EVALUATE PERFORMANCE OF RUBBER DAMPER CONNECTOR IN STRUCTURES SUBJECT TO DYNAMIC LOAD

E. Ebrahimi¹, F. Hejazi²* and M.S. Jaafar³

ABSTRACT

The beam-column joints are playing important role for the stability of moment resisting structures subject to dynamic loads. Application of damper device in beam-column joints can be considered as alternative techniques to dissipate vibration energy in the structures. In this research, an attempt has been made to design and propose special rubber damper device to be implemented in frame joints as beam to column connector. Considering of high potential properties of natural rubber to dissipate vibration effect, high damping natural rubber (HDNR) is used in the developed damper connector in order to dissipate vibration effect in structures. The finite element model for proposed damper connector is developed in order to perform nonlinear analysis of frame structure equipped with damper connector under cyclic loading. Also, the parametric study has been performed to evaluate the effect of rubber thickness and number of rubber layers on the functioning of rubber damper connector in reducing the vibration transferred from the beam to the column. The numerical simulation is verified by conducting of experimental test for steel frame by imposing cyclic displacements using dynamic actuator. The analysis result indicated that developed damper connector effectively enhanced dynamic performance of frame by increasing the energy dissipation capacity of the structure. Also, the comparison of the hysteresis loop for the frame furnished with damper connector with various rubber thicknesses proved the enhancement of frame stiffness by decreasing of rubber thickness up to 5mm which is led to high energy dissipation. The proposed damper connector device is applicable for new and existing structure as retrofitting scheme with low cost of fabrication and installation.

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Evaluate Performance of Rubber Damper Connector in Structures Subject to Dynamic Load

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ABSTRACT

The beam-column joints are playing important role for the stability of moment resisting structures subject to dynamic loads. Application of damper device in beam-column joints can be considered as alternative techniques to dissipate vibration energy in the structures. In this research, an attempt has been made to design and propose special rubber damper device to be implemented in frame joints as beam to column connector. Considering of high potential properties of natural rubber to dissipate vibration effect, high damping natural rubber (HDNR) is used in the developed damper connector in order to dissipate vibration effect in structure. The finite element model for proposed damper connector is developed in order to perform nonlinear analysis of frame structure equipped with damper connector under cyclic loading. Also, the parametric study has been performed to evaluate the effect of rubber thickness and number of rubber layers on the functioning of rubber damper connector in reducing the vibration transferred from the beam to the column. The numerical simulation is verified by conducting of experimental test for steel frame by imposing cyclic loads using dynamic actuator. The analysis result indicated that developed damper connector effectively enhanced dynamic performance of frame by increasing of energy dissipation capacity of the structure. Also, the comparison of the hysteresis loop for the frame furnished with damper connector with various rubber thicknesses proved the enhancement of frame stiffness by decreasing of rubber thickness up to 5mm which is led to high energy dissipation. However, adding more number of rubber layers didn't showed noticeable effect on performance of device. The proposed damper connector device is applicable for new and existing structure as retrofitting scheme with low cost of fabrication and installation.

Introduction

Inhabitant protection and utilize of steel frame building subsequent most earthquakes is frequently restricted by damage to the structural frame system. The majority of this detriment is

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limited to the beam ends plastic hinge zones or the panel zones inside of column to beam connections. Currently, steel frame connections are design in order to diminish the dynamic excitation response by using sacrificial yielding at beam ends. Plastic hinges which is form at the ends of beams, give rise to constant damage and the risk of failure under extreme lateral displacements due to flange buckling or weld fracture. The related damage can be complicated, time consuming, and costly to repair. Therefore it is beneficial to have non-damage joints, get rid of pricey repairs and allowing businesses to operate with no causing extra financial loss to the owners.

Although one of the regular method for minimizing structural damage in beam-column connections is to provide a source of energy dissipation that is over and above the structure’s inherent damping, and that does not degrade with continued cycling. This involves using passive energy dissipation devices such as dampers. When incorporated into a structure, passive energy dissipation devices work by adding damping to the system to reduce the structural response during an earthquake. In one of the first study to explore the beam-column connection, the rubber damper have been proposed and experimentally characterized the viability of incorporating viscoelastic damper into a wood frame shear wall [1]. Result of the investigation illustrated the clear benefit of the devices, such as larger hysteresis loops and indicating greater energy dissipation in compare to those present in the frame without devices. A visco-elastic hysteretic damper which is employed with steel bars have been installed in a steel moment resisting frame connection and reported desirable energy dissipation capacity [2]. The beam to column steel moment resisting connection with the column’s weak axis have been utilized U-shape plates and results demonstrated that the hysteretic energy dissipation is concentrated in the U-shape plates and no damage was observed in beams and columns [3]. The steel curved damper has been placed in beam-column semi rigid joint and reported the stable hysteresis behavior under compression and tension by increasing the strength, stiffness and energy dissipation capacity [4]. The rotational friction damper which is act as structural fuses insert in steel moment frame and the results introduced the improvement of stiffness and drift control [5].The waste rubber damper placed at the beam-column connection of moment frame and the results indicated that the energy dissipation and plastic deformation were concentrated at the damper [6]. U-shaped steel damper were developed and installed in self centering steel moment resisting frame and the results showed the enhancement in energy dissipation capacity [7].The T-stubes connection elements placed at the beam-bottom-flange of MRF connection and result showed that composite effect increased of initial elastic stiffness and yield strength [8]. The investigation on impact of high force-to-volume damper extrusion as supplemental damping have been done and the result provided force capacity, and hence energy dissipation capacity in the same order of magnitude of significantly larger devices [9].

This paper presents the investigation on seismic performance of steel frame with implementing high damping rubber connector in the beam-to-column joints. The finite element model is developed in order to evaluate the performance of steel bare frame equipped with damper connector, in terms of force capacity, stiffness and energy dissipation. Also, an attempt has been made to conduct a parametric study about effect of rubber thickness and number of rubber layer on the performance of damper connector. The results of numerical analysis are verified through conducting experimental test on the steel bare frame by using dynamic actuator.
Proposed Damper Connector

In the present study an attempt has been made to design and proposed rubber damper connector to be implemented in beam-column joint in order to dissipate vibration transferred through beam-column rotation and diminish applied lateral dynamic load. The proposed damper consists of few layer of high damping natural rubber bounded with steel plate which some of them welded to side steel plate (named column plate) tied to column flange using high strength bolts or welding and the rest are welding to the top steel plate (named beam plate) which tied to the beam flange. During applied lateral vibration, the frame is moving laterally and rotation is appeared in the beam-column joint. This rotation is damped by implemented damper connector through transfer the rotation through beam plate and column plate which are tied to beam and column respectively, then dissipate by bounded rubber between steel plates. The configuration of proposed damper connector is showed in Fig. 1.

![Figure 1. Proposed damper, (a): General view, (b): Close up](image)

The rubber damper connector device operates with the change in angle between the beam and column joint. The damper connector device includes bounded rubber between steel plate to control maximum deformation of the frame during huge number of displacement and rotation. The damper was modeled in a shear configuration with four rubber layers of 5, 10, 15, 20, 25 and 28 mm thickness, bounded between 6mm steel plates. Each rubber lamina of material had a shear area of 96412.5 mm². However this area can be change depend on frame detail and considerable applied lateral load. The energy dissipation of damper connector is depend on rubber area and number of rubber and steel layers as well as shear modulus of rubber material.

The viscoelastic material chosen for proposed damper device as rubber which stiffness and energy dissipation of this material are calculate through Eq.1, and 2 respectively.

\[ K = \frac{G' A}{h} \]  
\[ E_d = \pi \delta^2 \frac{G'' A}{h} \]  

were \((G')\) is storage modulus, \((G'')\) is loss modulus, \((K)\) is the stiffness, \((E_d)\) is energy dissipation
of high damping rubber. Also $A$ is the shear area, $h$ is the thickness of the viscoelastic lamina, and $\delta$ is the shear deformation of the lamina. Note that the stiffness and energy dissipation of the damper are both proportional to the shear area and inversely proportional to the thickness of the material.

**The Finite Element Simulation**

In order to evaluate performance of proposed damper system the three dimension finite element model of rubber damper connector and its interaction in beam and column Frame were simulated. The finite element software ABAQUS ver. 6.14 [10] is implemented for simulation of steel frame furnished with rubber damper connector. To model the hyper-elastic behavior of rubber, results of the uniaxial/biaxial of tension test carried out by Yoshida et al. [11] have been implemented. Also for compression test, the results which is accomplished by Amin et al. [12] have been used.

The steel material properties were taken as mild steel (St37) with yield and ultimate stress of 240 and 370 Mpa respectively. For the element type and mesh size of rubber layer, the eight node linear hybrid reduced elements C3D8HR with a mesh size of 25 mm have been selected respectively. The surface to surface tie contact has been used to model steel and steel to rubber contact that both connected part moves together and no gaps develops between the parts in any direction. An isometric view of developed model and cross section of the device are shown in Fig. 2.

![Figure 2. Finite element simulation](image)

(a) Frame equipped with damper  
(b) Installation of damper connector

Fig. 3, illustrate the ISO schedule displacement controlled loading procedure that consists of two displacement pattern have been used in this study. The first pattern of Lateral displacement which be composed of five single fully reversed cycles were applied to the structural steel Frame joint at displacements of 1.25, 2.5, 5, 7.5 and 10 mm. Also, the second displacement pattern in the cyclic displacement history be made up of three fully reversed cycles of identical amplitude of 20, 40, 60, 80, 100 mm. The three fully reversed cycles have been taken to at each
displacement amplitude to obtain stable and reliable values of stiffness properties [13].

![Cyclic displacement schedule](image1)

Figure 3. Cyclic displacement schedule

The thickness of rubber layer in damper connector device which have been analyzed is 5, 10, 15, 20, 25 and 28 mm. The parametric study about rubber layer thickness is showed that the variation of rubber thickness didn't lead to reasonable change on the damper performance. Because by increase of rubber layers thickness, the shear strain is decreased and in contrast due to higher volume of rubber material, energy dissipation also is increased, which these two reverse outcomes tend to neutralize each other.

Fig. 4, shows the hysteresis behavior (The applied lateral displacement versus the reaction force) of bare frame and the 5 mm rubber thickness of damper connector numerical analysis results. As the graph illustrate the bare frame reached 63 kN of reaction force within the peak displacement of 100 mm. Also, the initial stiffness for 20 mm Displacement and final loop energy dissipation of the bare frame is 935 N/mm and 16E6 N*mm respectively. However, for the frame furnished by damper connector, the maximum force in the last cycle with same displacement is reach to 90 kN , which indicating that the structural response with damper connector effectively improved 43% in terms of force capacity. Also, for the initial stiffness and energy dissipation capacity, it shows the enhancement of 84 and 64% respectively due to function of damper connector during applied cyclic displacement.

![Hysteresis loops](image2)

Figure 4. Hysteresis loops

Stress distribution contour and plastic strain magnitude of analyzed frames are shown in
Fig. 5 and Fig. 6 respectively. As it can be seen in the stress contour, the peak stress in the bare frame is appeared in the beam-column joint or panel zones, which is the most important part of the frame for transferring the load from beam to the column and the key factor to provide the stability of structure. However, in the frame with supplementary damper connector, the location of peak stress is shifted from joint to the column which has high capacity to sustain the stress. The stress amounts also is high in the frame with damper in comparison with bare frame which is due to receiving higher lateral force during cycling analysis although the damper connector is absorbing the noticeable part of vibration stress by action of rubbers during rotation of joint.

Similar result is showed through strain counter for both frames. The maximum deformation is appeared in the joint in the bare frame however; the deformation is almost equally distributed in the beam and column for frame with damper due to functioning of damper connector.

![Stress distribution contour](image)

![Plastic strain magnitude](image)

The overall results of frame response with different rubber thickness effects with regard to bare frame under cyclic load are presented in Table 1. The results of analysis frame with various thicknesses of rubber layers for damper connector showed that the functioning of damper is lead to increase resistant force of frame effectively in range of 87 to 90 kN which is indicating
the average 40% higher performance in comparison to bare frame. However, variation of the rubber thickness has not too much effect on reaction force.

Also, the initial stiffness of frame is increased approximately 37 to 43 percent beyond six different rubbers thickness. The efficiency of damper connector can be more evaluated by energy dissipation of frame during applied cyclic load which indicating enhancement between 48 to 61 percent in comparison with bare frame. As it can be seen in the result, the maximum energy dissipation has been improved by 61 percent and the maximum initial stiffness is increased approximately 85 percent by implementing damper connector with 5mm thickness.

Table 1. An improvement of energy dissipation capacity and effective stiffness of frame with damper connector in compare to bare frame

<table>
<thead>
<tr>
<th>Rubber layers thickness (mm)</th>
<th>Peak reaction force (kN)</th>
<th>%</th>
<th>Initial effective stiffness (N/mm)</th>
<th>%</th>
<th>Peak effective stiffness (N/mm)</th>
<th>%</th>
<th>Final cycle energy dissipation (N*m)</th>
<th>%</th>
<th>Total energy dissipation (kN*m)</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>90.3</td>
<td>43.02</td>
<td>1729.6</td>
<td>84.8</td>
<td>894.4</td>
<td>42.25</td>
<td>25836.9</td>
<td>61</td>
<td>180.2</td>
<td>63.9</td>
</tr>
<tr>
<td>10</td>
<td>89</td>
<td>40.93</td>
<td>1642.7</td>
<td>75.5</td>
<td>881.4</td>
<td>40.17</td>
<td>24986.4</td>
<td>55.7</td>
<td>173.9</td>
<td>58.2</td>
</tr>
<tr>
<td>15</td>
<td>88.5</td>
<td>40.17</td>
<td>1598.8</td>
<td>70.8</td>
<td>874</td>
<td>39</td>
<td>24578.8</td>
<td>53.2</td>
<td>170.6</td>
<td>55.2</td>
</tr>
<tr>
<td>20</td>
<td>86.5</td>
<td>37</td>
<td>1521.8</td>
<td>62.6</td>
<td>856.5</td>
<td>36.21</td>
<td>23614.8</td>
<td>47.2</td>
<td>163.4</td>
<td>48.6</td>
</tr>
<tr>
<td>25</td>
<td>86.4</td>
<td>36.86</td>
<td>1518.7</td>
<td>62.3</td>
<td>855.7</td>
<td>36.09</td>
<td>23575</td>
<td>46.9</td>
<td>163.1</td>
<td>48.4</td>
</tr>
<tr>
<td>28</td>
<td>87</td>
<td>37.7</td>
<td>1526.3</td>
<td>63.1</td>
<td>858.1</td>
<td>36.47</td>
<td>23741.6</td>
<td>48</td>
<td>164.1</td>
<td>49.3</td>
</tr>
</tbody>
</table>

Also, the parametric study for damper connector with 4, 6 and 8 layers of rubber indicated that performance of steel frame is not significantly changed by variation of number of the rubber layers implemented in damper connector.

**Verification by Experimental Test**

In order to verify the numerical simulation, a steel frame constructed and subjected to lateral load by using dynamic actuator and results are compared with finite element results. Same displacement protocol as described in Fig. 3, is used for conducting cyclic test.

Fig. 7(a) present the experimental setup of the structural steel moment resisting frame tested in this research. A T-stub was fabricated through welding of steel plate with dimension of 200*150*14 mm which bolted to the top and bottom flange of the 150UC30 beam, and was bolted to same section column with M20 bolts. Furthermore, to prevent any movement in out of plane, two external columns furnished by cantilever beams placed at perpendicular direction as shown in Fig. 7(b) to support movement of frame in out of plane direction.
Cyclic displacement control was used to test the steel structural moment resisting frame up to a peak displacement of 100 mm provided by a 300-kN capacity hydraulic actuator with a 500 mm stroke. The hydraulic actuator was fastening to the top of the column in line with beam, 2.1 m above the base hinge connection that was connected to the laboratory strong floor. For attaching the column to the base hinge, an end plate was welded to the base of the column. Fig. 8(a) shows the installation of steel MRF in structure’s laboratory for conducting experimental test.

The experimental and numerical of bare frame observed lateral displacement versus reaction force is presented in Fig. 8(b) for all cycles. Base on the hysteresis loops maximum reaction force capacity of steel bare frame is 64.5 kN at ultimate displacement of 100 mm.

The experimental test of bare frame system in the previous section prepares a basis for the verification analysis and a reasonable similarities is observed between the two graphs, which is proofs the adequacy of the numerical modeling method of this study.
Conclusions

In this research work, proposing design for rubber damper connector applicable in beam-column joint in frame structure subjected to lateral dynamic load is presented. The damper connector system consisting of high damping natural rubber bounded between steel plates to dissipate the earthquake vibration effects on frame. The developed finite element model of steel frame equipped with rubber damper connector is excited by cyclic load and dynamic behavior of frame is investigated. Also, an attempt has been made to evaluate effect of rubber thickness as well as number of rubber layers sandwiched with steel plates on performance of damper connector in diminishing the applied excitation. The analysis results indicated significant increase of energy dissipation capacity by implementing of damper connector in compare with steel structural bare frame. The total energy dissipated and initial stiffness increased approximately 64 and 85 percent respectively for damper connector with 5 to 28mm thickness of rubber, in comparison with steel bare frame. Also, the analysis result showed that the number of rubber layer implemented in damper connector has not highly effected on functioning of device to dissipate vibration. The proposed damper connector can install into new frame to be constructed or implement in exciting structure for retrofitting to diminish the unfavorable effect of dynamic vibration and reduce the damage in the structures.

Acknowledgment

This work received financial support from Ministry of Science, Technology, and Innovation of Malaysia under Grant Number: 5450775 and was further supported by the University Putra Malaysia under Putra grant No. 9531200. These supports are gratefully acknowledged.

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