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Experimental and Numerical Assessment of the Seismic Behavior of Non-uniform Slit Dampers and Bar Dampers in Moment Resisting Reinforced Concrete Frames

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Abstract

The use of lateral bearing systems to rehabilitate reinforced concrete frames has been one of the most important research topics in structural engineering. Non-uniform Slit Dampers (NSD), as well as Bar dampers, are two types of novel yielding dampers whose effects on reinforced concrete structures have been evaluated in this research. In this research, three experimental samples with a one-third scale were constructed to assess the effect of the presence of NSD and Bar damper in reinforced concrete frames. Also, 16 numerical models were created to evaluate the number of used dampers in experimental specimens in order to determine the optimal mode of using these dampers. Seismic parameters of stiffness, ultimate strength, ductility, and energy dissipation capacity were investigated in this research. The research results showed that the use of lateral bearing systems with NSD and bar dampers can have a significant impact on the seismic performance of reinforced concrete moment resisting frames. Also, in the numerical models that were made using ABAQUS software, it was concluded that the use of a smaller number of dampers compared to the experimental models can still improve the seismic parameters of the system while the cyclic capacity of the system does not drop.

Keywords

RC frames, Non-uniform Slit Damper (NSD), bar damper, yielding damper, experimental assessment

1 Introduction

The failure of reinforced concrete and steel structures in major earthquakes in recent years has shown that research to rehabilitate the performance of load-bearing systems is one of the most important needs of the construction industry [1]. Widespread human and financial damage in earthquakes has led researchers to provide new systems to improve the seismic parameters of structures. Various lateral bearing systems have been presented in recent years, the main purpose of these systems is to increase energy absorption and prevent the destruction of the main elements in the structure. Lateral braces [2–4], shear walls, and different types of dampers are the main areas of research in recent years. Meanwhile, the use of yielding dampers is one of the easiest and most economical methods to improve the performance of structures.

There are different types of dampers that are used based on different methods of structural design. Yielding dampers are considered the simplest type of dampers that absorb earthquake energy by changing the geometric shape of the damper element. Yielding dampers, which are considered passive control systems, unlike other dampers, such as viscous or viscoelastic dampers, are not affected by temperature changes in their performance, and according to the needs of design engineers, they are available in different types and can be designed and presented in different geometric shapes. These systems increase the energy absorption of the structure to a significant amount, increase the stiffness and ultimate strength of the structure, and can also be effective in improving the plastic behavior of the structures [5]. In the following, the most important research in this field will be discussed.

Various dampers, including yield dampers, have been utilized thus far for retrofitting concrete frames [6]. Kelly et al. [7], in a study, proposed yielding dampers for the first time. They showed that by using these energy-absorbing elements, it is possible to reduce the stress concentration in the beam-to-column connections and transfer a large part of the energy dissipation to the dampers. There are different

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types of yielding dampers, Added Damping and Stiffness (ADAS) and Triangular-plate Added Damping And Stiffness (TADAS) dampers were presented by researchers as two types of yielding dampers that are widely used [8]. In another research, it was shown that the geometric characteristics of ADAS yielding dampers can be effective in the seismic performance of structures [9, 10]. The use of friction dampers as another type of active control system in the structure, which enters the load-bearing system by changing the shape of the structure, was investigated and its performance was compared with yield dampers [11].

Researchers have studied various types of dampers in recent years, including their effect on a structure's displacement, the use of aluminum materials, the impact on beam and column connections, and the use of yielding dampers at different energy levels during earthquakes. In this research, it was shown that the use of dampers makes the expected ductility of structures uniform on different floors and provides the possibility of identical performance between floors. Providing a design method for the use of aluminum yielding dampers has been one of the other results of this research. Also, this research showed that the use of yielding dampers causes more stable cyclic behavior in structures and the use of TADAS dampers in powerful earthquakes helps to improve the performance of the structure [12–15].

In another group of studies, the effect of the presence of steel yielding dampers with different geometries on the seismic behavior of structures has been investigated. In a study, an energy-based design method for structures with dampers was presented. In this research, various dynamic analyzes were performed in finite element software and a step-by-step design process was presented for the design of structures with yielding dampers [16]. Another research was presented regarding the effect of the presence of U-shaped yielding dampers on the seismic behavior of steel structures with moment resisting frames. This research showed that the use of U-shaped dampers reduces the base shear by 40% and the displacement of the roof by 57%. Also, the use of U-shaped dampers prevents torsion in the building to some extent due to reducing the drift between floors and creating coordination in them [17, 18]. In another experimental study, the use of bow-shaped yielding damper was investigated, the results of which showed high energy absorption and increased damping in the structure [19].

In other recent studies, the investigation of two-level yielding dampers as a new generation of yielding dampers and the optimal design of steel damper systems based on economic cost and functional life were presented. In this research, using the mathematical tools of finite element method and design based on genetic algorithm, the design methods of structures with steel dampers have been presented [20]. Wu et al. [21] propose a solution for the adverse effects of an RC slab on an RC beam-column frame, using a rectangular opening and top/bottom flanges of a damper. Results show improved stability and performance of the system. Xu and Ou [22] propose the use of combined rotational friction and flexural yielding metallic dampers for prefabricated structures, highlighting their impressive energy dissipation capabilities. Through low cyclic experiments, the authors demonstrate the superior performance of these dampers in terms of friction and plastic energy dissipation. This design concept provides a promising solution for precast structures in high seismic regions. In a separate study, Houshmand-Sarvestani et al. [23] investigate the impact of steel-plate ADAS dampers on steel shear walls. The findings indicate that incorporating ADAS dampers improves the seismic behavior of steel shear walls by reducing the pinching phenomenon, enhancing damping capacity, and increasing structural ductility.

In two experimental studies, TahamouliRoudsari et al. [24, 25] evaluated different types of bracing systems in reinforced concrete frames and also the use of ADAS and TADAS yielding dampers. Experimental tests on 1/3-scale reinforced concrete frames showed that ADAS and TADAS yield dampers outperform other bracing systems. The study also investigated the effect of the number of dampers in a system and identified the optimal dimensions and number of dampers for optimal performance.

Yielding dampers increase energy absorption and stiffness in frames, but optimal contribution of these systems' stiffness and energy absorption has not been evaluated through experimental or numerical studies. In this research, three reinforced concrete frames of one-third size were made and tested, in which Non-uniform Slit Damper (NSD) and bar dampers were used. First, the effect of the presence of these dampers in reinforced concrete frames has been evaluated based on the experimental results, and then with the help of ABAQUS finite element software, various models have been made to determine the effect of the number of dampers in a system on the seismic parameters of the case. The purpose of numerical analysis was to investigate how the number of dampers affects the stiffness, ductility, and ultimate strength of the frame. After verifying the findings based on experimental samples, pushover numerical analyses were conducted to investigate the impact of the number of dampers on the seismic performance of the frame. The experimental studies demonstrated that both dampers increase the ductility, stiffness, and ultimate strength of the concrete frame. Additionally, the numerical analysis revealed that the model with 4 and 5 BD and 2 NSD showed the best performance in terms of the ductility parameter. Furthermore, the plasticity of the frame equipped with BD was higher than that of NSD.

The research was conducted in the following steps: Firstly, the experimental models were designed to ensure the dampers yielded before the frame. Three frames were tested, two equipped with dampers, while one was a bare frame. The hysteresis diagram was extracted after the test. Then, the numerical model was calibrated according to the experimental results. Finally, numerical studies were conducted to investigate the effect of the number of yielding dampers on the elastic stiffness, ultimate strength, and ductility parameters of the frame.

2 Experimental plan

2.1 Test setup

The experimental samples in this research were three reinforced concrete frames with a scale of one-third, which were tested in the structural research laboratory of Azad University. All three samples had the same dimensions and the same concrete and rebar materials. The first sample of this study (RCMRF) is a reinforced concrete moment resisting frame in which the bracing system with a damper is not used to be compared as a control sample in the evaluations. In the second sample (RCMRF-NSD), four non-uniform slit yielding dampers were installed in the reinforced concrete frame by an eccentric brace (Chevron) which was designed as a buckling restrained brace system. The third experimental sample (RCMRF-BD) also has four bar dampers, which are placed in the reinforced concrete frame with the help of the Chevron brace system (which is also used in the RCMRF-NSD sample).

The dimensions of reinforced concrete frames and details of beams and columns are shown in Fig. 1. The experimental frames were determined based on the study of TahamouliRoudsari et al. [25] and the design guidelines in the ASCE 7-05 standard [26]. The same materials were used in the construction of reinforced concrete frames, and concreting was done simultaneously to maximize the similarity of the samples. In these examples, the length of the beam is 1.45 m and the height of the column is 1 m, so the ratio of length to width of a typical frame in reinforced concrete buildings can be scaled.

The square cross-section of the beam and column has the dimensions of 0.15 × 0.15 m, which was used to reinforce the elements in the column with 4 × F14 bars and in the beam with 4 × F10 bars. In the foundation, which had cross section dimensions of 0.2 × 0.3 m, 4 × F14 bars were used in the compression part and 3 × F14 bars in the tension part.

In the samples with a lateral damper system, a Chevron lateral brace was used, which is made of two legs, each of which is made of 2 angles with cross-sectional dimensions of L50 × 5. This brace was connected to the frame by steel plates and strong bolts. The dimensions of the chevron brace connection plates are presented in Fig. 2. NSD dampers were made of four steel plates with dimensions of 150 × 150 mm and thickness of 8 mm. In the RCMRF-BD sample, the brace used in the second sample was used and four F22 bars with a height of 150 mm were used as Bar Damper. The dimensions of NSD and Bar Damper are shown in Fig. 3.

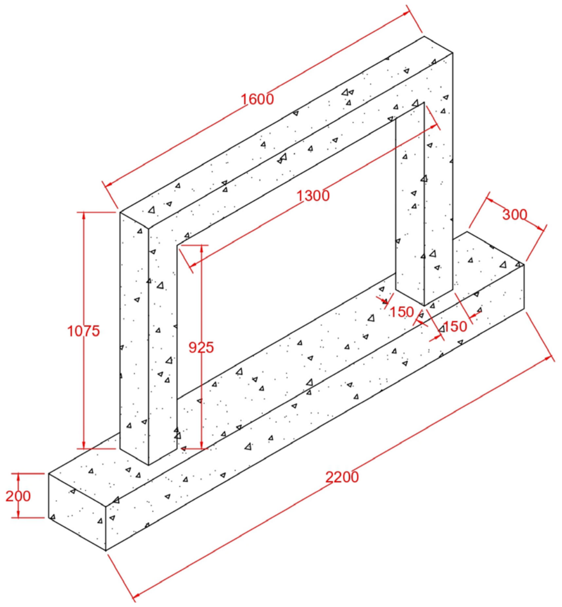


Fig. 1 Details of reinforced concrete frames of experimental samples

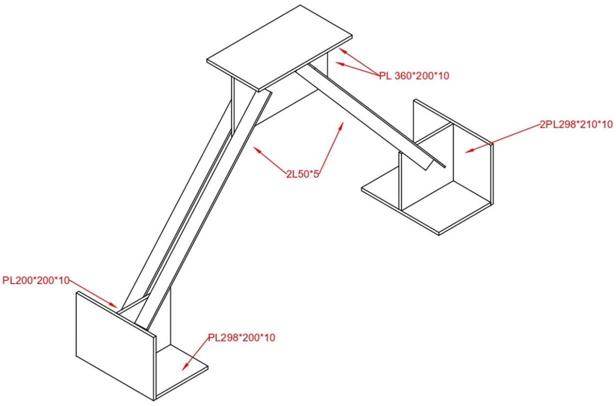


Fig. 2 Detail of eccentric braces used in specimens

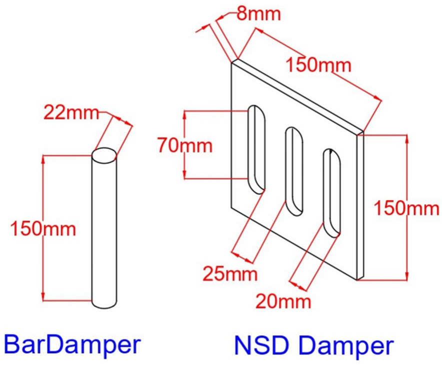


Fig. 3 Details of NSD and Bar Dampers

As previously mentioned, concreting for the experimental samples was performed simultaneously, and based on the results of the compression test of the cubic samples, the 28-day compressive strength of the concrete of the experimental samples was found to be 35.2 MPa. The steel used in the experimental samples was S235-R [27], which is construction steel used in the construction industry of Iran.

Loading in all samples was cyclic and based on ACI-374.1-05 [28] protocol. In this protocol, displacements applied in each drift are obtained based on the yield stress of the moment resisting frame system. Cyclic, quasi-static loading was applied to the samples at a very low speed in order to avoid recording the dynamic effects of the load during the test. Fig. 4 shows the loading protocol in experimental samples.

In the experimental samples of this research, a hydraulic jack with a capacity of 1000 kN was used to apply the load. A load cell with a capacity of 1000 kN and an accuracy of ±100 N was used to read the forces. A Linear Potentiometer Transducer (LPT) with a stroke length of 450 mm and an accuracy of ±0.05 mm was used to collect displacement values. To prevent out-of-plane movement of the samples, a lateral restraining system was used in the test setup, although the experimental samples in this research did not have significant out-of-plane movement during the test. Fig. 5 shows the layout of the test in the experimental samples.

2.2 Experimental report for specimens

In the experimental test of the first sample (RCMRF), the behavior of the sample was completely linear from the beginning of loading to displacement equal to 0.5% drift. The creation of small cracks at the connection of the beam and the column caused small permanent changes in the hysteresis diagram of the sample up to 1% drift, but the force increase rate remained relatively constant. After passing the drift of 1% and with the introduction of higher displacement values, the cracks started to increase at the joint of the beam and the column, and a few cracks were also created at the foot of the columns. By decreasing the force rate at higher loading values until the drift equivalent displacement of 3.5%, the force reached its maximum equal to 32.31 kN. With the increase of cracks and the change of plastic shape in the connection of the beam to the column, the system suffered an approximate loss in strength, and finally, the sample test was stopped at 8% drift. Fig. 6 shows the hysteresis diagram of the RCMRF experimental sample and specimen conditions in different loading drifts.

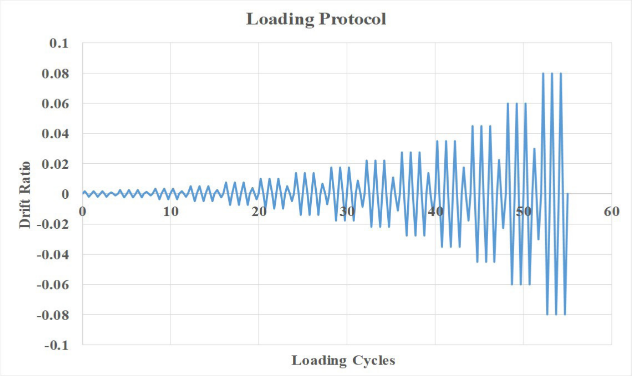


Fig. 4 ACI 374.1-05 loading protocol

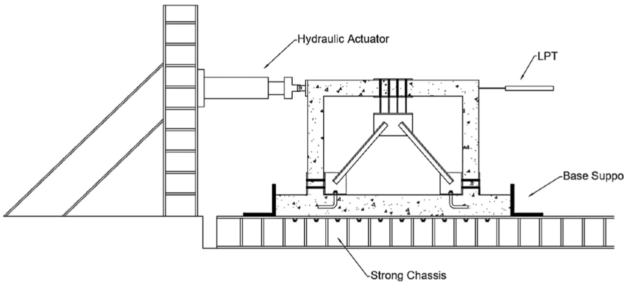
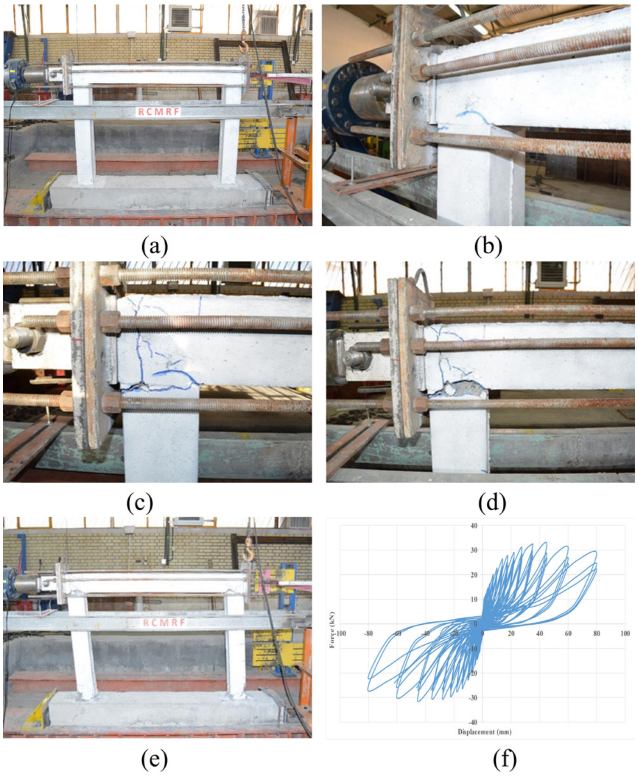


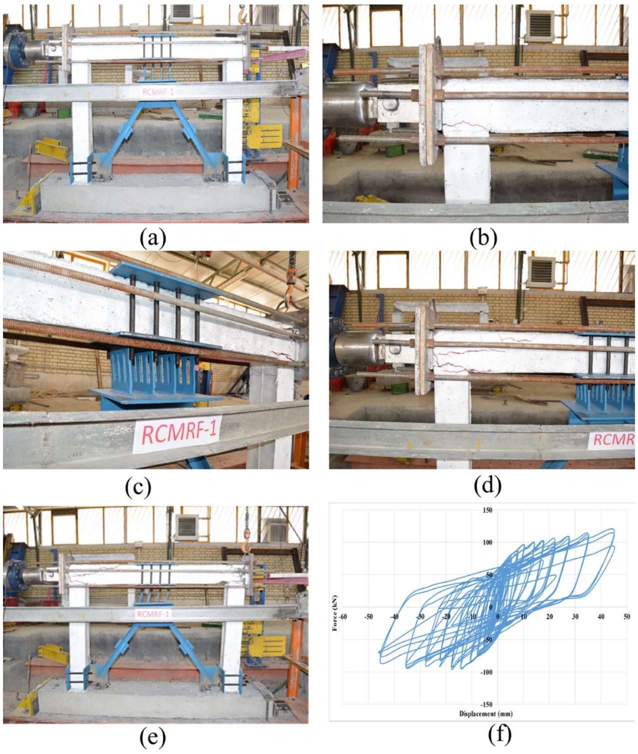
Fig. 5 Test setup

In the test related to the RCMRF-NSD sample, with the start of loading, the force increased significantly compared to the RCMRF sample. Due to the change of form in NSD yielding damper plates, the force increased significantly. No significant cracks were created in the frame until the displacement equivalent to 0.5% drift was reached, but the NSD dampers were deformed. After passing the drift of 0.5%, the force increase rate decreased, and the hysteresis diagram clearly entered the plastic phase. As the test continued, the cracks increased in the beam-to-column connection area, and the damage in the frame at the beam-to-column connection increased. The reason for larger cracks in this sample compared to the RCMRF sample can be seen as the increase in the capacity of the lateral bearing system due to the presence of NSD dampers. Due to the change in the cyclic deformations of the dampers, the specimen has



(a) (b) (c) (d) (e) (f)

Fig. 6 RCMRF experimental sample test procedure (a) at the beginning of test, (b) crack initiation in beam-to-column connection at 1% drift, (c) cracks at the beam-to-column connection at 2% drift, (d) beam-to-column connection at the end of the test, (e) the end of the loading and (f) the hysteresis diagram of the test output



(a) (b) (c) (d) (e) (f)

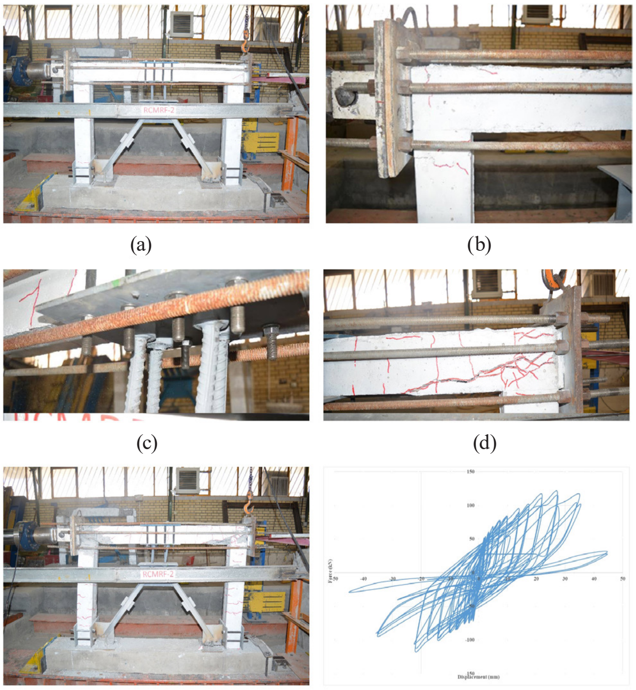
Fig. 7 Results of the RCMRF-NSD experimental sample and test images during loading (a) at the beginning of test, (b) beam-to-column connection cracks at 0.5% drift, (c) yielding of NSD dampers at 1% drift, (d) wide cracks at the beam connection to the column in the drift of 3.5%, (e) the end of loading, (f) the hysteresis diagram of the sample

not dropped in strength up to 4.5% drift, but the failures in the concrete cover at the beam-to-column connection increased. The ultimate strength in this test was recorded as 115.96 kN in 4.5% drift and the test was stopped in this drift. Fig. 7 shows the hysteresis diagram of this test and the images related to different drifts during loading.

In the third sample of RCMRF-BD, with the start of loading due to the presence of dampers and the lateral bearing system, the force increased significantly as in the second sample. Upon reaching 0.5% drift, the force increase rate decreased, and the sample entered the plastic phase. The cracks in this specimen are much more than in the first and second samples, which indicates the high stiffness and high energy absorption capacity of the dampers. By continuing to load the sample at 2.5% drift, it reached the maximum force of 118.86 kN, which remained almost constant at 3.5% drift. With the continuation of loading, failures in the concrete cover at the beam-to-column connection was created, but the concrete core was not damaged in the connection. The concentration of stress in the place where the damper bars are connected to the upper plate of the Bar Damper connection caused cracks and tears in the bars, which resulted in a severe drop in the strength of the specimen. For this reason, the test of this sample was stopped at 4.5% drift. Fig. 8 demonstrates the conditions of the RCMRF-BD sample during testing and the hysteresis output diagram of this sample. In the next section, the evaluation of the experimental results is discussed.

3 Experimental result assessment

By performing the tests, the experimental part of this research was finished. The hysteresis diagrams obtained in the laboratory contain information on the seismic behavior of the experimental samples. In order to properly evaluate the experimental results, it is necessary to extract the seismic parameters from the hysteresis diagrams and compare them with each other. In order to obtain the seismic parameters, the backbone diagram should be extracted from the hysteresis diagram of each sample and an equivalent bilinear diagram should be calculated based on the backbone diagram. Estimation of these calculations is done according to FEMA 440 [29]. Seismic parameters including ultimate strength, effective stiffness, ductility, and energy dissipation capacity can be obtained from hysteresis diagrams.



(a) (b) (c) (d) (e) (f)

Fig. 8 Experimental results of RCMRF-BD sample and loading images (a) Beginning of test, (b) Cracks in the beam-to-column connection area at 0.05% drift, (c) Damper buckling at 1% drift, (d) Cracks at 3.5% drift in the connection area bar to column, (e) end of experiment, (f) sample hysteresis diagram

Table 1 Seismic parameters obtained from the results of experimental samples

	Energy Dissipation Capacity (kN.mm)	Ductility	Ke (kN/cm)	Fu (kN)
RCMRF	12507	5.2	30.77	32.31
RCMRF-NSD	79486	8.8	176.61	115.96
RCMRF-BD	39903	14.3	311.74	118.86

Using the instructions of FEMA 440 regulations and obtaining bilinear equivalent diagram, mentioned seismic parameters were calculated and the result of these calculations is presented in Table 1. This table shows that the addition of lateral restraint systems with NSD and Bar Damper has a great impact on the ultimate strength of the reinforced concrete moment resisting frame system. The ultimate strength in samples with yielding dampers has been increased by about 4 times. In the evaluation of the stiffness parameter according to the obtained result from bilinear diagrams, it can be seen that the stiffness in the samples with damper has increased significantly compared to the reference sample so that in the RCMRF-NSD sample, this increase is more than 5 times and in the RCMRF-BD sample, this increase is about 10 times more than RCMRF specimen.

By evaluating the ductility parameter, it can be seen that the sample with NSD dampers has an acceptable increase with 70% growth, but in the RCMRF-BD sample, the growth ductility parameter number shows more than 250%. The increase in ductility can be seen as a result of increasing the stiffness and decreasing the yield point displacement. Although, due to the drop in force values in the samples with dampers at lower drifts, it can be said that the samples did not have an acceptable seismic behavior.

According to the energy dissipation capacity parameter, it can be said that both samples with yielding dampers have a higher energy dissipation capacity than the RCMRF experimental specimen, which due to the late drop in the RCMRF-NSD sample, a higher number has been recorded for this important seismic parameter.

With a general look at seismic parameters, the importance and superiority of using yielding damper systems in RC frames are quite evident. But it is necessary to maintain the balance in the use of these dampers in such a way that the stiffness and ultimate strength increase in such a way that there is no drop in the ductility and cyclic capacity of the sample. To Continue this research and in the numerical modeling section, the effect of the number of yielding dampers, NSD, and Bar Damper is evaluated so that the optimal mode can be provided in the use of these lateral bearing systems.

4 Numerical modeling

To evaluate the experimental samples in terms of the number of yielding dampers in the lateral bearing system introduced in the previous section, numerical models were built and analyzed. ABAQUS finite element software was used to create numerical models. For two experimental samples RCMRF-NSD and RCMRF-BD, eight different models with one to eight dampers were modeled and analyzed. Firstly, software models were verified based on the specifications of the materials and considering the geometric imperfections in the experimental samples. In these models, the chevron brace used, and other components of the reinforced concrete frame were made completely in accordance with the experimental samples, and in different models for the NSD damper, the same lateral anchor restraint system as the laboratory samples was used, but the number of NSD dampers was from one to eight variable damper plates. This approach was also used for Bar Dampers to determine the optimal mode in the design of these yielding dampers. In order for the numerical modeling to be more accurate, similar studies [30–33] conducted on concrete structures were used, including the simulation of boundary conditions, correct selection of element type and loading. Large deformations were considered in the numerical model. Since the rotation of the column at its connection to the foundation was almost zero, the modeling of the foundation was omitted, and the bottom of the columns was assumed to be fixed. The slippage between rebars and concrete was omitted. The models were made using solid elements to ensure the highest accuracy in terms of geometry. Truss elements were used to model the rebars. The characteristics of the materials were determined using the rebar tensile test which was performed on the rebars used in the experimental samples, and these characteristics are presented in Table 2.

Also, in addition to the characteristics of elastic materials, Concrete damage plasticity was used for the concrete in tension and compression behavior. In these models, a General Static analytical step was used, in which the effect of non-linear geometry was considered. All numerical samples were loaded uniformly and monotonically. It should be noted that mesh sensitivity analyzes were performed for numerical models and mesh dimensions were determined for different elements according to Table 3.

The models with NSD damper are named N1 to N8 and the numerical samples with Bar Dampers are named B1 to B8. Fig. 9 demonstrates the numerical models created in the ABAQUS software and the verification results of the experimental samples. After the numerical modeling, the equivalent bilinear diagram was drawn for all the numerical samples and the seismic parameters were calculated in each of the numerical models.

Table 2 Specifications of rebar materials based on tensile tests

Rebar size	Rupture Stress (MPa)	Ultimate Stress (MPa)	Yield stress (MPa)
Φ8	513	625	411
Φ10	518	587	363
Φ14	549	628	387
Φ22	582	653	459

Table 3 The dimensions of the meshes created in the numerical models for different elements

Structural Parts	Modeling Element Type	Meshing Size (cm)
Concrete	C3D8R	4 × 4 × 4
Rebar	B31	3
Brace	C3D8R	5 × 5 × 5
Joint Plate	C3D8R	5 × 5 × 5
Yielding Damper	C3D8R	0.6 × 0.6 × 0.6

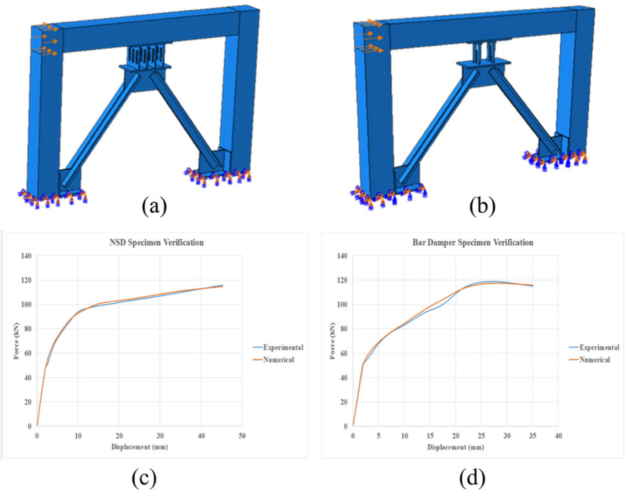


Fig. 9 (a) Modeling of RCMRF-NSD experimental sample in ABAQUS software, (b) Modeling of RCMRF-BD experimental sample in ABAQUS software, (c) Verifying chart of RCMRF-NSD sample, (d) Verifying chart of RCMRF-BD sample

5 Numerical result assessment

Numerical modeling and analysis of these models were performed according to the specifications stated in Section 4. In these models, NSD and Bar Dampers with different numbers were modeled and analyzed in the lateral bracing system of experimental frames. Seismic parameters evaluated in this section include stiffness, ultimate strength, and ductility. After the analysis, the equivalent bilinear diagrams were drawn based on the output of the ABAQUS software, and the seismic parameters were calculated according to the method used for the result of the experimental specimen. These parameters were evaluated for models N1 to N8 as well as B1 to B8.

5.1 Ultimate strength

In experimental tests, it was shown that the use of yielding dampers increases the ultimate strength by almost four times, which indicates the use of high-capacity dampers in experimental tests. By performing numerical analysis in ABAQUS software and comparing the ultimate strength in numerical samples, it was concluded that with the increase in the number of dampers, the ultimate strength increases almost linearly. Also, by reducing the number of yielding dampers from four dampers to one, the linear rate of reduction of the ultimate strength is almost constant. Meanwhile, by increasing the number of dampers from four dampers to eight dampers, the ultimate strength has been increased by 30% linearly, according to the experimental tests results, it seems that this increase in strength cannot improve the seismic performance of the models.

Fig. 10 shows the results of numerical modeling for ultimate strength for NSD and Bar Damper numerical models.

5.2 Stiffness

The comparison of stiffness values for numerical models shows that for models N1 to N4, the rate of increase in stiffness is relatively constant compared to the increase in the number of dampers, but with the increase in the number of dampers in models N5 to N8, the rate of increase in stiffness has a relative decrease. For models B1 to B8, the stiffness increase rate for numerical models is almost constant. Considering the extreme increase in stiffness in the experimental samples with dampers and also the manner of their failure, it can be said that the use of a smaller number of dampers compared to the experimental samples will help to increase the cyclic capacity of the system. Although, in the numerical models as well It is evident that Bar Dampers are stiffer than models with NSD dampers. Fig. 11 shows the stiffness diagram for numerical models.

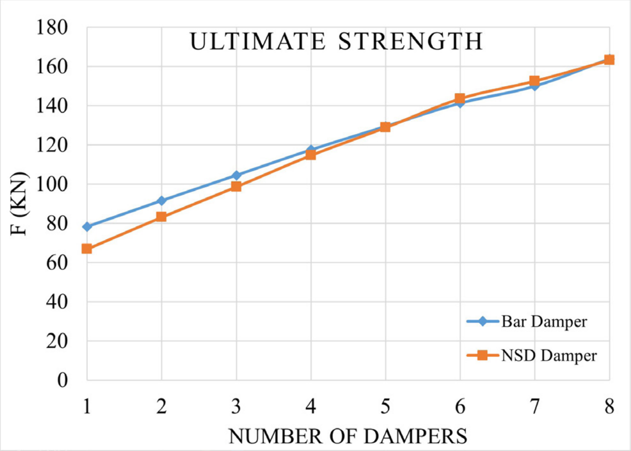


Fig. 10 Ultimate strength for numerical models

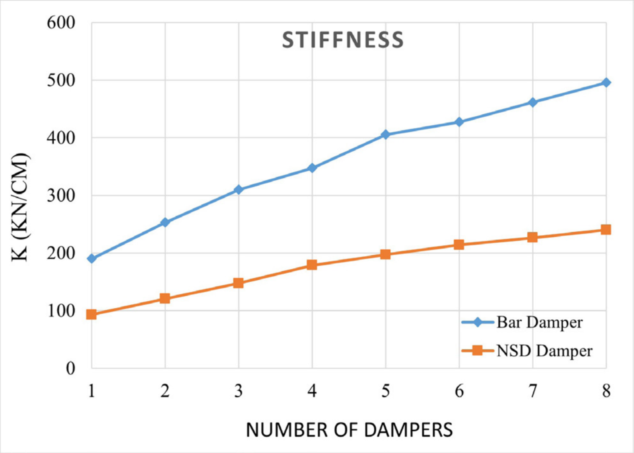


Fig. 11 Diagram of results of numerical models for stiffness parameter

5.3 Ductility

The results of numerical modeling for the ductility parameter show the drop of this parameter for more than four dampers in the models with NSD damper and Bar Damper. In models N1 to N4, the value of ductility is almost constant with a slight change, which shows that if a smaller number of NSD dampers are used, it can be expected that there will not be a noticeable drop in ductility. However, for models N5 to N8, with the increase in the number of dampers from 5 dampers to 8 dampers, we will see a 22% drop in ductility. In B1 to B4 models, however, the situation is different such that by reducing the number of Bar Dampers from 4 to one damper, a relative drop in ductility has occurred, and after passing 4 dampers for B5 to B8 models Again, there is a noticeable drop in ductility. These results show that the number of four dampers for Bar damper models is the optimal mode according to the ductility parameter. Fig. 12 shows a comparison chart for numerical models based on the ductility parameter.

By evaluating the numerical results and looking at the experimental results, it is possible to reach thoughtful results. In the experimental samples, the addition of the lateral bearing system with NSD and Bar Dampers improved the seismic characteristics of the reinforced concrete frames, but the stiffness and ultimate strength values increased sharply, which caused a decrease in the cyclic capacity of the structural system and a decrease of strength in lower drifts. Numerical modeling shows that in case of using a fewer number of dampers, assuming the use of the characteristics and geometric dimensions of the dampers used in experimental models, an optimal state can be achieved in the implementation of intended dampers. The use of the lateral bearing system with a number

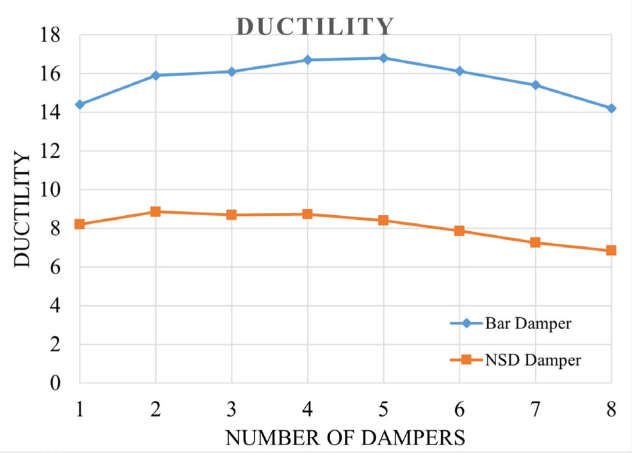


Fig. 12 Ductility parameter diagram for numerical models

of dampers less than four can provide a more balanced lateral bearing system in which the seismic parameters can be increased so that the increase in stiffness and ultimate strength has no significant effect on the ductility and cyclic capacity.

6 Recommendations

The studies conducted in this research showed that yielding dampers can improve the seismic behavior of concrete frames. Currently, there have been several types of yielding dampers introduced in laboratory form. However, conducting research on these dampers by testing them on concrete or steel frames has not been explored yet. Examples of these dampers are shear-and-flexural yielding damping [22, 34], dual function metallic dampers [35], and shear link dampers [36-38]. Experimental studies can eliminate gaps in understanding the different effects of dampers on concrete and steel frames.

7 Conclusions

The use of dampers as lateral bearing systems has been the focus of designers and engineers in recent years. Dampers can increase the ultimate strength and stiffness of different structures in a controlled way so that the members of the structure perform better against seismic stimulation. Among the various dampers, yielding dampers are one of the most obvious types of side load-bearing systems, which are particularly important due to their various geometrical types, affordability, and the possibility of being used in general structures.

In this research, the effect of two types of yielding dampers in reinforced concrete frames was investigated experimentally and numerically. Three experimental samples of reinforced concrete frames were made, two of which had a lateral bearing system. Non-uniform Slit Dampers and Bar Damper were considered in these experimental samples. The reinforced concrete frame sample (RCMRF), the frame with four NSD dampers (RCMRF-NSD), and the sample with four Bar Dampers (RCMRF-BD) were constructed. Laboratory tests were performed on the samples and cyclic loading was applied to the specimens. Based on the results of the tests, the seismic parameters of the experimental samples were compared with each other. Then, in a series of numerical modeling, the number of dampers in the second and third specimens was changed from one to eight dampers, and the numerical modeling results were evaluated for the effect of the number of dampers. The most important results of this research are as follows:

- The use of NSD and Bar Damper yielding dampers system can cause a significant increase in the seismic parameters of reinforced concrete frames. Both dampers increased stiffness, ultimate strength, ductility as well as energy dissipation capacity. Therefore, it can be said that the use of yielding dampers is a suitable method for optimizing the behavior of reinforced concrete frames.
- The ultimate strength in the experimental samples has increased by about nearly 4 times in the samples with dampers, and the stiffness in the RCMRF-NSD sample has increased by more than 5 times and in the RCMRF-BD sample by more than 10 times. This extraordinary increase can be attributed to the high thickness of NSD and bar dampers.
- The ductility of both RCMRF-NSD and RCMRF-BD samples has increased by 70% and 275%, respectively, compared to the reference sample, which is due to the intense increase in stiffness and the small value of yield point displacement. At the same time, the cyclic capacity of systems with dampers shows a sharp drop in experimental samples.
- Energy dissipation capacity as one of the most basic seismic parameters shows the positive effect of using dampers in experimental samples. In RCMRF-NSD and RCMRF-BD specimens, 6.3 and 3.2 times increase in energy dissipation capacity is observed, respectively, compared to the reference sample. The significant increase in energy dissipation capacity in the RCMRF-NSD sample was due to the drop in strength at higher drifts during the test.
- Numerical models of NSD dampers show that the use of fewer than four damper plates causes a decrease in the growth values of the stiffness and ultimate strength parameters, while the ductility values do not experience a significant drop. Therefore, for the use of NSD dampers, the number of dampers less than the number used in the experimental sample is suggested.
- The numerical models of the Bar Damper showed that with the increase in the number of dampers, compared to the experimental specimens, the ultimate strength and stiffness experienced a greater increase, while the ductility showed a drop of about 14% for the sample with 8 dampers. The important issue is that reducing the number of dampers in these models causes a drop in all the seismic parameters, which seems logical due to the extraordinary increase in the parameters in the experimental samples.

- The number of dampers, assuming constant geometric dimensions and their thickness, has generally shown predictable results in numerical samples. Increasing stiffness and strength by increasing the number of dampers and reducing parameters with fewer dampers. It seems that in order to obtain an optimal method for the design and selection of dampers, more studies should be done on other geometrical parameters such as the cross-section of dampers, the length of dampers, and the spacing intervals of dampers relative to each other.

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