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Cyclic Performance Evaluation of Steel Structures Retrofitted by Slit Dampers

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ABSTRACT

This study aims to assess the effect of slit dampers on chevron braced frame in steel structures with different number of stories under one-way and cyclic loadings. To assess and compare the results, a parametric research was performed on slit, non-slit and cavity dampers. 8 single-story and single-span frames in the form of moment frame, braced frame with non-slit damper, braced frame with slit damper, braced frame with cavity damper, and chevron 3-story frame with slit damper, chevron 5-story braced frame with slit damper and the 8-story chevron braced frame with slit damper were modeled and analyzed by ABAQUS finite element software. The results showed that the chevron braced frame with slit damper dissipated a large amount of earthquake input energy and reduced the base shear force with its behavior. Hysteresis curves with stability and without high dissipation indicated high energy absorption by the chevron braced frames equipped with slit dampers. In all chevron braced frames with slit damper, no plastic hinge was formed in the structural members, and the failure mode was concentrated in the slit damper element. Slit damper reduced the initial stiffness, secondary stiffness, and bearing capacity, which in addition to controlling the lateral displacement of the structure increased energy dissipation capability and ductility. The chevron braced frame with slit damper had a better ductility than other specimens and had a good seismic performance based on the results.

Keywords:

Chevron braced frame, Slit damper, Hysteresis curve, Ductility, Plastic hinge.

1. Introduction

In recent decades, by considering the destructive earthquakes, it is necessary to study the seismic performance of structures in order to reduce the life and financial damage caused by this natural phenomenon. The basis for designing conventional earthquake-resistant systems is according to lateral load resisting systems. So that in weak and strong earthquakes, the lateral load resisting systems control the lateral displacement and prevents the destruction of structural and non-structural members and they prevent the structural collapse by creating ductility and absorbing the appropriate energy from structural members [1-3]. Civil engineering constructions placed in areas prone to earthquakes or high winds will be subjected to severe vibrations during their lifetime. These vibrations can range from insignificant to severe, with the latter causing significant structural damage and potential structural failure. The conventional anti-seismic strategy is to raise the stiffness of structures by increasing the section of columns, beams, shear walls, or other elements, which will increase the seismic load due to the additional mass to structures. As a result, while the cost of structures using traditional anti-seismic techniques has grown significantly, the safety level of structures has not improved significantly. Another drawback of previous anti-seismic techniques is that they focus on the protection of the building while ignoring the amenities within the structure. As a result, it cannot be utilized in some structures with critical facilities, such as hospitals, municipal lifeline infrastructure, nuclear reactors, museum buildings, and buildings with exact instruments. Even though engineers cannot design a building that is damage-proof during earthquakes and severe winds, structural control seems promising in terms of decreasing structure vibration. In contrast to the classic anti-seismic approach, the structural control technique suppresses structural vibration by placing devices, mechanisms, and substructures in the structure to modify or adapt the structure's dynamic performance. The device type of the structural control system is often used to classify it, resulting in four main control types: passive, active, hybrid, and semi-active control. An active control system is one in which external source power control actuators, such as active tendon system (ATS) and active mass damper, apply forces to the structure in a mass damper (AMD). A passive control system, such as the base isolation technique, energy dissipation devices, tuned mass damper (TMD), and tuned liquid damper (TLD) does not require an external power supply. The term "hybrid control" refers to the employment of both active and passive control mechanisms. Semiactive control systems, such as active variable stiffness (AVS) systems and active variable damper (AVD) systems, are a type of active system in which just a minimal amount of external energy is required to modify the parameters of the control system [4-8]. Slit dampers are used in both braces and beam-to-column connections. These dampers are embedded in structures in a way that they flow through shear, bending or axial force, and in order to dissipate energy they must be carefully positioned so that they are deformed by the relative story displacement due to lateral loads, otherwise they do not absorb energy. Nowadays, according to the new approaches, the design priority is given to the ductility and energy dissipation. One way to achieve this goal is to use an energy dissipation mechanism in the structure itself. The equipment is designed to dissipate a part of the energy input to the structure and thus reduce the damage to the main structure [9]. Steel concentrically braced frames do not have good ductility, but their vulnerable members subjected to the limited earthquake and as a result their rebuild is much less expensive than moment frames. To address the weaknesses of concentrically braces and to provide desirable ductility, extensive research has been conducted by researchers over the past two decades and, several methods have been proposed by various researchers to increase the ductility of these braces, each of which has attempted to improve the ductility of concentrically braces [10]. The use of fuses is one of the suggested solutions. Fuses are manufactured in various forms with different flexural, shear or torsional performances. However, most of the research in this area has been based on flexural performance. In the following, the background of this research is presented. Benavent-Climent (2010) investigated a tube-in-tube brace damper with two hollow parts, the outer hollow portion having a series of holes through its wall. The damper demonstrated exceptional energy dissipation capability and steady hysteretic behavior, according to the test findings [11]. In addition, a hysteretic model has been given to estimate the damper's final energy dissipation capability. Ghabraie et al. (2010) used a modified BESO method to optimize the form of slit dampers reported by Chan and Albermani (2008). To achieve a high energy dissipation per unit volume, total plastic energy dissipation was increased. It was determined that the optimized shape of the slit damper dissipated 37% more energy than the previous specimen [12, 13]. Karavasilis et al. (2012) devised a minimal-damage seismic design technique for steel buildings that use slit dampers in tandem with viscous dampers. The steel MRF with slit devices and viscous dampers had lower residual drifts and peak total floor accelerations than the traditional MRF. As a result, the MRF with slit devices and viscous dampers sustained less damage than the traditional MRF [14]. Safari et al. (2013) performed a parametric analysis to determine the optimal design of slit dampers for various beam length-beam depth ratios. Steel slit dampers were utilized as an energy dissipation device to improve the ductility of beam-to-column connections [15]. Koken and Koroglu (2014) compared the behavior of beam-to-column connections with slit dampers to that of the extended end plate connection in practical and theoretical investigations. Unlike the extended end plate connection, the slit damper connections exhibited strong hysteretic performance while causing no damage to the beam or column [16]. Lima et al. (2015) investigated the performance of steel slit devices used as a link in eccentric bracings for seismic retrofitting of RC frames. Nonlinear time history studies of an existing RC frame with the specified bracings were performed, with low-cycle fatigue taken into account [17]. Lee and Kim (2015) used nonlinear dynamic analysis to explore the seismic performance of hybrid slit-friction dampers. The study findings showed that when the structure is fitted with hybrid passive dampers, the damage and residual displacements of the main structural elements are reduced [18]. Hedayat (2015) conducted a parametric research to estimate the force displacement behavior of various types and geometries of unbuckled slit dampers. Based on the finite element results, he proposed various formulae for each type of slit damper [19]. Tagawa et al. (2016) suggested a seesaw energy dissipation system using steel slit dampers to keep the bracing elements taut while improving damper stiffness and energy dissipation properties. They gave the lateral narrative stiffness and strength formulae for the system in question [20]. Lee and Kim [21] created hybrid damping devices by connecting steel slit and rotational friction dampers in parallel, and demonstrated that the hybrid dampers are particularly effective in reducing seismic responses for small to medium earthquakes when compared to slit or friction dampers of the same yield strength. Kim and Shin [22] used test and analysis to estimate the seismic loss of a structure retrofitted with slit-friction dampers. Naeem et al. [23, 24] examined the seismic performance of a self-centering hybrid slit damper with shape memory alloy bars. With reviewing the previous investigations, it was observed that the use of steel slit dampers in steel structures are not distributed. Therefore, In this study, 8 single-story and single-span frames in the form of moment frame, braced frame with simple damper, braced frame with slit damper, braced frame with cavity damper, and Chevron three-story frame with slit damper, Chevron 5-story braced frame with slit damper and the 8-story Chevron braced frame with slit damper were studied in ABAQUS finite element software. The novelty of this study is aim to investigate the seismic performance of steel frames with considering the slit damper versus simple and cavity dampers.

2. Modelling Procedure

2.1. Details of Numerical Modeling

In this study, 8 single-story and single-span frames in the form of moment frame, braced frame with simple damper, braced frame with slit damper, braced frame with cavity damper, and Chevron three-story frame with slit damper, Chevron 5-story braced frame with slit damper and the 8-story Chevron braced frame with slit damper were studied. Typically designing a single-span single-story frame based on actual loads results in small sections for structural members; therefore, it was decided to prevent or postpone the damage to other members of the frame by assuming the specifications of a chevron braced frame and designing the dimensions of the proposed element in such a way that the element is yielded before buckling in a compressive member of the brace and acted as a buckling control fuse of the brace by entering the nonlinear phase and forming a plastic hinge while absorbing input energy to the structure. During the process of modeling the samples by the software, a number of assumptions were used, including the geometrical properties of the frames, the type of analysis and the mechanical specifications of the materials. All models in this study were designed in Sap2000 software. Then, the nonlinear analyses are performed in ABAQUS software. Tables 1 to 4 shows the beam, column, and brace sections of the studied frames.

Table 1. Sections of a frame with single-story and single-span.

Section type	**Column**	**Beam**	**Brace**
Section name	IPB180	IPE200	Box100×100× 10mm

Table 2. Sections of an eight-story frame with Chevron brace equipped with slit damper.

Story No.	**Column**	**Beam**	**Brace**
1-2	Box40×40×2.5cm	IPB340	Box20×20×2cm
3-4	Box35×35×2.5cm	IPB300	Box20×20×2cm
5-6	Box30×30×2.5cm	IPB260	Box15×15×2cm
7-8	Box25×25×2.5cm	IPB200	Box15×15×2cm

Table 3. Sections of a five-story frame with Chevron brace equipped with slit damper.

Story No.	**Column**	**Beam**	**Brace**
1-2	Box35×35×2.5cm	IPB300	Box20×20×2cm
3-4	Box30×30×2.5cm	IPB260	Box15×15×2cm
5	Box25×25×2.5cm	IPB200	Box15×15×2cm

Table 4. Sections of a three-story frame with Chevron brace equipped with slit damper.

Story No.	Column	Beam	Brace
1-2	Box35×35×2.5cm	IPB300	Box20×20×2cm
3-4	Box30×30×2.5cm	IPB260	Box15×15×2cm
5	Box25×25×2.5cm	IPB200	Box15×15×2cm

The mechanical specifications of used steel "*ST37*" are considered in the modeling by *ABAQUS* software are provided in Table 5.

Table 5. Mechanical specifications of ST37.

Description	unit	number
Modulus of	Kg/cm^2	2100000
Ultimate strain	-	0.18
Yielding stress	Kg/cm^2	2400
Ultimate stress	Kg/cm^2	3700

Figure 1 shows the geometry of the studied frame and Fig 2 shows the geometry of the studied slit damper in this study by using *ABAQUS* software. The frame has a Chevron brace equipped with a slit damper. Parameters *B* and *H* represent the frame span length and frame height, respectively.

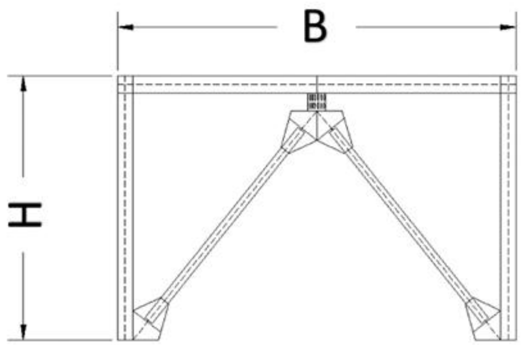

Figure 1. Geometry of the studied frame**.**

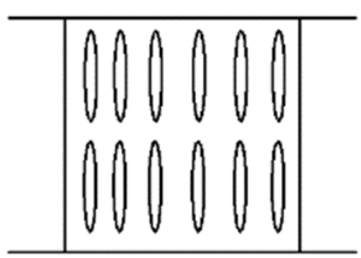

Figure 2. Geometry of the studied slit damper.

The loading was applied to the frames in one-way and cyclic way. Nonlinear static pushover analysis was performed using the control displacement method and accordingly, the target displacement was considered at 2.5% of the frame height in all models [25]. To investigate the behavior of steel slit dampers subjected to reciprocating forces, several specimens of these frames were loaded with steel slit dampers according to the proposed method in ATC-24.

2.2. Numerical Verification

For numerical modeling, the numerical modeling method is first validated by comparing the results with the experimental prototype. For this purpose, the slit damper specimen of Zheng et al. [26] was modeled numerically by ABAQUS software and the force-displacement curve of analytical results were compared with the experimental results. Fig 3 shows the configuration of the experimental specimen. Beams and slit damper were IPE200 and steel plate dimensions are 21 x 21 cm, respectively. The used steel is Q235. The lateral force applied to the beam at 7.5 mm. Fig 4 shows the comparative force-displacement curve of experimental prototype and the studied sample in this study. The maximum load bearing capacity of the damper in the experimental method of Zheng et al. is 26.8 kN and in the verification carried out in this study is 28.28 kN which shows 5.14% error rate. Therefore, there is a good agreement between the experimental and numerical results.

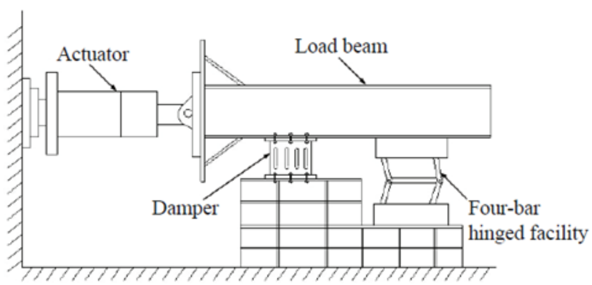

Figure 3. Configuration of the experimental prototype proposed by Zheng et al. 2015 [26].

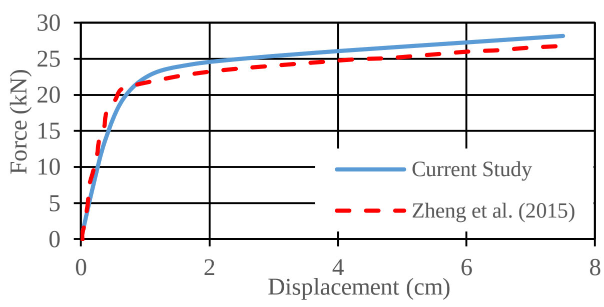

Figure 4. Comparative the force-displacement curve.

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3. Results and Discussions

3.1. Seismic behavior of a Single-Story Single-Span Frame

This section investigates the seismic behavior of a single-span frame in the cases of simple moment frame, Chevron brace without slit damper and a braced frame equipped with slit damper. The numerical model of the steel frame was first analyzed by nonlinear static pushover analysis and then assessed by cyclic loading based on the ATC-24 loading protocol. The comparison of pushover curves and hysteresis curve obtained from the results of numerical models in ABAQUS software have been used in order to evaluate the structural behavior of frames. Fig 5 shows a comparative curve of the base shear-displacement by the pushover load analysis for the simple moment frame, Chevron brace without slit damper and a braced frame equipped with slit damper. Fig 5 shows that the curve for the Chevron brace equipped with a slit damper has a completely incremental trend showing no reduction in strength and deterioration. In the other hand, the simple moment frame in the upper base section has been yielded and its curve had a decreasing trend, indicating low ductility compared to the other specimens. Figs 6 to 8 show the hysteresis curves of all three models under cyclic loading. According to the hysteresis curve of the presence of a slit damper, it significantly enhances the structural performance under cyclic loading. Obviously, in the Chevron braced frame with damper, unsTab hysteresis cycles, asymmetry, and indicate a poor performance of the system.

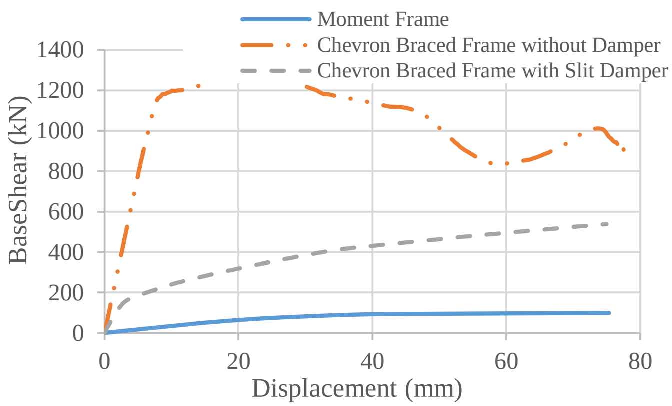

Figure 5. Comparative curve of base shear-displacement.

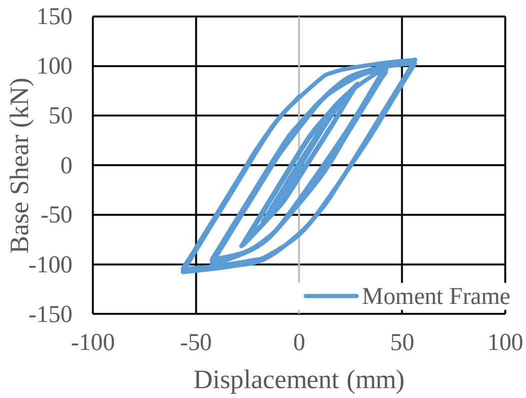

Figure 6. Hysteresis curve of the moment frame.

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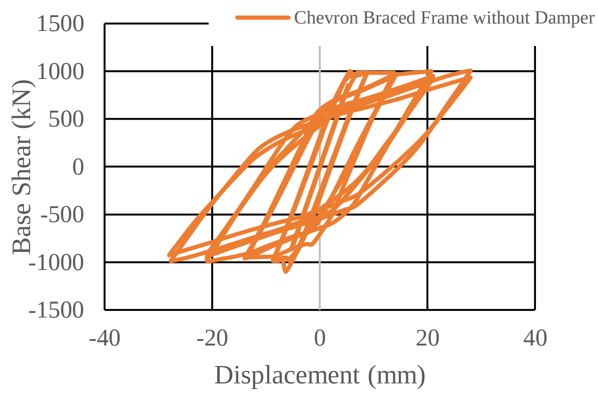

Figure 7. Hysteresis curve of the Chevron braced frame without damper.

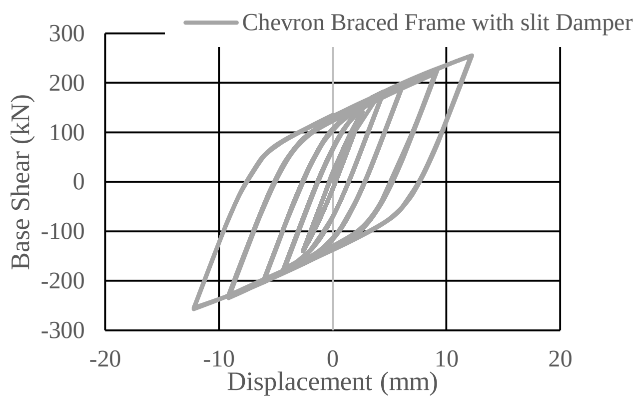

Figure 8. Hysteresis curve of the Chevron braced frame equipped with slit damper.

3.2. The Effect of Increasing Number of Stories on the Performance of Slit Damper

In this section, the effect of slit dampers with increasing number of structural stories is discussed. Four models with 1, 3, 5 and 8-story with considering Chevron brace equipped with slit dampers were analyzed by Abacus software with nonlinear static pushover analysis and the energy absorption percentage of slit damper was calculated. Fig 9 shows a comparative curve of the base shear -displacement for the models with 1, 3, 5 and 8-story Chevron braced frames equipped with a slit damper. Table 6 shows the energy absorption percentage of the damper to the whole structure with the number of specified floors. The energy absorption percentage of the damper decreased with increasing number of stories, indicating the proper performance of this type of dampers in short-rise structures. The highest percentage of energy absorption occurred in a single-frame with a rate of 67 percent and the lowest energy absorption percentage in an eight-story frame with a rate of 25 percent.

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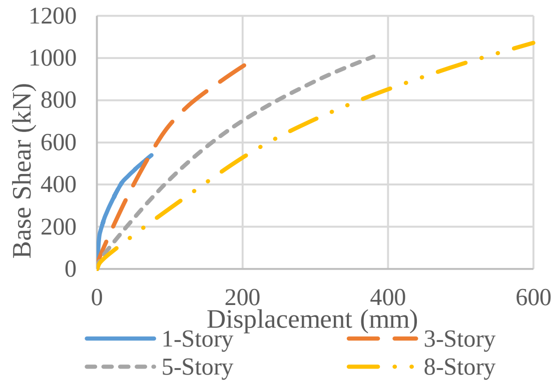

Figure 9. Base shear-displacement curve of chevron braced frame equipped with slit damper.

Table 6. Energy absorption percentage in the frames with different number of stories.

Number of stories	Energy absorption percentage of the damper
1	67%
3	46%
5	30%
8	25%

4. Parametric Evaluation of Numerical Models

In this section, we compared the behavior of a single-story single-span Chevron braced frame with a simple dampers, slit damper, circular cavity damper with a diameter of 38 mm and 50 mm by Von Mises failure criterion. Figure 10 shows the von Mises stresses created in the Chevron braced frame equipped with a simple nonlinear static analyzer with cyclic loading. In Figure 10, so many plastic elements have been occurred in the beam, and the simple damper has failed to play a key role in energy absorption. Figure 11 shows the von Mises stresses created in the Chevron braced frame equipped with slit damper subjected to a nonlinear static analysis with cyclic loading. In Fig 11, almost all the energy absorption of the system is occurred by the slit dampers and has not been formed in the main members of the plastic element structure. The greatest stress created by the chevron braced frame with slit damper at the rate of 2.463e + 08. Figure 12 shows the von Mises stresses created in the Chevron braced frame equipped with a circular cavity damper at the radius of 50 mm subjected to the nonlinear static analysis with cyclic loading. In Figure 12, the energy absorption of the system is not solely by the cavity damper and has been developed in plastic beams. The greatest stress of 3.700e + 08 was created.

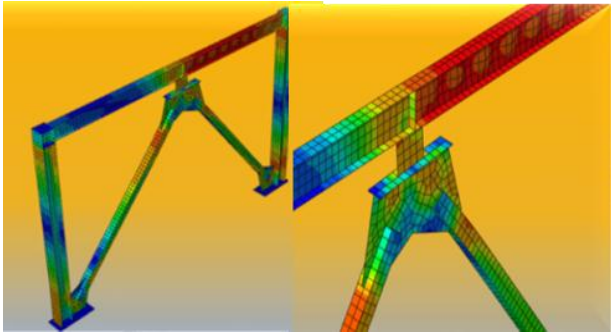

Figure 10. Chevron braced frame equipped with simple damper.

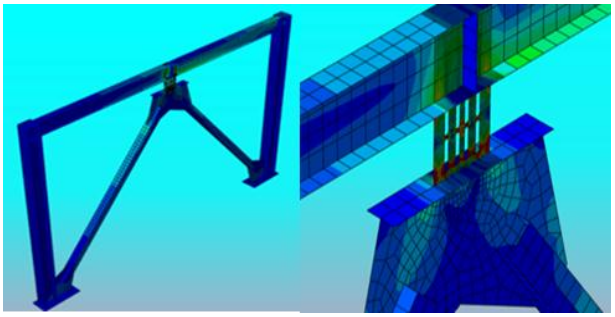

Figure 11. Chevron braced frame equipped with slit damper.

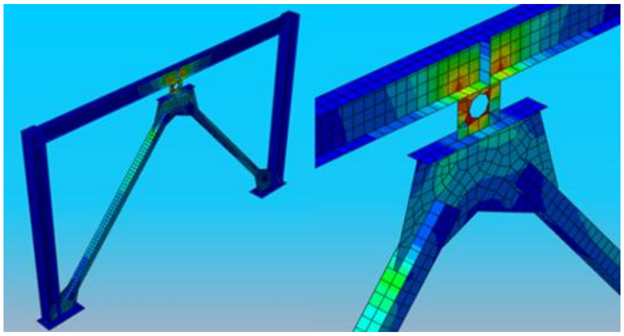

Figure 12. Chevron braced frame equipped with 50 mm cavity damper.

Figure 13 shows the von Mises stresses created in the Chevron braced frame equipped with a circular cavity damper of 38 mm radius, under static analysis with cyclic loading. In Fig 13, the energy absorption of the system was not solely by the cavitation damper and the plastic elements have been developed in the beam and partially formed by the brace member of the plastic element. The slit damper frame had better seismic performance than other dampers. Plastic elements were created only in the slit damper and other key members of the frame, such as beams or columns, did not enter the plastic phase, which could be an important advantage in the discussion of the repair ability of frame members after an earthquake.

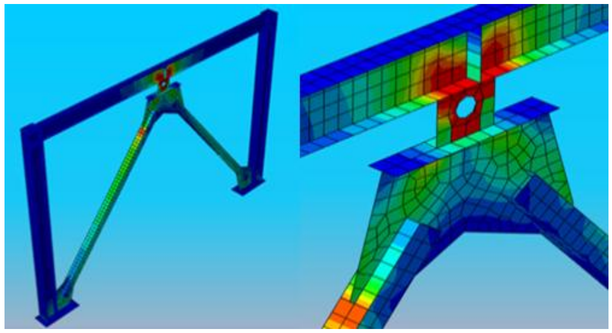

Figure 13. Chevron braced frame equipped with 50 mm cavity damper.

Nonlinear static pushover analysis is one of the most widely used structural analyzes. Important outputs such as behavior coefficient, ductility coefficient, over-strength factor, ductility ratio, energy absorption, initial and secondary stiffness, bearing capacity and force induced by the first plastic hinge can be obtained through this method. The base shear-displacement curve is extracted from ABAQUS software following the nonlinear static pushover analysis and is calculated by Young's bilinear method. To calculate the behavior coefficient, we continue the elastic part of the linear range until the area under the elastic curve is equal to the area under the curve of the bilinear curve.

Table 7. Parameters of the studied dampers.

	Type of damper			
Parameter	Cavity damper with radius of 38 mm	Cavity damper with radius of 50 mm	Slit damper	Simple damper
The force induced by the formation of the first plastic joint-V_s(KN)	414	291	152	567
Bearing capacity-V0(KN)	967	959	539	833
Initial stiffness- KE (KN/mm)	96.05	95.72	50.83	79.18
Secondary stiffness- K1 (KN / mm)	3.63	4.86	3.76	0.35
Energy absorption percentage of damper subjected to pushover loading	40	45	67	56
Energy absorption percentage of damper subjected to cyclic loading	80	88	97	27
Over-strength factor-Rs	1.74	2.15	1.82	1.42
Plasticity factor-Rμ	4.69	5.24	6.2	3.72
Behavior factor-R	8.18	11.28	11.32	5.31
Ductility ratio- μ	9.97	11.45	13.73	7.33

4.1. Force Induced by the Formation of the First VS Plastic Hinge

Figure 14 shows a comparative values of the force caused by the formation of the first plastic hinge in the models. The force due to the formation of the first plastic hinge of the slit damper is 179% lower than the average force caused by the formation of the first plastic hinge of the other three dampers. Plastic hinge in slit damper has occurred faster than other dampers.

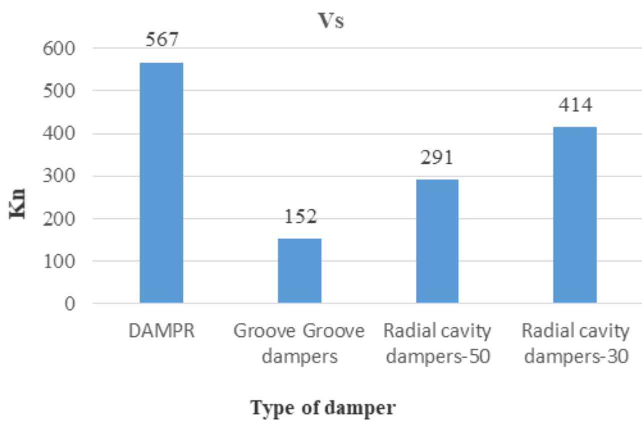

Figure 14. Comparative values of the force induced by the formation of the first plastic hinge**.**

4.1.1. Load bearing capacity V_0

Figure 15 shows the comparative values of the bearing capacity of the models. The bearing capacity of the slit damper is 71% lower than the average bearing capacity of the other three dampers and can be ignored due to the new ductility perspective.

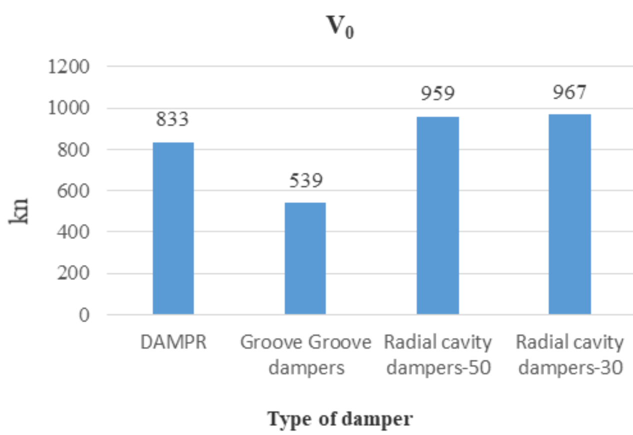

Figure 15. Comparative values of load bearing.

4.1.2. Initial stiffness k_E

Figure 16 shows the comparative values of the initial stiffness of the models. The initial stiffness of the slit damper is 77.6% lower than the average stiffness of the other three dampers. The cavity damper with a stiffness of 96.05 has the highest initial stiffness.

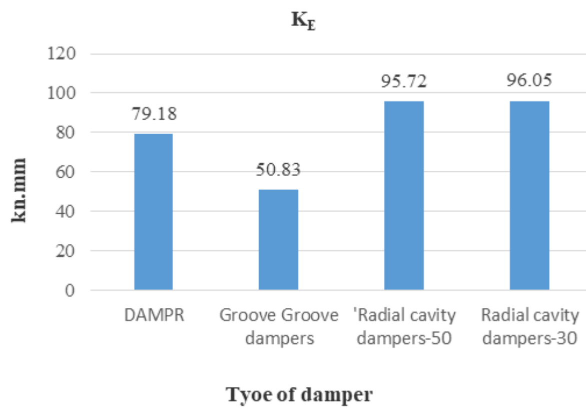

Figure 16. Comparative values of initial stiffness.

4.1.3. Secondary stiffness K_1

Figure 17 shows the comparative values of the secondary stiffness of the models. Secondary stiffness of the simple damper is significantly different from the secondary stiffness of other dampers. The high secondary stiffness of the slit damper and cavity damper and their close proximity to each other indicate the effect of the slit and cavity dampers on the increase in secondary stiffness in the dampers.

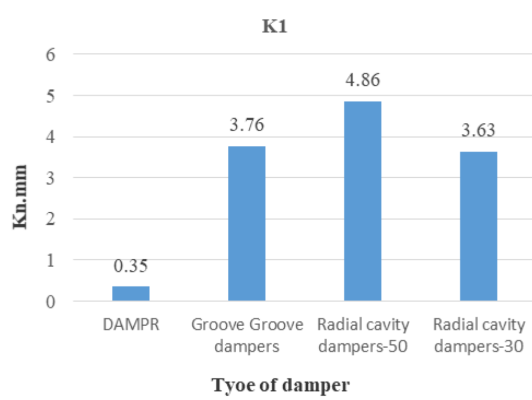

Figure 17. Comparative values of the secondary stiffness.

4.1.4. Energy absorption under pushover loading

Figure 18 shows the comparative values of the percentage of energy absorption subjected to pushover loading of the models. The energy absorption of the slit dampers is 29.9% higher than the average energy absorption of the other three dampers. The slit damper has shown good performance in terms of energy dissipation and have better seismic behavior than the other three dampers.

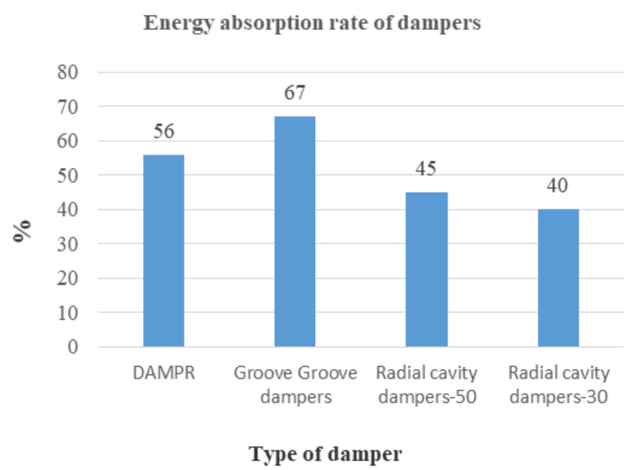

Figure 18. Comparative values of energy absorption percentage subjected to pushover loading.

4.1.5. Energy absorption under cyclic loading

Figure 19 shows the comparative values of the percentage of energy absorption subjected to the cyclic loading of the models. The energy absorption of the slit damper subjected to the cyclic loading is 33% higher than the average energy absorption of the other three dampers. A simple damper with 27% energy absorption has the most inadequate energy dissipation performance.

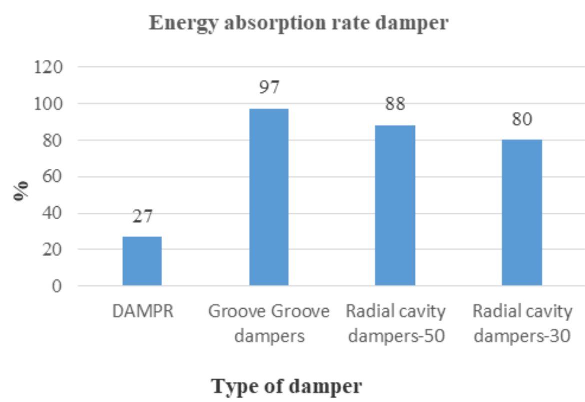

Figure 19. Comparative values of the energy absorption percentage under cyclic loading.

4.1.6. Over-strength factor R_S

Figure 20 shows the comparative values of the coefficients of resistance of the models. Cavity dampers with circular geometry with radius of 50 mm and slit damper have the highest over-strength factor of 2.15 and 1.82, respectively.

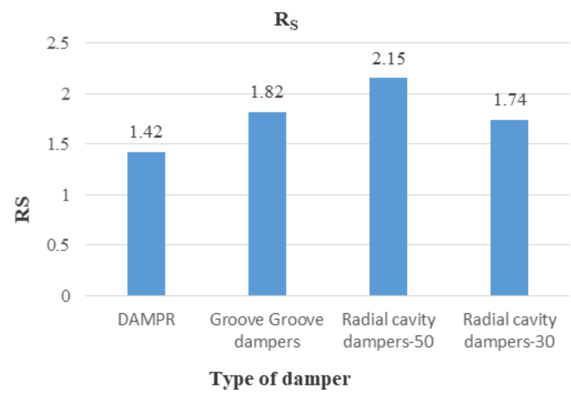

Figure 20. Comparative values of over-strength factor.

4.1.7. Plasticity factor Rμ

Figure 21 shows the comparative values of the plasticity factor of the models. The average plasticity factor of the slit damper is 26.6% more than the other three dampers. The simple damper with the value of 3.72 had the lowest coefficient of ductility among the specimens.

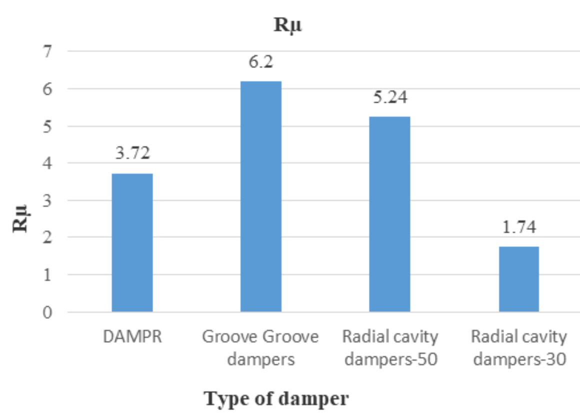

Figure 21. Comparative values of the plasticity factor.

4.1.8. Behavior factor R

Figure 22 shows the comparative values of the behavior factor of the models. The average behavior factor of the slit damper is 27.6% more than the average value of the other three dampers. The cavity damper with a circular geometry with a radius of 50 mm has a behavior factor of 11.28 and close to the value associated with the slit damper.

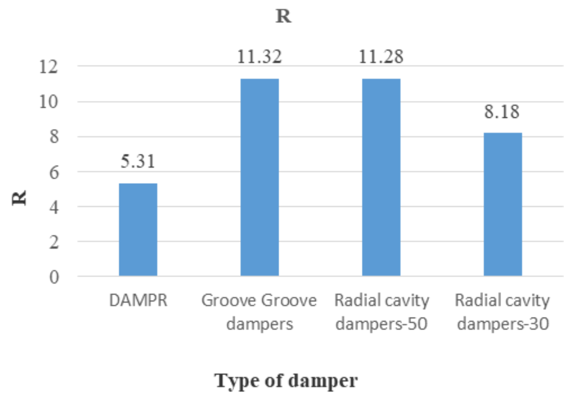

Figure 22. Comparative values of the behavior factor.

4.1.9. Ductility ratio μ

Figure 23 shows the comparative values of the models' ductility ratio. The average ductility ratio of the slit damper is 30.2% more than the other three dampers. The simple damper with a ductility ratio of 5.31 has the lowest ductility ratio among the specimens.

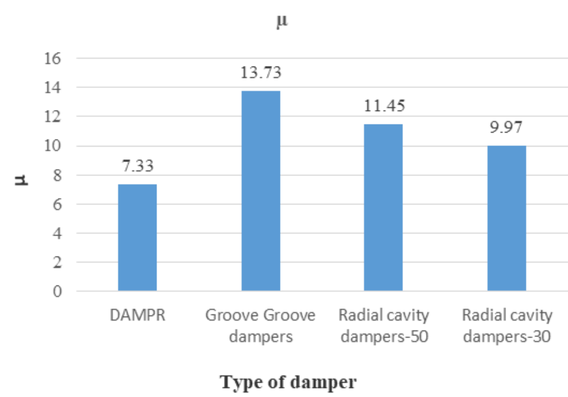

Figure 23. Comparative values of the ductility ratio.

5. Conclusions

In this paper, first, the effect of slit damper on the performance of Chevron braced frame under single and cyclic loading was investigated, then the effect of slit damper on the number of stories was investigated. Finally, the parametric study of slit, non-slit and cavity dampers was investigated. The results show the more suitable structural performance of the slit damper than the other dampers in the Chevron braced frame. In the investigated parameters, the behavior factor of the slit damper was 27.6% higher than the average behavior factor of the other three dampers. The ductility ratio of the slit damper is 30.2% higher than the average ductility ratio of the other three dampers, indicating the appropriate ductility and performance of this damper. The energy absorption percentage of slit damper under pushover loading and cyclic loading were respectively 29.9% and 33% higher than the average energy absorption rates of the other three dampers. Also, the key results are presented in the following:

1- The slit damper delays or avoids brace buckling with its ductile behavior so that the brace can dissipate a large amount of earthquake input energy without buckling and reducing the base shear force.

2- The obtaining suitable hysteresis curves without significant drop indicates high energy absorption of this type of bracing system.

3- The plastic hinge has been formed in none of the structural members in all of the Chevron braced frames with the slit damper, and the failure mode has been concentrated in the slit damper.

4- In general, the use of these elements reduces the initial stiffness, secondary stiffness and bearing capacity, which increases the energy dissipation in addition to control the lateral displacement of the structure.

5- In the slit dampers, higher ductility and plasticity ratios were obtained than the other specimens, indicating that the use of these elements has resulted in appropriate ductility values.

6- The use of slit dampers, considering the proper dimensions and thickness, significantly increases the performance of the structure, which is very important in terms of engineering and economics.

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