**Ministry of Higher Education
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College of Engineering**

Numerical Analysis of Portal Steel Frames with Steel-Rubber Bolt Connections Subjected to Seismic 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 Civil Engineering

By

Teeba Ali Jassim

(B.Sc. in Civil Engineering, 2016)

Supervised by

Prof. Dr. Amer M. Ibrahim

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CERTIFICATION

I certify that the thesis entitled " **Numerical Analysis of Portal Steel Frames with Steel-Rubber Bolt Connections Subjected to Seismic Loading** " is prepared by " **Teeba Ali Jassim** " under my supervision at the Department of Civil Engineering-College of Engineering- Diyala University in a partial fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering.

Signature: Prof. Dr. Amer
Supervisor:
Date: / /2021

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Name: Prof. Dr. Anees A. Khadom
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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

﴿ إِنَّمَا إِلَٰهُكُمُ اللَّهُ الَّذِي لَا إِلَٰهَ إِلَّا هُوَ
وَسِعَ كُلَّ شَيْءٍ عِلْمًا ﴾

صَدَقَ اللهُ العَظيم

مـــن ســورة طه ـ آيـــــة-98

Dedication

To the first and greatest lady who oozes with confidence and perfection gained from Allah , to my mother.

Teeba Ali Jassim

2021

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In the first place, all praise is to Allah who has enabled me to accomplish this valuable work.

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Abstract

The effect of earthquakes on structures, and possibility the increase of these earthquakes in the recent years in the state of Iraq, and the lack of design and implementation in line with the requirements of seismic design make it necessary to study how to reduce these seismic disasters and delay the time of building failure to give more time to evacuate the building and thus keep people safe. This study aims at reducing the seismic effect on steel structures specifically by using a damping system for linking the beam-column connection, and the base connection.

This study includes a numerical analysis using the ABAQUS/CAE 2017 program for several models related to steel structures. The results of simulating these frames agree well with the experimental models. Therefore, it can be established that the ABAQUS program is capable of simulating the behaviour of steel frames with the steel/rubber bolts subjected to both horizontal and inclined cyclic loads. The study also includes a set of variables that are studied by conducting a finite element method, including four groups.

The first group represents time history analysis, the second shows the models with steel/rubber bolts at the base connection and beam-column connection, the third offers the increase in the number of bolts to which rubber has been added in the beam-column connection tested under a horizontal cyclic load, and the fourth one differences in bolts location and the details tested under horizontal and inclined cyclic loads.

The results have shown that the acceleration value of the reference model tested under the seismic load without rubber is 62.016% which is higher than that of the model tested under seismic load which contains two rubber-sleeved bolts in the beam-column connection.

When rubber is added to the base connection and the beam-column connection, the residual displacement, cumulative energy, drift ratio, and the ductility index of the models containing rubber-sleeved bolts at the base and beam-column connections are (23.805, 256.819, 194.964, and 194.95)%, respectively which is higher as compared to the model that has rubber-sleeved bolts in base connection. This means that the model has become more flexible and has a greater ability to dissipate energy resulting from the seismic effect.

The comparison between the results of the models tested under a horizontal cyclic load and those of models tested under an inclined cyclic load, which takes into account the vertical component of the surface seismic wave, showed that the effect of this vertical component is significant and cannot be neglected.

The addition of rubber around one bolt in the beam-column connection with (4 and 5) bolts gives a behaviour and a resistance closer to that of the connection with all rubber-sleeved bolts.

The technique of adding rubber to the connection in order to resist seismic loads gives outstanding results in terms of behaviour , resistance and the facility of installation, maintenance, and sustainability. Also, rubber is highly efficient in stress redistribution and is able to absorb energy.

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List of Symbols

Symbol	***Definition***
Δ_u	Ultimate drift of models
$u^{\cdot}_{i}$	The velocity of the model
$u^{\cdot\cdot}_{i}$	The acceleration of the model
Δ_{yr}	Yield drift of the reference model
A_b	Area of the bolt. mm^2
A_n	Net area of a plate in tension
A_{nse}	Net-Shear Effective area of Shear tap in shear.
A_{nv}	Net area of a plate in shear.
$E_{cumulativ}$	Cumulative energy
$E_{elastic}$	Elastic energy
F_{cr}	Flexural Buckling Stress.
F_v	Shear strength of bolt
N_n	Nominal axial strength.
N_u	Factored normal force acting on the shear tab.
V_n	Nominal shear strength.
V_n	Nominal Shear Strength
δ_u	Ultimate Displacement at ultimate load
δ_y	Yeild Displacement at yeild load
φ_n	Resistance factor for fracture in the LRFD method=0.75.
Ω_n	Safety factor for fracture in the ASD method =2.
A_g	Gross section Area.
A_{vg}	Gross section area of Shear tap in shear
$E_{Modulus}$	Modulus of Elasticity
F_u	The minimum tensile strength of the steel
F_w	Specified the minimum strength of weld electrodes.
F_y	The minimum yield stress of the steel.
L_c	Clear distance from the side edge bolts.
L_{eh}	Distance from the centroid of the bolt to the edge of plate in horizontal direction.
L_{ev}	Distance from the centroid of the bolt to the edge of plate in vertical direction.
L_{min}	The minimum length of weld, mm
U_{bs}	1.0 Where tension stresses is uniform.
U_{bs}	0.5 Where tension stresses is non-uniform.
V_{br}	Resistance factor for the bearing in the LRFD method = 0.75
a_0	Initial Ground Acceleration

d_b	The Diameter of bolts.
$k^{\wedge}$	Constant Value
t_p	Shear Tap thickness.
t_p	The plate thickness
u_i	Lateral displacement of the model
Ω_{br}	Safety factor for bearing = 2.00 (ASD).
Ω_y	Safety factor for shear yielding in the ASD method = 1.50.
$\varepsilon_{Engineeri}$	Engineering Strain
ε_{True}	True Strain
$\sigma_{Engineeri}$	Engineering Stress
σ_{True}	True Stress
φ_y	resistance factor for yielding in the LRFD method= 0.90
Δ_e	Displacement at the 0.4*maximum load
a	The distance from the centerline of first line of bolt to the supporting member.
a	Acceleration of the structure site from the earthquake
C	Coefficient of moment that found in AISC manual in Chapter seven.
d	The depth of the plate
k	Stiffness of the connection
k	Stiffness of the model
N	Applied axial force
n	Number of bolts
P_{peak}	Maximum Load
t	The thickness of shear tap
V	Shear force
ƛ	The slenderness parameter

List of Abbreviation

Abbreviation	***Definition***
AISC	American Institute of Steel Construction
ASTM	American Society for Testing and Materials
FEM	Finite Element Method
IMOS	Iraqi Meteorological Organization and Seismology
LTHA	Linear Time History Analysis
LRFD	Load Resistance Factor design
LSL	Long slotted hole
OHS	Ordinary Head Stud connector
OVS	Oversize Stander Hole
PGA	Peak Ground Acceleration
RSS	Rubber sleeved Stud connector
ST	Shear Tap
STC	Shear Tap Connection
SSL	Short Slotted Hole
SDOF	Single Degree of Freedom
STD	Slandered Hole

CHAPTER ONE

INTRODUCTION

1. 1 General

The crust of the earth (the outer layer of the planet) is made up of a bunch of pieces, called plates. The plates move around by the liquid layers of magma underneath its crust. The plates are always bumping into each other, and are pulling away from each other. Earthquakes usually happen when two plates run into each other (Earthquake Resistant Steel Structures). The most important earthquakes are located close to the borders of the main tectonic plates which cover the surface of the earth. These plates tend to move relative to one another but are stopped due to friction until the stresses, between plates under the 'epicentre' point, become so high hence a move suddenly takes place. The local shock generates waves in the ground which propagate over the surface of the earth creating a movement at the bases (foundations) of structures. The importance of the waves reduces with the distance from the epicentre. Therefore, there exist regions of the world with more or less high seismic risk depending on their proximity to the boundaries of the main tectonic plates.

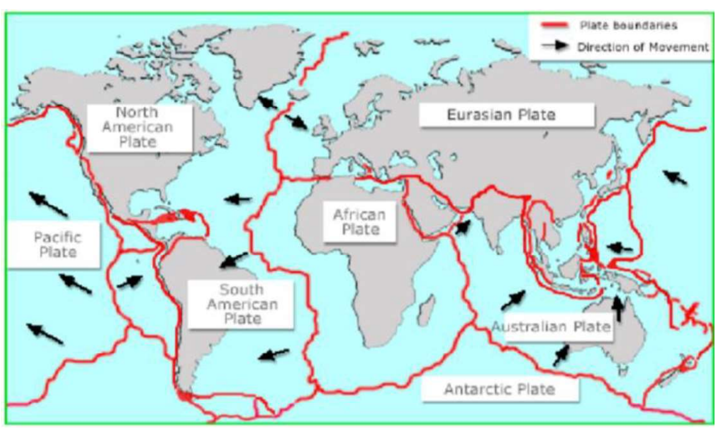


Figure (1-1) World Map Showing the Main Tectonic Plates (Earthquake Resistant Steel Structures).

Besides the major earthquakes that take place at tectonic plate boundaries others have their origin at the interior of plates at fault lines. The latter are called ‘interpolates’ earthquakes. These release less energy, but can still be destructive in the vicinity of the epicentre. Most earthquakes happen along the edge of the oceanic and continental plates. As a result of the frequent earthquakes in Iraq, especially in northern Iraq. It is necessary to develop new techniques to minimise the seismic effect. Requires to be designed and supported by human works and each part of which to resist the effects of land locks to protect them from collapse with reduced damage to property and buildings and avoiding human losses and ensuring that the services of important buildings and vital facilities continue as possible(Iraqi Construction Blog,2017). Action earthquakes occurring in Iraq are relative located in the north-eastern border of the Arab panel. Northern Iraq is exposed to earthquakes of an M7.3 in November 2017 another effect of an M6.3 in November 2018 near Iraq. More than 150 buildings were damaged by these earthquakes. Therefore, it is necessary to study the seismic effect and how to reduce this influence on buildings (Suhaib et al. 2020).

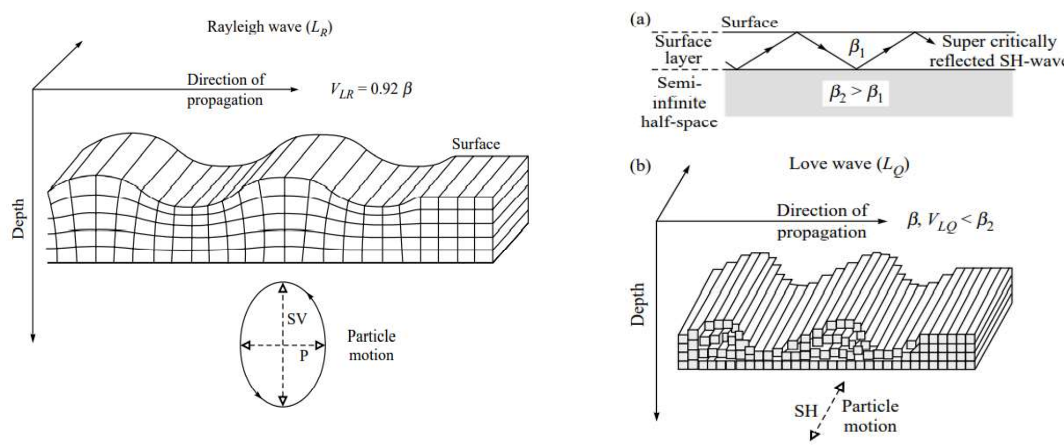
1. 2 Types of the Seismic Waves

When plates slip suddenly, the energy is released as seismic waves. There are two main types of seismic waves that radiate outwards in all directions from the earthquake source, traveling at different speeds and shaking the earth in different ways. The main types of seismic waves are body waves and surface waves. The body wave that moves through the earth is of two types: :

1. Primary waves (P-waves) are the fastest waves ever and can travel at up to 8km per second. Besides to their ability to travel to the surface of the earth easily, the primary wave can travel through solids, liquids, and gases. P-waves force the ground to move back and forth as it compresses and expands in the same direction of the waves. The P-waves can produce an audible sound when they arrive at the surface of the earth.

2. Secondary waves (S-waves) move slowly with a swaying, rolling motion and shake the ground up and down and back and forth in a perpendicular way to the direction of the waves.

Surface waves are the slowest moving waves. This means that the most intense shake comes at the end of the earthquake. They move along the surface of the earth and are responsible for most damage caused by earthquakes because they move up and down, therefore, they rock the foundations of any-made structure. There are two types of waves for the surface wave Rayleigh wave, and Love wave.



A: Rayleigh wave **B: Love wave**

Figure (1-2) Types of Surface Waves (Agrawal, P., & Shrikhande, M. 2011).

1. 3Action Applied to a Structure by an Earthquake

When an earthquake occurs, it sends shock waves all over the earth during short and fast periods in all directions. Buildings are generally constructed to handle vertical forces of weight and gravity, however, they cannot handle side-to-side forces resulting from earthquakes.

The horizontal load shakes the floors, walls, beams, columns, and connectors that link them. The difference in the movement between the upper and lower parts of buildings causes severe stress which in its turn, the supporting frame to rupture and the entire structure to collapse (Earthquake Resistant Steel Structures).

When a building experiences an earthquake, the base of the building moves with the ground shakes. However, the roof movement would be different from that of the base of the structure. This difference in the movement creates internal forces in the columns that tend to return the column to its original position . These internal forces are termed stiffness forces. The stiffness forces get be higher as the size of columns gets larger(Earthquake Resistant Steel Structures).

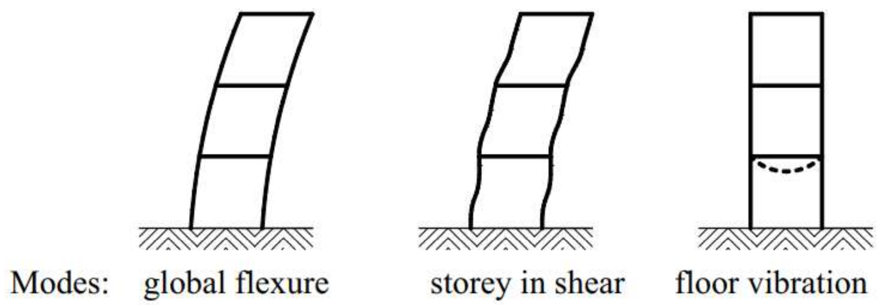


Figure (1-3) Vibration Modes of Structures (Earthquake Resistant Steel Structures).

1. 4 Effect of Earthquakes on Buildings

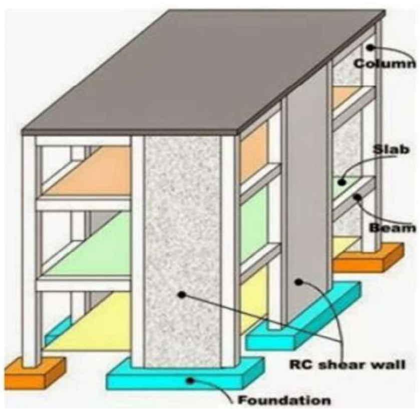
There are several effects of the earthquake on the buildings:

1. Ground shaking: Shaking the ground caused by the passage of seismic waves, especially surface waves near the epicenter of the earthquake, is responsible for a huge damage occurring during an earthquake.
2. Damage of man-made structures: Damage of man-made structures such as roads, bridges, dams, and buildings due to ground motion.
3. Fires: Fires are often associated with broken electrical and gas lines and are one of the common side effects of earthquakes. Gas is set free as gas lines are broken and a spark will start bringing "inferno". To complicate things water lines are broken and so there is no water to extinguish the fire.
4. Flooding: Flooding can come from many sources such as broken water main pipes, dams that fail due to earthquakes, and earthquake-generated tsunamis (Earthquake Resistant Steel Structures).

1. 5 Method to Reduce the Effect of Earthquakes

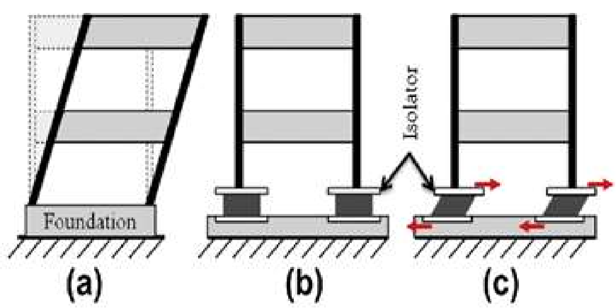
For any building or structure to be earthquake-proof its foundation has to resist sideways loads. The load becomes lesser if the building is light. To reduce the load of a building, you need to focus on the top as the maximum weight of the roof. However possible, the roof must be made of extremely lightweight material. There are several methods to reduce the risk of earthquakes on buildings among the most prominent of these methods are:

1. Shear wall system
2. Steel bracing.
3. The isolation system.



Shear Wall.

Steel Bracing.



Isolation system.

Figure (1-4) Methods of Reducing the Risk of Earthquakes on Buildings (Fadhil, H., et al. 2019).

1. 6 Reason of Using Steel Structure to Resist Earthquakes

The buildings that have a high mass are highly damped such as concrete buildings. As know that there is a reverse fit or relationship between the mass of the body and the time period in that the greater the mass of the body is the lesser the time period becomes. Also, the building mass affects the stiffness is due to the seismic effect which occurs in the building. Here the inertia force is proportional to the building mass. The building is prone to earthquakes through three stages. The first stage is called stiffness, and it is the phase during which people feel the movement of the building. High body mass is important at this stage. In the second phase which is called Strength a crack occurs in the concrete and fails and then therefore the concrete can not resist the second and third seismic effect stages, which is called Strength and Ductility. The stiffness stage refers to the initial stiffness of a building, even though the stiffness of the building reduces with an increasing damage. The strength stage refers to the maximum resistance that a building offers during its entire history of resistance to a relative deformation. Ductility towards a lateral deformation refers to the ratio of the maximum deformation and the idealized yield deformation (Murty 2012). Steel can resist earthquakes during the three stages passing by the structure.

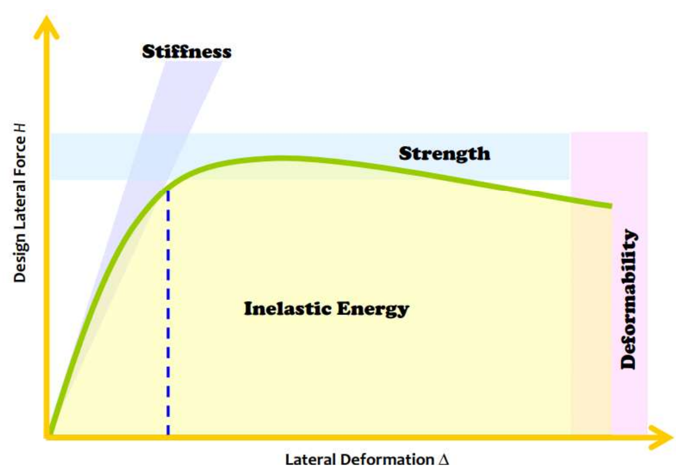


Figure (1-5) The Stages of Building During the Seismic Effect (Murty 2012).

The structure made from steel is composed of a set of lightweight materials such as plates, angles, and beams. It gives a high ductility and a large sequin to a structure in order to resist the bending effect without the fracture failure.

Despite the high resistance of steel structures for the impact of the earthquake, they cannot be considered 100% guaranteed especially under the influence of very high earthquakes. There is 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 effect (ArcelorMittal Europe).

1. 7 Energy Dissipation Capacity in Steel Structures

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

1. The ductility of steel material.
2. Many possible ductile mechanisms in steel elements and their connections are offered.
3. The effective duplication of plastic mechanisms at a local level.
4. Reliable geometrical properties.
5. Relatively low sensitivity of the bending resistance of structural elements to the presence of coincident axial force.

1. 8 The Most Dangerous Area in Steel Structure

The connection is the most dangerous area in a steel structure because this area is the most influential area during the seismic effect for a reason, that an area is more than one element and these elements are different among them in terms of resistance and steel type, installation of molecules and ultimate resistance. So the design of the connection is more complicated and the failure of the connection is the most dangerous among other failures in the building. In general, the detailed failure is the first failure if the connection is exposed to an unexpected force because the behaviour of the joint material is brittle to some loads and not all (Astaneh-Asl et al 2005).

1. 9 Reasons of Using the Shear Tap Connection

The shear tap (ST) is one of the commonly used connection components in steel structural designs, especially in areas of high seismic activity, due to its effective role in maintaining rotation at the end of the beam. Also, the (ST) is used to transfer the shear force from the beam to the supporting member. Besides, the (ST) must be flexible enough to rotate at the end of the beam. The (ST) connection must have sufficient shear force to resist the forces subjected to it, then the (ST) transfers the shear force to the support. But when the structure is under the influence of the gravity load, then the only force acting on the connection is the shear force. While when the structure is subjected to a seismic load, the function of the (ST) becomes to transfer the shear force, axial force, and bending moment from the end of the beam to the support. Also, the shear connection must have sufficient ductility to be able to withstand the rotation that results from the influence of the lateral loads represented by the seismic load and the gravity load (Abolhassan Astaneh-Asl et al.2005).

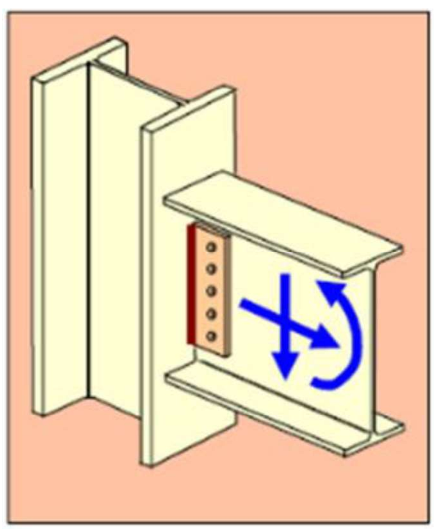


Figure (1-6) Shear Tap Connection (Abolhassan Astaneh-Asl et al.2005).

1. 10 Inclined Cyclic Load

Upon seismic effect, the surface wave of seismic waves causes a movement in the crust of the earth up and down, and as a result of this a movement occurs in the foundation of the structure. This movement mainly results in damage to the connection that connects the column to the beam. This movement is a cyclical force that is represented by the inclined system because it contains two components of loads. The first component represents the horizontal force and the second component represents the vertical one which in turn causes the building to move up and down. This leads to a damage in the beam-column connection and the foundation of the building. Based on that, it is evident that the presence of the vertical component has a very large impact on the bearing of the building (Suhaib et al.,2020).

1. 11 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 consistent with the requirements of seismic design.

The specific problem: Is all about lessening the influence of earthquakes on constructions. Here, the method used to reduce the impact of earthquakes has to do with the lower part of the structure where the column is connected to the foundations knowing that restricting a structure at the upper part costs much.

1. 12 Objectives of the Research

This study aims at investigating the structural behaviour of using steel-rubber bolts in the connection of steel frames under the cyclic loading and seismic load effect. Besides, it aims at studying the effective parameters that can influence the performance of steel frames. The objectives obtained from this study can be:

1. Studying the effect of using different types of loads by representing them in the ABAQUS program.
2. Studying the different bolts number.

3. Studying the numerical representation of using rubber material in the encapsulation of steel bolts.

1. 13 Scope of Study

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

1. The seismic load is analysed in two ways, which are a linear time history analysis and a non-linear time history analysis.
2. Two types of quasi-static cyclic loads are horizontal and inclined cyclic loads.
3. The use of rubber in the base of the model is a new study where the rubber is made in the form of a washer and the effect that occurs on the model to be studied.
4. The presence of rubber around the number of bolts in the connection is by 150% of the bolt diameter.
5. The difference in the number of bolts where four and five bolts are used in the connection.
6. The difference in the bolt location and details of bolts in the connection for the 4 and 5 bolt groups are also investigated.

1. 14 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 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 achieve the accuracy of the analysis.

The second part of this thesis includes a parametric study to investigate the effects of a parametric study on the behaviour of the steel frame and discusses the results to determine the better performance of the steel frame. Where the performance is assessed by the value of the residual displacement, cumulative energy, equivalent viscous damping, drift ratio, and ductility index.

1. 15 Layout of the Thesis

This study is presented in five chapters, as shown below:

1 **Chapter One** presents a general introduction about the earthquake, steel structure, and shear tap as well as the scope, objectives, and methodology of the study.

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

3 **Chapter Three** describes the FE model that is developed to predict the behaviour of the steel portal frame and presents the validation of the finite element model of the steel portal frame.

4 **Chapter Four** delineates the case study of the steel portal frame under cyclic loading and seismic load.

5 **Chapter Five** offers the main conclusions of the study along with some suitable recommendations for future work.