Steel and Composite Structures, *Vol. 36, No. 2 (2020) 197-211*
DOI: https://doi.org/10.12989/scs.2020.36.2.197

Experimental and numerical evaluation of an innovative diamond-scheme bracing system equipped with a yielding damper

Ghasem Pachideh, Majid Gholhaki* and Mohammadali Kafi

Department of Civil Engineering, University of Semnan, Semnan, Iran

(*Received February 29, 2020, Revised June 27, 2020, Accepted July 1, 2020*)

Abstract. Application of the steel ring as a type of seismic fuse has been one of the efforts made by researchers in recent years aiming to enhance the ductility of the bracing systems which in turn, possesses various advantages and disadvantages. Accordingly, to alleviate these disadvantages, an innovative bracing system with a diamond scheme equipped with a steel ring is introduced in this paper. In this system, the braces and yielding circular damper act in parallel whose main functionality is to increase ductility, energy absorption and mitigate drawbacks of the existing bracing systems, in which the braces and yielding circular damper act in parallel. To conduct the experimental tests, specimens with three types of rigid, semi-rigid and pinned connections were built and subjected to cyclic loading so that their performance could be analyzed. Promisingly, the results indicate both great applicability and efficiency of the proposed system in energy absorption and ductility. Moreover, it was concluded that as the braces and damper are in parallel, the use of a steel ring with smaller size and thickness would result in higher energy absorption and load-resisting capacity when compared to the other existing systems. Finally, to assess the potential of numerically modeling the proposed system, its finite element model was simulated by ABAQUS software and observed that there is a great agreement between the numerical and experimental results.

Keywords: innovative bracing system; diamond-scheme brace; circular yielding damper; cyclic load; energy absorption; ductility

1. Introduction

Many research attempts have been made in the last two decades on improvement in the ductility of the concentrically-braced frames (CBFs). Despite the advantages of CBFs such as ease of construction and replacement, their ultimate displacements have raised concerns about their application in earthquake-prone areas. Also, the ductility limitation of CBFs, have led to their inadequate seismic performance (Lotfollahi and Mofid 2008, Hsu *et al.* 2011). In this respect, different studies have been conducted proposing solutions such as the use of supplemental elements in moment-resisting frames equipped with bracing systems aiming to improve their ductility and energy absorption (Murthy 2005, Marshall and Charney 2010a, Marshall and Charney 2010b, Moghaddam and Estekanchi 1995, Amadio *et al.* 2008, Annan *et al.* 2009).

Kelly and Slinner carried out the early pioneering studies concerning the application of the steel dampers (Kelly *et al.* 1972, Kelly *et al.* 1975). These studies were focused on the effects of the dampers on seismic energy dissipation capacity.

Rakicevic and Jurukovshi (1998) and Roufegarinejad and Sabouri (2002) carried out several studies to evaluate the efficiency of a central frame installed at the intersection of the concentric braces. They found that inelastic deformations of the frame, results in the absorption of a portion of the seismic energy and as a result, increases the ductility of the bracing system.

In 2008, Chan and Albermani conducted a research study on the use of a novel energy dissipation system in the steel buildings. Accordingly, the system's performance was assessed through several tests indicating adequate ductility and energy absorption capacity (Chan and Albermani 2008). In another study, Kafi experimentally and numerically investigated the efficiency of the application of the steel ring in the CBFs and concluded that such rings greatly affect behaviour of the structures (Kafi 2008).

Motamedi *et al.* (2012) and Peng *et al.* (2018) studied the cyclic behaviour of the steel rings functions as the structural fuse. In follow-up studies on the development of the use of steel rings as dampers, Bazaz *et al.* as well as Andalib *et al.* during 2012 to 2015 ((Bazzaz *et al.* 2012, Andalib *et al.* 2014, Bazzaz *et al.* 2014, Bazzaz *et al.* 2015, Bazzaz *et al.* 2015)), investigated into seismic behaviour of the steel frames equipped with gate bracing system including a ring element. The results indicated that the ring element improves ductility and energy absorption of the frame. In 2016, Gao *et al.* proposed an innovative bracing system using a ring constructed from the shape memory alloy (SMA). To this end, a ring made out of the SMA was placed at the intersection of the diagonals, and accordingly, it was observed that the ductility and energy dissipation capacity of the whole system is enhanced (Gao *et al.* 2016).

∗Corresponding author, Associate Professor
E-mail: mgholhaki@semnan.ac.ir

http://www.techno-press.org/?journal=scs&subpage=8
ISSN: 1229-9367 (Print), 1598-6233 (Online)

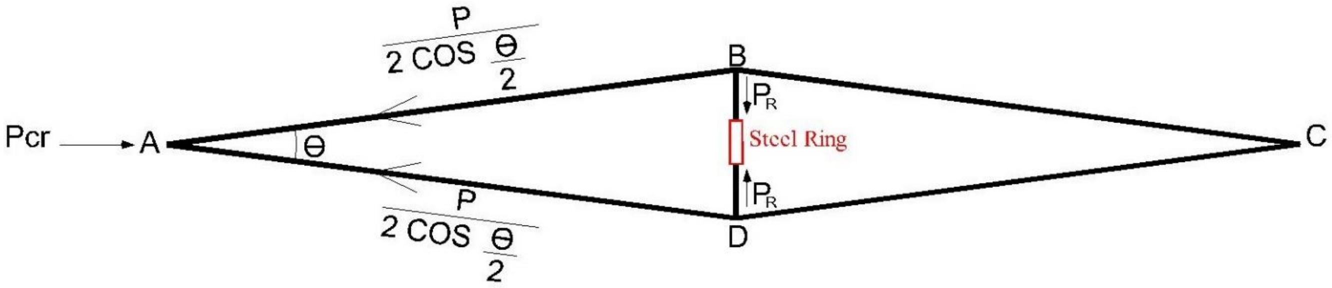


Fig. 1 General Geometry of Diamond-Scheme Bracing with Steel Ring

Andalib *et al.* numerically studied ductility and energy absorption of the steel rings constructed by rolling the steel plates. In their analyses, the rings were comprised of two half-steel rings and the effects of welding, bolts, ring plate thickness, and material properties were investigated on ductility and energy absorption (Andalib *et al.* 2018). In 2019, Peng *et al.* Analyzed the seismic behaviour of the steel frames equipped by chevron braces including a steel ring (Peng *et al.* 2019). Kheyroddin *et al.* (2019) experimentally managed to rehabilitate a reinforced concrete (RC) frame using a steel jacket and X-bracing system including and excluding the steel ring. Based on the results, whether the steel ring is included or not, the strength and stiffness of the RC frames are enhanced. Nevertheless, despite a little reduction in strength, energy absorption, and ductility of the system with the ring surpassed those of the case in which the ring is not utilized.

Review of the recent studies concerning application of different systems as dampers in the bracing systems such as steel rings, it can be found that in most of them, the element positioned inside the bracing system, acts in series and consequently, ultimate capacity and ductility of the system is directly dependent on characteristics of this ductile element. As a result, in the case when significant capacities are in demand, a large thick element has to be utilized by which design requirements could be satisfied. To overcome this challenge, an innovative bracing approach is introduced herein, whose capacity indirectly depends on the ring's capacity and using acting in parallel with diagonals, a system with a load-carrying capacity much greater than that of similar systems, could be attained. To examine ductility and energy absorption of the proposed system, a set of cyclic tests was conducted taking pinned, rigid and semi-rigid connections for the system, and the results were compared with those of the other already introduced systems. Lastly, for the sake of assessing the possibility of numerically modeling the newly-developed system, one of the experimental specimens was simulated and verified using ABAQUS software.

2. Theoretical fundamentals

The proposed bracing system is not merely limited to the use of a steel ring as the yielding damper. Thereby, each element or any structure by which energy absorption or ductility could be provided (e.g., ring, spring, damper, composite elements etc.), is capable of contributing to the system. Accordingly, with respect to the availability and low price of the steel ring and also, for the sake of making a comparison with previous works, a steel ring with desired specifications was prepared. Fig. 1 illustrates the general geometry of the proposed system.

3. Experimental program

3.1 Introduction of proposed system

As shown in Fig. 2, the proposed bracing system is comprised of diagonals configured in a diamond-scheme and in the middle of them; a circular yielding damper is placed. The system is configured such that diagonals and damper act in parallel and thus, ultimate capacity of the system is not directly dependent on the damper and using a damper with a certain capacity, can build a system whose capacity is several times greater which can be easily proved by virtue of the relationships derived from static and strength of materials sciences.

If a ring is subjected to P load as shown in Fig. 2, changes in diameter and bending moments in the elastic phase of behaviour can be calculated using the following Eqs. (12)

$$I = \frac{1}{12} t^3 . L \tag{1}$$

$$\Delta_y = -0.149 \frac{PR^3}{EI} \tag{2}$$

$$\Delta_y = +0.137 \frac{PR^3}{EI} \tag{3}$$

$$M^{+}_{max} = 0.3183\text{PR} \qquad \Theta = \frac{\pi}{2} \tag{4}$$

$$M^{-}_{max} = 0.1817\text{PR} \qquad \Theta = 0 \tag{5}$$

$$V = -\frac{1}{2} P \sin \Theta \tag{6}$$

$$T = -\frac{1}{2} P \cos \Theta \tag{7}$$

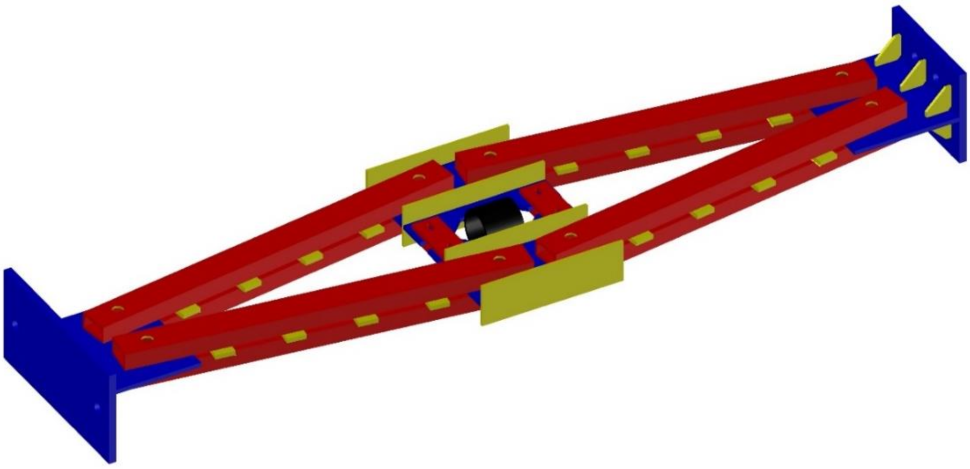


Fig. 2 3D View of Proposed System

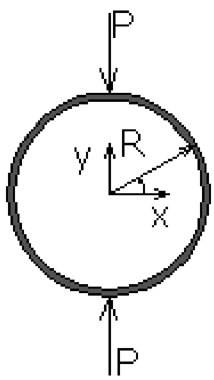


Fig. 3 Cross-Section of a Ring under concentrated Loads

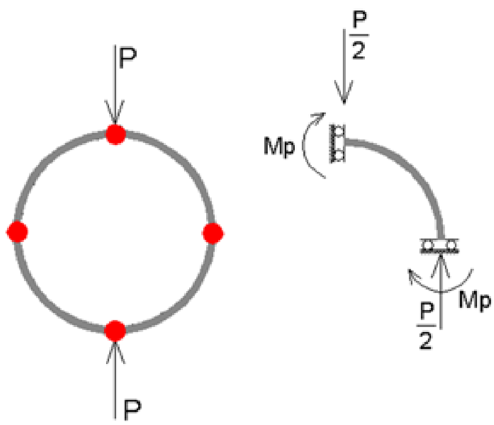


Fig. 4 Plastic Hinges in the Ring

In limit states, according to Fig. 4, four plastic hinges are formed in the ring whose equilibrium relations are given below (Eq. (8)). Based on these equations, the load-carrying capacity of the ring is in direct relation with length, yield strength, and thickness but there is a reverse relation with radius.

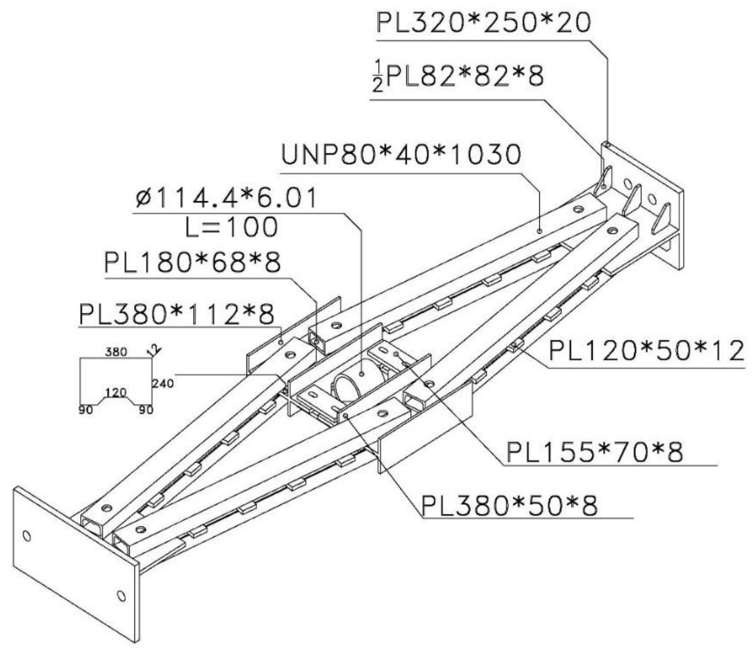


Fig. 5 Dimensions of Components used in the Bracing System

$$2M_P = \frac{PR}{2} \Rightarrow P = \frac{4M_P}{R}$$
$$M_P = \frac{t^2.L}{6}\sigma\frac{3}{2} \tag{8}$$

Ring Capacity (Kafi 2008)

$$P = \frac{t^2.L}{R}\sigma \tag{9}$$

Brace Capacity

$$P_{cr} = \frac{P}{\tan\frac{\theta}{2}} \tag{10}$$

Where t, L, and R stand for thickness, length, and mean diameter of the ring, and M_P represents the plastic bending moment of the ring's cross-section.

Moreover, σ represents the steel stress. It is worth noting that in the above equations, in the case when experimental data are used, yield stress (σ_y) has to be taken but for numerical data, ultimate stress (σ_u) needs to be taken into account.

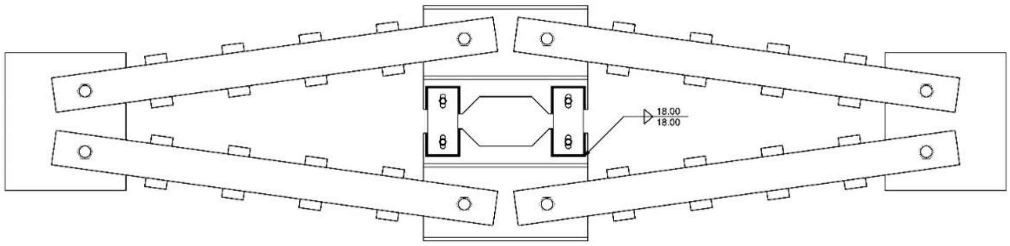
3.2 Test setup

Cyclic tests were carried out on three types of bracing systems with pinned, semi-rigid and rigid connections. Accordingly, connections, geometric and dimensional details are presented in Fig. 3. The components of this system include steel channels, plates, bolts, and nuts as well as the steel ring.

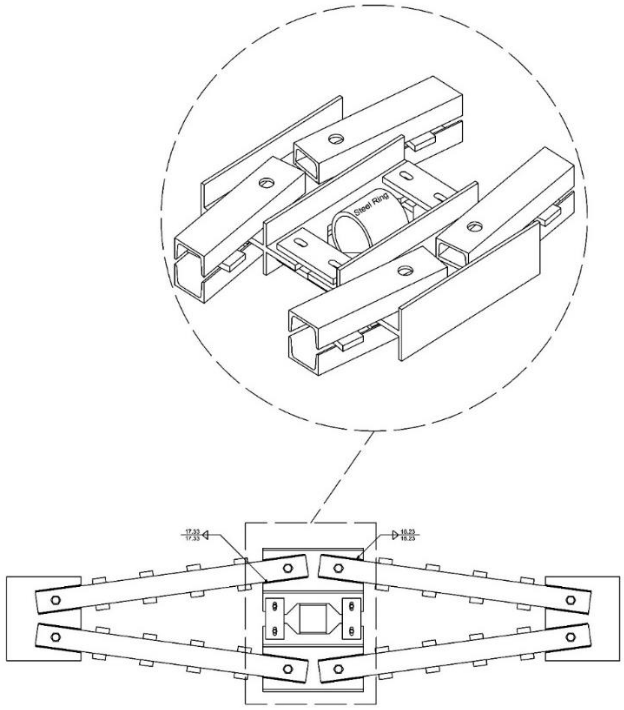
Notably, a difference of the pinned, semi-rigid and rigid model concerns inclusion or exclusion of the ring in the system and type of channels connections to the other components of the system. Accordingly, in both rigid and pinned cases, the steel ring has been utilized in such a way that in the case of rigid connection, channels are connected to the central plate using welds and bolts but in contrast, channels are bolted to the central plate (i.e., bearing type connection) in the case of pinned connection. In the case of a semi-rigid model, the channel connections are similar to those of the pinned model but the only difference is that the steel ring is not included and instead, the two connection plates are continuously welded. In Fig. 4, it has been attempted to far better demonstrate differences of the models. Moreover, one of the constructed specimens is shown in Fig. 5. It should be mentioned that the layout, diameter and properties of bolts have been determined in accordance with AISC 358-16 (AISC 2016). All bolts and nuts are M27, length of 15 cm and strength grade of A490.

According to Fig. 5, the specimen is located on rigid base of the laboratory and the cyclic loads have been applied from left side and also, the specimen is attached to the frame from right side. In general, for each specimen, 8 channel profiles have been used and on each profile, a strain gauge is installed to control the strains recorded by the data logger. Moreover, in left and right sides as well as center of the steel ring, strain gauges have been installed. To capture the hysteretic curve and measure displacements at different points of the brace, LVDTs with ability of recording displacements to 10cm, have been installed on each side of the stiffeners, on the plates connected to the ring and on the steel ring.

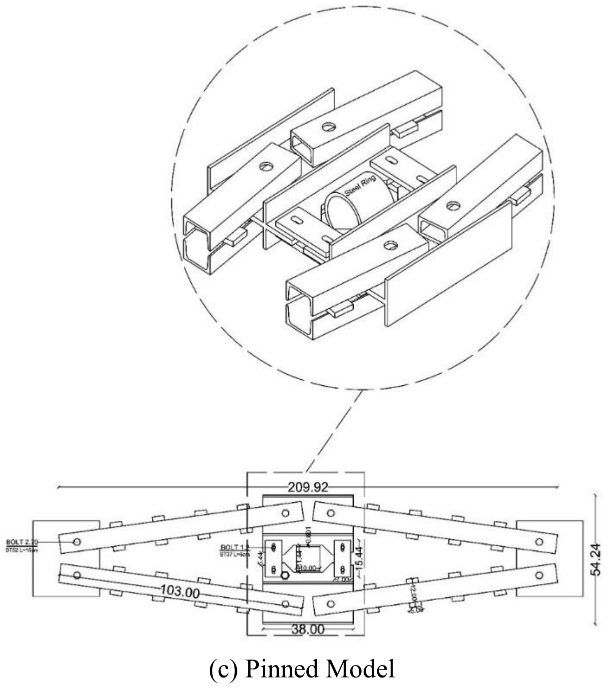
One of the notable features of the models concerns low angle (15.6°) between the diagonals. Accordingly, it has been attempted to develop a minimum possible angle between the elements considering all executive limitations, so that the global buckling potential of the system reaches the lowest extent.



(a) Semi-Rigid Model



(b) Rigid Model



(c) Pinned Model

Fig. 6 Comparative Illustration of Rigid, Semi-Rigid and Pinned Models

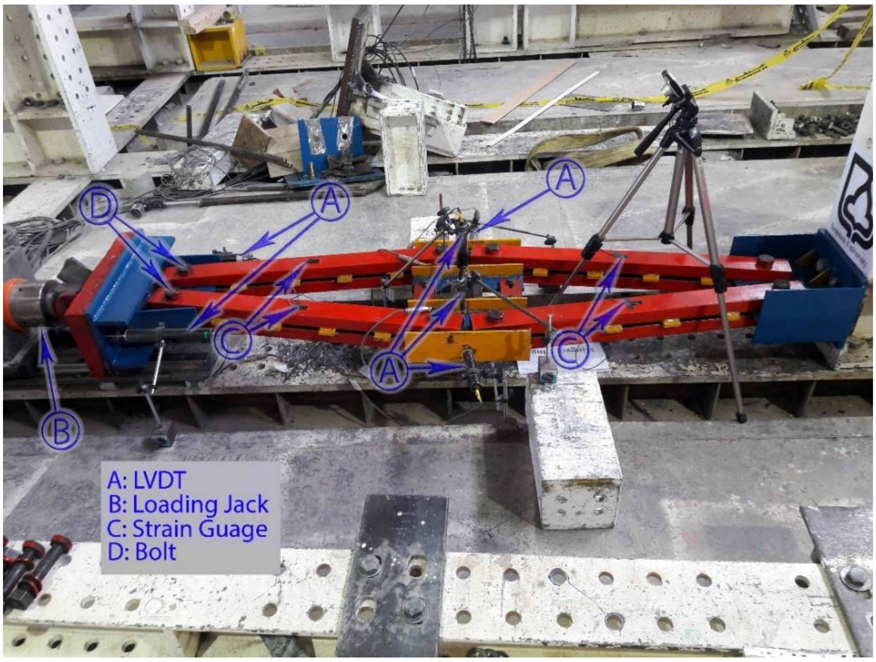


Fig. 7 General View of Proposed Bracing System

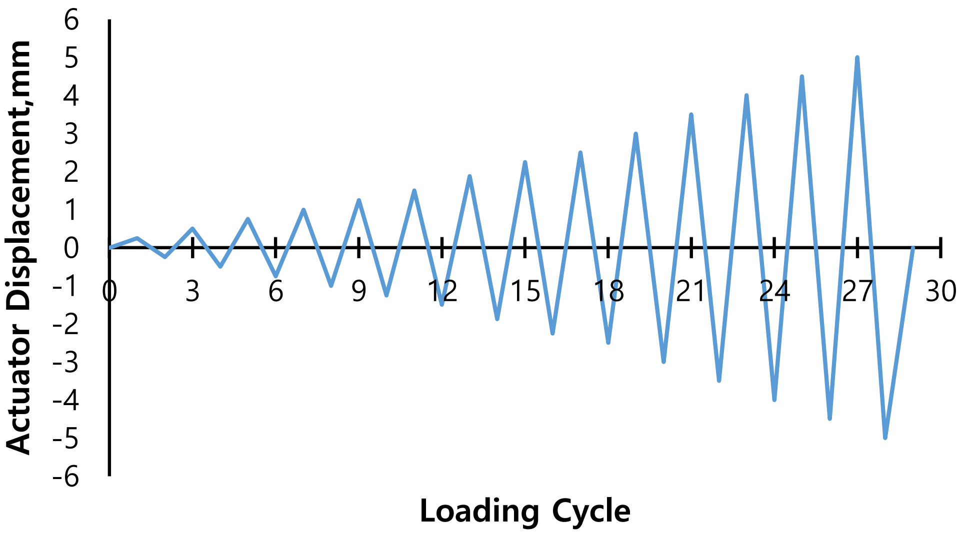


Fig. 8 Cyclic Loading applied to the Specimens

Table 1 Tensile Test Results

Component	Failure Strain (%)	Yield Stress (MPa)	Failure Stress (MPa)
Channel Plate	40	245	349
Steel Plate	29	365	571

In addition, according to the results of the tensile testing conducted on the channels and plates in materials engineering laboratory of Amir Kabir university, the obtained parameters are given in Table 1. Notably, in each test, 3 similar specimens were tested and average of the values was taken into account. The values given in Table 1, not only prove a detailed understanding towards behaviour of the materials, but also can be used in defining the material properties for numerical modelling process.

3.3 Loading procedure

All models were subjected to the cyclic loading defined based on loading protocol specified by ATC24 whose history is illustrated in Fig. 6.

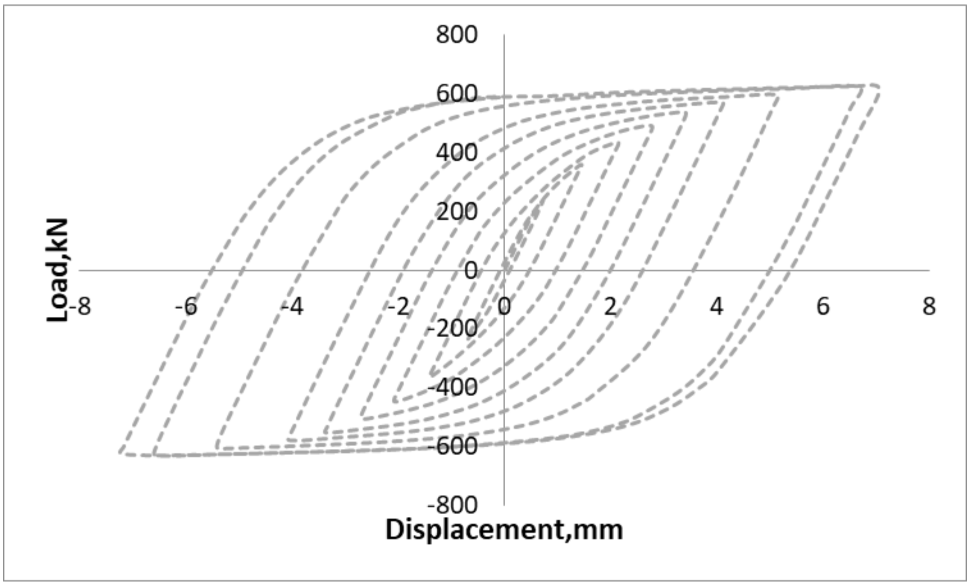


Fig. 9 Hysteretic Curve of the Semi-Rigid Model

4. Experimental results and interpretation

Cyclic tests were conducted on the rigid, semi-rigid and pinned models and accordingly, to study their behavior, a number of outputs such as stress-strain curves, maximum applied load, stiffness, displacement and failure modes were acquired which will be addressed in the following. In this respect, given the fact that the ring is excluded in the semi-rigid model, first, the results of this model are expressed as the basic system and then, the two other models are discussed and lastly, the final selected model is introduced.

4.1 Semi-rigid model

The stress-strain curve of the semi-rigid model in which yielding damper is not used is shown in Fig. 7. As the damper is not utilized in this case, the load is applied until the bracing elements fail and finally, the test has ended as the diagonals buckled. The results indicate that the maximum load applied to this model reaches slightly greater than 60 tons. One of the outstanding features of this model concerns its high energy absorption which is nearly 4400 ton-mm. Based on Fig. 7, it can be concluded that the proposed model is of adequate performance and can be efficiently used as the lateral load-carrying system although, on the one hand, buckling of diagonals and on the other hand, entering the elements into the nonlinear phase of behavior, stresses the need to further develop this system by utilizing a yielding damper. Thus, the two rigid and pinned models including a yielding steel ring are discussed in what follows.

4.2 Rigid model

In this model, a yielding steel circular damper is added by means of a rigid connection in the central core of the system and then, cyclic tests are carried out. Accordingly, the stress-strain curve is illustrated in Fig. 8. According to this figure, the proposed model benefits from an acceptable load-carrying capacity and energy absorption. However, the failure mode indicates that the yielding of the steel ring and buckling of diagonals occur simultaneously and undesirably, design purposes are not completely fulfilled. The buckling of the diagonals is shown in Fig. 9. Consequently, it is proved that this model needs modifications so that the diagonals remain elastic and only, the steel ring yields.

4.3 Pinned model

To cover up the drawbacks of the rigid model, it is attempted to change the connection type of diagonals, central plates, and damper. In this respect, they are attached together using the pinned connections to overcome limitations and disadvantages of the rigid model and in addition, develop a scheme that is reparable and takes advantage of appropriate load-carrying capacity and ductility. The stress-strain curve of the pinned model is presented in Fig. 10.

Analysis of the failure of mode of the pinned model indicates that the steel ring in the center of the system yields prior to the other bracing elements and they all remain elastic. Hence, the pinned scheme fully satisfies design purposes specified in this study and also, exhibits proper effectiveness to be practically used in the construction industry. The interesting point regarding the pinned model is that because of the damper failure and with respect to the criteria of the loading jack for termination of the test, the testing operation has ended but in real conditions, as the diagonals and steel ring act in parallel and the diagonals remain elastic, a multilevel bracing system is formed which is still able to further resist the induced loads.

In what follows, the three rigid, semi-rigid and pinned models are compared to evaluate their advantages and disadvantages.

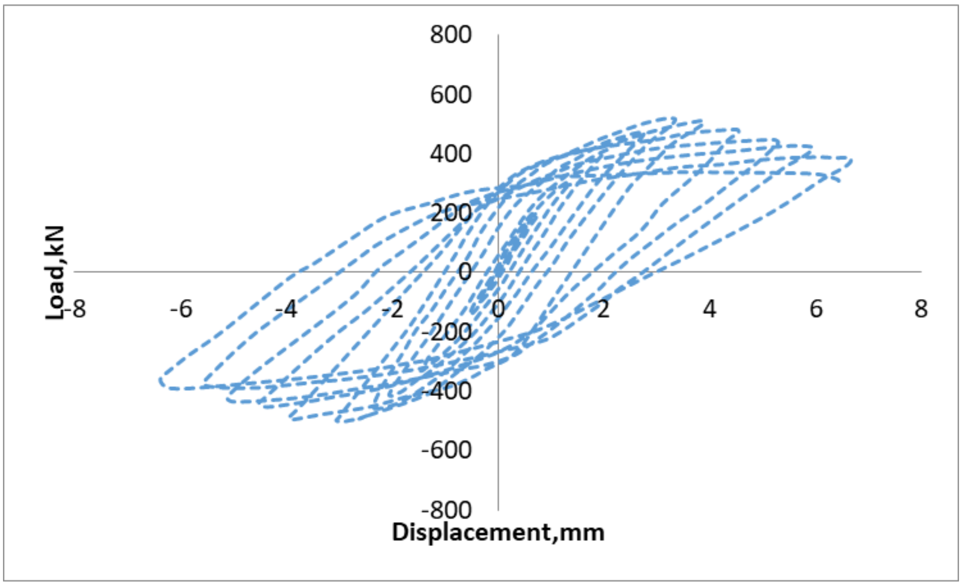


Fig. 10 Hysteretic Curve of Rigid Model

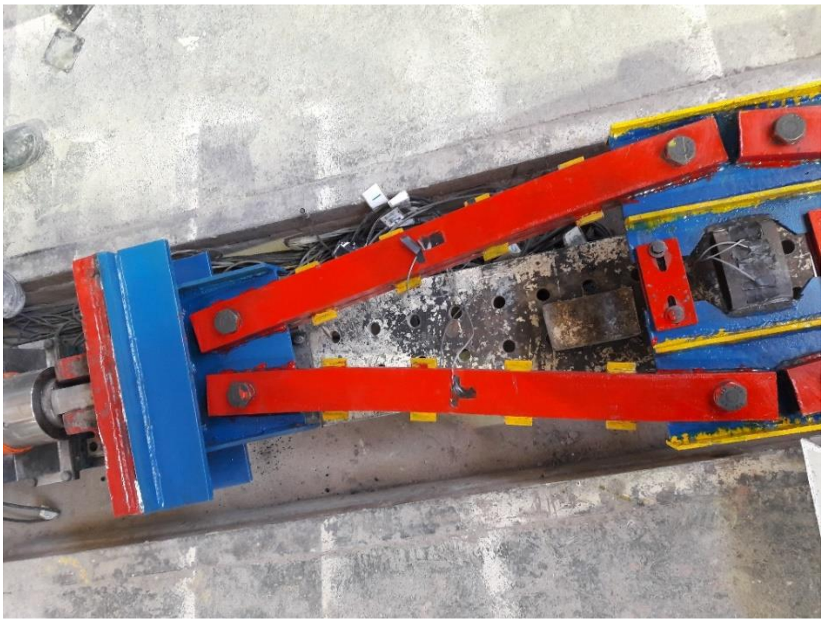


Fig. 11 Buckling of Diagonals

5. Comparison of proposed models

5.1 Comparison of results in direction of loading

Based on the stress-strain curves, maximum energy dissipation, maximum applied load, ultimate displacement and stiffness of the three models have been obtained as given in Table 2.

As observed in Fig. 11, unlike the two other models, energy absorption of the pinned model increases at each cycle such that at the last cycle and prior to failure, the maximum rate of energy absorption has occurred. In addition, analysis of the load-displacement curve of the semi-rigid model shows that this model is of a higher load-carrying capacity and ductility and the incremental trend at each cycle is observed in this case as well.

A review of the results indicates that the semi-rigid model benefits from higher energy absorption and load-carrying capacity in contrast to the pinned and rigid models. However, as stated earlier, the major objective of this study is to develop a bracing system that is practical and reparable and in addition, possesses a great load-carrying capacity, energy absorption and ductility. In conclusion, to satisfy these requirements and objectives, the pinned model surpasses the two other models. The major characteristics of the pinned model are briefly presented as follows:

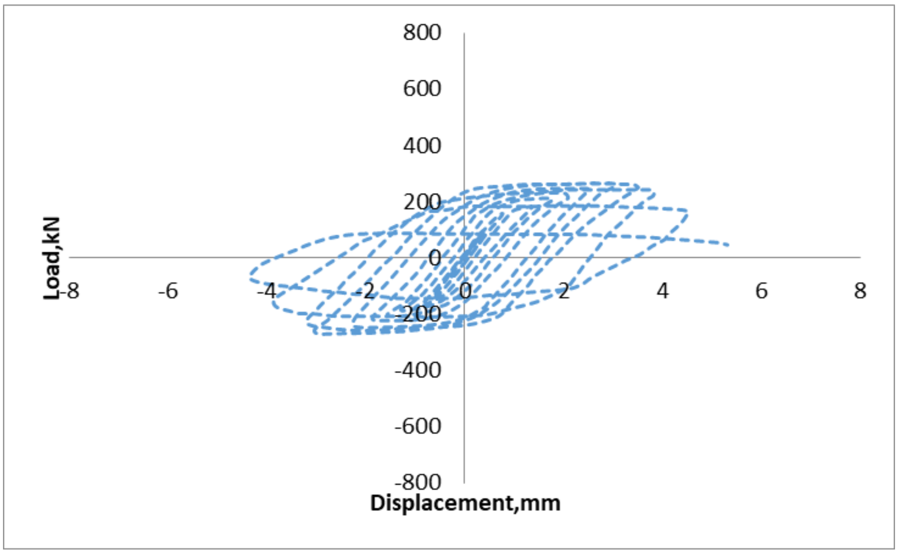


Fig. 12 Hysteretic Curve of Pinned Model

- In the case of the pinned model, the damper yields prior to the other bracing elements. On the contrary, in the rigid and semi-rigid models, the diagonals come into the nonlinear range of behavior and incur buckling. Thus, the capacity of all bracing components is directly used in the semi-rigid and rigid models and after the occurrence of failure and termination of the testing process, reloading is not possible and the system collapses.
- Only the pinned model is reparable.
- In the case of the pinned model, the capacity of the whole system could be enhanced by further increasing the thickness of the ring. However, in the two other models, as the diagonals and ring yield simultaneously, all elements need to be varied and redesigned.
- The pinned model is able to further resist loads after the failure of the ring. In fact, a multilevel bracing system is developed in this case.
- Parallel action of the diagonals and ring has occurred only in the case of a pinned model in which the ring acts as the fuse.

5.2 Study of load-carrying capacity in the direction perpendicular to that of loading

To better understand how the bracing system behaves, hysteretic curves of them for the direction perpendicular to that of loading has been presented. As presented in Fig. 12 and Table 3, the semi-rigid model possesses the lowest energy absorption and ductility due to the welded areas around the bean-shaped plate. However, in the rigid and pinned models, opening and closing the steel ring dissipates the induced energy and thus, a higher rate of energy absorption is achieved. It is noteworthy that displacement in the transverse direction of the bracing system indicates the rate of opening and closing of the steel ring as given in Table 3.

Table 2 Summary of Experimental Results

	Hinge	Semi Rigid	Rigid
Max Load (kN)	264.0	623.5	517.7
Max Displacement (mm)	5.3	7.1	6.3
Energy Dissipation (kN-mm)	9939.4	43859.5	21393.9
Stiffness (kN/mm)	55.5	87.9	82.1

Table 3 Summary of Analysis Results for the Direction perpendicular to that of Loading

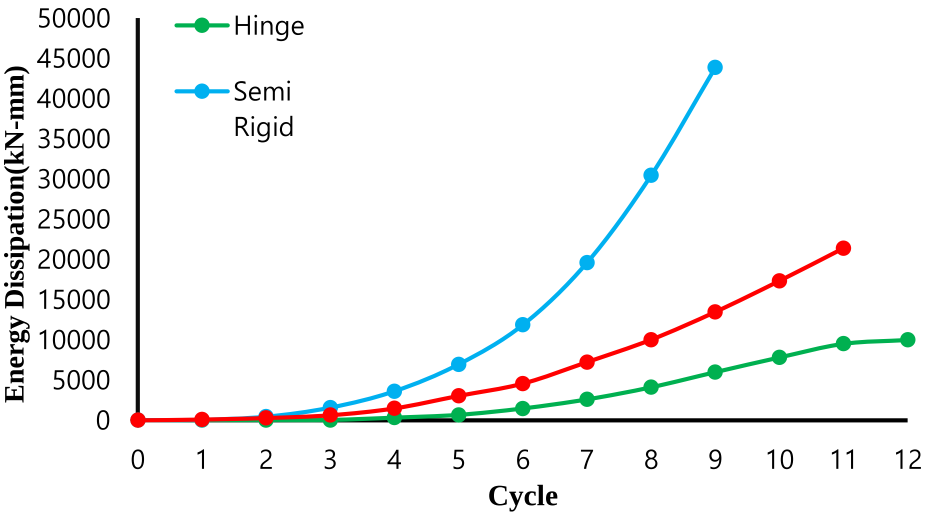
	Hinge	Semi Rigid	Rigid
Max Load (kN)	273.9	638.3	519.2
Max Displacement (mm)	17.4	1.8	16.5
Energy Dissipation (kN-mm)	37229.9	2484.4	66963.8
Stiffness (kN/mm)	17.2	456.7	29.9

5.3 Comparison with other innovative seismic energy dissipation systems

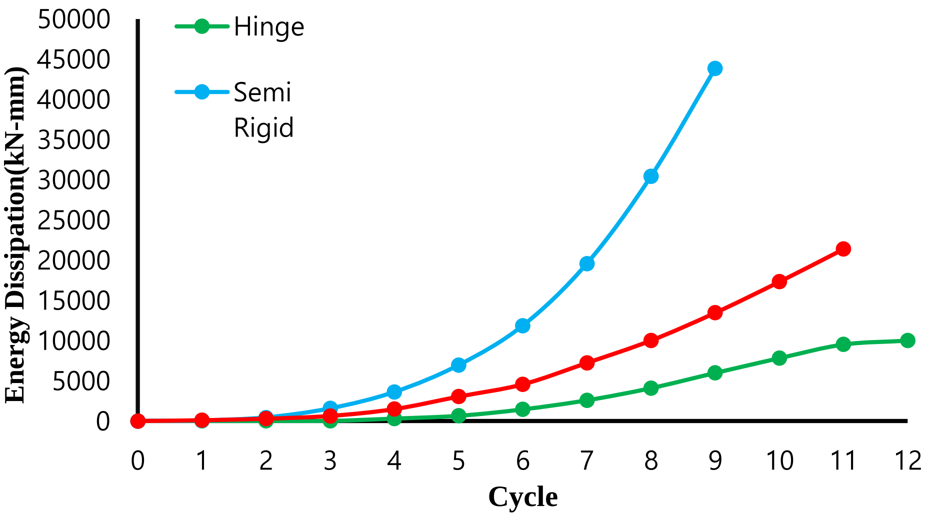
In this section, the innovative system developed in this study is briefly compared with the other novel lateral load-carrying systems.

Kafi *et al.* (2008) applied the ductile elements (i.e., seismic fuse) in the concentric braces aiming to improve energy absorption of the system. Accordingly, they utilized a steel ring with an outer diameter, thickness and length of 22, 1.2 and 10cm, respectively by which a capacity equal to 8 tons was added to the system (diagonals and fuse acted in series).

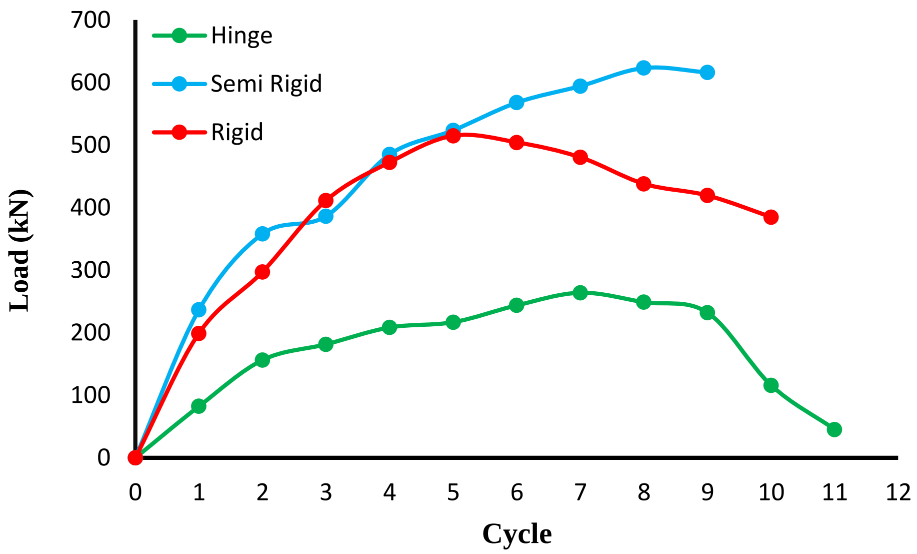
Andalib *et al.* (Bazzaz *et al.* 2012, Andalib *et al.* 2014, Bazzaz *et al.* 2014, Bazzaz *et al.* 2015, Bazzaz *et al.* 2015) carried out experimental and numerical tests to investigate



(a) Cumulative Energy at each Cycle



(b) Load-Displacement Curve



(c) Value of Load at each Cycle

Fig. 13 Performance of Rigid, Semi-Rigid and Pinned Models at each Cycle

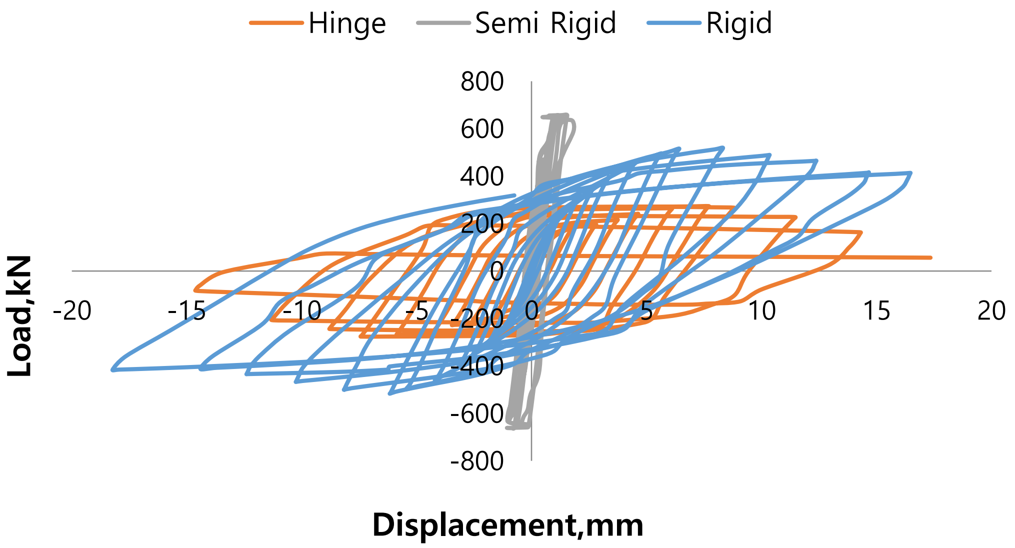


Fig. 14 Comparison of Load-Carrying Capacity in a direction perpendicular to that of Loading

the effectiveness of the steel ring as the structural fuse on the performance of the off-center bracing system. They utilized a ring with a diameter and thickness of 20 and 2cm, respectively. Based on the failure mode, they found that the ring has brought 100 kN additional load resisting capacity and the other components, remain in the elastic phase of behavior.

Gao *et al.* (2016) developed a new bracing system comprised of 4 tension cables and a ring made out of shape memory alloy (SMA) with diameter and thickness of 25 and 5.7 cm, respectively. In this system, the cables and ring act in series by which a capacity equal to 160 KN, was provided.

A review of the innovative bracing system proposed in the literature indicates that despite advantages, these systems are involved with common drawbacks highlighting the need for a new system to overcome these limitations and drawbacks. Some of these limitations are as follows:

- Prior to the rupture of the seismic fuse, the whole of the system fails and actually, the system would be no longer able to resist the induced loads.
- The seismic fuse and bracing elements act in series which in some cases, undesirable, push the bracing elements to the nonlinear range of behavior.
- Use of the rings with great diameter and thickness aiming to increase load-carrying capacity and as a result, an uneconomic design.
- Limitations pertained to the connection of the structural fuse to the bracing elements.
- Executive limitations.

Unlike the abovementioned limitations and deficiencies pertaining to the previously developed lateral load-carrying systems including structural fuses, it is observed that the system proposed herein has managed to exhibit a greater capacity with smaller diameter and thickness. Surprisingly, this system not only benefits from sufficient reparability, it enables the structure to continue providing services and the whole structure does not collapse after the failure of the steel ring. Hence, it is concluded that the proposed system is technically and economically, more efficient than the other similar systems and deserves to be further studied for practical purposes.

6. Numerical modelling

As mentioned earlier, there bracing systems with various connection types of pinned, semi-rigid and rigid are studied experimentally herein. Subsequently, in order to assess if the proposed bracing system can be properly simulated, the pinned model is numerically analyzed using the commercial finite element software, ABAQUS. In this respect, Solid elements are utilized for modeling the diagonals and connection plates and also, the steel ring is simulated using Shell elements. Moreover, the boundary conditions and loading procedure determine the restraints, symmetry, displacements and loads being applied to the model. Similar to the experimental tests, the numerical model was subjected to the displacement-controlled loading procedure as specified by ATC-24 (Applied Technology Council 1992). The 3D solid elements (C3D8R) have been selected to simulate the concrete materials in all models for which the full integration has been taken to calculate the required parameters (C3D8R:8-node linear brick element). Besides, the S4R shell elements have been taken for the steel plates whose computations are conducted via a reduced integration approach.

Properties of steel ring materials are similar to those used in Kafi (2008) studies in which he has used a type of steel ring called CT20. Moreover, material hardening is Kinematic and nonlinear behavior of the materials has been simulated using multi-linear curves. In Table 4, behavior of the ring materials has been presented. It should be noted that the other properties of brace materials are based on ST37.

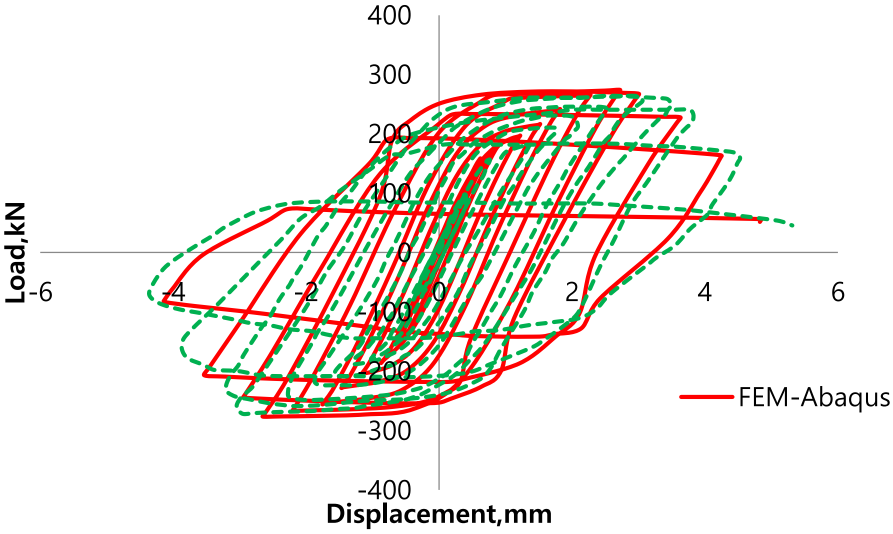


Fig. 15 Numerical and Experimental Hysteretic Curves of Pinned Model

The analyses steps are General Static and NLGeom function was deactivated. The ring and connection plates were separately simulated and for modeling the weld, Tie constraint was utilized and the nodes were jointed to each other. In some parts such as bolts, Hinge constraint was applied. Connection of the shear studs to the channels was integrated and meshed using Assembly module.

To analyze mesh sensitivity, capacity and stiffness of the pinned model were determined for different mesh sizes and then, the results were compared with those of experimental tests. In Table 5, the difference between numerical and experimental values of capacity and stiffness for the case of the pinned model, is shown. As observed, the difference is slightly affected as the mesh sizes are reduced to less than 15mm and undesirably, only the processing duration is prolonged. Consequently, the average mesh size of 15 mm is taken for the numerical analyses.

As can be seen in Fig. 13, there is a great agreement between the numerical and experimental results. In quantitative terms, value of the ultimate load in experimental and numerical models is equal to 264 and 274 kN, respectively, indicating a difference of about 3.6%. Additionally, there is a 0.9% difference between the initial stiffness of the numerical and experimental models approving acceptability of the numerical modeling process.

Table 4 Ring Material Behavior

Yielding Stress (MPa)	Plastic Strain
300	0
585	0.22
450	0.3
220	0.4
120	0.5
50	0.6

Table 5 Mesh Sensitivity Analysis

Avg Mesh Size (mm)	50	25	20	15	10	5
Max Load (Difference %)	4.1	4.4	3.8	3.6	3.7	3.6
Stiffness (Difference %)	14.1	12.6	13.2	9.4	9.4	9.3

Moreover, the accuracy of the numerical results could be examined using Equations 9 and 10 as presented in Eq. 11. Properties of the ring modeled in ABAQUS are as follows:

t = 6.01 mm L = 100 mm R = 54.145 mm σ_u = 585 N/mm^2 (Kafi 2008)

Thus, load-carrying capacity of the ring is calculated as follows

$$P_R = \frac{t^2.L}{R}\sigma_u = \frac{6.01^2 \times 100}{54.145} \times 585 = 39025 \ \ N \cong 39 \ \ kN = 3.9 \ \ ton \tag{11}$$

Now, based on Eq. (10), the total capacity of the proposed bracing system is calculated as

$$P_{cr} = \frac{P_R}{\tan\frac{\theta}{2}} = \frac{3.9}{\tan\frac{15.6}{2}} = 28.5 \ \ ton \tag{12}$$

In sum, the experimental, numerical, and analytical results of load-carrying capacity are given in Table 6.

Table 6 Comparison of Load-Carrying Capacity Results (ton)

Experiment	Simulation	Analytics
26.4	27.4	28.5

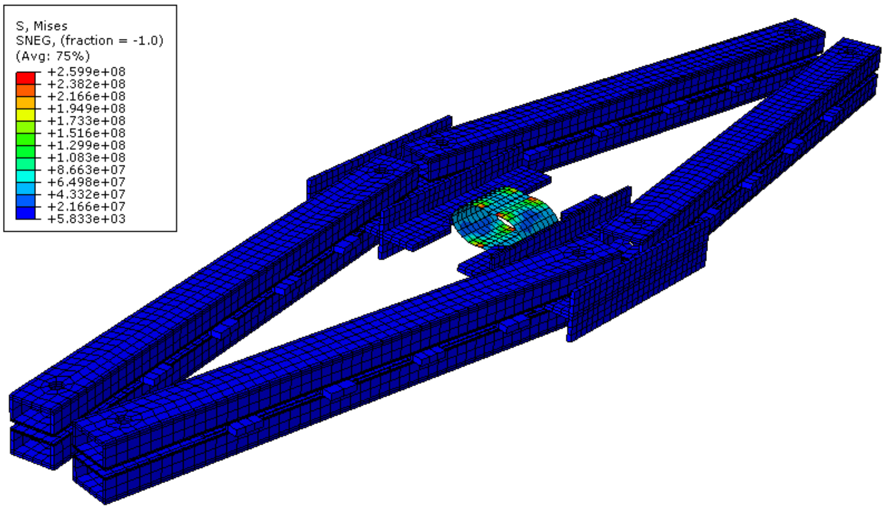


Fig. 16 Von-Mises Stress Contour of pinned Model

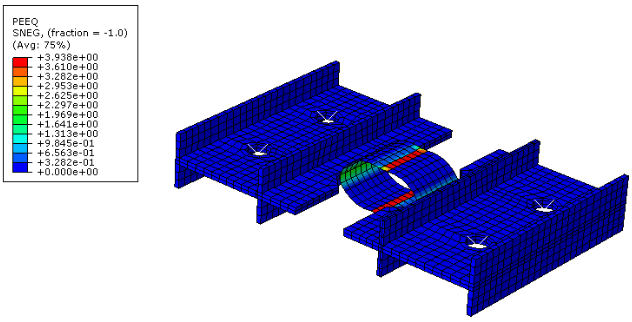


Fig. 17 Equivalent Plastic Strain Contour of Pinned Model

According to Table 3, the analytical results are markedly close to the numerical and experimental results. Consequently, one of the advantages of the proposed bracing system is that by knowing the ring's capacity, the total capacity of the whole system could be attained.

Fig. 14 demonstrates the contour plots of Von-Mises stress developed in the diagonals that have been deformed under loading cycles. According to the stress contour, maximum stress has been developed in the steel ring and the values of stress in the diagonals are much less than their elastic strength indicating that the diagonals have remained in the elastic range of behavior.

Moreover, the contour plot of the equivalent plastic strain is illustrated in Fig. 15. As can be seen, the values of plastic strain are of greater value in the middle of the ring.

7. Economic comparison

After evaluating and comparing performance and technical aspects of the proposed bracing system, this system is economically compared with the conventional bracing systems. One of the most important issues in civil construction projects, concerns economic issues. As the pinned model including the ring, was chosen as the target model, economic issues of this were compared with those of the diagonal bracing system that is a very common system. It is of note that comparison was provided such that cross-sectional area of the diamond-scheme and diagonal bracing systems, would be equal. Thus, all materials required for construction of the diagonal braces, could be easily calculated. In Table 7, weight and price of each bracing system is separately presented. As can be seen, sum of costs for construction of the diamond-scheme bracing system is equal to 228.62 USD and cost of diagonal brace is equal to 138.95 USD. This means that compared to the diagonal bracing system, construction of the diamond-scheme system is 61% costlier. The important point is that economical issues are not only limited to construction costs but also, a design engineer or contractor has to account for the post-quake costs. Given the fact that after occurrence of earthquake, diagonal braces incur buckling and lose their functionality, the brace together with its connections have to be replaced. Hence, an additional cost around 138.95 USD has to be considered. Promisingly, in the case of diamond-scheme bracing system, only the steel ring has to be replaced which is an east task due to the functional mechanism of this system. Post-quake costs of the diamond-scheme system is just equal to 1.9 USD.

Table 7 Economic Comparison between Diagonal and Diamond-Scheme Bracing Systems

Model	Components	Number	Weight (kg)	Price (USD)	Sum of Costs (USD)
Diamond	UNP80 , L=1 m	8	180	108	228.62
	Steel Ring	1	1.7	1.9	
	Bolt	8	-	66.5	
	Shear Stud	16	7.54	2.92	
	Stiffeners	4	15	10	
	Connection Plates of Ring to Brace	2	33	12.8	
	Welding	-	-	16.5	
	Cutting and Perforation	-	-	10	
Diagonal	UNP80	8	180	108	138.95
	Shear Stud	10	4.5	1.8	
	Bolt	2	-	16.65	
	Welding	-	-	5	
	Cutting and Perforation	-	-	7.5	

By concluding the above-mentioned issues, it is understood that costs of production, execution and replacement of the diagonal and diamond-scheme bracing systems are equal to 277.9 and 230.52 USD, respectively indicating that diagonal brace is totally 17% more expensive. Hence, use of diamond-scheme bracing is justifiable both technically and economically. Of course, by conducting further studies regarding the proposed system, a more economic model could be developed as well.

8. Conclusions

This paper introduces an innovative diamond-scheme bracing system equipped with a steel ring acting as a yielding damper. Accordingly, three specimens with three types of pinned, semi-rigid and rigid connections were tested using cyclic loading with aiming to identify and evaluate its performance in contrast to the other available systems. Most notably, this system is majorly intended to present a mechanism by which high energy absorption and adequate reparability could be attained while properly taking advantage of the damper's capacity. The most significant conclusions drawn from this experimental-numerical study are as follows:

- The stress-strain curves of all three models were extracted based on the cyclic tests and then, energy absorption, maximum applied load and stiffness were computed. The results approve of the sufficient performance and applicability of the proposed system.
- Comparison of the three developed systems, indicates that the semi rigid model has higher energy dissipation, maximum applied load, ultimate displacement and stiffness than other models. Also, the pinned model has provided the best performance given its failure mode in which the damper has yielded and the other components of the system have remained elastic. On this basis and also the aim of the investigation, the pinned model is introduced as the final selected model of the proposed bracing scheme.
- On the contrary to the other systems previously developed in the literature, in the pinned system proposed herein, the ring and diagonals act in parallel. Hence, not only the damper capacity is maximally utilized but also in the case of damper failure, the system is still able to withstand the induced loads and failure of the steel ring does not lead to disrupts the performance of the whole system.
- Among the three models, the type of connections in the pinned model, provides a great ability to repair or replace the steel ring.
- Numerical model of the final proposed system (pinned model) was simulated and verified in ABAQUS software and the results indicate an appropriate agreement between the experimental and numerical results. Thus, to develop the proposed system in future studies and further analyze its performance, use of FEM analysis is adequate.
- Economic comparison of the diagonal and diamond-scheme bracing systems implies the point that sum of construction and fabrication costs as well as post-quake expenditures of the diamond-scheme system is nearly 17% less than that of the diagonal brace.

References

AISC, A. (2016), "Prequalified connections for special and intermediate steel moment frames for seismic application", Chicago, USA.

Amadio, C., Clemente, I., Macorini, L. and Fragiacomo, M.

(2008), "Seismic behaviour of hybrid systems made of PR composite frames coupled with dissipative bracings", *Earthq. Eng. Struct. D*., **37**(6), 861-879. https://doi.org/10.1002/eqe.790.

Andalib, Z., Kafi, M.A., Bazzaz, M. and Momenzadeh, S.B. (2018), "Numerical evaluation of ductility and energy absorption of steel rings constructed from plates", *Eng. Struct.*, **169**, 94-106, https://doi.org/10.1016/j.engstruct.2018.05.034.

Andalib, Z., Kafi, M., Kheyroddin, A. and Bazzaz, M. (2014), "Experimental investigation of the ductility and performance of steel rings constructed from plates", *J. Constr. Steel Res.*, **103**, 77-88. https://doi.org/10.1016/j.jcsr.2014.07.016.

Annan, C.D., Youssef, M.A. and El Naggar, M.H. (2009), "Experimental evaluation of the seismic performance of modular steel-braced frames", *J. Eng. Struct*., **31**(7), 1435-1446. https://doi.org/10.1016/j.engstruct.2009.02.024.

Applied Technology Council. (1992), "Guidelines for seismic testing of components of steel structures", Report of ATC-24, Redwood City, CA, USA.

Bazzaz, M., Andalib, Z., Kafi, M. and Kheyroddin, A. (2015), "Evaluating the performance of OBS-C-O in steel frames under monotonic load", *Earthq. Struct.*, **8**(3), 697-710. https://doi.org/10.12989/eas.2015.8.3.699.

Bazzaz, M., Andalib, Z., Kheyroddin, A. and Kafi, M. (2015), "Numerical comparison of the seismic performance of steel rings in off-centre bracing system and diagonal bracing system", *Steel Compos. Struct.,* **19**(4), 917-937. https://doi.org/10.12989/scs.2015.19.4.917.

Bazzaz, M., Kheyroddin, A., Kafi, M. and Andalib, Z. (2012), "Evaluation of the seismic performance of off-centre bracing system with ductile element in steel frames", *Steel Compos. Struct.,* **12**(5), 1-20. https://doi.org/10.12989/scs.2012.12.5.445.

Bazzaz, M., Kheyroddin, A., Kafi, M., Andalib, Z. and Esmaeili, H. (2014), "Evaluating the seismic performance of off-centre bracing system with circular element in optimum place", *Int. J. Steel Struct.*, **14**, 293-304. https://doi.org/10.1007/s13296-014-2009-x.

Chan, R.W.K. and Albermani, F. (2008), "Experimental study of steel slit damper for passive energy dissipation", *Eng. Struct.*, **30**(4), 1058-1066. https://doi.org/10.1016/j.engstruct.2007.07.005.

Gao, N., Jeon, J.S., Hodgson, D.E. and DesRoches, R. (2016), "An innovative seismic bracing system based on a superelastic shape memory alloy ring", *Smart Mater. Struct.*, **25**(5), 1-16. doi:10.1088/0964-1726/25/5/055030.

Hsu, H.L., Juang, J.L. and Chou, C.H. (2011), "Experimental evaluation on the seismic performance of steel knee braced frame structures with energy dissipation mechanism", *Steel Compos. Struct.*, **11**(1), 77-91. https://doi.org/10.12989/scs.2011.11.1.077.

Kafi, M.A. (2008), "Analytical and experimental study of effect of steel ring on ductility of concentric braces", The degree of Doctorate of Philosophy, Civil Engineering Department, Iran University of Science and Technology, Tehran, Iran.

Kelly, J.M., Slinner, R.I. and Heine, A.J. (1972), "Mechanisms of Energy Absorption in Special Devices for Use in Earthquake Resistant Structures", *Bull. New Zealand National Soc. Earthq. Eng.*, **5**(3), 63-88.

Kelly, J.M., Slinner, R.I. and Heine, A.J. (1975), "Hysteresis Dampers for Earthquake Resistant Structures", *Earthq. Eng. Struct. Dynam.*, **3**(3), 287-296. https://doi.org/10.1002/eqe.4290030307.

Kheyroddin, A., Sepahrad, R., Saljoughian, M. and Kafi, M.A. (2019), "Experimental evaluation of RC frames retrofitted by steel jacket, X‐brace and X‐brace having ductile ring as a structural fuse", *J. Build. Pathology Rehabilitation*, **4**(11), https://doi.org/10.1007/s41024-019-0050-z.

Lee, K. and Bruneau, M. (2005), "Energy dissipation demand of compression members in concentrically braced frames", *Steel. Compos. Struct*., **5**(5), 345-358. https://doi.org/10.12989/scs.2005.5.5.345.

Lotfollahi, M. and Mofid, M. (2008), "Innovative method in seismic design of slab-on-girder steel bridges", *J. Construct. Steel Res.*, **64**(12), 1420-1435. https://doi.org/10.1016/j.jcsr.2008.01.017.

Marshall, J.D. and Charney, F.A. (2010a), "A hybrid passive control device for steel structures, I: Development and analysis", *J. Construct. Steel Res*., **66**(10), 1278-1286. https://doi.org/10.1016/j.jcsr.2010.04.005.

Marshall, J.D. and Charney, F.A. (2010b), "A hybrid passive control device for steel structures, II: Physical testing", *J. Construct. Steel Res*., **66**(10), 1287-1294. https://doi.org/10.1016/j.jcsr.2010.04.002.

Moghaddam, H. and Estekanchi, H. (1995), "On the characteristics of off-centre bracing system", *J. Constr. Steel Res*., **35**(3), 361-376. https://doi.org/10.1016/0143-974X(94)00050-R.

Motamedi, M., Hafezi, M. and Yekrangnia., M. (2012), "Analytical Study of Steel Ring Connections as Hysteretic Metallic Damper", *15 WCEE*.

Murthy, A.N.C.K. (2005), "Application of visco-hyperelastic devices in structural response control", The degree of Master of Science; Civil Engineering Department, Blacksburg Polytechnic Institute, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

Peng, X., Lin, C., Cao, Y. and Duan, W. (2019), "Nonlinear Finite Element Simulation on Seismic Behaviour of Steel Frame-Central Brace with Ring Damper", *IOP Conf. Series: Materials Science and Engineering*, **472**, 23-25. doi:10.1088/1757-899X/472/1/012031.

Peng, X.T., Lin, C., Cao, Y.M. and Duan, W.X. (2018), "Seismic behaviors of the composite central brace with steel ring damper", *Proceedings of the 7th International Conference on Energy and Environmental Protection*, 1089-1092.

Rakicevic, Z. and Jurukovshi, D. (1998), "Behavior factor (q-factor) for non-standard dual steel frame structures", *Proceedings of the 11th European Conference on Earthquake Engineering*.

Roufegarinejad, A. and Sabouri, S. (2002), "Nonlinear behavior of yielding damped bracing frames", *Proceedings of the 15th ASCE Engineering Mechanics Conference*, Columbia University, New York.

Xu. L., Fan, X., Lu, D. and Li, Z. (2016), "Hysteretic behavior studies of self-centering energy dissipation bracing system", *Steel Compos. Struct*., **20**(6), 1205-1219.: https://doi.org/10.12989/scs.2016.20.6.1205.

Zahrai, M. and Jalali, M. (2014), "Experimental and analytical investigations on seismic behavior of ductile steel knee braced frames", *Steel Compos. Struct*., **16**(1), 1-21. https://doi.org/10.12989/scs.2014.16.1.001.

DL