks of the SidePlate along with preserving its advantages.

1.4 Significant of Study

Earthquakes are one of the most feared natural phenomena that are relatively unexpected and whose impact is sudden due to the almost instantaneous destruction that a major earthquake can produce. In the aftermath of the past earthquake, damage to steel special moment frame connections spawned concern about the reliability of established design and construction procedures. A number of buildings experienced damage in beam-to-column connections that underwent only moderate inelastic demands. Failures included fractures of the bottom beam flange-to-column flange complete-joint-penetration groove welds, cracks in beam flanges, and cracks through the column section. The fractures were a result of the basic connection geometry, lack of control of base material properties, the use of weld filler metals with inherent low toughness, uncontrolled deposition rates, inadequate quality control and other factors.

Meanwhile, in recent times many structures have been subjected to blast loads due to acts of terrorism and steel frames form a major part of these targeted structures. Hence the behaviour of structural steel connections subjected to blast loads is of interest. For facilities subjected to blast loads, the connections details have been shown to play a major part in the response of the structure of such high rate dynamic loading. Thus a better understanding of behaviour of structural steel connections under blast loads is very important. The guidelines currently used for the design of structural steel connections subjected to dynamic loads induced during blasts or earthquakes have proved to be inadequate judging from the poor performance of steel frames during the bombings in recent times and also during seismic events like the 1994 Northridge earthquake. Important design modifications were introduced for connections subjected to seismic loads after extensive assessments of the observed damage. However these modified design details might prove to be insufficient when subjected to high rate dynamic loads such as those generated during an explosion. Therefore it is important to assess the behaviour of such structures under blast loads.

The proposed study aims at providing a better understanding of the behaviour of steel connections under blast loads through experimental and numerical simulation. The adequacy of steel connections that were proposed for resistance against seismic loads will be assessed when these connections are subjected to blast loads.

1.5 Objectives of the Study

In the light of current world developments, engineers are increasingly being required to consider extreme loading event mitigations as a basic design criterion. One method of efficiently achieving this goal is to utilize a multi-hazard approach to structural system selections. Besides, the suggested technology should address virtually for any design application and/or condition, making design and implementation an effortless engineering process. The research in this dissertation is aimed at evaluation of the performance of a new proposed “Saddlebag” beam to column connection to resist seismic and progressive collapse loading conditions. In this perspective, the specific objectives of the research are:

i. To assess the performance of the proposed “Saddlebag” connection during progressive collapse.

ii. To assess the performance of the proposed “Saddlebag” connection during the cyclic loading condition.

iii. To assess the energy absorption capacity of the proposed “Saddlebag” connection.

iv. To compare the seismic and progressive collapse performance of proposed “saddlebag” connection with Reduced Beam Section “RBS” and SidePlate moment connection system.

v. To verify the accuracy of the experimental results by comparing the values of plastic rotation angle and cyclic response obtained from the numerical simulation to those obtained from the experimental study.

1.6 Scope of the Study

The experimental and numerical investigation on the behaviour of steel beam-to-column connections in case of column removal scenario and cyclic loading was carried out within the scope stated below:

i. Experimental and numerical progressive collapse assessment was performed under column removal scenario conducted by quasi-static loading (monotonically increasing force).

ii. The seismic evaluation under cyclic loading was conducted by a hydraulic actuator installed at the tip of the beam and simulated with numerical modelling.

iii. The numerical part of the study was conducted using the commercially available software package (Abaqus/Standard) to validate the experimental results.

iv. All the specimens were scaled-down to 1/6th of their real scale and material properties were assumed to be the same for all specimens. The reason to choose this scale was related to the limited capacity and length of reacting frame.

1.7 Structure of the Thesis

Following is a brief description of the 6 chapters comprising this report.

Chapter 1: Introduction. A general overview of the research program is given. The objectives and scope of the current study are highlighted and an introduction to other chapters is presented.

Chapter 2: Literature review. Important topics related to the seismic and progressive collapse are reviewed including: past studies on seismic and progressive collapse of structures; building code requirements for prevention of progressive collapse; structural steels and the process that influence ductile fracture in steels; and current strategies tom mitigate the progressive collapse hazards.

Chapter 3: Design procedure of saddlebag connection subjected to extreme loading. Evaluation of saddlebag connection to extreme loading condition were investigated. Design procedure of saddlebag connection was addressed through a case study example. Design procedure for RBS and SidePlate to address seismic and progressive collapse requirements also considered in this chapter.

Chapter 4: Experimental and numerical simulation. Case studies under investigation were developed for seismic and progressive collapse assessment. Loading protocol and acceptance criteria for both seismic and progressive collapse were explained. Fabrication procedure and modelling setup for each loading protocol explained point by point. Finally the numerical simulation was explained in this chapter.

Chapter 5: Results and discussion. This chapter presents the experimental and numerical results for the saddlebag connection subjected to cyclic and progressive collapse tests conducted in this research. The results grouped into seismic and progressive collapse performance for saddlebag connection and compared to the SidePlate and RBS beam to column connections. Stiffness degradation and energy dissipation capacity of all three connections were also investigated in this chapter.

Chapter 6: Conclusion and recommendations. This chapter presents a brief summary of the report and key conclusions that can be extracted from the research project. It also includes recommendations for the future research for progressive collapse studies.

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