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Evaluation of Seismic Behavior of the Effect of Yielding Slit Dampers on Steel Beam to Column Connections

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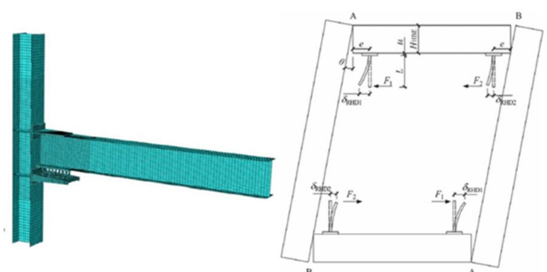
Abstract

During the Northridge and Kobe earthquakes, many steel bending frames were damaged in beam-to-column joints. Excessive deformation due to structural stiffness and rigidity limits the use of this system. Ductility of joints causes more energy to be lost before joints fail. As a solution, slit steel dampers were used in the joints to prevent brittle damage to the joints and damage to the main members of the structure. In the present study, a yielding slit damper has been validated in the laboratory using data from a valid article; it is done through ABAQUS finite element software. The evaluation and comparison of nonlinear and numerical analysis of yield slit dampers will be presented hereafter. The first part of this assessment is about the vertical load of the beam connected to the steel column, which will be followed by the evaluation of the research variables, i.e., the different modes of change in thickness, state and reinforcement of the slit damper, in the connection of the beam to the steel column. The results show that increasing the damper thickness increases its strength, hardness and absorbed energy but decreases its ductility. The same results also indicate that internal strengthening of a yielding slit damper in beam-to-column connections increases strength, stiffness and laterally absorbed energy but decreases the ductility. Meanwhile, the proposed specimen and idea of a yielding slit damper in the connection of the beam to the steel column, has proved that the reinforced specimen of the proposed specimen has the best performance among the specimens and transfers the plastic area into the damper range in the connection of the beam to the steel column.

Keywords: slit steel dampers, beam-to-column connections, absorbed energy, finite element, abacus

1. Introduction and background

Providing adequate stiffness and lateral strength is one of the principles of structural design in earthquake-prone areas. Considering the importance of earthquake resistance of existing buildings and the advantages of using new ancillary systems in steel buildings, it is necessary to study how these systems work in terms of increasing strength or changing the ductility of the structure [1]. The lateral reinforcement system is a set of vertical members (columns), horizontal members (beams) and a lateral reinforcing element that are connected to each other. In this system, the lateral reinforcing element resists lateral forces by creating stiffness and ductility, which prevents or delays the structure from collapsing. As a way to reduce seismic damage, the damage control system, which uses hysteretic steel dampers, has been widely used in countries such as the United States and Japan since the mid-1990s. This system has a stable hysteretic behavior and has been evaluated as an economical method to assess seismic resistant [1]. In general, such hysteretic steel dampers with different support elements are installed on plates formed by beams and columns of a structure. From support elements, different types of braces and studs are commonly used in these structures. Parallel dampers in a building can reduce the seismic response by providing building rigidity and additional horizontal resistance. In particular, they can reduce the damage to major organs because they waste a lot of plastic energy from earthquakes; Therefore, the damaged control system, which connects the beams directly to the columns with complex joints, has been developed since the beginning of 2000 in countries such as Japan and the United States. This helps prevent brittle fractures in the welded areas of the beam. (Figure 1) [2].**2.**



In a set of experimental and numerical researches by Sang-Hoon Oh et al. (2009), a mechanical connection is provided as a beam-to-column connection to a metal damper. The main feature of this system is that the plastic deformation is limited to the slit dampers in the lower flange, the test results of which show that the proposed mechanical connection has a very good hysteresis behavior; moreover, energy loss, plastic deformation in this system is only concentrated in slit dampers and prevents the abnormal behavior of beams and columns by designing the appropriate capacity [3]. In a similar numerical study by Saffari et al. (2013), slit dampers reduced the plastic pressure at the joint of the column, significantly; thus prevents the formation of plastic joints from the surface of the column [4]. In an article entitled "Seismic behavior of beam-to-column joints with elliptical slit dampers" Farahi Shahri et al. (2018) concluded that the stress distribution along the structures in the proposed slit damper is improved by the elliptical slits and the stress concentration in the end parts of the spots is reduced, which improves the seismic performance of steel slit dampers in beam-to-column connections [5]. The results of research by Mehmet Alpaslan et al. (2018) show that the damper produced with L-slits consumes a lot of energy, but has a low load carrying capacity in one direction of the cyclic load. It has also been observed in this study that the geometry of dampers has changed not only the load bearing capacity but also behaviors such as flexibility and stiffness [6].

Steel plate dampers are considered to be passive and yielding metal dampers. Steel plate dampers are produced in X-shaped triangular types and are installed in structural bracing. The following are some of the advantages of this type of damper [2]:

•By installing steel plate dampers, the damper percentage is increased by 30 to 40%, which reduces the internal forces and changes the locations of the structure.

•This damper has a stable waste cycle without a drop in its stiffness and has high resistance to cyclic loading.

•Unlike inactive tools such as viscose, viscoelastic and friction, steel plate dampers do not need to be maintained and inspected and are more valuable among consumers due to the simplicity of their mechanisms.

•Replacing parts and restoring the structure to its original state after an earthquake is easy due to the bolted joints.

•In steel plate dampers, due to the number of plates in each damper, high indefinite degrees occur.

•Bean grooves and free movement of pins do not create axial force under gravity loads and engineering compatibility.

•By applying the steel plate damper, the displacement of the roof and floors is significantly reduced.

•Steel plate dampers, by changing the large and inelastic deformations, prevent the creation of high forces in the braces and members of the structure and reduce the demand on the structure.

Many studies have been performed to improve the seismic performance of the beam-to-column connection. In particular, the use of new technologies such as dampers has been studied by researchers, although each system has its own advantages and disadvantages. In this paper, the use of a yielding slit damper is studied to improve the seismic behavior of the beam-to-column connection. The proposed damper system is made of a relatively simple configuration that after being placed at the point of connection of the beam to the column can absorb a large part of the input energy due to imposed vibrations and can curb any damages to the main structural elements such as beams, columns, braces and joints; therefore, in this paper, an attempt has been made to investigate the connection behavior of the beam to the column with a yielding slit damper exposed to a vertical load at the end of the beam under additional load analysis.

This research is modeled by micro-modeling in Abacus finite element software in several purposeful analyzes; moreover, it is analyzed and oriented conceptually through analyzing the graphs obtained from vertical load-displacement diagrams. The performed analysis is of non-linear static type and in the related temporal steps, the analysis of the previous steps is transferred to subsequent steps and as a result, large deformations can be modeled and analyzed. In this research, the effect of a yielding slit damper on the connection of the beam to the column in the vertical bearing capacity of the frame is investigated. From among research variables we can name changes in thickness, the state and reinforcement of yielding slit damper in the performance of connecting beam to the column. In addition, lateral performance factors including maximum strength, hardness, ductility and energy absorption capacity in all specimens are calculated and compared.

2. Validation of analysis (base model)

In order to prove the accuracy of modeling and presenting model numbers with executable cases, the validation of a laboratory work is required. To evaluate the accuracy of finite element modeling, a laboratory specimen of a yielding slit damper attached to a beam-to-steel column, tested by Jung Park et al at Busan Dahak University in South Korea in 2020 [7] is used under static and cyclic loading. How to select the 6R1 specimen from 6 laboratory specimens and its dimensional details are shown in Table 1. The details of the yielding slit damper are also shown in Figure 2. The properties of the materials related to the yield stress and the final stress of the steel used in these experiments are shown in Table 2.

Table 1- How to select 6R1 specimen from 6 laboratory specimens [7].

Specimen information.

Specimen	T-stub type	Design damper/beam yield strength ratio, α	Number of strips, n	Length parameter (mm)			r (mm)	B (mm)	t (mm)	H′/B
				H	H′	H_T				
4NR	General	0.4	8	70	70.3	100	15	32	25	2.20
6NR	General	0.6	12	70	70.3	100	15	32	25	2.20
6R1	with vertical rib	0.6	12	70	70.3	100	15	32	25	2.20
6R2	with vertical rib	0.6	12	70	70.3	100	15	32	25	2.20
6R3	with vertical rib	0.6	16	70	70.3	100	15	28	25	2.51
6R4	with vertical rib	0.6	4	70	70.3	100	15	56	25	1.26

※ Specimen name : 6 R 1
: Design damper-to-beam yield strength ratio (4:0.4, 6:0.6)
: R: with vertical rib in T-stub; NR: no vertical rib in T-stub
: Classification according to shape of lower connector and aspect ratio of damper

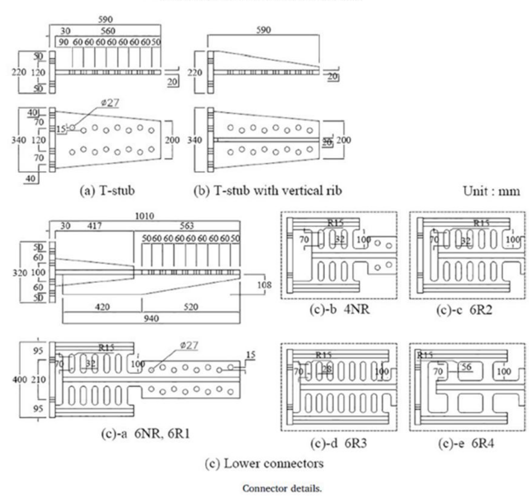


Fig. 2. Details of the desired yielding slit damper [7].

Table 1- Properties of materials related to yield stress and final stress of steel used in this experiment [7].

Average material properties of structural members from coupon tests.

Location	Young's modulus (MPa)	Yield stress, σ_y (MPa)	Ultimate stress, σ_u (MPa)	Elongation (%)	σ_y/σ_u
Beam	206,886	258.03	440.05	30.6	0.59
Column	214,023	313.93	458.89	29.3	0.68
Damper-a	190,565	290.37	418.82	29.9	0.69
Damper-b	199,741	303.28	460.96	30.4	0.65

In accordance with Figure 2, Tables 1 and 2, the yielding slit dampers selected for validation are evaluated in order to assess the yielding slit dampers under deformation and validity of the behavior hypotheses. Six specimens are fabricated and tested under cyclic loading. The deformation is tested in a simulated damper and then the damper is tested experimentally, as shown in detail in Figure 3.

Fig. 3 . Details of specimens made related to laboratory work for validation [7].

The method of lateral loading of the constructed specimens of the yielding slit damper, which is inserted into the lateral part by the hydraulic jack, is shown in Figure 3. The detailed boundary conditions of the beginning and end of the specimens are also known. For validation and numerical modeling of the 1R6 model of the yielding slit damper, Abacus finite element software is used [8] and all models are prepared in the part module and assembled in the assembly module according to the laboratory specimen specifications. Figure 4 shows the details of the modeling.

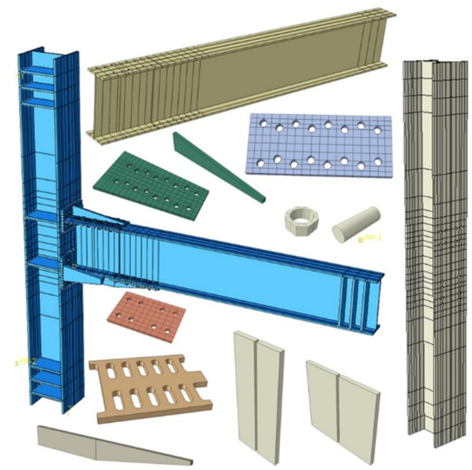


Fig. 4. Details of numerical modeling of the specimen.

The definition of concrete material properties is based on the material properties module, according to which the steel used in the software is of the type presented in table 2. In property module of the Abacus finite element software, the material properties of steel cores are ordinary steel, which is assigned to the modeled elements. The analytical step is quasi-static and the element type in all cases is solid C3D8R (cubic element with 1st class function and reduced integration), for grading, decreasing calculation time and obtaining results with high accuracy, reduced integration fear formulation has been used in modeling, and the result of nonlinear analysis of large deformations is also been considered.

The results of numerical analysis of the fabricated specimen of yielding slit damper can be presented in finite element software. According to the performed examination the color contours from the exits of this module show the validity of entrances and exits: for this reason von Mises tension contours define the intensity range of tensions. Figure 5 shows the von Mises tension contours of the constructed specimen in the assumed yielding slit damper. Figure 6 also compares the color contours of the plastic strain of a specimen made with a yielding slit damper of a laboratory specimen.

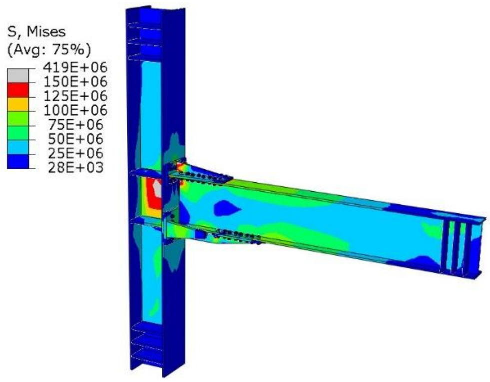


Fig. 5. Color contours related to von Mises stress show the intensity range of tensions.

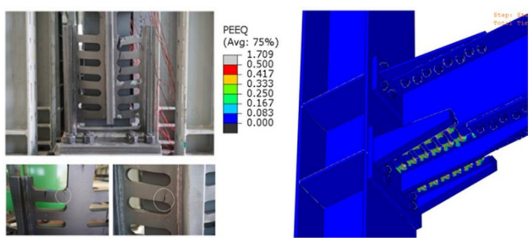


Fig. 6. Comparison of color contours of deformed slit damper specimen with laboratory specimen.

As shown in Figure 3-24, the comparison between the laboratory work and the numerical results of the study by Jung Park et al. [7] with the numerical study of the present study is formally close to each other, which in this regard indicates that good validation has been taken. If the information about the hysteresis diagram is compared with the load-displacement diagrams of the paper [7] (laboratory diagram for specimen 6R1), the validity can be checked. So Figure 7 shows this comparison.

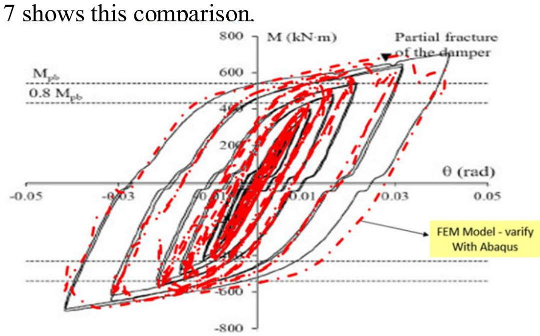


Fig. 7. Comparison and validation between two laboratory charts [7] and numerical specimen of this research.

According to figure 6, there is good conformity between the obtained chart from the limited element analysis and laboratory results, which indicates the acceptable accuracy of finite element modeling and can be used as a basis for further studies.

3. Introducing parametric examples of connecting the beam to the desired column

The purpose of micro-model analysis of beam to steel column connection with yielding slit damper in this study is to investigate the performance of beam to steel column connection, in accordance with the properties of the slit damper validated by ABAQUS finite element software. This paper investigates the effect of different modes of change in thickness, state and reinforcement of a yielding slit damper on the performance of connecting a beam to a steel column by finite element method. To start calculating the performance of beam-to-column connection with the validated yielding slit damper (base), the maximum amount of vertical loading of the beam, 17 cm, and the maximum lateral strength of the braced frame is 300 KN, which can be shown in figure 8 through a two-line diagram.

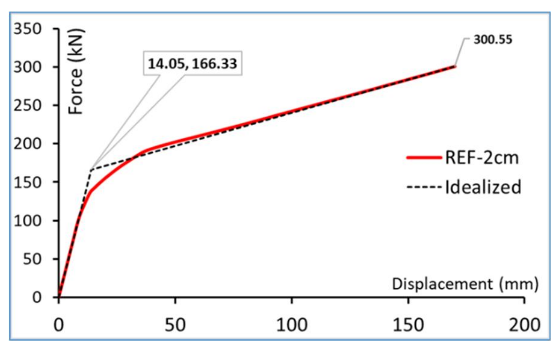


Fig. 8. Two-line diagram of vertical load-displacement in the base specimen.

To start the parametric calculation of the connection performance of the beam to the steel column with a yielding slit damper (with a validated damper feature), we can focus on the idea that if the thickness of the damper increases, the behavior and performance of the beam connection to the steel column will change. For this purpose, the yielding slit damper, which was considered with a default thickness of 2 cm, with thicknesses of 3 and 4 cm, is also examined. The results showed that by increasing the thickness of the damper from 2 cm to 3 and 4 cm, the resistance increases by 24 and 38%, respectively. Also, with this increase in the thickness of the damper from 2 cm to 3 and 4 cm, the hardness increases by 14 and 22%, respectively. This increase in thickness increases the absorbed energy by 43% and 75%, respectively, and decreases the ductility by 21% and 32%, respectively.

Further research can be focused on the idea that if the position of the yielding slit damper holes changes, what effect will it have on the performance of the connection of the beam to the steel column with the yielding slit damper in the vertical loading of the beam. The introduction and naming of the specimens are based on the position of the larger holes, in a way that in figure 9 the specimen "M-Co" is named after the specimen where the larger holes are assembled in the shape of the letter M. Similarly, the "M-Op" specimen is named after the specimen where the larger holes are opened in the shape of the letter M. The example "M-Cen" is named after the example where the larger holes are in the shape of the letter M in the center. Also, the "Full" specimen is named after specimen that has no holes (to check the effect of the holes).

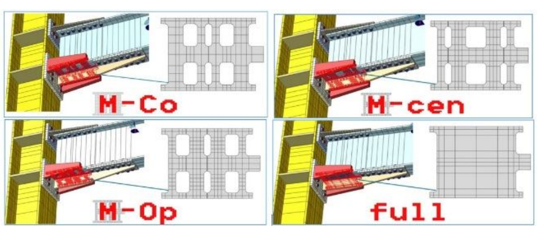


Fig. 9. Introduction of yielding slit damper specimens to investigate the effect of changing the position of damper holes.

The results of this part of the analysis show that among the specimens, Full specimen has the highest strength, hardness and energy absorbed and the least ductility, but as mentioned earlier, the joint formation and plastic area is out of the damper range. Therefore, from among specimens other than the Full specimen, the M-Cen specimen can be named, which has the best performance.

It remains to be investigated what effect the performance of the connection of the beam to the steel column with the yielding of the slit damper will have on the vertical load of the beam if the condition of the slit damper holes changes. Therefore, since good performance was seen in the full specimen, but the plastic area was outside the damper range, a specimen can be designed that has the desired properties, figure 4-16 shows specimen "D" and the reason for this name is due to the fact that the inner holes are similar to the letter D. This specimen has a hole inside to guide the joint into the damper (Figure 10).

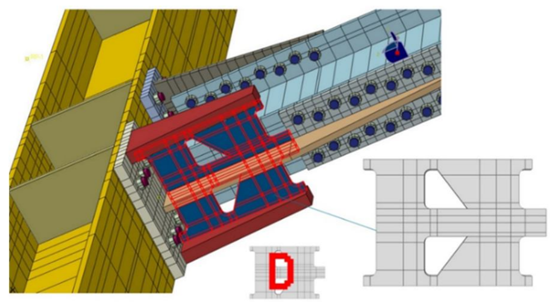


Fig. 10. Introduction of a yielding slit damper specimen to investigate the effect of changing the state of the damper holes.

Like the Full specimen, although a hole was made inside the damper, the plastic area was formed outside the damper, so the idea of reinforcing the same area is proposed to move the plastic area into the damper by increasing the local stiffness in this area. Figure 11 is the "D-Boost" specimen, which means boosting the D specimen.

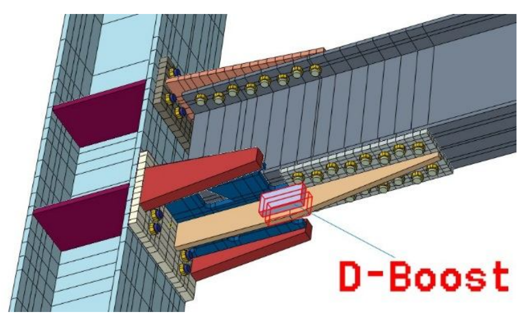


Fig. 11. Introduction of reinforced yielding slit damper specimen of specimen D.

4. Evaluation of the parametric seismic response of the beam-to-desired column connection

Putting together all the information about the functions of the specimens in question they can be commented on. Therefore, the lateral load-displacement diagram of the beam-to-steel column connection with the yielding slit damper is shown in all specimens in Figure 12. Moreover, in table 3 all specimens are compared with each other in terms of performance.

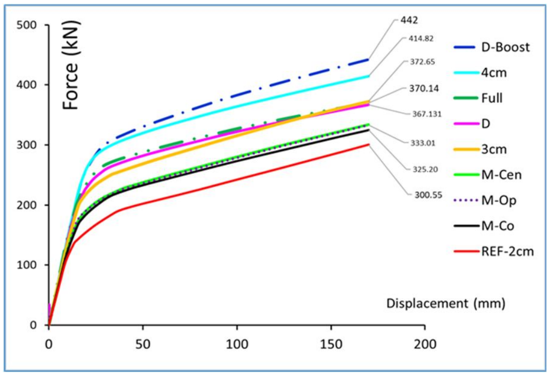


Fig. 12. Load-displacement diagram of vertical load beam at the connection of the beam to the steel column with a yielding slit damper.

Table 3- Performance of connecting the beam to the steel column in all specimens of yielding slit damper.

SPECTRUM / PER	$V_{max\ (kN)}$	$K_{(kN/mm)}$	μ	$E_{(kN*m)}$
D-Boost	441.99	14.32	8.00	48.53
4cm	414.82	14.46	8.26	47.52
3cm	372.65	13.51	9.52	38.86
Full	370.14	14.28	9.10	42.83
D	367.13	14.01	9.17	41.73
M-Cen	334.30	12.61	10.25	33.81
M-Op	333.01	12.61	10.35	33.51
M-Co	325.20	12.37	10.29	33.05
REF-2cm	300.55	11.84	12.10	27.11

As shown in table 3, all models perform better than the base model, and D-Boost model is the best specimen, which means that the model that was designed and then reinforced has high performance. After the reinforced specimen, the specimen with the thickness of 4 cm is in the 2^{nd} rank, which means that increasing the thickness of the damper is very effective in its performance. In addition, the M-Co specimen has the least increase in strength, hardness and absorbed energy, while the M-Op specimen with a decrease of 14% ductility compared to the base specimen shows the least reduction in ductility. The highest increase in hardness with an increase of 22% is related to the 4cm specimen, while the D-Boost specimen with an increase of 79% in absorbed energy and 47% in resistance has a good performance.

5. Discussion and conclusion

In this research after software validation, first the overlay study was performed on modeling the seismic behavior of a yielding slit damper in the connection of beam to steel column, and the results were recorded as force-reaction diagrams and then properties were studied in different modes of change, thickness, shape and reinforcement of the yielding slit damper in the shear performance of the beam-to-steel column connection and the results were recorded. Comparison between the results indicates the fact that applying the yielding slit damper in the connection of the beam to the steel column in the model has good behavior and performance, which are described and concluded below:

1 .According to the study, it has been found that with increasing the thickness of the yielding slit damper in the connection of beam to steel column, the strength, hardness and energy absorption increase but the ductility of the connection of the beam to the steel column decreases.

2 .The results also show that by changing the position of the yielding slit damper holes in the connection of the beam to the steel column, the seismic performance of the connection of the beam to the steel column changes intentionally and optionally, in a way that this change was negligible; however, it is found that the seismic performance of all changes in the position of the proposed damper holes is higher than the base specimen. Among these, the M-Cen model is functionally better than other models.

3 . Full specimen (hole-less damper specimen) has high performance but can not be used in connecting the beam to the steel column because the results show that the full specimen imposes the load to the connection with the lower retaining plate and yields in that part. This phenomenon can cause a wrong result in the connection and the result is that the plastic area takes place outside the damper range.

4. The proposed model and idea of a yielding slit damper in the connection of a beam to a steel column is the "D" model and its reinforced model is the "D-Boost" model. The results of this part of the study show that the "D" specimen, like the Full specimen, has a plastic area outside the damper range, but its reinforced specimen, the "D-Boost" specimen, has the best performance among the specimens and moves the plastic area into the damper area at the beam connection to the steel column.

5. The final results of the research show that the recommended "D-Boost" model is of the best performance and the 4cm model is also of good performance.

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