Seismic Analysis of the Steel Frame with Rubber-Sleeved Bolt in the Column-Base Connections

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Abstract. When earthquakes occur, catastrophic damage occurs, and hundreds of people are killed. It became necessary to find an effective method to reduce the seismic effect on the Structure. This is done by using rubber-sleeved bolts in the connection of the steel frame. This study is a numerical study that contains four models that were analysed in the ABAQUS program. The difference between these models is the presence of rubber at the base of the model only and the presence of rubber at the base of the model and in the connection between the column and the beam. The results showed that the residual displacement, cumulative energy, drift ratio, and ductility index of the model containing rubber in the base connection and the beam-column connection increases by (2.536,46.029, 155.613, and 155.626) % respectively, compared to the model that contains rubber in the base connection only.

Keywords: Steel Frame, Earthquake, Rubber, Damping, Connection.

1 Introduction

When an earthquake occurs, it results in a ground movement that travels in the form of a wave in the earth's crust, then this wave movement is transmitted to the base of the structure, where this wave movement is in two directions, a horizontal direction, and a vertical direction [1]. Earthquake is also defined as a geophysical phenomenon, formed in the form of waves, and these waves result in movement in the earth's crust up and down, as this movement resulting from the seismic wave moves to the foundation of the structure, then this movement resulting from the seismic wave works on violation of the vertical movement of the structure and this results in a failure in the foundation of the structure [2]. Therefore, it became necessary to study the effect of the seismic wave on the buildings and how to reduce the effect of the seismic wave on the buildings. For any building or structure to be earthquake-proof, its foundation must be resistant to sideways loads. The load will be lesser if the building is light. To reduce the load of the building, you need to focus on the top as the maximum weight is on the roof. However possible, the roof should 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 shear wall and steel bracing.

IMDC-IST 2021, September 07-09, Sakarya, Turkey

DOI 10.4108/eai.7-9-2021.2314884

Fadhil, H. et al. (2018) studied the use of steel corrugated shear walls in seismic impact resistance. Models for this study were tested under seismic load to note their effect on the performance of the shear wall under the seismic influence [3].
Shamivand, Abbas et al. (2019) studied an aside strengthening system that is in the form of a loop and is called Shami lateral bracing system (SLBs)). This system provides a new component that has a good ability to dissipate energy in addition to giving sufficient flexibility to the system [4]. However, these methods require a large amount of time and cost, in addition to the fact that these methods result in a high weight based on the structure [5].
This study suggests the use of rubber-sleeved bolts that is affordable in addition to being easy and quick to install compared to other energy dissipation methods. This study is a numerical study, which includes the use of rubber-sleeved bolts in the shear-tap that connects between the beam and the column in the steel frame and using the rubber-sleeved bolts in the base connection of the steel frame. This study aims to develop the connection of the steel frame using the rubber-sleeved bolts, as the rubber-sleeved bolts absorb the energy resulting from the seismic effect, increases the bearing load of the steel frame, and increases the amount of displacement.

2 FEM and Validation

2. 1 Validation of the Experimental Models

Relying on the researcher's experimental models [6] (suhab-2020), the finite element models were analysed, using the (ABAQUS-2017) [7] program to verify the validity of these results. This part includes the analysis of two experimental models tested under inclined quasi-static cyclic load. The design of the models was based on (AISC-14Th) [8]. Each model consists of one beam (IEP160) with a depth of 1000 mm. And two columns HW125×125 with a depth of 1500 mm. The beam is connected to the column on each side using a shear tap, with dimensions of 110 x 90 x 8 mm. The shear tap is connected to the beam by a one-line of bolts and each column by a line of the weld. The right column support of the model is pin-support, and the left column support is fixed-support, whereby the right column is strengthened by 4 stiffeners that in turn strengthen the column to prevent failure and focus the failure position on the bolts of the connection between the column and the beam.
The diameter of the bolt used is 7 mm, the diameter of the bolt holes in the beam and the shear-tap is 8.5 mm for the first model, which is the reference model, and the diameter of the bolt holes in the second model in which the connection bolts between the beam and the column are rubber-sleeved is 17. 5 mm.
Where the symbol for the first experimental model is the reference model (I.0.STD.1), as this model does not contain rubber-sleeved bolts in the beam-column connection. The second model is a symbol (I.150.LSL.2), which contains rubber-sleeved bolts in the beam-column connection by 150% of the bolt diameter, where the diameter of the rubber-sleeved bolt becomes 17.5 mm, and the thickness of the rubber is 5.25 mm on each side of the rubber-sleeved bolt. The shape of the numerical model, the experimental model, and the shape of the rubber-sleeved bolts are shown in Fig 1.

B: FEM model A: experimental model C: Details of the rubber-sleeved bolts.

Fig. 1. The FE Model and Experimental model.

The effect of each material and geometrical proprieties is considered. The first important geometric condition is the selection of element shapes. During this study, different orders and types of the element were tested in the FEM models until arriving at the element order and that type gives results that are close to the results of the researcher's [6] (suhab-2020) experimental analysis. The solid type sections are used because the thickness of the section, compared to other dimensions, is not small. In addition, first-order reduced integration C3D8R was selected for all the frame modelling.

2. 2 The Material properties

For the Poisson ratio, young's modulus, and density, hardening-isotropic material were used in the elastic zone. The ABAQUS program required input data such as elastic modulus, density, and Poisson's ratio as illustrated in Table 1 for the rubber and the steel components of the model.

Table 1. The Mechanical properties for Components Model [6].

The Sections	Density	Elastic Modulus MPa	Elongation Ratio
Steel-Beam	7.83 e -09	1.95 e +05	0.3
Steel-Column	7.83 e -09	1.87 e +05	0.3
Shear-Tap	7.83 e -09	2.11 e +05	0.3
Steel-Bolt	7.83 e -09	2.75 e +05	0.3
Steel-Washer	7.83 e -09	2.75 e +05	0.3
Rubber	1.52 e -09	91.120	0.5

In simulation programs (the ABAQUS program), the values of the engineering strain and stress data are not used, but they are converted to true values by using the following equations [6].

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

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

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

The true strain and stress values that were converted through the above equations and based on the engineering strain and stress values that were used to define materials in the ABAQUS program are shown in Table 2.

Table 2. The True Value of the Properties [6].

Steel Section	Yield-stress MPa	Plastic-Strain mm/mm
Steel Beam	250.4375	0
	400.7	0.301135883
Steel Column	250.4375	0
	400.7	0.283362250
Shear Tap	312.546	0
	422.7385	0.283242381
Steel Bolt	588.6	0
	648	0.073721041

2. 3 Boundary condition and mesh design

At the beginning of the meshwork, the sections must be first divided into pieces for these to be uncomplicated sections. In other words, the program does not understand the non-divided sections because their mesh is complex and thus does not give correct results.

The First order-hexahedral cubic elements were used for regularly shaped regions of model mashing. The mash size for columns, beam, stiffeners, shear tap, nut, bolt, rubbers, and washers are (100,50, 100, 25, 10, 10, 10, and 10) mm respectively.

The type of load used in this study is an inclined cyclic load that was applied depending on the protocol like the loading protocol in the experimental program. In all models, the load is placed on the top and side edges of the right and left columns, also, boundary conditions consisted of a pin and fix, as shown in Fig 2.

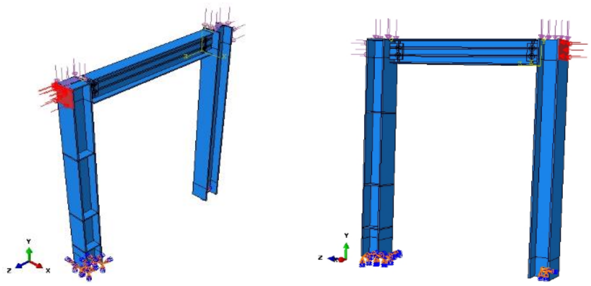

Fig. 2. Load Case and boundary conditions in the ABAQUS Program.

2. 4 The Validation Results

Through the numerical representation of the model and then comparing the form of failure and the results of the numerical analysis with the experimental test, it was found that there is a great convergence in the form of failure between the experimental and numerical models.

Whereas in the experimental model, the failure is concentrated on one area, where is the connection between the column and the beam, a fracture occurs in the bolts for most models which is induced a fracture of the rubber covering the bolt. To clarify the form of convergence, the shape of failure in the experimental and numerical test models is presented in Figure 3.

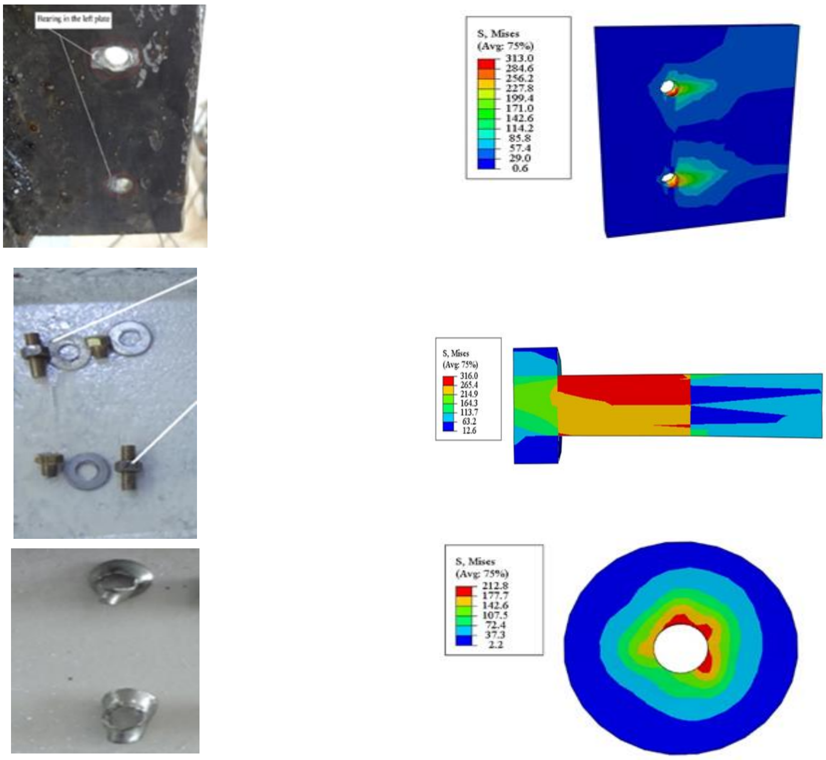

Fig. 3. Failure Shap of Experimental and Numerical Models.

When comparing the results obtained from the numerical program with those obtained from the experimental results, the envelope curve is shown in Figs 4 and 5.

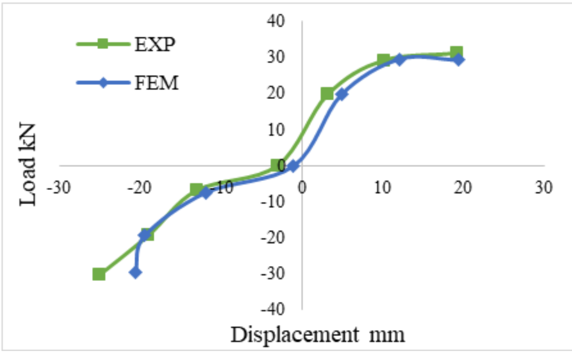

Fig 4. Envelope Curve for Experimental and Numerical Analysis of the I.0.STD.1 Model.

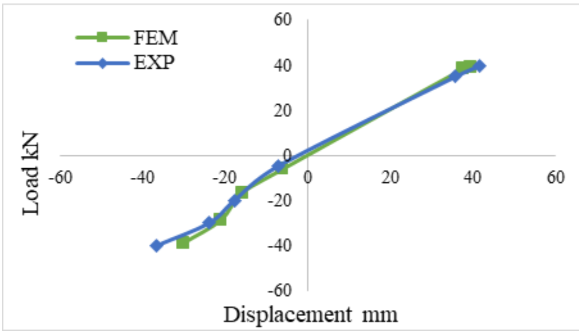

Fig 5. Envelope curve for Experimental and Numerical Analysis of the I.150.LSL.2 Model.

From these figures, we can prove that the result convergence very largely. In addition, this convergence, which is shown in Table 3, includes the results of the experimental and numerical models in terms of displacement and loading.

Table 3. Displacement and Load Result for Experimental and Numerical Analysis.

Model name	Load kN		The ratio of convergence of load (FEM/EXP)	Displacement mm		Ratio of convergence of displacement (FEM/EXP)
	FEM	EXP		FEM	EXP	
I.0.STD.1	29.187	31.053	0.939	19.347	19.265	1.00
I.150.LSL.2	39.087	39.927	0.978	39.478	41.468	0.952

3 The Case Study

In this study, two models were tested, each model contains 2-bolts in the beam-column connection and 8-anchors bolts in the base connection. The first model contains rubber around all base connection bolts at 50% of the bolt diameter. The second model contains rubber around the connection bolts between the column and the base at 50% of the diameter of the bolt and contains rubber at 150% of the diameter of the bolt connection between the beam and the column. The models of this group were tested under inclined cyclic loads. The effects of residual displacement, cumulative energy, equivalent viscose damping, drift, and ductility index are discussed. Models with rubber in the connection between the beam-column and the base connection, the role of the rubber was evident by increasing the displacement and load value of the models. The sections are designed to depend on the AISC Manual. The reason for the use of the inclined cyclic load, when the structure is exposed to seismic effect, the beam-column connection is subjected to shear force, moment, and axial forces. Based on what the researcher [9] mentioned, who says that these forces lead to a rotation in the connection, and to represent this rotation and this effect, the inclined cyclic load was used, in which one of its components is the vertical component that results in a moment in the beam-column connection resulting from the drift that it gets between the bolt line and the welded. The load applied in this type of loading is at an angle of 10 degrees. The load is shed on the upper side end of both columns, which represents the horizontal component, while the vertical component is shed on the upper end of both columns of the model. The shape of the model that is tested in the ABAQUS / CAS (2017) program is shown in Fig 6. Section (A) shows the shape of the rubber at the base of the model, where this rubber works as the damper which is used in the bases of models to dampen seismic intensity.

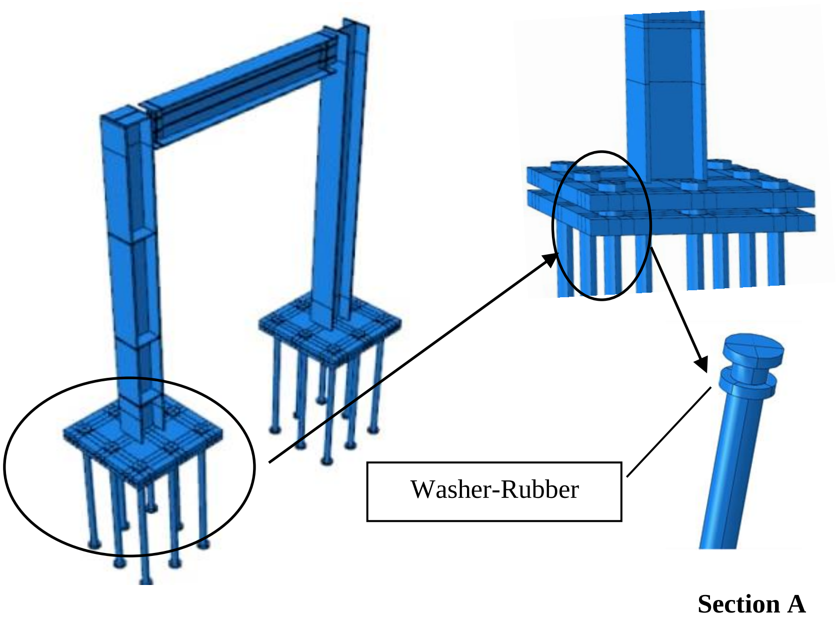

Fig. 6. The Washer-Rubber in the Base of the Model.

The symbolize of all models that study in this paper is listed in Table 4.

Table 4. The Symbolize of all models that study in this paper.

<table>
<tr><th rowspan="2">No.</th><th rowspan="2">Name of the Models</th><th rowspan="2">Type of load</th><th colspan="2">Number of Bolts</th><th colspan="2">Rubber ratio%</th><th rowspan="2">Location of Rubber</th></tr>
<tr><th>Shear Tap</th><th>Base Plate</th><th>Shear Tap</th><th>Base Plate</th></tr>
<tr><td>1</td><td>RF.I.2B.50A.</td><td rowspan="2">Inclined-cyclic-load</td><td rowspan="2">Two bolts</td><td rowspan="2">Eight anchor bolts</td><td>0%</td><td>50%</td><td>Rubber around 8 anchor bolts in the base plate only.</td></tr>
<tr><td>2</td><td>F.I.2B.50A.150B.</td><td>150%</td><td>50%</td><td>Rubber around 8 anchor bolts and 2 bolts in the shear tap connection</td></tr>
</table>

4 The Numerical Results

4. 1 The Residual displacement

These curves are represented by special equations where the equation for the x-axis represents the ratio of the highest displacement value in each cycle of the hysteresis curve divided by the yield displacement value, which is the value from which the model shifts from the elastic stage to the inelastic stage, where this ratio is called the displacement ductility, as the text of the equation is explained below:

$$\text{Displacement Ductility}=|d_m/d_y| \quad (4)$$

Where: d_m: Maximum displacement in each cycle of the hysteresis curve.
dy: Yield displacement[10].

While the y-axis represents a ratio of the residual displacement index 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, where this ratio is called the residual displacement index, as the text of the equation is explained below, [10]:

$$\text{Residual displacement ratio}=|d_r/d_y| \quad (5)$$

Where: dr:- Residual displacement.
dy:- Yield displacement.

Through the above equations, comparison curves were made.

In this section, the model that contains the rubber at the base connection is compared with the model that contains the rubber at the base connection and in the beam-column connection. The residual displacement of the two models of this study compared with experimental models is shown in Fig 7.

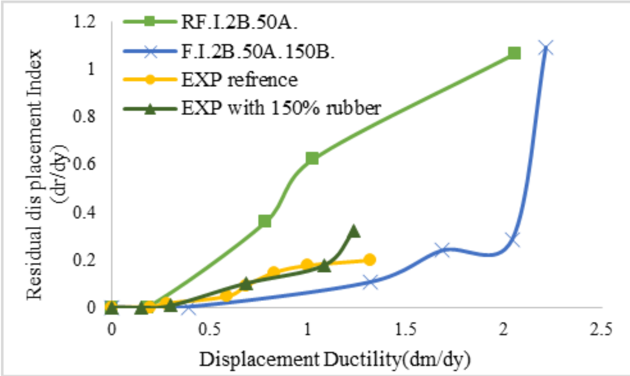

Fig.7. Displacement Ductility versus Residual Displacement Index.

The presence of rubber only at the base connection increased the residual displacement by 447.692% compared to the reference experimental model that does not contain the rubber and increased the residual displacement by 233.75% compared to the experimental model that contains the rubber in beam-column connection.

The residual displacement of the model containing rubber in the base connection and the beam-column connection increases by 2.536% compared to the model that contains rubber in the base connection only, increase by 242.438% compared to the experimental model that contains rubber in beam-column connection only, and increases by 462.051% compared to the reference experimental model that does not contain the rubber.

The presence of rubber in the two most influential regions, the beam-column connection and the base connection of the model increased the flexibility of the model due to them that the displacement value after the elastic stage is large, then this means that the model will be exposed to plastic deformations, and these plastic deformations will continue to the stage after the end of the seismic effect.

These plastic deformations occur in the places of greatest damage, which are in the beam-column connection because of these areas it is made up of more than one material, such as bolts, plate, beam, net, washer, and so on from the materials in the connection, so each connection material has a different behaviour than the other material in the same area, so the level of potential damage in these dangerous areas cannot be assessed. We work to reduce future damage and give rise to sudden failure.

4. 2 The Cumulative Energy

A relationship between displacement ductility and cumulative energy is drawn to see how much energy the model would dissipate if the rubber were used in the base connection and beam-column connection. The energy for the model is counted by calculating the area under the envelop curve according to the researcher [10]. Displacement ductility represents the maximum displacement value at each hysteresis curve divided by yield displacement [11]. The cumulative energy of the two models of this study is compared with experimental models and is shown in Fig 8.

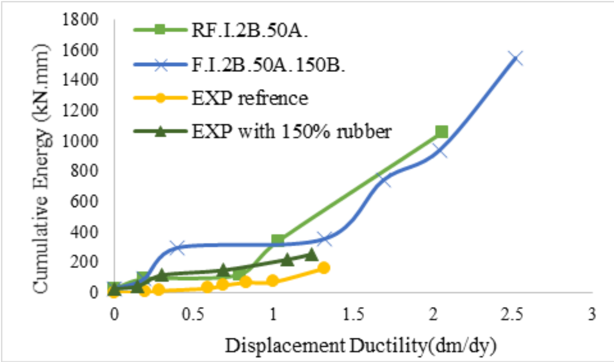

Fig.8. Displacement Ductility versus Cumulative Energy.

All models behave the same at a displacement ductility value of about 0.25. After this value 5 of displacement ductility, the variation in the behaviour of the models begins to appear. The rate of cumulative energy of the model containing the rubber in the base connection is 564.839% higher compared to the reference experimental model and 313.140% higher as compared to the experimental model containing the rubber in the beam-column connection.
The cumulative energy of the model containing the rubber in the base connection and the beam-column connection is 46.029% higher compared to the model containing the rubber in the base connection, 503.306% higher as compared to the experimental model containing the rubber in the beam-column connection, and 870.860% higher compared to the reference experimental model. The reason that the model that contains rubber in the base connection and the beam-column connection has a higher cumulative energy is that this model gives a load of 64.704 kN and a displacement of 222.455 mm, and the model that contains rubber in the base only gives a load of 29.423 kN and a displacement of 86.841 mm, since it depends the cumulative energy depends on the value of the maximum load and the displacement of the model, so the model that contains the rubber at the base connection and the beam-column connection has higher cumulative energy. The presence of rubber at the base connection and the beam-column connection gives a high displacement of the model because the presence of rubber dissipates energy and stress and makes it spread over a larger area and that the presence of rubber at the base of the model increases the flexibility and reduces the stiffness, so when the flexibility increases, it increases the ability of the model move more to the right and left.

4. 3 The Equivalent Viscous Damping

Damping is defined as the amount of loss in system energy, and that this loss results from the energy that may be internal or external, such as friction energy. A relationship between displacement ductility and equivalent viscous damping is drawn to see damping properties. Equivalent viscous damping was calculated using the following relationship [11]:

)(6 $$\xi_{eq.} = \frac{1}{4\pi} * \frac{E_{cumulative}}{E_{elastic}}$$

Where:
Cumulative energy.$E_{cumulative}$
$E_{elastic}$: Elastic energy.

The equivalent viscous damping of the two models of this study compared with experimental models is shown in Fig 9.

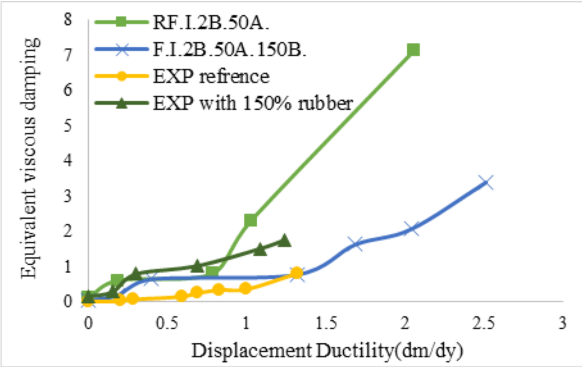

Fig. 9. Displacement Ductility versus Equivalent Viscous Damping.

The equivalent viscous damping is about 1 during the elastic response of all models and then increased to approximately 7.126 in the model that containing rubber in the base connection. The equivalent viscous damping is 807.771% higher in the model that containing rubber in the base connection than the reference experimental model. Also, the equivalent viscous damping is 308.133% higher in the model that containing rubber in the base connection than the experimental model that contains rubber in the beam-column connection only. Also, the equivalent viscous damping is 110.704% less in the model that containing rubber in the base connection and beam-column connection than the model containing rubber in the base connection only. Also, the equivalent viscous damping is 93.699% higher in the model that containing rubber in the base connection and beam-column connection than the experimental model that contains rubber in the beam-column connection only, and 330.828% higher in the model that containing rubber in the base connection and beam-column connection than the reference experimental model. The equivalent viscous damping of the model that contains rubber in the base connection is higher than the model that contains rubber in the base connection and beam-column connection because the cumulative energy in the elastic phase of the model that contains rubber at the base connection is 223.171% less than the cumulative energy in the elastic phase of the model that contains rubber in the base connection and beam-column connection.

4. 4 The Drift ratio

The ratio of the difference between the displacement values of two stories and the division of these two displacements by the height of this story is called the drift ratio. For the multi-story buildings, the difference between the displacements of the two-story is divided this different on the height of the story. As for one-story buildings, which areas in our study, we divide the greatest displacement of the model by the height of the whole model, which is the height of the column.

In Table 5, the drift values are calculated for two models of this study tested under inclined cyclic load and compare with the drift ratios of experimental models.

Table 5. The Drift of the Models that Contains Rubber in Base Connection and Connection that Tested under Inclined Cyclic Load.

Model name	($\delta_y$mm)	Yield drift ($\delta_y/1500$)	($\delta_u$mm)	Ultimate Drift ($\delta_u/1500$)
EXP. reference	18.98	0.012	19.2647	0.0128
RF.I.2B.50B.	42.218	0.0282	86.841	0.0579
Exp. With 150% rubber	32.29	0.021	41.468	0.0277
F.I.2B.50A.150B.	100.419	0.0669	222.455	0.148

$\boldsymbol{\delta_y}$: Yield displacement at yield load,$\boldsymbol{\delta_u}$: Ultimate displacement

By observing the results, the drift of the model containing the rubber in the base connection is 352.343% higher compared to the reference experimental model and 109.025% higher as compared to the experimental model containing the rubber in the beam-column connection.
The drift of the model containing the rubber in the base connection and the beam-column connection is 155.613% higher compared to the model containing the rubber in the base connection and 434.296 % higher as compared to the experimental model containing the rubber in the beam-column connection. The drift value of the model that contains the rubber in the base connection and the beam-column connection is higher than the drift value of the model that contains the rubber at the base connection only because the model that contains the rubber in the base connection and the beam-column connection give high displacement than the model containing the rubber in the base connection only the drift of the model that containing the rubber in the base connection and the beam-column connection give high drift.

4. 5 The Ductility Index

It is defined as the ability of a material to have a plastic deformation without failure in this structure. Mathematically, it is defined as the ratio of drift at the highest load to a ratio of yielding drift of the reference model. Whereas the reference model for this group is the model that contains rubber in the base connection only. A material with high ductility will be deformed without fail, and this material is called the ductile material, while a material that is of little ductility is referred to as a brittle structure and early failure occurs in this structure before the deformation becomes of high value compared to the ductile material. In Table 6, the ductility index is calculated for two models of this study tested under inclined cyclic load and compare with the ductility index of experimental models.

Table 6. The Ductility Index of the Models that Contains Rubber in Base and Connection that Tested under Inclined Cyclic Load.

Models name	Yield drift Δ_y	ultimate drift Δ_u	Ductilityindex Δ_u/Δ_{yr}
EXP. reference	0.012	0.0128	1.0667
RF.I.2B.50B.	0.0282	0.0579	2.053

EXP. With150% rubber	0.021	0.0277	2.308
F.I.2B.50A.150B.	0.0669	0.148	5.248

Δ_{yr}: Yield drift of the reference model, Δ_u: Ultimate drift.

The presence of rubber has a great effect on increasing the ductility index, the ductile index of the model containing the rubber in the base connection is 92.463% higher compared to the reference experimental model and 12.421% less as compared to the experimental model containing the rubber in the beam-column connection only. The ductile index of the model containing the rubber in the base connection and the beam-column connection is 155.626% higher compared to the model containing the rubber in the base connection and 127.383% higher as compared to the experimental model containing the rubber in the beam-column connection only. The presence of rubber at the base connection and in the beam-column connection increased the ductility of the model because the value of ductility depends mainly on the drift value of the model, and the model that contains the rubber in the base connection and the beam-column connection gives a drift of 46.064% higher than the model that contains the rubber in the base connection only, so the ductility of the model that contains the rubber in the base connection and the beam-column connection is high due to the presence of rubber in the connection, which led to an increase in the portability of the model in movement and the distribution of stresses in the connection over larger areas.

5 Conclusions

By testing the models under inclined cyclic load, the following was concluded:

1. The presence of rubber in the two most influential regions, the beam-column connection and the base connection of the model increased the flexibility of the model and then increase the residual displacement of the model.
2. The presence of rubber in the beam-column connection and the base connection of the model makes the displacement value after the elastic stage is large, then means that the model will be exposed to plastic deformations, and these plastic deformations will continue to the stage after the end of the seismic effect.
3. The presence of rubber in the beam-column connection and the base connection of the model increases the flexibility and reduces the stiffness, so when the flexibility increases, it increases the ability of the model to move more to the right and left.
4. The presence of rubber in the connection, which led to an increase in the portability of the model in movement and the distribution of stresses in the connection over larger areas.
5. The equivalent viscous damping of the model that contains rubber in the base connection is higher than the model that contains rubber in the base connection and beam-column connection.
6. The drift and ductility index of the model that contains the rubber in the base connection and the beam-column connection is higher than the drift and ductility index of the model that contains the rubber at the base connection only.
7. Finally, the presence of rubber at the base connection of the model and in the beam-column connection increases the flexibility of the connections, which leads to a delay in the failure time of the model and thus improves the performance of the model.

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