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Effect of using Rubber in Base and Joint Connection on Structural Performance of Steel Frame Under Cyclic Loading

A Thesis Submitted to Council of College of Engineering, the University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Structural Engineering

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CERTIFICATION

I certify that the thesis entitled **" Effect of using Rubber in Base and Joint Connection on Structural Performance of Steel Frame Under Cyclic Loading"** is prepared by **" Qader Abdulsattar Mohammed "** under my supervision at the Department of Civil Engineering-College of Engineering-Diyala University in partial fulfillment of the requirements for the Degree of **Master of Science in Structural Engineering.**

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

﴿أَفَمَنْ أَسَّسَ بُنْيَانَهُ عَلَىٰ تَقْوَىٰ مِنَ اللَّهِ
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يَهْدِي الْقَوْمَ الظَّالِمِينَ﴾

صَدَقَ اللهُ العَلِيُّ العَظِيم

من سورة التوبة – آية (109)

Dedication

To the soul of the greatest and most precious person in my heart, to my dear mother, may God have mercy on her, who always wanted me to succeed in my life and complete my master's studies.

To my wife, who has supported me during my journey, I would not have been able to do it without you.

To My beloved children are a source of my inspiration and happiness.

Qader Abdulsattar Mohammed

2022

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Abstract

The world in general and Iraq in particular are exposed to many earthquakes, which cause damage, destruction and death when it occurs. The poor design and construction of buildings that meet seismic design requirements, as well as, the maintenance that needs a long time and high cost, it has become necessary to develop an alternative method that is simple to install with lower costs in comparison with other methods, such as using the smart connection technology of using rubber-steel bolts in steel structures.

This study is divided into two parts. The first part includes a numerical analysis of the previous studies using the Abaqus program for three experimental models; the results show a high degree of convergence between the experimental and numerical programs. The second one includes a study of the behaviour of models with rigid connections for five groups and a group of variables using the finite element method. The first group represents models by using rubber washers of different thicknesses in the beam-column connection under a horizontal cyclic load whereas the second one represents the interaction effect of using rubber in the base and the beam-column connection. The third group represents using rubber with different types and locations at the base and the beam-column connection whereas the second and third groups were tested under a horizontal and inclined cyclic load. The fourth and fifth groups are like the second and third ones in details of using the rubber material respectively but

with a difference in details of the steel frame where one of whose sides is a shear tab connection and it is tested under using the horizontal cyclic load only.

The results showed that the use of a rubber washer with a thickness of 3 mm under the heads of the bolts in the beam-column connection improves the performance of the model in terms of load resistance, consumed energy, residual displacement, ductility index, drift ratio and the equivalent viscous damping by about (47.3, 364, 519, 148.2, 148, 221.4) %, respectively as compared to the rigid model having no rubber.

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A List of Symbols

Symbol	***Definition***
A_b	Area of the Bolt. (mm^2)
A_{el}	The Aria is Enclosed by Elastic Energy. ($kN.mm^2$)
A_g	Gross Section Area. (mm^2)
A_{gv}	Gross Section Area of Shear Tab in Shear. (mm^2)
A_{hys}	The Aria Under Hysteresis Curve or Cumulative Energy. ($kN.mm^2$)
A_{nt}	Net Area of a Plate in Tension. (mm^2)
A_{nv}	Shear Rupture of the Plate. (mm^2)
A	The Distance from the Centerline of the First Line of the Bolt to the Supporting Member. (mm)
A	The Connection (N.A) Location Parameter
C	Coefficient of a Moment that found in the AISC Manual in Chapter Seven.
D	Size of Welding in (1/16) of an inch
D	(ST) Depth. (mm)
d_b	The Diameter of Bolts. (mm)
D.I	Ductility Index
dm	Maximum Displacement in Each Cycle. (mm)
dr	Residual Displacement in Each Cycle. (mm)
δy	Yield Displacement. (mm)
E	The Distance from the Center of the Bolt Group to the Face of the Support
E	Modulus of Elasticity. ($kN.mm^2$)
F_{cr}	Critical Stress. (MPa)
F_u	The Minimum Tensile Strength of the Steel. (MPa)
F_v	Shear Strength of a Bolt. (MPa)
F_w	Specified the Minimum Strength of Weld Electrodes. (MPa)
F_y	The Minimum Yield Stress of the Steel. (MPa)
I	Moment of Inertia. (mm^4)
K_s	The Stiffness of the Connection at the Service Load Level. ($kN.mm^2$)
K	Stiffness of the Model. ($kN.mm^2$)
L	Length of the Beam. (mm)
L_{c1}	Clear Distance from the Side Edge Bolts. (mm)
L_{min}	The Minimum Length of Weld mm. (mm)
N	Applied Axial Force. (kN)
N	Number of Bolts
N_{br}	Bearing Capacity of Bolt Group in the Direction of Axial Force
N_n	Nominal Axial Strength. (kN)

N_u	Factored Normal Force Acting on the Shear Tab.
P_u	Maximum Load. (kN)
t_p	(ST) Thickness. (mm)
V	Shear Force. (N)
V_{br}	The Resistance Factor in the LRFD Technique for the Bearing is 0.75
V_n	Nominal Shear Strength. (N)
V_u	The Vertical Shear Force Acting on the Shear Tab. (N)
δ_u	Ultimate Displacement at Ultimate Load. (mm)
δ_y	Yield Displacement at Yield Load. (mm)
φ_n	The LRFD Method's Resistance Factor for Fracture is 0.75.
Ω_n	Safety Factor for Fracture in the ASD Method =2.
Ω_{br}	Safety Factor for Bearing = 2.00 (ASD).
Ω_y	The ASD Method's Safety Factor for Shear Yielding is 1.50.
$\varepsilon_{Engineering}$	Engineering Strain
ε_{True}	True Strain
ξ_{eq}	The Equivalent Viscous Damping
$\sigma_{Engineering}$	Engineering Stress
σ_{True}	True Stress
φ_{br}	Safety Factor for Bearing= 0.75 (LRFD).
φ_y	The LRFD Method's Resistance Factor for Yielding is 0.90.
λ	Slenderness Parameter

A List of Abbreviations

Abbreviation	***Definition***
AISC	American Institute of Steel Construction
ASD	Allowable Stress Design
ASTM	American Society for Testing and Materials
FEM	Finite Element Method
IMOS	Iraqi Meteorological Organization and Seismology
LRFD	Load Resistance Factor Design
LSL	Long Slotted Hole
OHS	Ordinary Head Stud Connector
OVS	Oversize Stander Hole
RSS	Rubber Sleeved Stud Connector
ST	Shear Tap
STC	Shear Tap Connection
SSL	Short Slotted Hole
SDOF	Single Degree of Freedom
SPSS	Statistical Package for the Social Sciences
STD	Standard Hole

CHAPTER ONE
INTRODUCTION

1. 1 General

The most powerful earthquakes strike near the edges of the major tectonic plates covering the globe surface. These plates naturally tend to move to one another, but friction prevents them from doing so until the stresses between plates under the 'epicentre' point get so high that they suddenly shift. This is an earthquake .The local shock causes waves in the ground to travel throughout the earth's surface, causing movement at structural foundations. The waves become less important as one gets further away from the core. As a result, depending on their proximity to the main tectonic plate borders, there are parts of the world with a higher or lower seismic risk as indicated by the red lines in Figure (1-1) (Schubert, G. 2015).

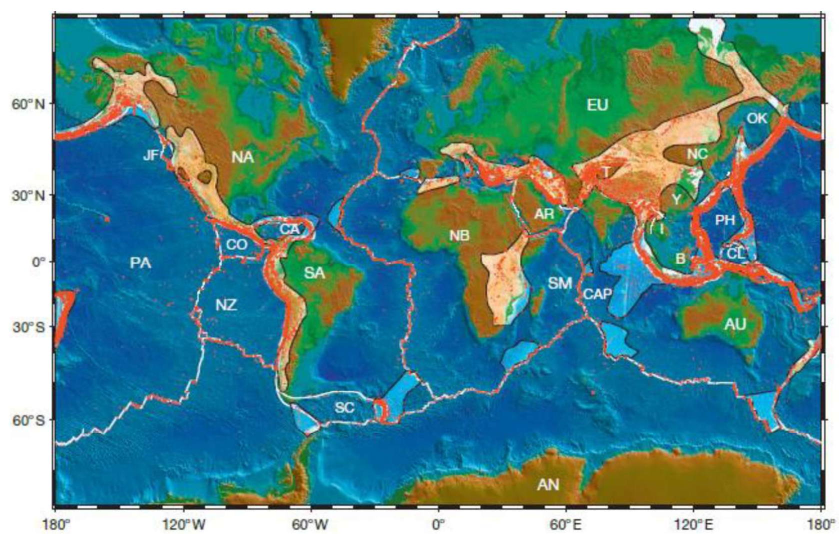

Fig. (1-1) The World Map Showing the Main Tectonic Plates (Schubert, G. 2015).

Aside from big earthquakes that occur at tectonic plate boundaries, some earthquakes occur within plates at fault lines. These are referred to as interpolative earthquakes. Although they release less energy, they can be destructive especially near the epicentre. Most earthquakes occur at the intersection of the oceanic and continental plates.

Shock waves are generated when an earthquake occurs owing to abrupt movements in the fault zone of the earth crust. Before reaching the construction site, these waves which are of various types and speeds travel in different paths exposing the earth beneath the structure to various concussive horizontal and vertical movements. The displacements in a moderate-intensity earthquake range from 8 to 12 cm whereas in a high-intensity earthquake, the displacements can reach up to 20 cm causing vibrations in the soil beneath the foundations which in turn make the foundations move in different directions. Besides, the exposure of the upper part of buildings to relative vibrations is associated with the foundation movement. Thus, shear forces at various levels of origin emerge. In some situations, buildings may collapse (Iraqi Construction Blog 2017).

It is well understood that earthquakes cannot be accurately predicted. Therefore, the main objective of this study is to try to mitigate the effects of the earthquake, which requires a unique engineering approach, by building earthquake-resistant structures to avoid human loss, ensure the continuity of construction services, protect buildings and facilities from collapses that cause the loss of life and property and reduce damage to property and buildings (Suhaib et al. 2020).

In Iraq, active earthquakes are mostly seen around the Arab panel's north-eastern border. In November 2017, an earthquake with a magnitude of M7.3 struck the north of Iraq, followed by another with M6.3 in November 2018. The earthquake caused more than 150 structures to be damaged. As a result, more research is needed into the seismic effect and how to reduce its effect on structures (Suhaib 2020).

1. 2 The Seismic Waves

Seismic waves come in a variety of shapes and sizes. The energy releases as seismic waves when plates move suddenly. Two primary types of seismic waves move at different speeds and shake the earth in distinct ways as they spread outwards in all directions from the earthquake source. Body waves and surface waves are the two basic forms of seismic waves. There are two sorts of body waves that move through the earth:

1. Primary waves (P-waves) are the world's fastest waves traveling up to 8 kilometers per a second. Aside from quickly reaching the earth surface, primary waves may also pass-through solids, liquids, and gases. As the ground compresses and expands in the same direction as the waves, P-waves, cause it to move back and forth. When P-waves reach the earth surface, they can make an audible sound.
2. Secondary waves (S-waves) travel slowly in a swaying and rolling motion, shaking the ground up and down and back and forth in a direction perpendicular to the wave's direction. The slowest moving waves are surface ones. As a result, the strongest shaking occurs at the end of the earthquake. They migrate along the earth surface and are responsible for most earthquake damages because they move up and down rocking the foundations of any artificial structure. There are two types of waves for the surface wave: the Rayleigh wave and the Love wave. Figure (1-2) shows the types of seismic waves (Shashikant K. Duggal 2013).

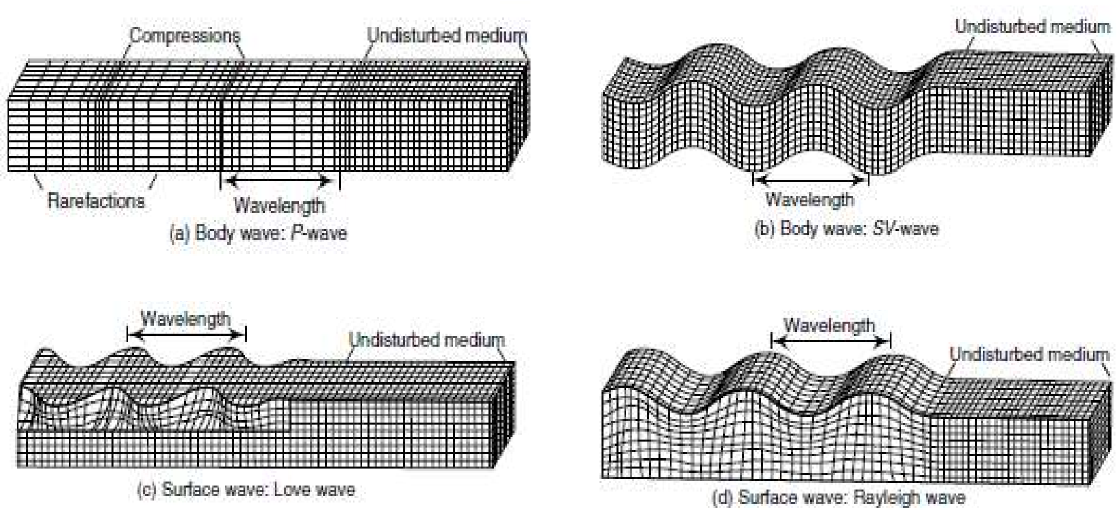

Fig. (1-2) Types of Surface Waves (Shashikant K. Duggal 2013).

1. 3 The Behaviour of Structures Subjected to an Earthquake

The effect of earthquakes on the behavior of buildings depends mainly on several factors (Murty 2012), including:

1- Effect of Stiffness: Building rigidity and mass are increased by increasing the size of the columns. However, the natural time shortens when the percentage increase in stiffness brought on by a bigger column dimension is greater than the percentage increase in mass.

2- Effect of Mass: The seismic mass of a building is the mass that contributes to lateral oscillation during earthquake shaking. Full dead load plus the necessary percentage of live load equals seismic mass at each floor level. A building's natural period lengthens as its weight increases.

3- Building Height Effect: A building's mass increases as it becomes taller, yet its overall rigidity reduces. As a result, as a building gets taller, its natural period lengthens.

4- Column Orientation's Impact: Along with two horizontal axes, the orientation of rectangular columns affects the lateral rigidity of buildings. Therefore, altering column orientation alters the natural period of buildings.

The ground motion caused by the earthquake has two parts: a horizontal component and a vertical component. Because horizontal forces are more difficult for structures to bear than gravitational ones, horizontal motion is the most observable aspect of earthquake action. The vertical component of an earthquake typically makes up about half of the horizontal component, except in the epicenter (ArcelorMittal 2011).

The structure is horizontally and dynamically displaced by ground movement. There is no displacement of the structure relative to its base if it is infinitely stiff and all of its points are displaced equally by the amount of ground movement. The movement of each point in a flexible structure is determined by the mechanical properties of all structural elements (stiffness) and the distribution of masses within the structure. As a result, a dynamic response occurs, encompassing all the structure's vibration modes. Some modes are global and affect the entire building, while others, such as floor vibrations, are more localized, as shown in Figure (1-3).

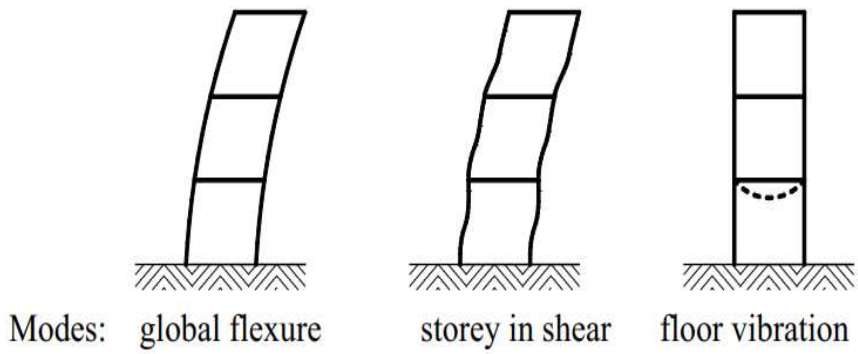

Fig. (1-3) Vibration Modes of Structures (ArcelorMittal 2011).

1. 4 Reasons for Using Steel Structure to Resist Earthquakes

Buildings with a high mass have highly damping such as concrete buildings. It is known that there is a direct relationship or relationship between body mass and time period. An increase in body mass leads to an increase in the time period. Also, the building mass affects the stiffness due to the seismic effect in the building. Here the inertia force is proportional to the building mass. The building is prone to earthquakes through three stages, as shown in Figure (1-4). The first stage is called stiffness during which people feel the movement of the building. High body mass is important at this stage. In the second stage, called strength, a crack occurs in the concrete and fails; therefore, the concrete cannot resist the second and third seismic effect stages, which are called strength and ductility, and here the advantage of steel structures stands out. The building stiffness decreases as more damage is done to it knowing that the stiffness stage refers to the building initial stiffness. The term "strength stage" describes the highest level of resistance to relative deformation that a building has ever provided. The ratio of the greatest deformation to the idealised yield deformation is known as ductility toward a lateral deformation (Murty 2012). Steel can resist earthquakes during the three stages passing by the structure.

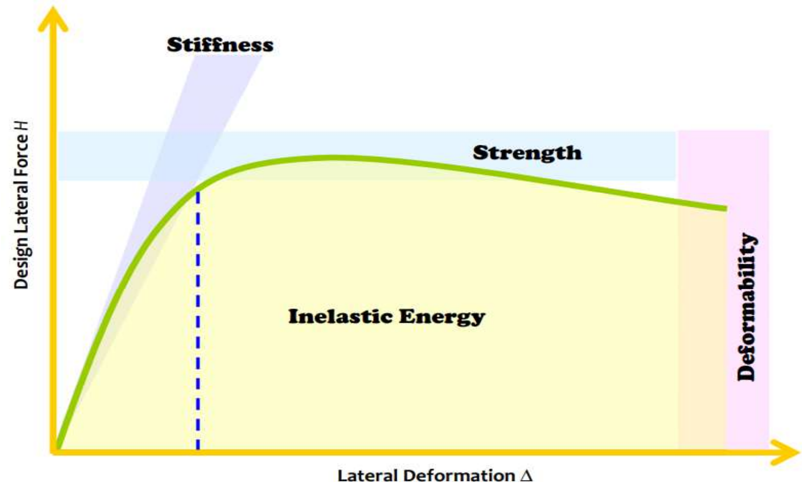

Fig. (1-4) The Stages of Building During the Seismic Effect (Murty 2012).

The structure made of steel is composed of a set of lightweight and highly deformable materials such as plates, angles, and beams. This gives a high degree of flexibility and high tensile strength to a structure to resist the bending effect without fracture failure. Despite the high resistance of steel structures to earthquake impact, they cannot be considered 100% guaranteed, especially under the influence of very high earthquakes. A direct relationship between the weight of the structure and the seismic effect is the relationship between the inertia force and the mass of the building. So, reducing the mass of the building results in reducing seismic force. Therefore, a steel structure gives a higher bear and provides safety for people at seismic effects (ArcelorMittal 2011).

1. 5 Technique for Minimizing Earthquake Damage

Under the earthquake effect, joint failure is the most prevalent and frequent failure in steel structures. It is possible to design a steel member very precisely, but the equations for the connection design grow more complicated when the maximum load is sought and the connection is designed for maximum strength. Steel structures are designed to withstand the effects of earthquakes and must meet the fundamental design standards in the following manner:

- After moderate earthquakes, the steel structure must be restored.
- To avoid any structural damage, side displacement must be kept under control.
- The construction must be built to withstand a large earthquake that occurs only once in a lifetime.

Many techniques may be used to minimise the risk of earthquakes on structures.

1) System of shear walls: Include numerous traits and drawbacks, including low stiffness and energy dissipation, massive moment connections, and significant losses in the non-structural component, are present when using the hypothetical design of this technology.
2) Steel bracings: this technology is highly expensive to produce the diagonal strut connections. It requires an additional structural support beneath the flooring and is quite heavy.
3) The damping system: using of modern techniques that are easy to implement and inexpensive and at the same time do not increase the weight of the facility which will be clarified in this study.

1. 6 Energy Dissipation Capacity in Steel Structures

Steel structures are particularly good at providing an energy dissipation capability due to: (ArcelorMittal 2011).

1) The flexibility of steel material.
2) There are numerous potential ductile mechanisms in steel elements and their connections.
3) The effective duplication of plastic mechanisms at a local level.

4) Reliable geometrical properties.
5) The bending resistance of structural components is only somewhat sensitive to the existence of the concurrent axial force.

1. 7 Types of the Connection

The types of connections may be classified into two categories: The first category is based on rotational stiffness and the force resulting from the transfer of bending moment, and according to this classification, the type of connection can be rigid connections, hinges, and semi-rigid joints that have intermediate behaviour. In the second category, a connection may be classified as either a partial force capacity. It means that it can resist calculated actions but not the greater actions that the connection member can transmit, or a complete force capacity meaning the joint can withstand the maximum force that the connection member can convey (Boracchini 2018).

In addition, there is another concept to know if the type of connection where rigid joints develop more than 90% of the ideal rigid joint moment while hinged joints develop less than 10% of the ideal rigid joint moment. Still, semi-rigid joints develop moments and rotations in between (Boracchini 2018).

1. 8 The Concept of Cyclic Loading

The cyclic loading representing the effects of earthquakes. The cyclic loading that was applied to the specimens was in line with the United States Steel Buildings Test Protocol (ATC-24 1992) which is a protocol that is used exclusively for testing the components of steel structures. The yield deformation (Δy) determines how to proceed with this technique. The protocol (ATC-24) states that when examining any sample, three cycles are applied for each loading stage, provided that it is six cycles of it before the yield load-deformation point and three cycles at (Δy), then followed by three cycles at double yield load-deformation point ($2\ \Delta y$) and then three cycles at three times the yield deformation (3 Δy) after that a load is applied gradually until the failure of the model occurs.

1. 9 The Inclined Cyclic Load

When an earthquake occurs, the secondary S-wave is generated. It is similar to an inclined cyclic load that contains two components of load vertical and horizontal which causes the movement of the earth surface up and down, and thus movement of the structure foundation up and down causing a damage to the connection between the column and the beam. This is a true representation of a building exposure to the seismic influence with the weight of the building. It is clear from this that the presence of the vertical component has a very large impact on the resistance of the building (Suhaib 2020).

1. 10 The Problem Statement

For every research, there are two problems:

The general problem: The impact of earthquakes on the structure, especially with the increase of these earthquakes in the recent period in the state of Iraq, and the weakness of design and implementation are consistent with the requirements of seismic design.

The specific problem: It is about minimizing the impact of earthquakes on construction. Here, the method used to reduce the impact of earthquakes has to do with the lower and upper parts of the structure. It is done through the use of smart joint technology in steel structures represented by the use of rubber materials.

1. 11 The Objectives of the Research

This study investigates the structural behaviour of using steel-rubber bolts in the base and joint connection of steel frames under the cyclic loading effect.

Besides, it aims at studying the effective parameters that can influence the performance of steel frames. The objectives obtained from this study are:

1) Studying the effect of a horizontal and inclined cyclic load by representing them in the ABAQUS program.
2) Elucubrating the different uses of rubber material as a washer and a sleeve.
3) Studying the interaction effect of using rubber in the base and joint connections.
4) Investigating the interaction effect of a shear tab and a rigid connection with rubber material of different types and locations.

1. 12 The Scope of Study

This study is limited to searching for the parameters for the performance of the steel frame as shown below:

1. Two types of quasi-static cyclic loads are horizontal and inclined cyclic loads.

2. Using rubber at the joint connection as a washer with different thicknesses (1,2 and 3) mm and a diameter with a ratio of 50% of the bolt diameter.

3. Using rubber at the joint connection as a sleeve the bolts with a ratio of 25% of the bolt diameter.

4. The use of rubber in the base of the model where the rubber is made in the form of a washer with a thickness of 10 mm and a diameter with a ratio of 50% of the anchor bolt diameter.

1. 13 Methodology

To complete this study, experimental programs (Suhaib 2020) are used as a guideline for the adopted form and validation of the FE model of a steel frame. The ABAQUS / CAE (2017) is used to build the FE models. After that, the numerical results from the analysis of the models are compared with the experimental data to check the solution and to achieve the accuracy of the analysis.

Then the research includes studying a model with rigid connections, investigating the effects of a parameters study on the behaviour of the steel frame and discussing the results to determine the best performance of the steel frame. The performance is evaluated by the value of the load failure, displacement, cumulative energy, residual displacement, ductility index, drift ratio and equivalent viscous damping.

1. 14 The Layout of the Research

This study is presented in five chapters as shown below:

1 **Chapter One:** presents a general introduction to the earthquake, steel structure properties, types of connection, the scope of the study, objectives, and the methodology of the research.

2 **Chapter Two:** views some previous studies concerning the experimental and numerical studies carried out on the shear tap and the rigid connection and the use of rubber in the connection.

3 **Chapter Three:** includes the representation of five models of previous experimental and numerical studies to verify the validity of the representation of the models and an introduction to the researcher's numerical study.

4 **Chapter Four:** displays a parameters study of a rigid steel portal frame under cyclic loading and for various variables.

5 **Chapter Five:** is all about the main conclusions with some appropriate recommendations for future work.