UNIVERSITI PUTRA MALAYSIA

FLEXIBLE SELF-LOCKING INTERMODULAR CONNECTION FOR PREFABRICATED MODULAR STEEL BUILDINGS

NADEEM GOHAR

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By

NADEEM GOHAR

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

May 2022

DEDICATION

To Al-Quran, the greatest source of knowledge

"Such as remember Allah, standing, sitting, and reclining, and consider the creation of the heavens and the earth, (and say): Our Lord! You created not this in vain. Glory be to You! Preserve us from the doom of Fire" (Surah Al-Imran 3: 191)

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To my beloved parents

&

To my son the late Muhammad Ibrahim

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

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Chairman : Nor Azizi binti Safiee, PhD
Faculty : Engineering

The modular building uses factory-built 3D or room-sized volumetric modules. They assemble on site as the building's key structural elements. Compared to conventional construction, modular constructions are different in detailing requirements, construction method, structural performance, and load-transfer mechanism. In conventional steel structures, the structural members have a high degree of connectivity, whereas in modular construction, the modules are connected at their corners only by inter-modular connections (IMC), and these connections are the most vulnerable points of failure. In the connecting region, numerous small beams and columns meet together, which poses new challenges to structural design. Currently, the inter-modular connections are pinned connections, which are provided in the form of a connection plate and a high-strength bolt. An access hole in the column is provided for the erection of the bolt, which causes cross-sectional loss of the column and is unfavorable for the "strong column-weak beam" seismic design concept, leading to unfavorable failure mechanisms which can threaten the entire structure. This study proposed a self-locking connection to address these issues of IMCs. The proposed connection uses a simple mechanism of spring to be fixed, does not require extra workspace between modules, and is suitable for interior, exterior, and corner joints. Proposed connection comprises of upper and lower adapters, flat spring, spring pin, center plate and middle plate the center plate and adapter are welded together; the flat spring is free at the one end to move, while it is fixed through welding at other end. The adjacent module in internal as well as exterior joint are connected by middle plate. The middle plate is positioned on top of the upper adaptor, the upper adaptors are inserted through square spaces providing on middle plates. Dowel pins are provided at each corner of the center plate to allow for the alignment of the modules that are joined to the middle plate during assembly. The distance between floors beam as well as the ceiling beam is similar as total thickness of middle plates and the center plate. This interconnection will transfer the primary failure locations away from important structural parts like columns and provide adequate seismic load stress mitigation. The connection components can be fabricated off-site and assembled on-site. Finally, this would result in a multistory modular building structure entirely manufactured off-site and assembled as a full-frame capable of withstanding gravity and lateral loading. Experimental tests were performed to verify and analyze the strength and the predicted ductile failure pattern of the newly proposed inter-modular connections. The details of the test specimens were selected based on a six-story modular residential building design; a height of 3m and width of 3.6m of the module was considered. T- shaped specimens were fabricated to simulate the corner joint of MSB; half of the original height and width of a module was adopted presuming that beam and column inflection points coincide at the center length of the member. Under monotonic and cyclic load, three full-scaled specimens were tested to compare the joints' mechanical behaviour. Extensive numerical studies were carried out utilizing established methodologies for finite element modeling to investigate and compare the proposed connections in terms of seismic response and slip mechanisms with those of a standard inter-modular connection currently used in steel modular buildings. Finite element models were discretized by employing the appropriate mesh elements. Due to the higher accuracy, all parts were modelled with brick elements (hexahedral) For steel modelling a nonlinear steel behavior signified by bi-linear stress-strain relationship was considered. Furthermore, the surface-Surface technique was employed to define property between bolt shank, bolt hole and surfaces of the plates. Parametric sensitivity analyses were conducted to determine the parameters and the components that influence the performance and failure mechanisms of the proposed connection. The experimental and finite element analyses show that the proposed intermodular connections have better seismic behavior across a range of response characteristics, including moment-carrying capacity, energy dissipation capacity, and ductility. The ductile failure patterns were observed among beams, with no severe plastic deformations in critical structural components like columns or joints. The findings provide ideas for the design and analysis of intermodular connections that meet the requirements of entirely modular buildings. This research will lead to considerable improvements in the dynamic response and life safety of modular structures subjected to lateral loads in general and seismic loads in particular.

Abstrak tesis yang dikemukan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

SAMBUNGAN ANTARA MODULAR TERKUNCI- SENDIRI YANG FLEKSIBEL UNTUK BANGUNAN PRA-FABRIKASI MODULAR KELULI

Oleh

GOHAR NADEEM

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Bangunan modular menggunakan 3D atau modul volumetrik bersaiz bilik binaan kilang. Ia dipasang di lapangan sebagai elemen struktur utama bangunan. Berbanding dengan pembinaan konvensional, pembinaan modular adalah berbeza dalam memperincikan keperluan, kaedah pembinaan, prestasi struktur, dan mekanisme pemindahan beban. Dalam struktur keluli konvensional, anggota struktur mempunyai tahap ketersambungan yang tinggi, manakala dalam pembinaan modular, modul disambungkan pada sudutnya hanya dengan sambungan antara modular (IMC), dan sambungan ini adalah titik kegagalan yang paling terdedah. Di kawasan penghubung, banyak rasuk dan tiang kecil bertemu, yang menimbulkan cabaran baharu kepada reka bentuk struktur. Pada masa ini, sambungan antara modular adalah sambungan pin, yang disediakan dalam bentuk plat sambungan dan bolt berkekuatan tinggi. Ruang akses dalam tiang disediakan untuk pemasangan bolt, yang menyebabkan kehilangan keratan rentas tiang dan tidak sesuai untuk konsep reka bentuk seismik "rasuk lemah-tiang kuat", yang membawa kepada mekanisme kegagalan yang tidak menguntungkan yang boleh mengancam keseluruhan struktur. Kajian ini mencadangkan sambungan kunci kendiri untuk menangani isu-isu IMC ini. Sambungan yang dicadangkan menggunakan mekanisme pegas yang mudah untuk diperbaiki, tidak memerlukan ruang kerja tambahan antara modul, dan sesuai untuk sambungan dalaman, luaran dan sudut. Sambungan yang dicadangkan terdiri daripada penyesuai atas dan bawah, pegas rata, pegas pin , plat tengah dan plat tengah plat tengah dan penyesuai dikimpal bersama; pegas rata adalah bebas pada satu hujung untuk bergerak, manakala ia tetap melalui kimpalan di hujung yang lain. Modul bersebelahan dalam sambungan dalaman dan luaran disambungkan oleh plat tengah. Plat tengah diletakkan di atas penyesuai atas, penyesuai atas dimasukkan melalui ruang persegi yang disediakan pada plat tengah. Pin dowel disediakan di setiap sudut plat tengah untuk membolehkan penjajaran modul yang disambungkan ke plat tengah semasa pemasangan. Jarak antara rasuk lantai dan rasuk siling adalah serupa dengan jumlah ketebalan plat tengah dan plat tengah. Penyambungan ini akan memindahkan lokasi kegagalan utama dari bahagian struktur penting seperti tiang dan menyediakan pengurangan tegasan beban seismik yang mencukupi. Komponen sambungan boleh dibuat di luar tapak dan dipasang di tapak. Akhir sekali, ia akan menghasilkan struktur bangunan modular berbilang tingkat yang dikeluarkan sepenuhnya di luar tapak dan dipasang sebagai kerangka penuh yang mampu menahan graviti dan beban sisi. Ujian eksperimen telah dilakukan untuk mengesahkan dan menganalisis kekuatan dan corak kegagalan mulur yang diramalkan bagi sambungan antara modular yang baru dicadangkan. Spesimen ujian telah dipilih berdasarkan reka bentuk bangunan kediaman modular enam tingkat; modul ketinggian 3m dan lebar 3.6m telah dipertimbangkan. Spesimen berbentuk T telah direka untuk mensimulasikan sambungan sudut MSB; separuh daripada ketinggian dan lebar asal modul telah digunakan dengan mengandaikan bahawa rasukdan titik infleksi tiang berlaka pada titik tengah anggota. Di bawah beban monotonik dan kitaran, tiga spesimen berskala penuh telah diuji untuk membandingkan kelakuan mekanikal. Sambungan kajian berangka yang meluas telah dijalankan dengan menggunakan metodologi yang telah ditetapkan untuk pemodelan unsur terhingga untuk menyiasat dan membandingkan sambungan yang dicadangkan dari segi tindak balas seismik dan mekanisme gelinciran dengan sambungan antara modular sedia ada yang kini digunakan dalam bangunan modular keluli. Model unsur terhingga telah dibangunkan dengan menggunakan elemen jaringan yang sesuai. Disebabkan ketepatan yang lebih tinggi, semua bahagian telah dimodelkan dengan elemen bata (hexahedral), Untuk pemodelan keluli, kelakuan keluli tak linear yang didefinasikan oleh hubungan tegasan-tegangan dwi-linear telah dipertimbangkan. Tambahan pula, teknik permukaan-permukaan digunakan untuk mendefinasikan sifat antara batang bolt, lubang bolt dan permukaan plat. Analisis sensitiviti parametrik telah dijalankan untuk menentukan parameter dan komponen yang mempengaruhi prestasi dan mekanisme kegagalan sambungan yang dicadangkan. Analisis eksperimen dan elemen unsur terhingga menunjukkan bahawa sambungan intermodular yang dicadangkan mempunyai kelakuan seismik yang lebih baik merentasi julat ciri tindak balas, termasuk kapasiti pembawa momen, kapasiti pelesapan tenaga dan kemuluran. Corak kegagalan mulur diperhatikan di antara rasuk, tanpa ubah bentuk plastik yang teruk dalam komponen struktur kritikal seperti tiang atau sambungan. Penemuan memberikan idea untuk reka bentuk dan analisis sambungan antara modular yang memenuhi keperluan bangunan modular sepenuhnya. Penyelidikan ini akan membawa kepada peningkatan yang ketara dalam tindak balas dinamik dan keselamatan hayat struktur modular yang tertakluk kepada beban sisi secara am dan beban seismik khususnya.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

F_{sRd}	Design Slip Resistance
F_{slip}	Total Slip Load
I_b	Moment of Inertia of beam
K_e	Elastic Stiffness
K_s	Secant Stiffness
K_{slip}	Initial Slip
L_b	Length of Beam
M_j	Design Moment Resistance of Joint
M_n	Maximum Moment
M_p	Plastic Moment
Sj_{ini}	Initial Rotational Stiffness
θ_u	Rotation Capacity of joint
σ_{cr}	Elastic Critical Plate Buckling Stress
μ	Displacement Ductility Factor
3D	Three dimensional
AISC	American Institute of Steel Construction
ASTM	American Society for Testing and Materials
ATC	Applied Technology Council
E	Modulus of Elasticity
EVD	Equivalent Viscous Damping
FEA	Finite Element Analysis
FEM	Finite Element Model
FEMA	Federal Emergency Management Agency

HC	Horizontally Connecting
IMC	Inter Modular Connections
IMF	Intermediate Moment Frame
MC	Modular Construction
MSB	Modular Steel Buildings
MSC	Modular Steel Constructions
PFC	Parallel Flange Channel
SHS	Square Hollow Section
SMF	Special Moment Frame
VC	Vertically Connecting

CHAPTER 1

INTRODUCTION

1.1 Background

Modular construction (MC) is a growing concept in the construction industry that can produce built environment buildings at considerably higher standards than traditional construction methods (Kim, 2019). Three-dimensional or room-sized volumetric units usually are fitted out at a factory and transported to the site as the primary structural parts of the building in modular construction. (Lawson, & Ogden, 2014).

Modular construction is ideal in facilities with repeating units, such as residences, schools, offices, dorms, hotels, and hospitals. Because of the repeating modules, the benefits of modular construction will be enhanced for high-rise applications. (Lawson, Ogden, & Bergin, 2012). There has been an increasing trend in modular building when the cost of labor and unaffordable housing is a significant concern for post-disaster emergency lodging and hospitals. In a recent example, a post-disaster hospital in Wuhan, China, was successfully built in ten days using modular steel construction, assisting in the fight against the virus COVID-19 (Deng et al., 2020). The Little Hero apartment complex in Melbourne, Australia as shown in Figure 1.1(a), Croydon Tower in the United Kingdom, the Clement Canopy in Singapore, and B2 Tower Hudson Yards in Brooklyn, New York, are among the world's major modular buildings. However, modular construction has also been extensively applied for low-rise buildings over the last three decades(Gunawardena, 2016; Jellen & Memari, 2013; Thai et al., 2020).

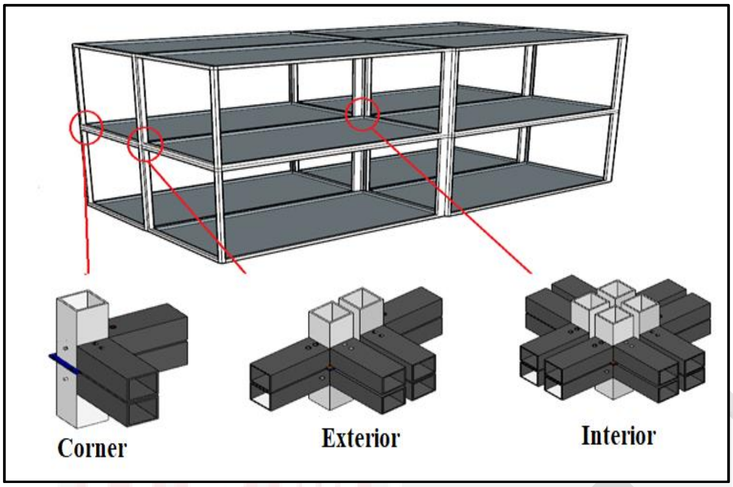
(a) **(b)**

(c)

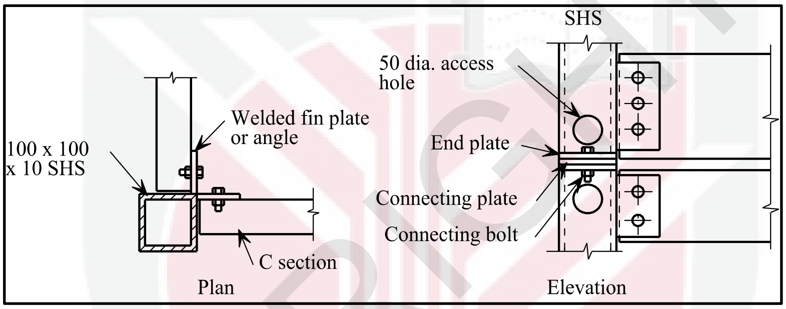
Figure 1.1: Modular Buildings:(a) Little Hero apartment building. (b) Modular hospital building (*portakabin*) (c) Housing building (*portakabin*)

A joint is defined as the zone in which two or more members are connected. For structural design, the joint includes each of the components needed to model the structural behaviour given the applied actions. For example, in a traditional steel structure the beam-column joint (BCJ) includes the column web panel and the adjacent connections. In modular steel structures, the joints between modules are known as the inter-module joints (IMJs). There are three different types of IMJ which can occur in a modular structure depending on the location: corner, end, and internal. The IMJs are made up of the Inter Modular Connections (IMC) and the adjacent portions of the columns. The BCJ includes the beam-to-column connection and the adjacent portion of the column. The length of the IMJ depends on the vertical distance between the floor and ceiling beam centrelines. Vertical space between the beams provides easy access to the IMCs and allows services, e.g., air conditioning ducts, to run between the beams. The size of the IMJ varies among different modular structures. Some structures have a small gap between the beams, while other structures have a very small gap or no gap. Even with zero gap between the beams, however, the distinction between the IMJ and the IMC remains valid, and it can be likened to the BCJ which includes the beam-to-column connection plus a portion of the steel members (Lacey et al., 2022a). Compared to conventional construction, modular constructions are different in detailing requirements, construction method, structural performance, and load-transfer mechanism (Chen et al., 2017; Deng et al., 2018). The design and construction guidelines for modular structures are not well-established yet to address the unique structural systems. Hence, available building construction guidelines are adopted to design modular construction which lacks to provide different designs for these two different structural systems. Consequently, inter-modular connections are now built to withstand gravity loads, and it is predicted that they will provide an effective load path for horizontal shear and diaphragm forces (Sendanayake, 2020). Despite their widespread use, Modular Steel Constructions (MSC) are mostly used in non-seismic locations. This is partly due to a lack of research on the seismic performance of MSC connections, which is critical to structural stability and desired lateral resistance (Deng et al., 2018). As a result, modular buildings cannot be designed, erected, or studied in the same way traditional buildings can. An investigation into the research sector focuses on the significance of their dynamic performance. Therefore, designers and construction engineers are hesitant to allow a module assembly to stand alone. On the other hand, most modular structures are made up of lateral load resisting systems such as in-situ reinforced concrete / monolithic steel cores podiums bracing systems (Park & Ock, 2016; Lawson, 2010).

In conventional steel structures, the structural members have a high degree of connectivity. In modular construction, the modules are connected at their corners only by inter-modular connections; these connections are the most vulnerable points of failure. In traditional steel frame structures, a continuous single column section continues from the base of the first story to the rooftop. These columns are vertically connected using several methods in traditional practices, such as splices, base and cap plates, and welding; by contrast, in Modular Steel Buildings, the entire structure has many sub-structures, and each structural unit has its frame system. In the connecting region, numerous small beams and columns meet together Figure 1.2(a), and this arrangement poses new challenges to structural design (Chen et al., 2017). In Figure 1.2a, the corner joint has two columns and four beams, the exterior joints have four columns and eight beams, and the interior joint has eight columns and 16 beams. Each modular unit member must be properly connected to ensure the transfer of lateral loads, axial forces, and bending moments generated from external loads. A connecting plate and a high-strength bolt make the intermodular connections between modules. The provision of an access hole for the erection of the bolt results in cross-sectional loss of the column, as shown in Figure 1.2(b). which is undesirable for the "strong column-weak beam" seismic design concept. Presently, bolted or welded end plate connections that are in practice as intermodular connections are pinned connections that do not meet the structural requirements of modular steel structures subjected to seismic effect. In recent years, research to avoid access holes in columns has been done. Modules connected to one another simply by beams and connections; this method resulted in sections of disconnected columns, which proved to be undesirable (a gap between higher and lower columns) when dynamic lateral stresses were applied.(Chen, Liu, Yu, et al., 2017; Dai et al., 2019). It was mention in these studies that the separation between column caused pinching effect which resulted in loss of stiffnes of the joints. A further disadvantage of these inter-modular connections is that they offer the structure with insufficient and restricted energy-dissipating capacity. The incapability to deform in a ductile way results in adverse failure mechanisms, which might compromise the integrity of the entire structure. (Deng et al., 2018; Sendanayake, 2020).



(a)



(b)

Figure 1.2: Connections in modular steel buildings (a) Position of Inter Modular Connection (b) Details of connection for current IMC
(Quale, 2017)

In a steel frame, beam-column joints are vital to ultimate bearing capacity, normal service capacity, and structural collapse. In traditional steel frame structures, some or all beam-column joints are manually welded on-site, deviating from the design. In the 1994 Northridge Earthquake in the U.S., beam-column joints joined by welding indicated damage or brittle fracture, and some structures collapsed as a result. It wastes resources and generates economic losses, affecting building restoration and urban functions. Through reasonable building structure design, fully assembled steel beam-column joints can reduce or eliminate on-site welding (Li & Huang, 2022).

These probabilities demand research into novel types of connections that are more suitable for modular steel buildings than conventional connections. Consequently, this research is intended to propose connection for steel modular buildings that do not need access holes in columns, which can fix efficiently between modules and can provide adequate seismic performance by mitigating the damaging consequences of column failure and shifting the key points of failure from the columns to the connecting beams (strong column-weak beam joint).

1.2 Problem Statement

In earthquake-prone areas, modular steel structures are extremely vulnerable. They are questionable in terms of habitability. Their weakness is heightened by weak intermodular connections that cannot support low-to-high-rise structures without in-situ external lateral load resisting systems, deprecating the benefits of modular construction. Off-site manufactured with cladding interior and exterior finishes, the three-dimensional volumetric modules are inherently robust and rigid as required for handling, transport and erection without any damage caused during that process. The dynamic lateral load (such as from earthquakes and wind) resisting performance of the assembled modular building relies on the inter-modular connecting system. The inter-modular connections, which usually consist of plates, welds, and bolts, are currently in use. These connections are not specifically designed for modular frames and are unable to undergo ductile deformations and energy dissipation. The modules are bolted through a cross-shaped connection plate. However, these types of joints are difficult to be used for interior joints, Figure. 1.2(a) because of no operation spaces for middle columns in between modules. An access hole is provided for the erection of the bolts, which causes cross-sectional loss of the column and is unfavorable for the "strong column-weak beam" seismic design concept.

Due to a lack of information about their dynamic response, the connections are not designed to resist wind and earthquake loads. Dynamic (time-dependent) earthquake stresses affect a structure based on earthquake-induced ground vibrations and its natural frequency, stiffness, and mass (Beards, 1996). Inter-modular connections are a modular frame's weakest point. Unlike conventional monolithic steel structures, modular components are only connected at their corners horizontally and vertically and are discontinuous everywhere (Annan et al., 2009; Ogden et al., 2012; Lawson et al., 2008). While individual modules have more rigidity and strength in their box-like frames for transport and assembly, the somewhat weaker inter-modular connections determine the system's integrity and robustness (Yu, 2016). Due to module discontinuity, the connections allow units to spin and deform independently, causing significant pressures on vertical and horizontal connections and creating inter-storey drifts. During earthquakes, resonance effects amplify this. In a modular system without shear walls or cores, failure of these connections will cause partial or entire module collapse. A fully modular system (without shear walls or cores) must have robust module connections to sustain structural stability during an earthquake with substantial time-varying loads (Sendanayake, 2020).

Current building codes Eurocode3 (BS EN 1993-1-8, 2003), American National Standard (ANSI/AISC 341-10, 2011a) and Australian Standard (AS 1170.4—2007) do not provide criteria for an assessment of the design and seismic capacity of inter-modular connections. In recent years research has been conducted to avoid access holes in columns, modules connected through beams and connections only; this approach made unconnected columns regions, which proved as problematic (separation between upper and lower columns) under the application of dynamic lateral loads. Therefore, the behavior and reliability of intermodular connections must be investigated and predicted, and a specialized connection must be developed that has the strength and performance needed to generate ductile failure mechanisms and mitigate seismic loads in modular steel structures.

These considerations necessitate research into new types of connections that are better suited to modular structural systems than traditional connections. As a result, the focus of this research is to propose a new self-locking connection that can be installed between modules without requiring an access hole or additional space between modules, as well as to improve the seismic performance of steel modular buildings by reducing adverse effects of column failure and shifting the main failure locations (if any) away from the columns to the beams. The performance requirements of inter-modular connections within a lateral load resisting system that is not braced by shear walls will be investigated in this study.

1.3 Aims and objectives

The aim of this research is to propose a new self-locking connection that can be installed between modules without requiring an access hole or requirement additional space between modules, as well as with improved seismic performance for the construction of steel modular buildings in seismic-prone areas. In this regard, the following objectives are set out.

1. To develop, design and fabrication of a new self-locking inter-modular connection that can be jointed between modules with limited access restrictions.

2. To conduct experiments on new self-locking inter modular connection and characterization of connection in terms of strength, stiffness, ductility and energy dissipation capacity under monotonic and cyclic loading.

3. To develop a detailed 3-D finite element analysis of new self-locking connection and to conduct validations, parametric studies and characterization of finite element models under monotonic and cyclic loading in terms of strength, stiffness, ductility and energy dissipation capacity.

1.4 Scope of the study

This study proposes a new self-locking inter-modular connection to be used in prefabricated modular steel structures. The contributions of the present study include experimental and numerical studies by which the proposed connection is optimized, and its performance and failure mechanisms are investigated. In line with the recommendations of ATC-24 (Applied Technology Council, 1992) and cost consideration of this project, this study is conducted by experimental testing of 3 specimens. The specimen ES1 (without stiffeners) was subjected to monotonic loading.

The value of yield force Q_y was measured to conduct a cyclic loading on identical model using FEA. While due to the seismic point of view, the specimen ES2 (with stiffeners) was tested under monotonic load to know the yield force Q_y. In third specimen ES3 the cyclic loading was applied to the ES3 utilizing the yield force Q_y determined from ES2 specimen. Furthermore, the validation of FEA with experimental specimens revealed the satisfactory results which made a confidence to conduct extensive parametric study by FEA, while 3D finite element simulation techniques were used in investigating the effect of influencing parameters on the connection performances through a parametric study. The experimental tests are conducted on a symmetrical portion of the external joint, which may also reflect internal and external connections behavior. The results and conclusions presented in the research will only cover corner-supported type modules utilizing hollow sections as columns and beams.

The performance indicator data obtained from the parametric sensitivity analysis can be used as a potential guideline for designers as applicable to the inter-modular connection and other heights and forms of modular frames of the same inter-modular connection can be evaluated using the finite element modeling techniques used in this study.

1.5 Significance of the study

There is a substantial knowledge gap in the understanding of Modular Steel Building's structural behavior, and many of the buildings are therefore essentially over-designed to ensure their safety and structural stability. This knowledge gap becomes more significant in medium to high-rise buildings. When subject to lateral forces, the connections that transfer these lateral loads are critical to the safety and stability of the system. The understanding of behavior against both wind and earthquake forces is essential in this respect. This study explores the way of reducing the adverse effects of critical response parameters of dynamically loaded modular buildings by strengthening the inter-modular connections to exhibit an expected strength and ductile response and ensuring that failure mechanisms move away from the column or joint panel to the ceiling beam and avoid excessive damaging of inter-modular structure. Furthermore, the concept of the self-locking mechanism of the proposed connection eliminates the access requirement in between modules which will result in the use of hollow sections as columns without reducing their area.

The outcomes of this research will also include the development and implementation of novel inter-modular connections that will be able to provide modular building systems with the required ductile energy dissipation mechanisms. An enhancement to the limited literature on advanced modular connection systems would be new insights from the experimental research evaluating the real behavior of the proposed connectors.

1.6 Hypothesis of the study

Based on the literature review, prior examination, and preliminary analysis the hypothesis of this study was developed that presently intermodular connection are provided with an access hole in the column which causes significantly reduction in cross sectional area of column, and that separation between columns produces which affects the performance of modular joint. A self-locking mechanism by utilizing mechanical spring in intermodular joint can be used to address the issues associated with unconnected region in column-beam joint. This new type of mechanism will provide a better seismic performance.

1.7 Thesis Outline

This thesis is divided into five chapters, each of which is summarized as follows:

Chapter 1: This chapter covers the background of the study, the research problem statement, the research aims as well as its objectives, the scope and limits of research, and the significance of the research.

Chapter 2: This chapter includes the literature review of existing intermodular connections. Similarly, this chapter highlights the geometric designs of existing modular connection and their capabilities, structural performances, and current design practices for modular steel construction.

Chapter 3: This chapter explains the research methodology adopted in this research. The research methodology consists of preliminary finite element analysis, an experimental program, and the parametric study through numerical analysis.

Chapter 4: This chapter discusses the results of experimental and numerical studies that were used to assess the proposed connection's performance in terms of response characteristics, including ultimate moment and rotation capabilities, ductility, stiffness degradation, and energy dissipation.

Chapter 5: This chapter presents a summary of the research's major findings, contributions, and conclusions. Future work recommendations are also presented.

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