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Development of Steel Structure with Rigid Connection Subjected to Horizontal Cyclic Load By Using Rubber Washer

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ARTICLE INFO	ABSTRACT
	An earthquake is a dangerous natural phenomenon that exposes buildings to collapse and human life to danger. Due to the weakness and cost of design and implementation by seismic design requirements. Therefore, a way must be found to reduce the impact of the earthquake risk, by using the smart joints technology in steel structures. Two experimental models were analyzed theoretically, The results showed a great convergence between the experimental and theoretical programs. The case study is a numerical study containing four rigid specimens that were analyzed in the ABAQUS / CAS (2017) program with applied a horizontal quasi-static cyclic load. The difference between these samples is the difference in thickness of the rubber washer used in the specimen where it is placed under the bolt head in the beam-column connection of the rigid steel frame. Two bolts connect the column with the angle, and the beam with the angle at the top, bottom, in both sides, and two bolts that connect the beam with the shear tab (ST), and in both sides too. Thus, the total number of bolts is twenty and the total number of rubber washer are forty. The results showed that the resistant load of the model containing rubber washer with the thickness (1,2,3 mm) in the beam-column connection increased by (11.5%, 33.8%, and 47.3%), respectively, as well as a significant improvement in the cumulative energy, the ductility residual displacement, The ductility index, The drift ratio, and the equivalent viscous damping compared to the model without rubber.

1. Introduction

Most earthquakes happen near the edges of the major tectonic plates that cover the globe's surface. These plates have a natural tendency to move concerning one another, but friction prevents them from doing so until the stresses between them are high enough to cause a rapid movement. This is an earthquake, which is a horizontal and vertical ground movement. Because of its strength and because structures are often better designed to resist gravity than horizontal forces, horizontal displacement is the most distinct feature of earthquake action [1]. Earthquake is also defined as a geophysical phenomenon that takes the form of waves and

causes movement in the earth's crust up and down. As this movement from the seismic wave moves to the foundation of the structure, it causes the vertical movement of the structure to be violated, failing the structure's foundation [2]. As a result, it became important to research the effects of earthquakes on structures and how to minimize the impacts of earthquakes on buildings. Because seismic forces are proportional to the mass of the structure, a reduction in mass will unavoidably result in lower seismic design forces. There are various strategies for reducing the risk of earthquakes on structures, the most well-known of which are shear walls and steel bracing. [3] Studied the effect of using stiffed rigid steel plate to

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strengthen the ordinary beam-column connection to enhanced the seismic performance of structure by using the finite element method. The results showed that the rigid plate application in a steel frame increases the failure capacity compared with a bare frame and improved the seismic performance of steel structures. [4] Studied the effect of using corrugated steel sheet shear walls (CSPSW) as seismic shock resistance systems. The model consists of a steel frame (beam and column), where many variables were studied, and the results showed that (CSPSW) has a clear effect on the initial hardness, strength, ductility, and energy dissipation. [5] Studied the effect of using a ring-shaped lateral brace system called the Shami lateral bracing system (SLBs) that removes joint tension and compression members with their connections to the structure as an alternative, and the results of the analysis show that (SLBs) have good performance and high ductility during cyclic loading as well as adequate energy dissipation by this system, but expensive.

These procedures add a heavyweight to the foundation of the structure, in addition to high time and cost [6].

In comparison to alternative energy dissipation strategies,[7] Studied the effect of using rubber around the bolt at the beam-column connectin in the Shear tab connection model by using the ABAQUS program and the result showed enhanced load, displacement, drifting, damping ratio, ductility index, energy dissipation. in this study, rubber washers are used because they are economical and easy to install. This is numerical research that involves the usage of a rubber washer under the bolt heads in the portal steel frame's rigid connection model. The goal of this research is to improve the connection of the steel frame by using a rubber washer to absorb the energy generated by the seismic effect, raise the steel frame's bearing load, and increase the amount of displacement.

2. Validation of the experimental models
2.1 The geometry of the model

The finite element models were analyzed using the ABAQUS-2017 program to validate the correctness of the results, based on the researcher's experimental models (suhaib-2020). This section analyzed two experimental models that were tested under a horizontal quasi-static cyclic load. The models were designed using AISC-14Th [8]. Each model consists of one beam (IEP160) with a length of (1000) mm as shown in Figure (1). Also included are two (1500) mm long (HW125125) columns. On each side, a shear tap (ST) with dimensions of (110 x 90 x 8) mm connects the beam to the column as shown in Figure (2). A single line of two bolts with a diameter of 7 mm connects the shear tap to the beam, and each column is joined to the shear tab by a line of weld, this represents the reference model. As for the second model, the bolts are sleeved with rubber by ratio 50% of the bolt's diameter, which means the diameter of the rubber is (10.5)mm. Figure (3) shows the representation of the experimental model in the ABAQUS program.
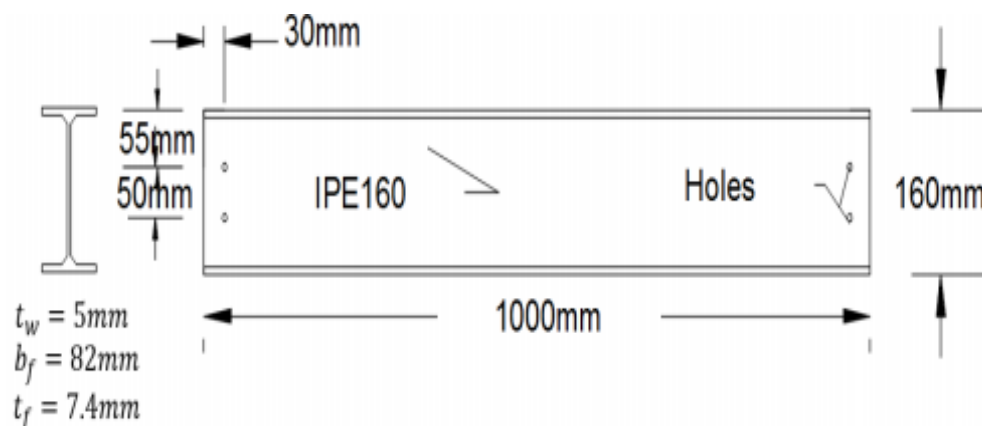

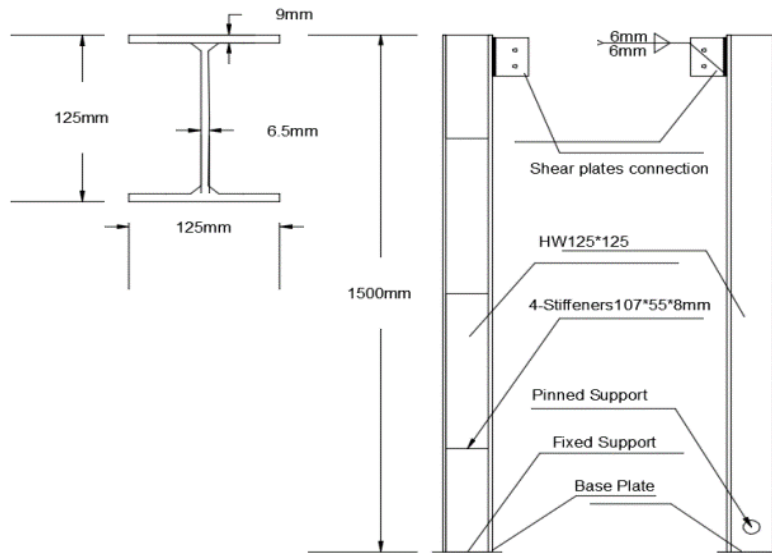**Figure 1.** The steel beam section, (Suhaib-2020)

Figure 2. The steel column sections, (Suhaib-2020)

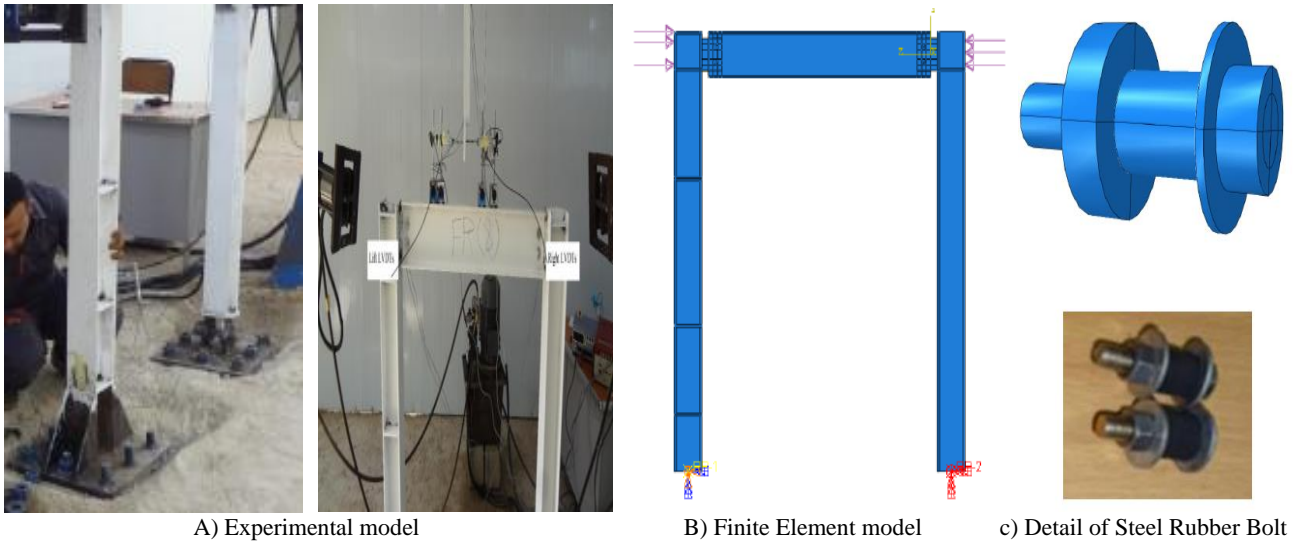| A) Experimental model | B) Finite Element model | c) Detail of Steel Rubber Bolt |

Figure 3. The FEM and Experimental Models

2.2 The property of the model

Table (1) and Table (2) showed the material properties and the stress-strain magnitude of the elements respectively which were used in the ABAQUS program to truly represent the models. The stress-strain value obtained from the practical programs represents the engineering value, while the ABAQUS program deals with the real value. Therefore, the engineering value must be converted to a real value, which is converted using the following equations: -

$$\sigma_{True} = \sigma_{Engineering} * [1 + \varepsilon_{Engineering}] \quad (1)$$

$$\varepsilon_{True} = \ln[1 + \varepsilon_{Engineering}] \quad (2)$$

$$\varepsilon_{Plastic} = \ln[1 + \varepsilon_{Engineering}] - [\sigma_{True}/E_{Modulus}] \quad (3)$$

Table 1: The material properties of the elements (Suhaib-2020)

The Element	Density (T/mm³)	Elastic Modulus (MPa)	Poisson Ratio
Beam	7.83 e -09	195000	0.3
Column	7.83 e -09	187000	0.3
Shear Tap	7.83 e -09	211000	0.3
Bolt	7.83 e -09	275000	0.26
Steel Washer	7.83 e -09	275000	0.26
Rubber	1.52e -09	91.12	0.5

Table 2: The stress and strain magnitude of the elements, (Suhaib-2020)

The Element	Yield-stress (MPa)	Plastic-Strain (mm/mm)
Beam	250.4375	0
	400.7	0.301135883
Column	250.4375	0
	400.7	0.28336225
Shear Tap	312.546	0
	422.7385	0.283242381
Bolt	588.6	0
	648	0.073721041

2.3 The mesh design

Each form must be divided into segments, according to the ABAQUS program's unique manual, to make the process of analyzing the model easier and faster. In which each form is divided into cube or wedge segments. For model mashed zones with regular shapes, first-order hexahedral cubic elements were used. Columns, beams, stiffeners, shear taps, nuts, bolts, rubbers, and washers all have a mesh size (60,50, 60, 15, 4, 4, 4, and 4) mm respectively. as shown in Figure (4).
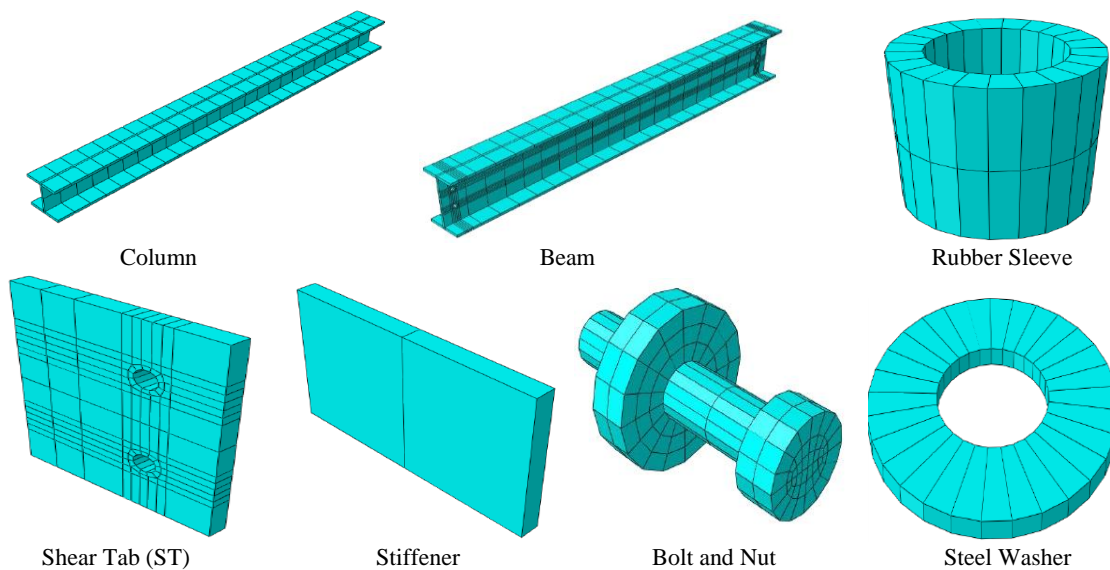

Column   Beam   Rubber Sleeve

Shear Tab (ST)   Stiffener   Bolt and Nut   Steel Washer

Figure 4. The Mesh of the Elements in the ABAQUS Program

2.4 The load case and the boundary condition

In the ABAQUS program, a horizontal quasi-static cyclic load was applied. This load is applied according to the protocol ATC-24-1992[9] Similar to the special loading protocol in the experimental program. The position of the load at the top end of the column. This loading mechanism is similar to the seismic impact that buildings experience during an earthquake, where cyclic loads are applied at the ends of frames, causing the building to move right and left, generating reaction forces in the foundation. As for the boundary condition, according to the experimental model, one of the columns is tightly fixed and does not allow any movement, So the end of the column was represented as fixed and the other is only allowed to rotate in one direction, So the end of this column was represented as a pined. The applied load and the boundary condition are shown in Figure (5).
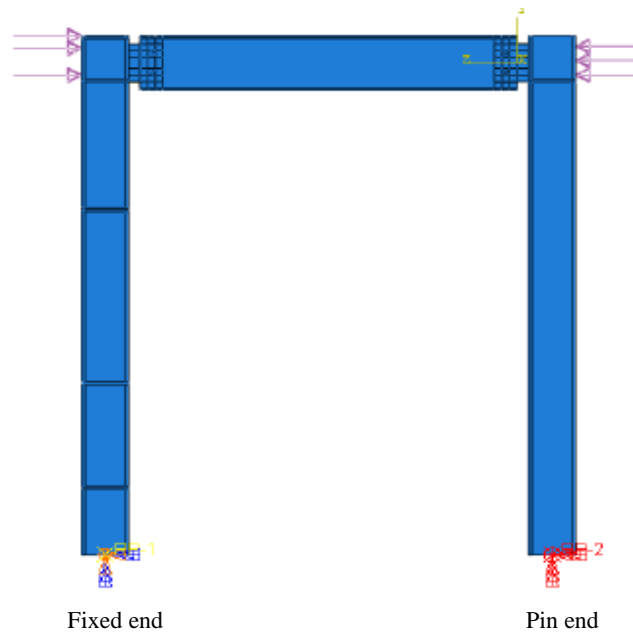

Fixed end   Pin end
Figure 5. The load case and boundary condition of the model in the ABAQUS program

2.5 The validation results and discussion

Two models (Shear Tab Connection) of the experimental program (Suhaib-2020) were represented (H.0.STD.1), (H.50.OVS.2), where the letter (H) represents the horizontal quasi-static cyclic load and the number (0, 50) represent the percentage of rubber used in sleeve the bolt in the two models respectively, STD means using the standard hole for the Shear Tab and Beam and OVS means using an oversize hole, finally, number (1,2) mean the first model and the second model respectively as shown in Figure (6). By comparing the failures of the two models, it was found that there is great convergence between the experimental and numerical models, as shown in Figure (7).

When comparing the results between the numerical and experimental programs as shown in Table (4) we can prove that the convergence between the results is very large also through the comparison by drawing an envelope curve of the results that are shown in Figure (8) and Figure (9).

In addition, the presence of the rubber in the model increases the ability of the model to resist the load and increases the ductility of the model.
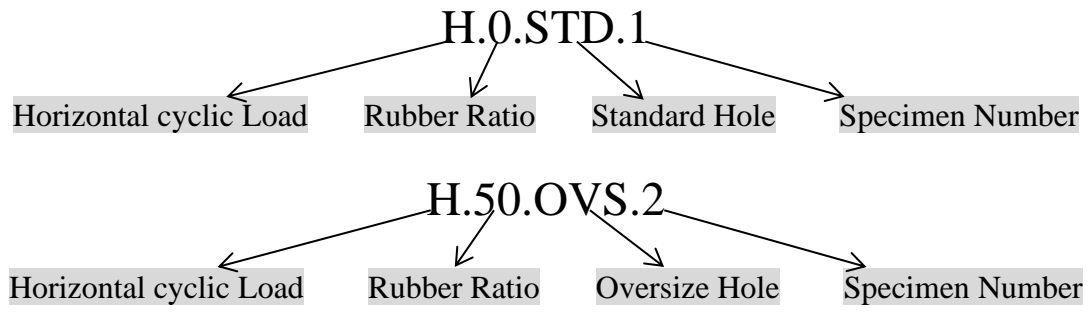
H.0.STD.1

Horizontal cyclic Load   Rubber Ratio   Standard Hole   Specimen Number

H.50.OVS.2

Horizontal cyclic Load   Rubber Ratio   Oversize Hole   Specimen Number

Figure 6. Experimental Two-Samples scheme.

Shear tab (ST)

Bolt and Nut

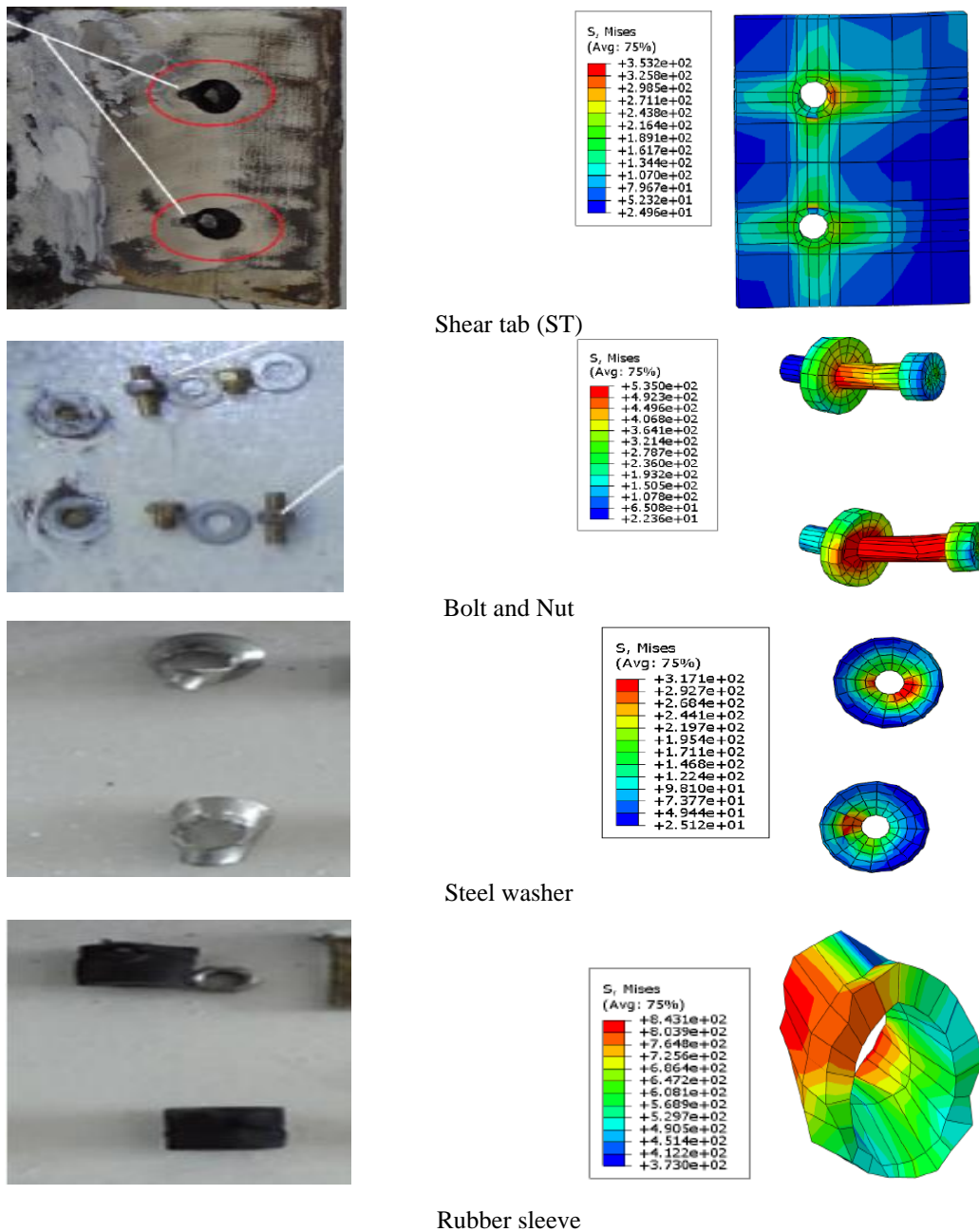Steel washer

Rubber sleeve

Figure 7. Compare the failure between (EXP&FEM) elements

Table 4: The load and displacement results for experimental (EXP) and numerical (FEM) models

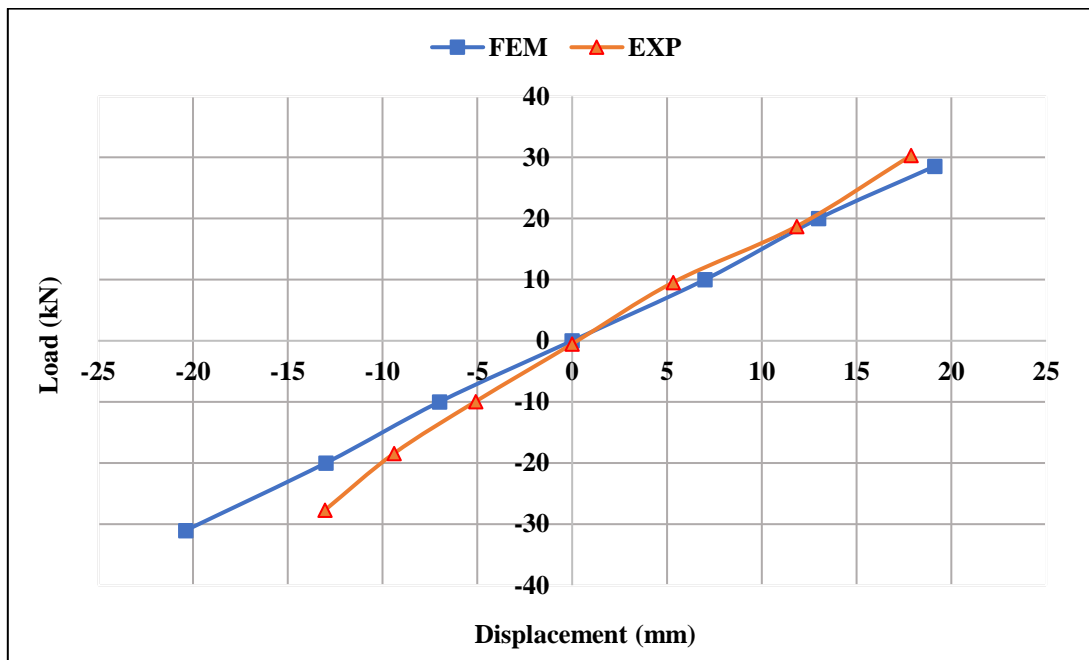| The Model Name	Load (kN)		The ratio of convergence of load (FEM/EXP)	Displacement (mm)		The ratio of convergence of Displacement (FEM/EXP)
	FEM	EXP		FEM	EXP	
H.0.STD.1	31.04	30.323	1.024	20.396	17.878	1.141
H.50.OVS.2	39.16	40.773	0.96	26	26.121	0.995

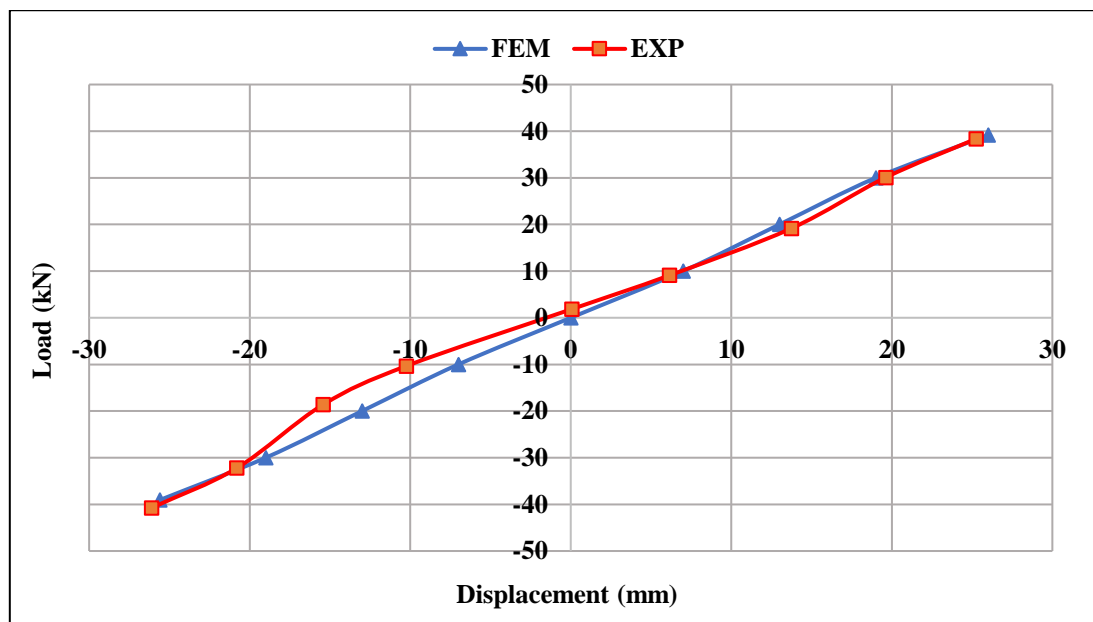**Figure 8.** Envelope curve (FEM &EXP) of the H-0-STD.1

Figure 9. Envelope curve (FEM &EXP) of the H-50-OVS.2

3. The case study

The purpose of validation of the experimental models is to represent the model (Shear tab connection) of the researcher (Suhaib-2020) and the method of adding the rubber material to the model in addition to the method of applying the horizontal quasi-static cyclic load, theoretically, to ensure the extent of the ability of the ABAQUS program to represent experimental models and thus benefit from this model to form a model with rigid connection by adding double angle have the same characteristics of the shear tab with dimensions (90 * 90 * 8 mm) and wide 82mm at each side at the top and the bottom to connect the beam with the columns at the flange using a line of two bolts as shown in the Figure (10) indicating the method of adding the rubber washer. Even after the moment frame has deformed, rigid connections ensure that the angles between the columns and the foundations, as well as the angles between the columns and the beam, remain approximately 90, plastic yielding in the members will occur before brittle failure of the connections if the connections are stronger than the linked members. In a pin-supported beam, one is capable of creating a moment at the beam end more than or equal to 90% of the fixed end moment while the end rotation is less than or equal to 10% of the rotation [10]. Any joint that develops more than 90% of the ideal rigid joint moment is classed as rigid, while any joint that develops less than 10% of the ideal rigid joint moment is categorized as hinged; and joints that develop moments and rotations in between are referred to as semi-rigid joints [11]. The Rigid connections transfer not only a significant amount of bending moments but also shear and axial forces. Based on the test results of the reference model, the connectors of this model showed a rigid behavior. In this paper, four rigid models were tested. Each model contains the same elements in terms of characteristics and dimensions that were mentioned in (Suhaib-2020) research, in addition to, the double angle section that was mentioned previously. The first model (RC.H.RW0) is the reference, which is free of rubber. The second model (C.H.RW1) contains a rubber washer with a thickness of 1 mm, which is placed under the head of all bolts. The third model (C.H.RW2) contains a rubber washer with a thickness of 2 mm and the fourth model (C.H.RW3) with a thickness of 3 mm as shown in Figure (11). The models of this group were tested under horizontal quasi-static cyclic load. The results of residual displacement, ductility index, cumulative energy, viscose equivalent damping, and drift ratio are discussed. The role of rubber was evident by increasing the load and displacement magnitude of the models. The sections are designed to depend on the AISC Manual. On all models, the load was applied to the upper end of the columns. When the load affects the upper ends of the steel frame, the model will move to the left and right. From this movement, the forces generated in the model which distributed in the form of moment and stress at the joints of the model. As a result, the rigid connection between the columns and the beam, the bending moment is transferred from the beam to the columns, and then the columns resist the bending moment and compressive force which is transferred to the base. The loading is done as three cycles of 5 kN, then three cycles of 10 kN, then three cycles of 20 kN, then three cycles of 25 kN, and the increase continues for every three cycles of 5 kN until the failure of the model occurs, note that all models failed in the bolts which connecting the beam with the angles after the plastic deformation at the end of the beam at the connection occurred. The shapes of the models tested in ABAQUS / CAS (2017)[12].
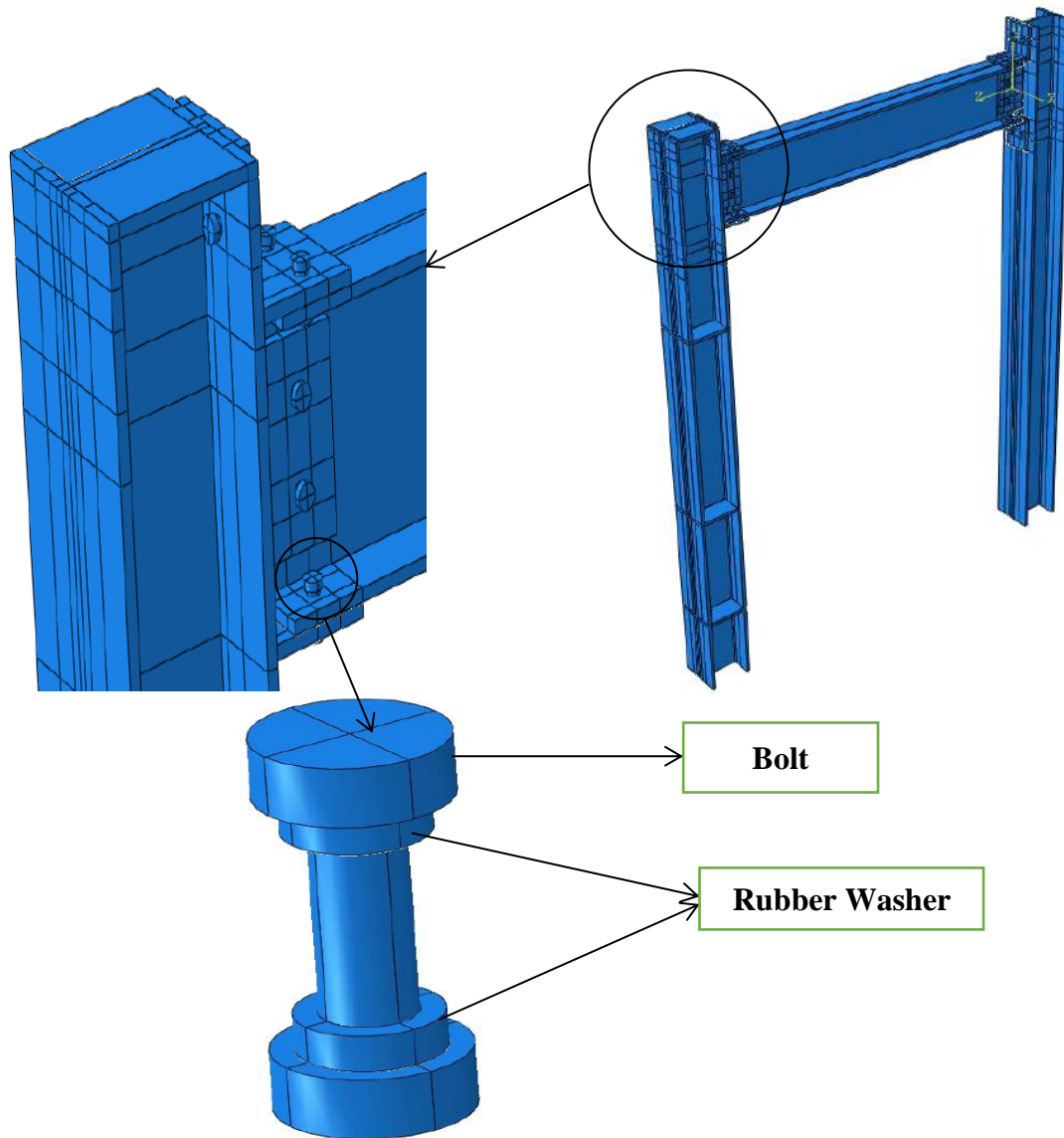
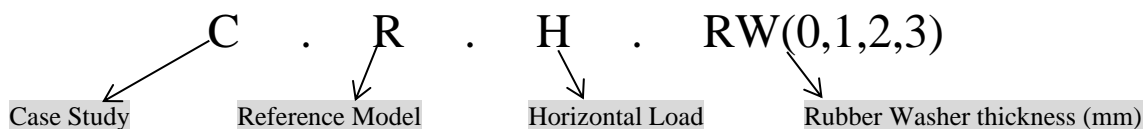**Figure 10.** The rubber washer at the connection of the rigid model

Figure 11. Case study samples scheme

4. The finite element results and discussion

4.1 The load failure and displacement

Four specimens were tested under horizontal quasi-static cyclic load. The ultimate failure load, displacement, and the number of cycles are illustrated in table (5). As the failure occurred in the bottom bolts that connect the beam with the angle on the left side and the upper bolts on the right. The result showed that the presence of rubber material at the joints exceeds the resisting load and displacement higher than the specimen without rubber. Where the specimens which content rubber washer by thickness (1,2,3) mm, the ultimate load increased by (11.5%, 33.8%, 47.3%), and the displacement exceed by (26.3%, 79%, 148%) respectively. The rubber in these specimens acts as a damper, so it reduces the effect of the applied load and delays the failure time of the bolts, and this increases by increasing the thickness of the washer and this is evident from

the table below. The number of cycles for the reference specimen until failure is reached (19) and the number of cycles (22, 28, 31) for the specimens that contain rubber washers by thickness (1,2,3mm) respectively as shown in Figure (12).

Table 5: The (FE) results for specimens

The specimens	P_u (kN)	The rate of increase in the load (%)	δ_u (mm)	The rate of increase in the displacement (%)	Number of Cycles
C.R.H.RW0	44.4	-----	13.3	-----	19
C.H.RW1	49.49	11.5	16.8	26.3	22
C.H.RW2	59.4	33.8	23.8	79	28
C.H.RW3	65.4	47.3	33	148	31

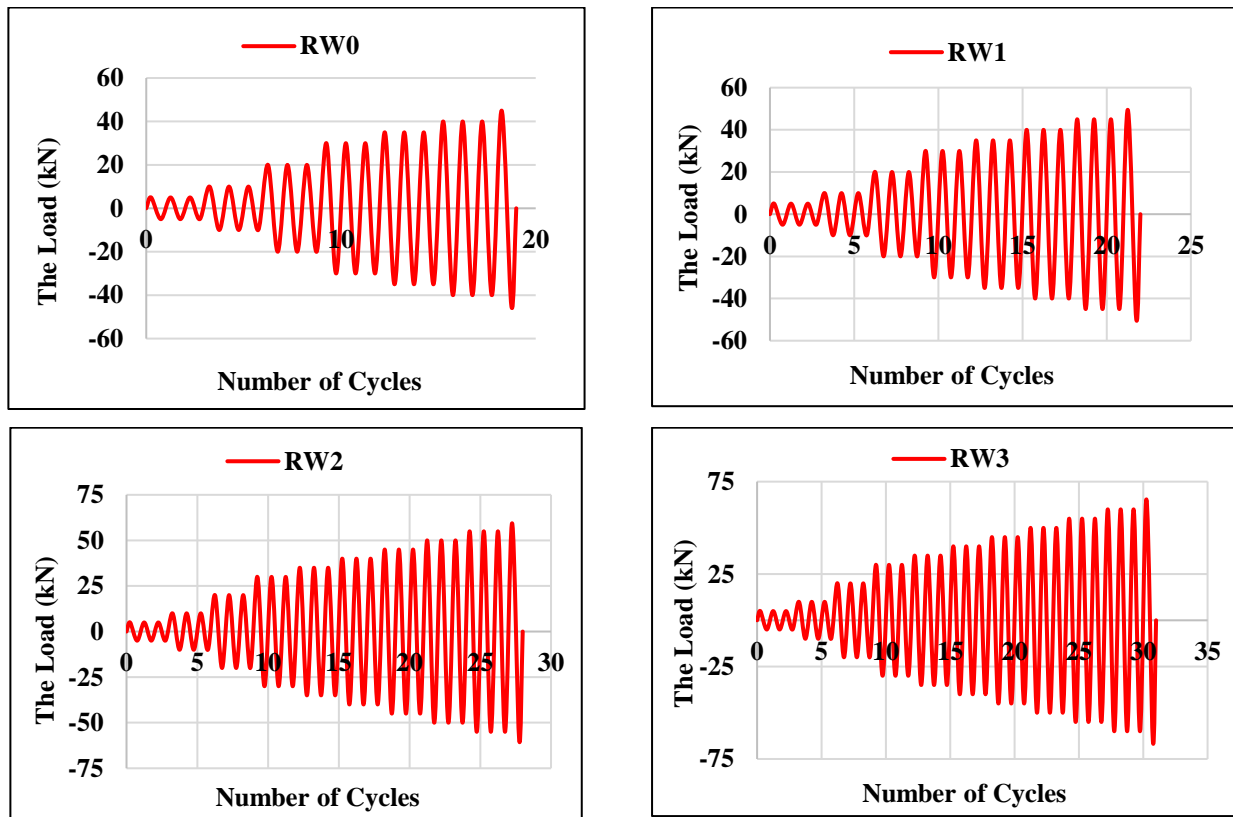P_u: Ultimate Load , δ_u: Ultimate Displacement , N_c: Number of Cycles

Figure 12. The load and the number of cycles for the specimens

4.2 The cumulative energy

It is important for models subject to seismic influence to have the ability to disperse the energy gained from the seismic impact because the ability of the structure to remain stable during an earthquake depends on its ability to dissipate energy.

According to the researcher [13], the energy for the model is computed by computing the area under the envelop curve as shown in Figure (13). Figure (14) shows the total consumed energy for the four samples stated above. Where the term (RW0) represents the model that does not contain a rubber-washer while the (RW1, RW2, RW3) represents the models that contain a rubber-washer with a thickness (1, 2, 3mm) respectively. The purpose of this study is to find out how much energy dissipates if using rubber at the connection. After 19 cycles, the total energy consumed for sample (C.R.H.RW0) was 328.26 kN mm, 490.623 kN mm for (C.H.RW1) after 22 cycles, 796.56 kN mm for (C.H.RW2) after 28 cycles and 1524.6 kN mm for

(C.H.RW3) after 31 cycles. According to the figure, the samples under horizontal load with a rubber washer thickness of (1,2,3 mm)

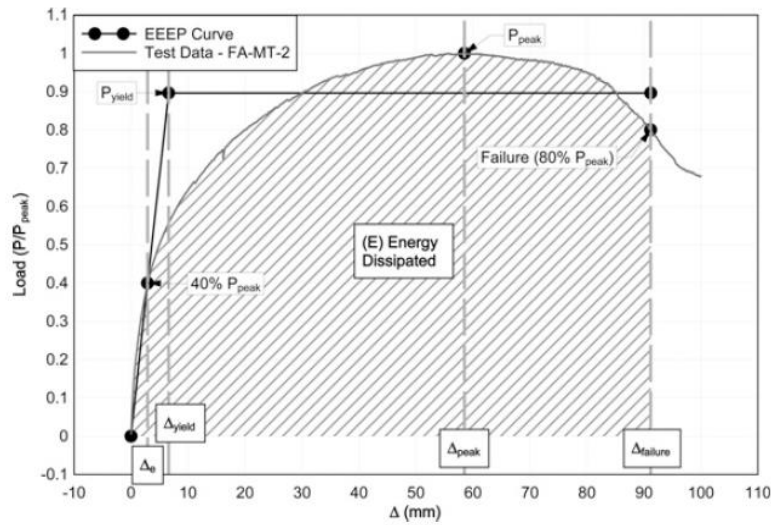consumed more energy than a reference model without rubber.

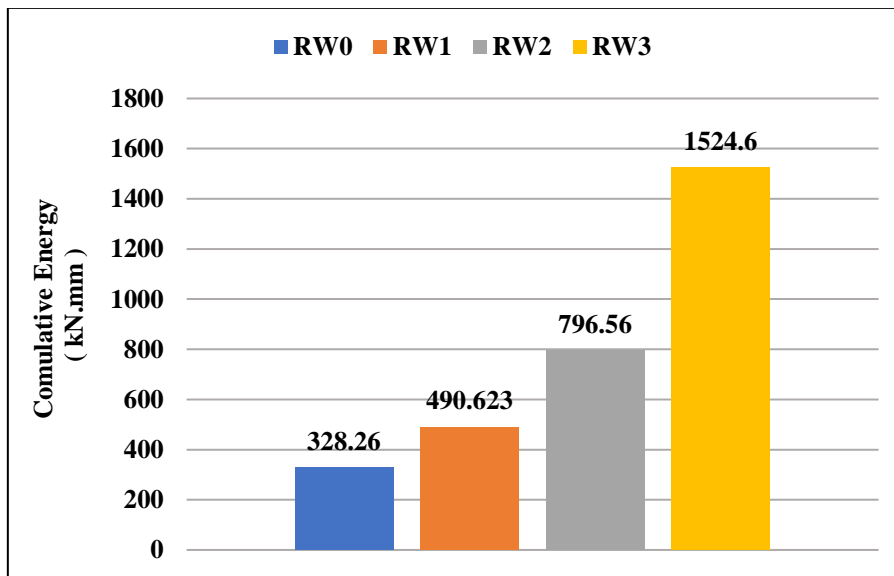**Figure 13.** Method for computing energy by an envelope curve (Seaders et al. 2009)

Figure 14. The cumulative energy for the models

4.3 The ductility and residual displacement

In this section, we will study the relationship between the displacement ductility and the residual displacement ratio and it is represented by curves, where the displacement ductility represents the x-axis and the residual displacement ratio represents the y-axis. The displacement ductility represents the ratio of the highest displacement value in each cycle of the hysteresis curve divided by the yield displacement value (dm∕dy)[14], which is the

value from which the specimen shifts from the elastic stage to the inelastic stage, While the residual displacement ratio represented by the value of the intersection of the curve of each cycle of the hysteresis curve with the x-axis divided by the yield displacement value (dr/dy)[14].

where :

dm : Maximum displacement in each cycle.

dy : Yield displacement.

dr : Residual displacement in each cycle.

The addition of rubber in the model's beam-column connection improved the model's ductility.

If the model's behavior is the most pronounced along the x-axis, which is the axis of ductility-displacement, it suggests that the model does not effectively disperse stresses, but rather generates huge distortions in the model before failing. However, if the model's behavior is the most extreme in the direction of the y-axis, which is the axis of the residual displacement index, then the model is distributing stresses too widely and causing damage to the model that can be repaired without the model collapsing. Figure (15) shows the relationship between the above-mentioned terms for the four models. The presence of the rubber washer at the beam-column connection gave the specimen residual displacement higher than the specimen without rubber. the specimens that content rubber washer by thickness (1,2,3mm) exceed the residual displacement with ratio (150%, 192%, 541%) respectively.

The increase is due to the presence of rubber, which redistributes stress and strain and lessens the model's reaction effect when a cyclic load is applied. The rubber also increases the model's left and right movement tolerance, resulting in less damage .Additionally, the presence of rubber in the beam-column connection helps to disperse stress and loads over a broader region, transforming the connection from a rigid to a flexible one.
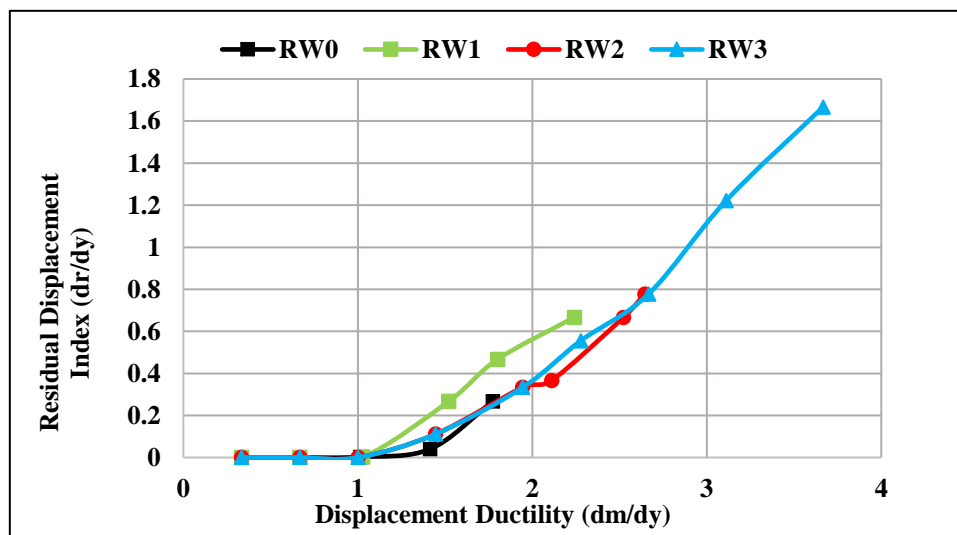

Figure 15. The relationship between displacement ductility and residual displacement

4.4 The ductility index (D.I)

It is described as a material's capacity to deform plastically without causing structural failure. It is mathematically defined as the ratio of displacement at the maximum load to the reference specimen's yielding displacement. The (RF-H-RW0) is the reference specimen.

A material with high ductility can be deformed without failure, but a material with low ductility is referred to as a brittle material, and early failure happens in this structure before the deformation becomes of significant value compared to the ductile material. Table (6) the ductility index calculated for the specimens and compared the results with the reference specimen and showed the effect of the presence of the rubber material at the connection of the specimens. The results showed that the ductility index increased with the presence of the rubber material. The ductile index of the specimens containing the rubber washer with a thickness (1,2,3 mm) under the head of the bolts at the connection is (26.5%,79%,148.6%) respectively higher compared to the reference specimen, this means the specimens with the presence of rubber material increase the specimen's portability in movement and the stress distribution in the connection over a broader region.

Table 6: The ductility index of the specimens content different thickness of rubber washer under horizontal cyclic load

The specimen	δ_y (mm)	δ_u (mm)	D.I (δ_u/δ_{yr})	The rate of increase the (D.I) %
C.R.H.RW0	7.5	13.3	1.77	-----
C.H.RW1	7.5	16.8	2.24	26.5
C.H.RW2	9	23.8	3.17	79
C.H.RW3	9	33	4.4	148.6

δ_y: Yield displacement , δ_u: Ultimate displacement , **D.I:** Ductility Index

4.5 The drift ratio

The drift ratio is the ratio of the difference between the displacement values of two stories divided by the height of this story. The difference between the displacements of the two-story in multi-story buildings is apportioned differently depending on the story height. In the case of one-story buildings, as in our study, we divide the specimen's maximum displacement by the specimen's overall height, which is the height of the column.

The drift values for four specimens in this group evaluated under horizontal cyclic load are obtained in Table (7) and compared to the drift ratio of reference models. By comparing the results, the drift of the specimens containing the rubber washer with a thickness (1,2,3 mm) at the connection is (26.2%, 78.9%,150.9%) respectively higher compared to the reference specimen.

Table 7: The drift of the specimens that contain rubber washer in the connection that tested under horizontal cyclic load

Specimens	δ_y (mm)	Yield drift ($\delta_y/1500$)	δ_u (mm)	Ultimate drift ($\delta_u/1500$)	The rate of increase in the Drift %
C.R.H.RW0	7.5	0.005	13.3	0.00887	-----
C.H.RW1	7.5	0.005	16.8	0.0112	26.2
C.H.RW2	9	0.006	23.8	0.01587	78.9
C.H.RW3	9	0.006	33	0.022	150.9

δ_y: Yield displacement at yield load, δ_u: Ultimate displacement

4.6 The equivalent viscous damping

The quantity of energy lost in a system is referred to as damping, and this loss is caused by internal or external energy sources, such as friction energy. Figure (16) shows the amount of equivalent viscous damping which was calculated by using the following relationship[14]: -

$$\zeta_{eq} = 1/(4\pi) * (A_{hys} / A_{el}) \qquad (4)$$

where
ζ_{eq} = The equivalent Viscous Damping.
A_{hys} = The Aria Under Hysteresis Curve or Cumulative Energy.
A_{el} = The Aria enclosed by the elastic energy.

The presence of the rubber washer at the beam-column connection gave the specimen equivalent viscous damping higher than the specimen without rubber. the specimens that content rubber washer by thickness (1,2,3mm) exceed the equivalent viscous damping with ratio (51%, 104%, 291%) respectively.
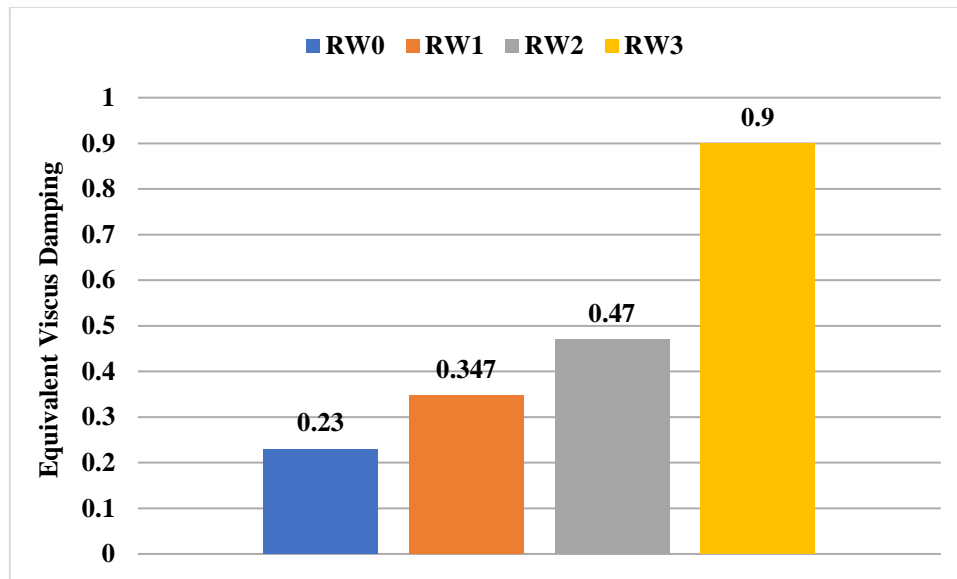
Figure 16. The equivalent viscous damping for the models

5. Conclusion

We conclude from this study several points that can be summarized as follows: -

1. When comparing the results between the numerical and experimental programs, we can prove that the convergence between the results is very large.

2. The load failure and the displacement for the verification study of the reference model (Shear Tab Connection) are (30.323kN,20.396mm), it was shown that the initial stiffness is lower but the ductility is higher when comparing the results with the reference model (Rigid Connection) (44.4kN, 13.3mm).

3. The presence of rubber improves the resist load and displacement, so it reduces the effect of the applied load and delays the failure time of the bolts.

4. Using the rubber washer increased the number of cycles that are carried by specimens where the number of cycles for models' content rubber with a thickness (1,2,3mm) increased by 16%,47%, and 63% respectively compared with the reference model without rubber.

5. The consumed energy amount for the models' content rubber with a thickness (1,2,3mm) increased by 49.4%,142.7%, and 364.4% respectively compared with the reference model without rubber.

6. The rubber washer in these samples acts as a damper and works to redistribute the stresses, and this increases by increasing the thickness of the washer.

7. The addition of rubber as a washer at the specimen connection improved the model's flexibility, increasing residual displacement.

8. The inclusion of rubber in the specimen's beam-column connection causes the displacement value after the elastic stage to be high, indicating that the specimen will be subjected to plastic deformations, which will last until the duration of the seismic effect.

9. Finally, the presence of rubber at the specimen's connection enhances flexibility while reducing stiffness, allowing the specimen to travel further to the right and left.

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