Development of steel structure connections for seismic resistance using composite steel bolts / rubber

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Abstract. This study scoped to develop the connections of steel structures using composite steel bolts/rubber to connect beam-to-columns joints of steel structures instead of conventional steel bolts. Four steel plane portal frames were tested under horizontal cyclic quasi-static load. The study included testing different diameters of composite steel bolts/rubber: 0.5\(d_{\text{bolt}}\), 1.0\(d_{\text{bolt}}\), and 1.5\(d_{\text{bolt}}\), that are used to connect the beam with columns and these results were compared with traditional beam-to-columns connections without rubber. The rubberized connections are working at high structural standards through reducing the effect of the stresses resulting from the earthquakes by absorbing damping process. They protect the bolts that are used in joints of steel structures from corrosion due to friction, and they are economically feasible because the rubber that was used for covering the bolts is taken from old tires. The experimental tests proved that using the rubber material around the bolts as much as one - half times bolt diameter raises the specimen’s resistance by 166.66%, increases the displacement by 163.30%, and reduces the strain by 48.13%, as compared with bolts that do not have a rubber (steel bolts only). All these results will be discussed in detail in this report.

Keywords: Earthquake; Cyclic Load; Shear Tab Connection; Rubber.

1. Introduction

In recent years, Iraq has been subjected to several earthquakes, especially the earthquake that occurred in Sulaymaniyah - Halabja region in 2017 (7.3 on Richter scale), and the last earthquake near Iraq (6.3 Richter) in 2018. Therefore, it becomes necessary to study how to reduce the influence of earthquakes and wind loads on steel structures, especially since the previous buildings were not designed to resist seismic effect, by using the Smart Joints Technology at steel structures. The tab connections are usually designed to transfer shear force and to be suitably flexible to conform to end rotation of the beam. Under the combined effects of lateral and gravity loads (earthquake effects or wind load), shear tab connections are exposed to combined shear with axial cyclic load and cyclic rotation (Astaneh-asl 2005). AISC-14th edition (2011). Specification requirements confirm that the shear tab connection under combined force can resist the lateral and gravity load; however, it should have sufficient rotational ductility to afford cyclic rotation during the seismic effect. Joints failure are the most common and more frequent type of failure in steel structures. It is possible to design a steel member very accurately, while for the design of connection, the calculations have become more complicated by the search for the maximum load and then design connection for maximum strength. Generally, the
connections are failing if there is an unexpected force because it is logical that any steel section of the steel structure can resist secondary loads since the section is cast one part while the connections are behaving in a brittle way, where it can take some loads and not all. Therefore, the idea of studying and developing steel connections for the purposes of absorbing and dispersing these loads through the use of composite steel bolts/rubber is the main objective of this research. In this study, single shear connections are used to connect the beam with columns. The two main objectives of this paper are:

1. Simulate seismic load by applying horizontal cyclic-quasi-static load on steel portal frame.
2. Develop column-beam connections that are able to absorb the energy resulting from the exposure of steel structures to the horizontal movement under the effect of earthquakes. A parametric study is an obtainable database on the behavior of steel portal frame with shear tabs connection and rubber under seismic effect. The results are used to develop the specimens that can establish the global rotational drift and ductility of shear connection with composite steel bolts/rubber.

2. Past Research on Shear Tabs Subjected To Combined Forces

(Crocker and Chambers 2004), investigated the response of many specimens of full-scale tests on shear tab connections with 10 mm thick T-type beam-column specimens, bolted by three, four and six 19mm (ASTM -A325) bolts in a single vertical row shape. This study suggested 8.6 mm as limiting value of defatamation shear connection, and given design rotation on single plate connection can be obtained from equations; these equations presented and provided an accurate estimate of the initial connection rotation capacity.

(Daneshvar and Driver 2017), attempted to simulate the experimental work on shear tab connections exposed to combined shear, axial and moment force by using the ABAQUS program. The researchers did verify nine model tests from Thomson (2009). The FE model that was used, consisted of two beams connected in the middle column and bolted by a single shear plate, at the ends of the test beams were simulated as true pins each other. Accumulated gravity and seismic rotation in the experimental test were (0.08 radian), while the rotation of the connection at FE model experienced was (0.1 radian). Specimens presented high ductility abilities due to bearing round holes in the shear plate. The FE models delivered a suitable response as compared to the experimental results. (Asl, Farivar, and Momenzadeh 2019), 317 FE models were investigated of different size of shear tab connection and beam size for obtaining behaviour of connection rigidity and classification under service load. The plastic deformations in the shear tab connection and the plastic section modulus of the shear connection show significant characters to determine the rotational rigidity of the shear plate connection by using the following equations: 

\[
\frac{Z_{\text{Beam}}}{Z_{\text{Tab}}} < 4.27 \rightarrow \text{semi-rigid connection},
\]

\[
4.27 < \frac{Z_{\text{Beam}}}{Z_{\text{Tab}}} < 5.08 \rightarrow \text{cannot be determined},
\]

\[
5.08 \rightarrow \text{simple connection where the } Z_{\text{Beam,Tab}} \text{ is plastic section modulus of beams and tabs. The researchers found that by using the equation }\frac{Z_{\text{Beam}}}{Z_{\text{Tab}}}, \text{ the connection rigidity can be extra perfectly expected. Consequently, they recommended this equation to be used for calculating the connection rigidity.}

3. Experimental Research - Design Specimen, Instrumentation, and Loading

3.1. Design Specimen

The specimens tests are used for this study designed according to AISC-14th edition (2011). The Steel Portal Frame is composed and welded, a steel section (HW125 × 125) with height 1500 mm for columns, and (IPE160) with the length of (1000) mm for the beam. The columns are welded at steel bases. One of these bases is fixed support and the other is a pinned support. The bases are fixed by eight-anchor bolts with diameter 32 mm type -B7. Single shear tab connection is bolted at the web of the beam at each side and welded at the flange of the column. Shear tab dimensions were equalled to
110mm, 90mm, and 8mm length, width, and thickness, respectively, as the layout of specimen details are shown in Figure (1).

![figure](image)

**Figure 1** Specimen dimensions, Section (A-A) connection properties, Section (B-B) pinned support, Section (C-C) fixed support.

Mechanical properties for the columns, beam, and plates are listed in Table (1). The properties of the sections are found according to the standard test method A370 − 17a) in Diyala University laboratories:

| Member    | Yield Point (MPa) | Ultimate Strength (MPa) | Elongation (%) | Elastic modulus (MPa) |
|-----------|-------------------|-------------------------|----------------|-----------------------|
| Column    | 250               | 400                     | 35             | 1.95$\times$10$^5$    |
| Beam      | 250               | 400                     | 32             | 1.87$\times$10$^5$    |
| Plate (8mm)| 312               | 422                     | 31             | 2.11$\times$10$^5$    |

Steel bolts Grid A307-N 7mm $\times$ 35mm are used according to ASTM specification to connect the shear tabs at the beam. For design purposes and to confirm the failure at bolts, 7 mm diameter bolts
with tensile stress $F_{\text{tt}} = 600\text{MPa}$ and shear strength $F_{\text{sv}} = 302\text{MPa}$ are used to determine their efficiency and tolerance to tensile and shear stresses. The rubber is used to cover the bolts in three different diameters of the bolt $0.5d_{\text{bolt}}$, $1.0d_{\text{bolt}}$, and $1.5d_{\text{bolt}}$ as illustrated in Figure (2). The rubber is taken from the old and used tires.

![Figure 2 Composite Steel Bolts/Rubber.](image)

The rubber tests were tested at the University of Technology - Applied Sciences Laboratories. The tensile stress of the rubber found according to the standard test method (D638 − 14) using the Jianqiao Testing Equipment was 15.09 MPa and the elongation was 1204.17%. The hardness test was performed using Shore a Hardness Tester Th200, where the rate of five readings is taken (84.7-89.9-82.7-84.7-86.3). The rubber hardness that was used in this study is found to be 85.66 Shore A. Finally, comparison test of rubber was conducted according to standard test method (D695 − 15). The rate of change in sample length at each load phase is taken to the extent of the failure and the results of the compression test rubber are obtained, as shown in Table (2).

### Table 2 Compression Test Rubber

| Force (N) | $\Delta L$ (mm) | $\sigma =P/A$ (MPa) | $\epsilon=\Delta L/L$ | Young's modulus (MPa) |
|-----------|-----------------|---------------------|----------------------|----------------------|
| 0         | 0               | 0                   | 0                    | 0                    |
| 500       | 1.24            | 20                  | 0.124                | 161.4                |
| 700       | 3.94            | 28                  | 0.396                | 70.7                 |
| 900       | 8.72            | 36                  | 0.872                | 41.28                |

3.2. Instrumentation

Load-Deflection hysteresis can be used to represent and simulate earthquakes, according to Seismic Provisions for Structural Steel Buildings, ANSI/AISC 341-10 to (Taranath 2012), through the applied horizontal cyclic load on steel portal frame, and calculation on displacements and stress can be done for each specimen. To achieve this study and for applying loads on specimens in this way, a machine test is manufactured in which a servo-motor is used to control it through a control panel with steel frame system to fix two hydraulic jacks, as shown in Figure (3). The hydraulic jacks could be available with $+500\text{mm}$ all-out stroke displacement, and $+300\text{kN}$ push force. The velocity of the stroke jacks could be controlled by minimum value (10mm/ min) and the maximum value (100mm/ min). Loads measured by using load cells are connected at the end of jacks, displacements are established by using two instruments of Liner Variable Differential Transducers (LVDTs), as well as the strain gauges are used at an important positions to find the strain and stress at steel sections.
3.3. Loading

Horizontal cyclic–quasi-static load is applied to each specimen, according to the Guidelines for Cyclic Seismic Testing of Components of Steel Structures for Buildings (ATC-24, 1992). ATC-24 is one of the first official protocols developed in the United States to assess the seismic performance of components using the periodic load date. Loads have been applied at the specimens by two hydraulic jacks in which compression load cells are connected at ends. A number of cycles and load speed are controlled by the control panel. Three slow cycles are applied for each load phase. Six cycles before the yield point (Amplitude \(< \Delta_{\text{yield}}\)), and then three cycles at yield deformation stage (3cycles - \(\Delta_{\text{yield}}\)), three other cycles with a displacement equivalent to twice displacement times at yield point deformation (3cycles -2\(\Delta_{\text{yield}}\)), and three other cycles with a displacement equivalent to three times at displacement the yield point deformation (3cycles -3\(\Delta_{\text{yield}}\)) as shown in Figure (4). The relative increase in loading the specimen continues to the extent of failure.

![Deformation history for multiple-step test.](image1)

**Figure 3** Horizontal cyclic load machine testing (Simulation seismic load).

![Deformation history for multiple-step test.](image2)

**Figure 4** Deformation history for multiple-step test.
Shear tab connections welded at columns and bolted at the beam by two of composite steel bolts/rubber are installed on each joint of the steel frame. The same load and the test protocol are applied on all these bolts. For investigating, the behaviour and the effect of the specimens are tested in the case of conventional steel bolts and when these conventional bolts are covered by varying percentages of strong rubber (rubber from old and used tires) as detailed in Table (3).

### Table 3. Specimen Details

| No | Description of Specimens                  | Schedule         | Composite Steel Bolts / Rubber |
|----|------------------------------------------|------------------|--------------------------------|
| 1  | (FR1) steel portal frame without rubber  | Horizontal/Cyclic| 7.0mm                          |
| 2  | (FR2) steel portal frame with (50%) rubber| Horizontal/Cyclic| 10.5mm                         |
| 3  | (FR3) steel portal frame with (100%) rubber| Horizontal/Cyclic| 14.0mm                         |
| 4  | (FR4) steel portal frame with (150%) rubber| Horizontal/Cyclic| 17.5mm                         |

### 4. Test Results and Desiccations

#### 4.1. Measurement of the Specimens at Yield and Ultimate Points

The test is done for four specimens. The results of the examination are found as shown in Table (4) where the following conclusion is obtained:

- At yield points, the resistance of specimens containing composite steel bolts/rubber (FR2-FR3-FR4) is increased by (50%-100%-100%) respectively, as compared with the specimen without rubber (FR1).
- At the failure stage, the effect of the rubber was cleared, the resistance of specimens is raised by (33.33%- %33.33%-166.66%) for the frames with rubber, as compared with the frame without rubber (FR1).
- The results are presented, the specimens load (FR1, FR2) is (20 and 30 kN) at yield point, while at failure the load is (30 and 40 kN), that means the yield point and failure are closed. The load of specimen (FR3) at the yield point and the failure was the same equal to (40kN), while the difference in the fourth frame (FR4) between the point of yield and the point of failure is 40kN-80kN, respectively. This shows that the effect of the use of steel bolts / rubber, where the addition of rubber as much as one and a half times of diameter steel bolt, makes the steel frameworks Redistribution Moments and then delays the failure of the frame completely.

### Table 4. Displacement of Specimens Tested under Horizontal Cyclic Loading Regime

| No. Of Specimens | $P_y$ (kN) | Yield-Dips (mm) | $P_u$ (kN) | Ultimate-Dips (mm) | Max Drift Ratio (%) | No. of Cycles |
|------------------|------------|-----------------|------------|---------------------|------------------|--------------|
|                  | Left      | Right           | Left      | Right               |                  |              |
| FR1              | 20        | 9.125           | 11.92     | 30                  | 17.85            | 1.19         | 10           |
| FR2              | 30        | 21.70           | 20.02     | 40                  | 26.24            | 25.10        | 1.74         | 16           |
| FR3              | 40        | 26.24           | 25.10     | 40                  | 41.18            | 35.92        | 2.74         | 16           |
| FR4              | 40        | 26.99           | 20.88     | 80                  | 40.00            | 47.00        | 3.13         | 40           |

#### 4.2. Maximum Drift of the Specimens at Failure

The global drifts are calculated from the measurement of the peak displacement divided by the height of the column which is 1500 mm, where the increase in the drift is noticeable for the frames containing the composite steel bolts/rubber as shown in Table (4). The drift value of the frame (FR2) is increased by 46.21%, so the frame FR3 was about of 130.25%, while the frame FR4 has the highest drift of all specimens at 163% as compared with the non-rubber frame. Increase in the displacement was clear by the increased rubber ratio where the composites steel bolts/rubber were used at the steel
connections required to expand the diameters of the holes that led to the increase in the connection rotation and displacement as well as transformation the steel joints from the rigid or semi-rigid to flexible joints.

4.3. Number of Cycles for Specimens
According to the ATC-24- protocol, the specimens are loaded by using two hydraulic jacks it's applied to horizontal cyclic load-quasi static load where the used rubber around the bolts increases the number of cycles that are resisting the specimens. The number of cycles for FR2 and FR3 were the same and equal to 16 cycles, while the number of cycles of frame FR4 were 40 cycles, as compared to the FR1 frame (steel bolts only), in which the steel bolts were a fracture and reached at the failure on 10 cycles, as shown in Figure (5 to 8). That shows the effect of composite steel bolts/rubber are used in connections, where the rubber has led an important role in reducing the axial, vertical Shear and moment at the connection. Moreover, the addition of rubber led to a reduction of the influence of bearing in the shear tab connections. This is expected because the rubber around the bolts prevents friction between the bolts and steel plates to a certain extent of the load.

![Figure 5. FR1 Load-No.of Cycles.](image1)

![Figure 6. FR2 Load-No.of Cycles.](image2)

![Figure 7. FR3 Load-No.of Cycles.](image3)

![Figure 8. FR4 Load-No.of Cycles.](image4)

4.4. Specimens Strain
Table (5) shows a comparison between the strains data recorded for the columns specimens sections that were tested. The results of strain data give an indication about the resistance and change of
stresses on these parts due to the use of different diameters of composites steel bolts/rubber at steel connection of the frames. From the Table, a mark at the yield point on reference specimen FR1 appeared at eight cycles and the ultimate strain was recorded on ten cycles before fracture of the steel bolts at the connections. The strain on the column specimen FR2, with rubber ratio 50% of steel bolts, is declined by 15% and 22% at yield and ultimate point, respectively. The specimen FR3 has the rubber ratio 100% of steel bolts, where the reduction at the strain was significant at yield point for almost 48% and an ultimate point for more than 37%. In the fourth specimen test FR4, the rubber ratio used were 150% of the steel bolts where the yield point was near to yield point of the third frame was more than 48% and approximately 23% at the ultimate point. In general, the results show that the strain is significantly reduced at yield point more than the strain reduced on the ultimate point where the rubber absorbs and dampens the stresses generated by applied cyclic loads on frames than where the rubber has been gradually trending downwards causing resistance to the loads due to fatigue condition, as well as the frames are trying to resist the applied loads until the yield zone than the resistance of these frames declined when the loads are increased.

**Table 5 Difference in strain and compared with the reference frame (FR1)**

| Specimens of FR1 | Elastic Strain | Ultimate Strain before Fracturing bolts |
|------------------|----------------|----------------------------------------|
|                  | Cycles | $\varepsilon_y \times 10^{-6}$ | %Diff of FR1 | Cycles | $\varepsilon_u \times 10^{-6}$ | %Diff |
| FR1              | 8      | 1257                         | .....        | 10      | 1400                         | .....    |
| FR2              | 8      | 1065                         | 15.27        | 10      | 1097                         |          |
| FR3              | 8      | 655                          | 47.89        | 10      | 877                          |          |
| FR4              | 8      | 652                          | 48.13        | 10      | 1080                         |          |
| FR1              | 21.64  | 26.24                        | 137%         | 41.18   |                                | 131%     |
| FR3              | 37.35  | 41.18                        | 187%         | 79.19   |                                | 131%     |

4.5. Failure Modes

Failure patterns are similar on almost all specimens. In general, the fracture of the steel bolts are prevalent where the failure of the steel bolts of the reference **Frame FR1** is at the tenth cycles and max actuator load 30 kN, as well as the amplitude displacement, is 17.851 mm. Local Buckling appears near the base of the fixed column at the ninth cycle at load (20kN) and the effect of the bearing is clear on shear tabs connections as illustrated in the Figure (9 to 12).

**Frame FR2:** The maximum yield displacement was 21.70 mm and the maximum ultimate displacement was equal to 26.24 mm, that means using the rubber by half-time of steel bolts diameter delay the yield point occurs until to displacement arrive 137% and approximately 187% of ultimate displacement more than the reference frame. The failure type for this frame was bearing on shear tab connections and fracture of steel bolts, where the local buckling was not visible until the frame failure so the bearing effect on shear tab connections was lesser than the bearing effect of the specimen reference. **Frame FR3:** The behavior of this frame was close to the second frame at yield displacement just over 26.24 mm but at ultimate displacement, the third frame gave displacement more than twice of the second frame which was equal to 41.18mm. The rubber by this ratio has increased the yield and ultimate displacement by 187% and 131% of the reference frame. The mode failure of this frame was similar to the second frame bearing than bolts fracture. The effect of using the rubber on the connection of the steel frame was cleared, where the rubber was damping the
vibration of the frame during the loading and unloading process. **Frame FR4**: Using the rubber by the one-half time of the steel bolt diameter gives the flexibility for this frame by increasing the yield and ultimate displacement by 195% and 163%, respectively, as compared with the reference frame. The failure mode for this specimen was bearing on the shear plates and flexural bending on shear tab connections, local buckling appeared at the bottom flange of a fixed column at the last cycles so the weld on bottom stiffener are fractured then the some of the composites steel bolts/rubber are fractured and some of the bolts are pulled out of the plane. This rubber ratio enhanced the behavior of the frame under the applied loads, where the frame resisted the cyclic loads for a long time of the residue specimens and the damping properties were more pronounced. This phenomenon is necessary to protect the occupants of the structures and giving enough time to evacuate before the collapse during an earthquake effect. The results in this section show that on all the specimens that were tested, the yield displacement ratio was bigger than an ultimate displacement ratio, this explains that rubber resisted cyclic loads effectively at yield points while the resistance reduced gradually by increasing the number of cyclic loading and arriving the rubber to the fatigue condition.

**Figure 9.** Failure mode for specimens tested FR1.  
**Figure 10.** Failure mode for specimens tested FR2.  
**Figure 11.** Failure mode for specimens tested FR3.  
**Figure 12.** Failure mode for specimens tested FR4.
Figure (13) illustrates a comparison between four specimens that were tested under the effect of the horizontal cyclic loads. The results observed that the highest load was 80kN for the specimen FR4 and the least load was 30kN for the specimen FR1.

![Load-Displacement Curve](image)

**Figure 13** Comparison of envelope curve for all specimens test.

5. Conclusion
- The earthquake effect can be represented by applying horizontal cyclic loads on the top ends of the frames by using two hydraulic jacks working in alternate method.
- Use of the rubber around the steel bolts in steel joints structures increases the resistance and reduces the strain of the steel sections, as well as increases the displacement capacity for the steel structures that are exposed to the earthquakes or wind loads, because of absorption and damping by the rubber.
- The results presented that the yield point appeared at 20 kN and a failure point occurred at 30 kN in a reference frame system, but at 30kN-40kN in the frame with 50% rubber ratio. As well as the frame which used rubber ratio 100% of steel bolts on it, the yield point and failure occurred at the same load 40kN. While the difference was at the fourth frame with the rubber ratio of 150% of diameter steel bolts between the yield point and the failure point (40kN-80kN), respectively. That shows the effect of the use of steel bolts/rubber, where the addition the rubber as much as one and a half times diameter of the steel bolts makes the steel frameworks Re-Distribution Moments and then delays the failure of the frame completely so the rubber has reduced the corrosion in joints of steel structures between the bolts and plates in the structures that are exposed to dynamic loads.
- The process of manufacturing rubber from old tires is an economical process for recycling and reusing the rubber of consumed tires. The practice of replacing traditional bolts with composites steel bolts/rubber is the easy application of steel structures constructed without resorting to destruction or alteration of designs for the previous structures that were not designed under seismic effect.
- The use of composite steel bolts/rubber technique in steel structure joints decreases by more than one-third of the cost as compared to the total cost incurred to manufacture a framed steel bracing.

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