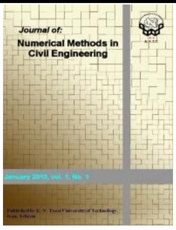

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The innovative energy-absorbing damper hybrid of steel and GFRP rods

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Abstract:

In the present study, a novel hybrid damper is introduced based on the combination of steel and glass-fibers reinforced-polymer (GFRP) rods. Sharing effort of the appropriate energy absorption properties of steel subjected to hysteretic loads and the GFRP rod reversibility due to their elastic behavior create a unique energy-absorbing system that, in addition to being economical, has a good efficiency during seismic excitations. In this research, at the first stage the materials have been tested to better understand their behaviors used in the fabrication and analytical modeling of proposed hybrid dampers and employed in numerical modeling to acquire more accurate results. Then several analytical models of damper were prepared and analyzed according to the various compositions of the materials. In the following, a hybrid damper specimen has been fabricated and tested to obtain a good comparison of actual damper behavior and the results of numerical models. The results showed that the innovative hybrid dampers achieved good performance for their assigned tasks The ease of fabrication, availability of materials, and cost-effectiveness of the damper construction have distinguished the features of an economical and high-performance hybrid damper. The damper can be used as a convenient, reversible and economical energy absorbing system for the seismic control of structures in high-risk earthquake prone areas.

1. Introduction

The traditional philosophy of designing structures to withstand unexpected events, such as earthquakes has changed in recent years. The destruction of many structures designed using conventional methods to resist seismic loads has led to new methods for designing and improving structures [1]. The passive control of structures is a suggested method in seismic design and retrofitting. The functional philosophy of this method is to reduce damage, decrease structural demand and absorb earthquake energy into a particular system. Passive control includes a wide range of materials and technologies that work by converting mechanical energy to increase damping and strength while decreasing stiffness [2-7].

Although passive controllers reduce structural and non-structural damages, they generally cannot reduce the residual displacement in the structure.

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If in addition to the energy-absorbing property, a reversibility property is also added to the control systems, residual displacement of the structure will decrease after being exposed to seismic excitation and this will increase the efficiency and performance of the seismic retrofitting system [2-7].

Energy-absorbing systems have various types including viscous-elastic, elasto-plastic, frictional, and viscous dampers. Traditional systems for resisting lateral forces in structures are primarily aimed at ensuring the safety of occupants during an earthquake of a certain design level. However, if these systems result in excessive deformation or damage to certain structural elements, this can have a substantial effect on the overall condition of the structure. Consequently, retrofitting or replacing both structural and non-structural elements may become necessary, leading to an increase in costs. In such cases, it may be more practical and feasible to consider renovating the entire structure. Self-centring systems are devices which can re-center deformed structures to their initial shapes after the occurrence of a strong earthquake. Several self-centering systems have been

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proposed and developed. Figure 1 provides an example of a variety of self-centering systems [8-10]

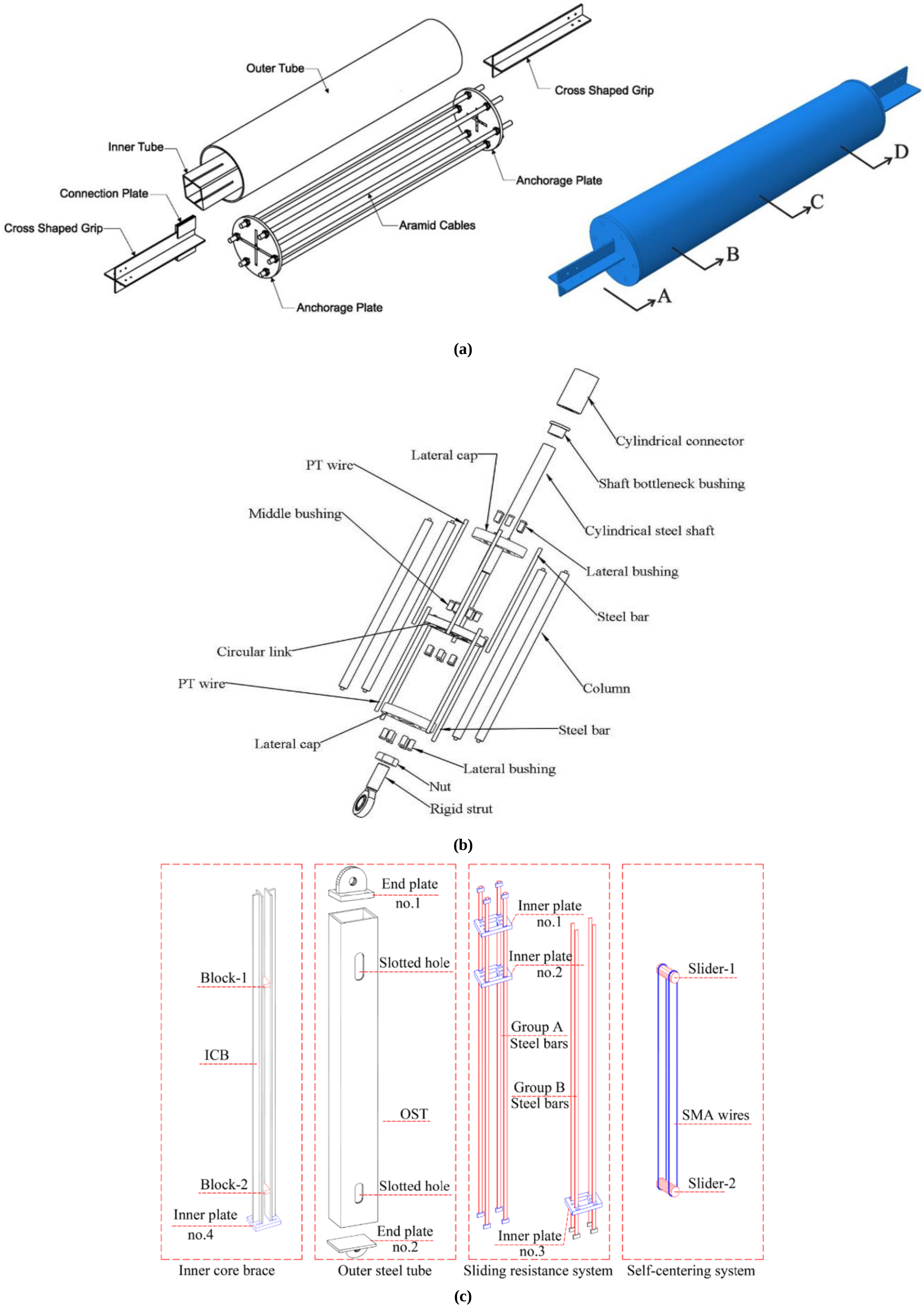


Fig. 1: The schematic images of some types of dampers. (a) Coreless self-centering braces [8]; (b) Mechanical self-centering yielding brace [9]; (c) Post-tensioned self-centering yielding brace by using SMA wires [10]

As noted, one of the common problems with passive control systems is the permanent displacement of structures after experiencing moderate to severe earthquakes. In this regard, an innovative and economical hybrid damper using steel bars and GFRP rods is suggested.

Different hybrid dampers have been invented so far. Especially when there is a need to reduce residual deformations and increase the reversibility property, hybrid dampers are devised using shape memory alloys (SMA) and researcher tried to provide reversibility with this kind of smart material. The researchers have conducted a variety of studies on dampers using shape memory alloy. These researches have been conducted with the aim of enhancing damping efficiency with respect to reversibility for instance, Zhang and Zhu (2008) used the super elastic Nitinol SMA wire in two cases of unprestrained or prestrained ones in damper to control the seismic response of nonlinear steel frame [11]. Ozbulut and Hurlebaus (2015) used SMA to obtain reversibility. They introduced the friction surfaces damper that connected with low diameter of SMA [12]. Another damper was offered by Falahian and Asadi (2021), in this damper one pair of steel rods and a set of SMA wires so that the wires were always in tension under both tensile and compressive forces [13]. Steel tubes as a portrait link and two lateral pairs of SMA cables were used in damper by Asgarian and Salari to attain re-centering capacity (2016) [14]. Enferadi and Ghasemi (2019) have used vibration control devices by using super elastic SMA to control the jacket platform oscillations. Alloys were used for two purposes: energy absorption and reversibility [15]. Weikang Feng and Cheng Fang (2019) presented a novel type of asymmetric self-centering steel connection that equipped by SMA. In their research the bottom flange of the beam armed by the SMA damper. With this method, the bending moment capacity and restoring force is improved by shape memory alloys. [16]. Huang and Chang (2020) employed SMA in tuned mass damper to manage larger excessive vibration to the structure [17].

High cost, lack of economic viability and limited availability of SMAs are the major drawbacks of these types of combinations in dampers especially in third world countries. On the other hand, the energy absorption and reversibility properties of SMA bars depend significantly on the construction technology, the composition percentage of the alloy (such as Ni and Ti in Ni-Ti SMA) and impurity levels. So different results of reversibility can be achieved in the dampers [18-22].

The present study, introduces a hybrid damper has been introduced using steel and glass-fibers reinforced-polymer (GFRP) rods. Leveraging the hysteretic behavior of steel for energy absorption under cyclic loads, combined with the elastic behavior of GFRP rods, that exhibit minimal residual strain after unloading, a good reversible property can be obtained. Other features of this innovative hybrid damper are its ease of construction, easy access to the required materials and, consequently, the cost-effectiveness of the hybrid damper. Another unique characteristic of the hybrid damper is that, the steel and GFRP rods are simply affected by tensile stresses, therefore, due to the lack of buckling in the damping rods, low diameter rods can also be used in its construction. This makes the dampers unique in terms of efficiency and economy and increases the strength of the GFRP rods in the dampers.

To capture optimum damper in view of high energy absorption along with proper reversibility a couple of dampers with various composition of steel and SMA rods were modelled and simulated using finite element method. The real behaviour of materials achieved by coupon tests has been used for numerical analysis of models. Afterwards, the hybrid damper specimen was fabricated and tested to verify the analytical models. The results of this study showed that the new innovative damper can be used as a passive control device to reduce the seismic response of the structures.

2. Overview of FRP Properties

The FRP composite is a combination of polymer fibers with matrix material. The FRP fibers are a major component of composite bearings with high strength and elastic properties. Matrices are also adhesives such as epoxy resin or polyester resin that hold the fibers together. Resins also serve to transport load to the fibers [23- 25].

When a FRP composite rod is subjected to tensile load, it does not exhibit plastic behaviour until it reaches the yield point. The tensile behaviour of FRP rods is affected by the type of fibers and is proportional to their stress-strain behaviour until the moment of rupture. It should be noted that the volume fraction of fibers has a significant effect on the tensile behaviour of the composites. However, the orientation of the fibers strongly influences the tensile properties. Unlike the steel bars, the tensile strength of FRP rods can be changed according to their diameters. As can be seen while the diameter increases, the strength decreases [23-25].

FRP has several types, one of the FRP polymer composites is GFRP. Glass fibers are used in this type of reinforcing material. These composites are a series of glass fibers derived from the heating of minerals which are cooled before crystallization process. Other features of this material include its low price and cost, low weight and low density, appropriate fatigue and impact strength [26, 27].

3. Strategy and steps of research

The aim of the present study is to introduce a new innovative damper that can provide an appropriate reversibility in addition to the energy absorption property. Besides, it is easy to build and economical. Before modelling and numerical analysis of the damper, the materials utilized in the damper were tested and their physical properties extracted to use in the numerical modelling. Next, the finite element models of hybrid dampers with different combinations of steel bars and GFRP rods has been constructed and analysed. Based on,the results of the analyses, the optimal model was specified with a focus onmaximum energy dissipation and reversibility.

In order to extract the actual behaviour of the damper and indeed verification of numerical models a sample of the optimal innovative hybrid damper was manufactured and tested in the laboratory, under cyclic loading.

A very good correlation has been achieved between numerical results and experimental measurements. Figure 2 presents the research strategy of a glance.

4. Testing of materials

In order to obtain the actual behaviour of the materials and their use in numerical modelling of the damper, the materials were tested to determine the stress-strain behaviour of the rods. These materials included steel bars and GFRP rods.

All bars with a diameter of 10 mm were tested after preparation. The experiment was performed at the ambient temperature (220C). The test frequency was 0.01 Hz and an extensometer with a span of 15 mm was used during the experiment. Figure 3 shows a sample of materials prepared for testing and a sample image of the tested materials.

The materials were tested according to ASTM A370 and ASTM E8 / E8M-09 standards [28]. Three samples were prepared from each of the materials and the mean results of all three samples were identified as materials behaviour.

Steel is commonly used in the structural engineering industry, and its stress-strain behavior is well-known., In order to improve the accuracy of the results of the research and to select the appropriate steel for use in the dampers, it was necessary to test several types of used AIII steel manufactured in several steel plants in Iran including Kavir, Khorasan, and Isfahan steel company. After testing and extracting the results, the steel sample of Isfahan steel company was selected for its high ductility (ε_u=0.43). During the testing of materials, the samples were loaded until they reached the failure level. The diagram of the stress-strain relationship extracted by the tensile test of steel samples has been given in Figure 4. Table 1 also provides the GFRP rod test results.

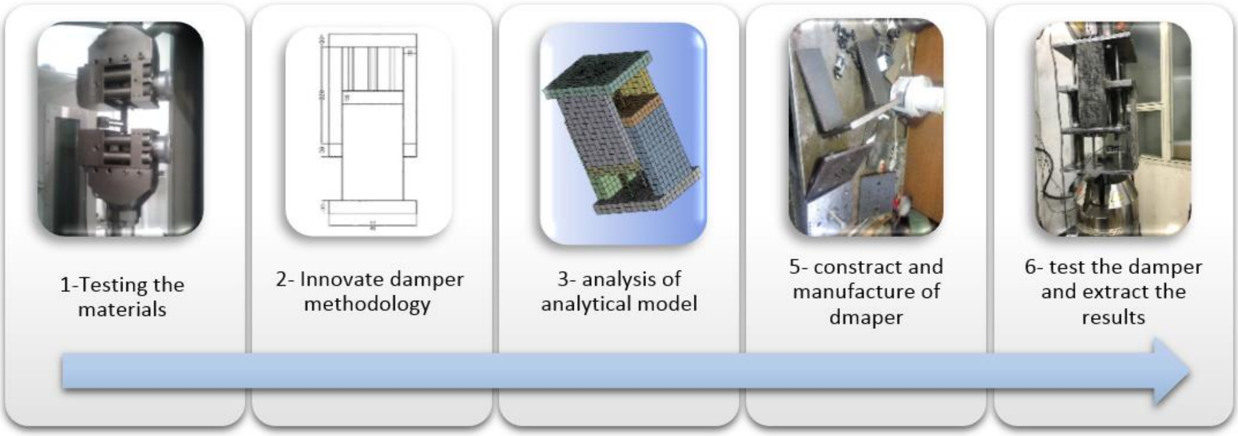


Fig.2: Research strategy

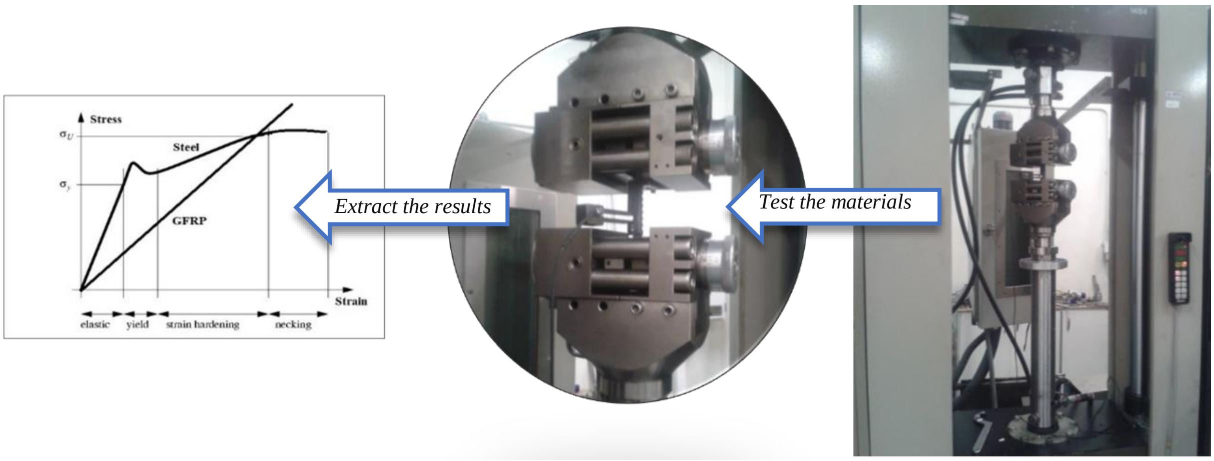


Fig. 3: Laboratory test scheme

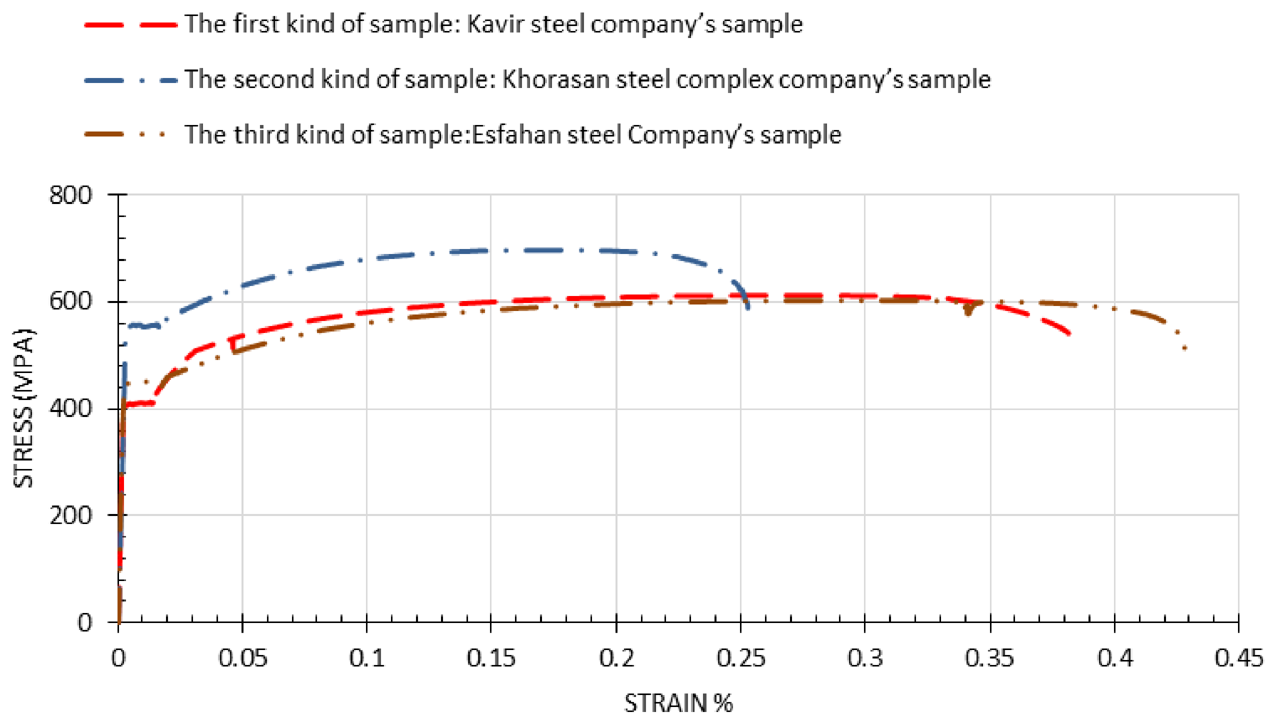


Fig. 4: The stress strain diagram obtained from testing steel specimens

Table1: The test results of GFRP specimens

SHEAR MODULUS (GPA)	BULK MODULUS (GPA)	POISSON'S RATIO	YONG'S MODULUS (MPA)
34.76	67.42	0.28	8900

5. Hybrid Damper Performance

In the innovative hybrid dampers, the parallel performance of steel bars and GFRP rods has been considered. The superior characteristics of the damper, which are the energy absorption by using the steel bars and the reversibility property obtained by using a GFRP rods has been achieved. The geometry of the damper is designed such a way that the bars are merely were under elongation while the damper was subjected to both compression and tension forces. For this purpose, the bars were placed between high-strength steel plates (HSS). Four high strength steel plates are named 1 to 4 and the bars placed in parallel form between these plates. Two side plates 1 and 2 are used to connect the damper to the structure. There are also four other high strength steel plates, which we call the connecting plates. These plates are used as connectors and interfaces between plates 1 to 4. Connector plates interconnect plates 1 and 3, as well as two plates 2 and 4.

Three groups of bars are placed between the plates. Group A bars are between plates 1 and 4, group B bars are between plates 3 and 4, and the group C bars are placed between the plates 2 and 3.

All bars are fastened in the plates on one side and, on the other side, can be ejected in the cavity embedded on the opposite plate. They are subjected to tensile stresses while returning to the last position due to the bar bead fixed at the behind of the plate. Figure 5 shows the damper structure.

6. Finite Element Analysis of hybrid dampers

In order to obtain the behavior of the damper subjected to cyclic loads, various models of damper were analyzed by ANSYS finite element program. Eight node SOLID185 elements are used for numerical modeling of the devices. This type of element is used for 3-D modeling of solid structures [29]. It is defined by eight nodes having three degrees of freedom at each node: translations in the nodal x, y and z directions. The displacement of end plates is restrained in all six degrees of freedom and the two thick end plates of the device can be made up of high-strength steel (HSS).

In these models, the various cross sectional area ratio of the two materials that is steel bars and GFRP rods, has been incorporated. The results of the numerical analyses of dampers with different composition ratios have been extracted and compared with each other.

In general, these dampers can be classified into two groups. The first group of dampers where only steel bars have been used, the second group of dampers using a combination of steel and GFRP rods, which are called hybrid dampers and the percentage of using steel and GFRP was varied. In the first series of dampers, the effect of steel on the energy absorption was investigated by changes in the number of steel and in the second series of dampers, the effects of changes in the composition of both materials on the energy absorption and reversibility of dampers were investigated. Steel dampers have been studied for the purpose of obtaining a proper comparison of the hybrid damper material placement in changing the damping physical properties. Tables 2 and 3 present the percentage of composition of materials in dampers. In the hybrid dampers the parameter ρ is introduced. This parameter is the cross-sectional area ratio of steel bars to those GFRP rods. Figure 6 is a schematic view of the hybrid dampers.

$$\rho = \frac{\text{the percentage of using steel}}{\text{the percentage of using GFRP}} \quad (1)$$

Table2: Introducing the first group of dampers

	Name of sample	**Sample no.1**	**Sample no.2**	**Sample no.3**
The number of steel bars	Steel	3 bars	5 bars	9 bars

Table3: The amount of material composition in different types of hybrid dampers

	Name of sample	**Sample 1**	**Sample 2**	**Sample 3**	**Sample 4**	**Sample 5**
Percentage of substances	Steel	20	40	50	60	80
	GFRP	80	60	50	40	20
ρ	------	0.25	0.66	1	1.5	4

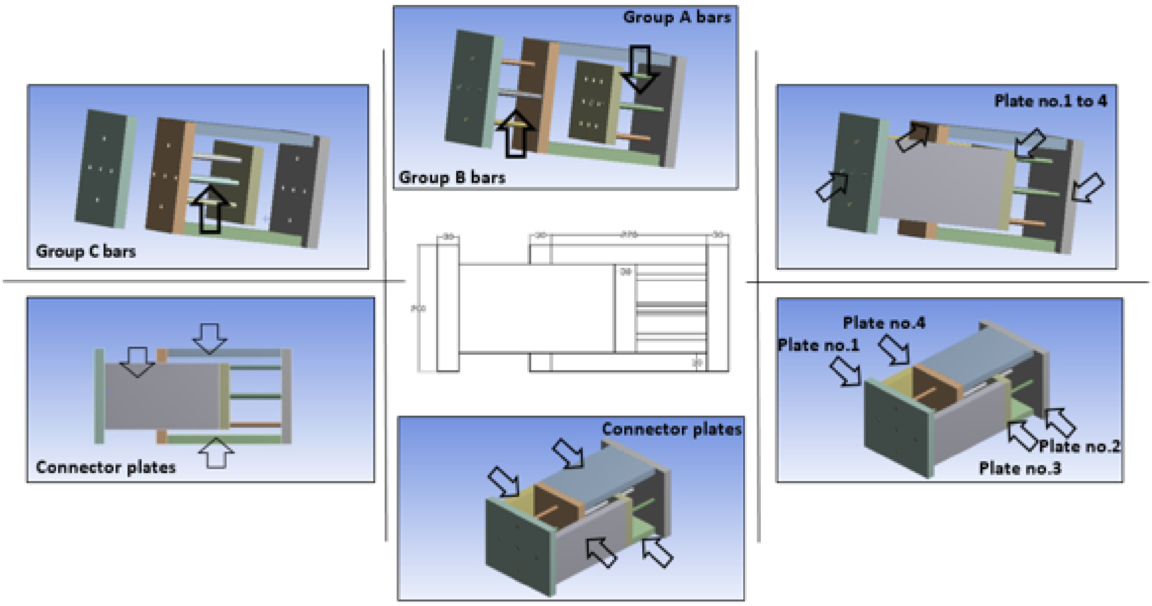


Fig. 5: View images of a hybrid damper

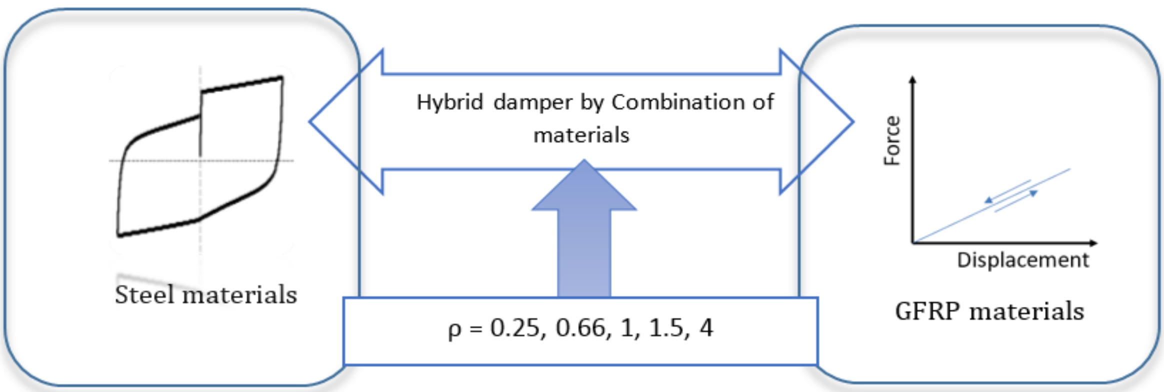


Fig. 6: Schematic view of the hybrid dampers.

Two groups of dampers were analyzed separately and the results of their analysis were extracted.
Figure 7 shows the results of the finite element analysis of the dampers. The result of the last loop obtained from the analysis has been shown in the figures 7 and 8 to make a proper comparison between the different states.
As shown in Figure 7, with increasing the number of steel bars, the energy absorption of the dampers increases, this property exhibits the same behavior as each bar group increases. GFRP rods are then used in order to add reversibility to the dampers and hybrid dampers are examined.
Figure 7 shows that by decreasing the coefficient ρ, i.e. decreasing steel content or increasing GFRP content, the energy absorption has a decreasing trend and the reversibility is increasing. The results of the analysis showed that the hybrid damper was able to perform both energy absorption and reversibility tasks well. Figure 8 compares damper samples from both types of dampers.
According to figure 8 by comparing Sample No. 1 of steel damper and Sample No. 3 and 4 of hybrid damper, it is found that, although replacing steel bars with GFRP rods reduces energy absorption, but it has been able to improve the reversibility property. By comparing the analytical results of two typical hybrid dampers, damper No. 3 (ρ = 1.0) and damper No. 4 (ρ =1.5), the effect of the application of GFRP rods on the reversibility property is confirmed. As it is clear in the Figure 8, the increase of an GFRP rod in sample number 3 compared to sample number 4 has caused a 4% increase in the reversibility property. Also, due to the fact that this rod replaces the steel rod, it will result in a reduction of about 109 (kJ) in energy absorption.

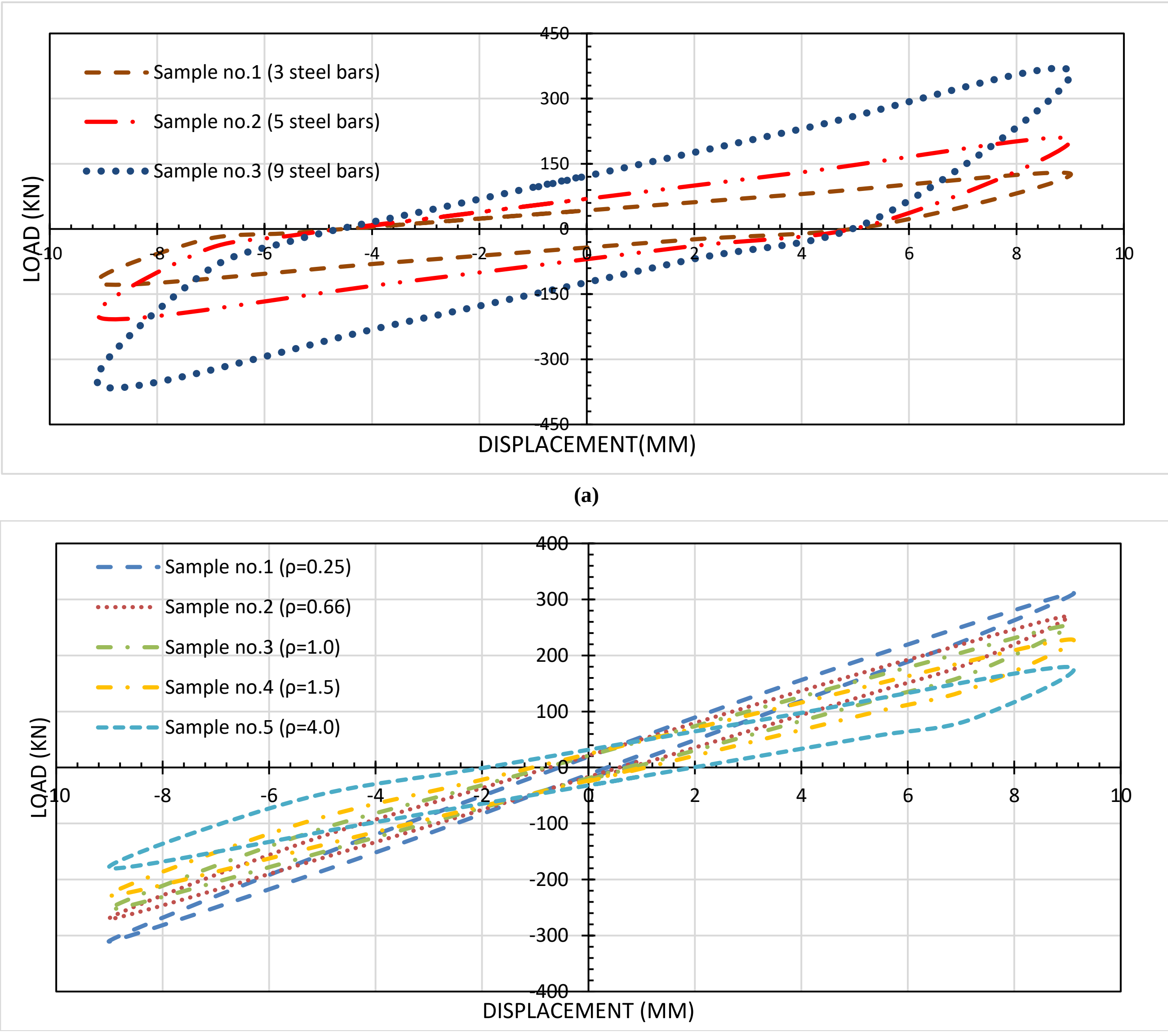


Fig. 7: The Results of analysis: (a) First series of dampers (b) Hybrid dampers

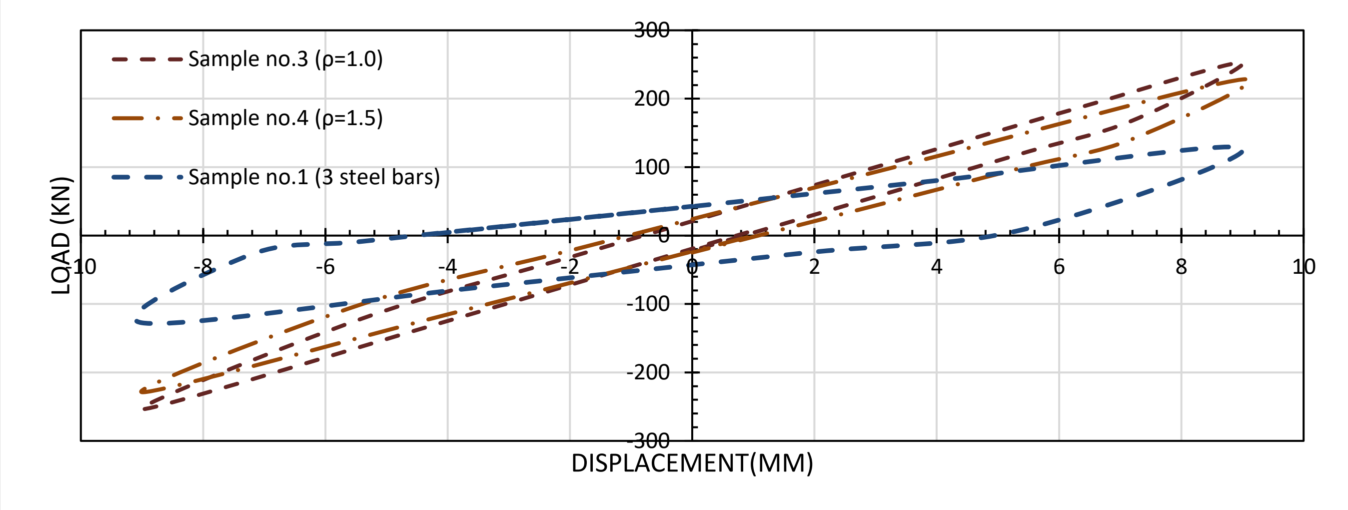


Fig. 8: Comparison of analysis results in three samples

The equivalent strain and stress (von-Mises) of the hybrid damper with the coefficient ρ = 0.0 have been shown in Figure 9, respectively. The equivalent strain is obtained by using the following equations [30].

According to Figure 9, it can be found that the stress applied to the steel bars is higher than that of the GFRP rods, confirming that steel plays a major role in stiffness and strength of damper.

The equivalent strain diagram shows that the strain in the bars is the same, although it should be noted that the stress and strain at the joints inside the steel plates was slightly reduced due to the confinement by the steel inside the cavity. The stress and strain on the connecting plates indicates they have successfully transferred most of the stresses to the bars, as expected in the design of the damper.

$$\varepsilon_{eq} = \frac{2}{3}\sqrt{\frac{3(e_{xx}^2 + e_{yy}^2 + e_{zz}^2)}{2} + \frac{3(\gamma_{xy}^2 + \gamma_{yz}^2 + \gamma_{zx}^2)}{4}} \quad (2)$$

The ε and γ values are determined as:

$$\begin{aligned} e_{xx} &= +\frac{2}{3}\varepsilon_{xx} - \frac{1}{3}\varepsilon_{yy} - \frac{1}{3}\varepsilon_{zz} \\ e_{yy} &= -\frac{1}{3}\varepsilon_{xx} + \frac{2}{3}\varepsilon_{yy} - \frac{1}{3}\varepsilon_{zz} \\ e_{zz} &= -\frac{1}{3}\varepsilon_{xx} - \frac{1}{3}\varepsilon_{yy} + \frac{2}{3}\varepsilon_{zz} \end{aligned} \quad (3)$$

$$\gamma_{ij} = 2 \times \varepsilon_{ij} \quad (4)$$

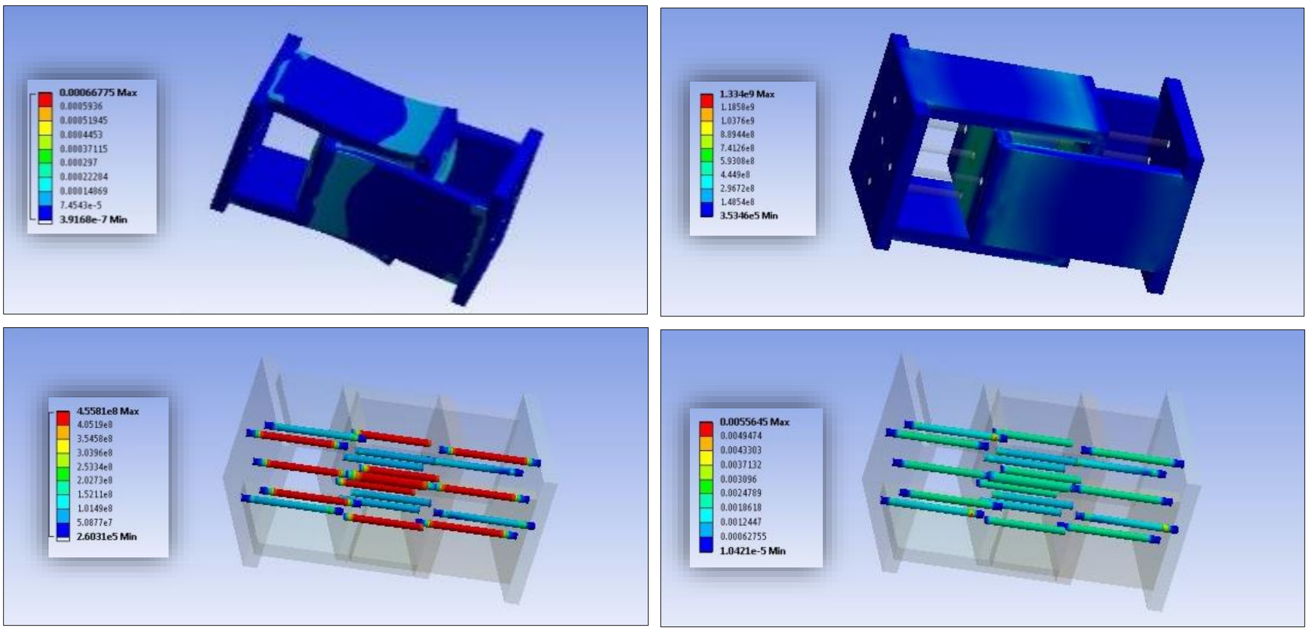


Fig. 9: Results of finite element analysis: a) equivalent stress contour, b) equivalent strain

7. Analytical Parameters of Hybrid Damper

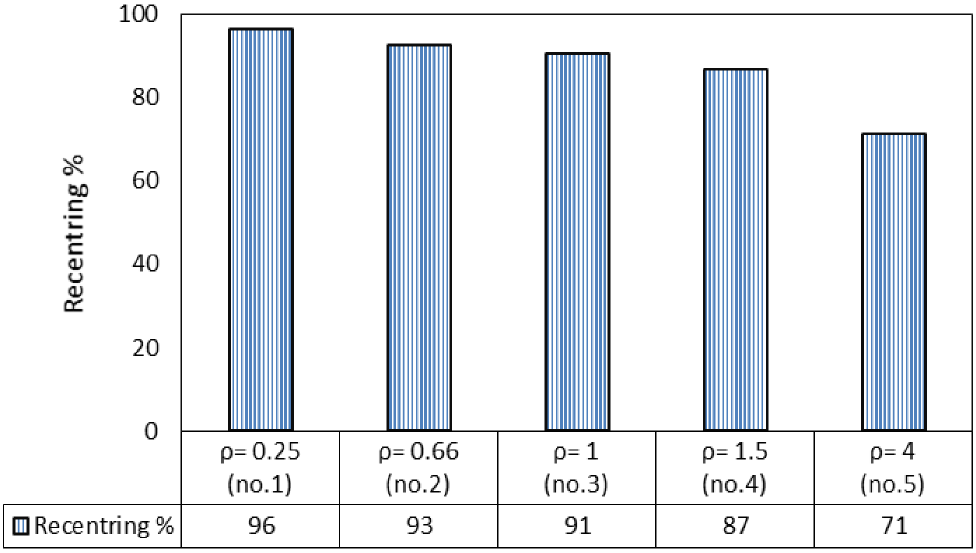
As mentioned, the two major characteristics of the new hybrid damper are energy absorption and reversibility. These two properties were extracted for dampers. Figure 10 shows the energy absorption and reversibility of each of the dampers against parameter ρ.

The reversibility in the samples (D_{re}) is determined by equation 5, where in D_i is the utmost inflicted displacement which is equal to 9 mm according to the loading protocol and D_{pe} is the permanent displacement.

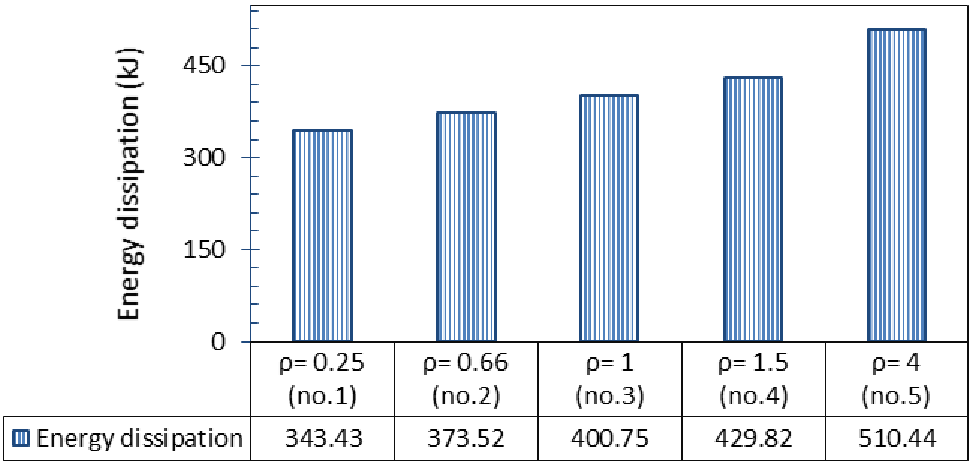
$$D_{re} = \frac{D_i - D_{pe}}{D_i} * 100(\%) \quad (5)$$

According to Figure 10 the decrease in the parameter ρ, which represents increasing use of the GFRP rods, has a significant effect on increasing the reversibility. Therefore, it can be concluded that the use of GFRP rods is a good choice to increase reversibility characteristic in hybrid dampers. The highest reversibility and the lowest absorption rate are associated with the damper No. 1 (ρ = 0.25) and the lowest reversibility and highest energy absorption are associated with the damper No. 5 (ρ = 4).

By replacing two GFRP rods with steel bars in the specimens, the reversibility improved by 7.8% and, by replacing GFRP rods by two steel bars with, the energy absorption rate shows an increasing trend at an average rate of 10.4%.



(a)



(b)

Fig. 10: The results of (a) reversibility and (b) energy absorption of Hybrid dampers

It is clear that this change is due to the increased consumption of steel bars in the specimens. As can be seen in Fig. 10, the highest variation rate in the two properties of reversibility and energy absorption is reported in the change in the specimens' No. 4 to 5. Equivalent stiffness is obtained by using the Eq. 6. The maximum force of the tensile and compression force and the corresponding displacement are used in calculating this parameter. Due to the symmetry of the damping geometry, the numerical results of the analysis also show symmetric behavior. Therefore, the maximum force and displacement can be used to calculate the difficulty of the argument [32].

$$K_{eff} = \frac{|F_{max}^{-}| + |F_{max}^{+}|}{|\Delta_{max}^{-}| + |\Delta_{max}^{+}|} = \frac{|F_{max}|}{|\Delta_{max}|} \quad (6)$$

Eq. 7 represents the viscosity damping equivalent where $W_D$the area of force-displacement curve of one cyclic is loading cycle and Δ_{ave} is the average displacement per loading cycle [32]. The equivalent damping and stiffness for a composite damper specimen based on the last loading loop have been presented in Table 4.

$$\zeta_{eq} = \frac{W_D}{2\Pi\, K_{eff}\, \Delta_{ave}^2} \quad (7)$$

As expected, the stiffness equivalent is increased with decreasing ρ. In contrast, the damping equivalent has an increasing trend.

Table 4: The results of equivalent stiffness and equivalent viscous damping of hybrid dampers

Sample number	ρ	Equivalent Stiffness (kN/mm)	Equivalent Viscous Damping
Sample no.1	0.25	34.37	0.165
Sample no.2	0.66	29.97	0.288
Sample no.3	1	28.10	0.412
Sample no.4	1.5	25.36	0.566
Sample no.5	4	19.93	0.687

8. Experimental evaluation of hybrid damper

In order to acquire the pragmatic behavior of the hybrid damper and verify the results of numerical analysis, a hybrid damper specimen with ρ = 1.5 was selected. The numerical analysis of the damper was shown desired results in terms of energy absorption and reversibility. It can therefore be used as a suitable sample for Laboratory experience. In the manufacture process of dampers, it has been attempted to use the maximum accuracy during construction.

Instron-8502 multipurpose device has been used to test the manufactured damper. The loading protocol includes incremental cyclic loads up to 6% strain, with incremental steps of 1% (Figure 11) the test was performed at room temperature 20 °C and the loading speed during the test was 0.3 mm/min. Figure 12 shows the illustrations of the dampers, the loading setup, and how the dampers are placed in the machine.

Figure 13 shows the results of numerical analysis and testing. Table 5 also shows the damper properties in both analytical and experimental conditions.

The reversibility property of the analytical damper results is about 87% and in the test, results is about 76%. Therefore, the test result shows a difference of about 14.5% in its reversibility.

Contrary to the reversibility property, the energy absorptions in the experimental results are higher than the analytical results. This difference is lower and negligible in the early loading cycles however, as the loading cycles increase, the difference has also increased so that the maximum difference has been created in energy absorption in the end cycle occurs. Equivalent viscosity damping and equivalent stiffness exhibit a decreasing trend with increasing loading cycles. The equivalent stiffness in the laboratory results is higher than the equivalent stiffness in the analytical results, with an average difference of about 5.6%. Also, this difference in the damping equivalent in the first loading cycle is about 4.2% and continues to 19% in the final loading cycle.

Examination and comparison of analytical and experimental results show that although experimental results have differences especially at higher loading cycles, however, the new hybrid dampers have been able to adequately perform the two tasks of energy absorption and reversibility. It should be emphasized that the economical aspect of the hybrid damper is its ease of construction and the availability of the materials.

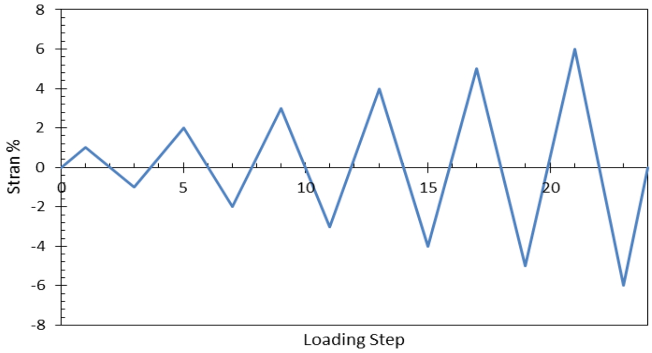


Fig. 11: The protocol of loading test of damper

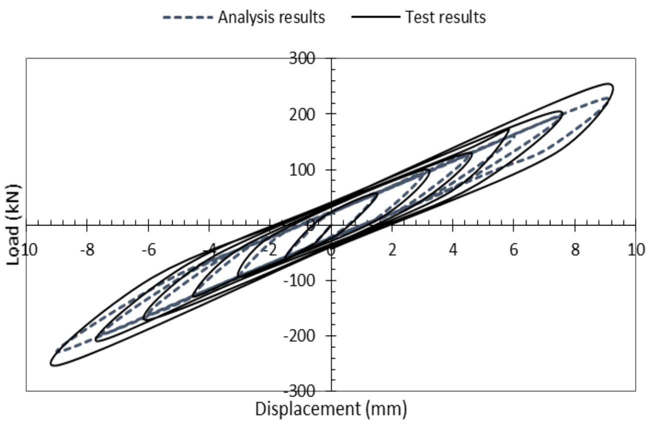


Fig. 13: The result and the comparison of cyclic testing of the damper

Table 5: The comparison of equivalent stiffness, equivalent viscous damping and dissipated energy for each cycle of loading (test and analysis results)

	Equivalent Stiffness (kN/mm)		Equivalent Viscous Damping		Dissipated energy (kJ)	
Cycle no.	Test results	Analysis results	Test results	Analysis results	Test results	Analysis results
1	38.27	38.09	0.263	0.248	1.34	1.19
2	31.02	30.53	0.251	0.232	4.13	3.40
3	28.95	28.02	0.234	0.176	4.82	3.95
4	28.73	26.77	0.210	0.145	6.19	4.64
5	28.41	26.01	0.195	0.138	7.68	5.72
6	28.22	25.36	0.167	0.129	11.08	7.91

Fig. 12: The manufactured damper and the testing setup

7. Conclusion

This research introduced an innovative hybrid damper combining two materials of steel and glass-fibers reinforced-polymer (GFRP) rods.

The supremacy of this innovative device was demonstrated through numerical finite element analysis and experimental evidence. In order to accurately use the mechanical properties of the materials in numerical model of the damper, a series of coupon tests were carried out. To verify the results obtained from laboratory's outcomes the selected specimen was manufactured and then tested. Because rods sustain just tensile stress, the behavior of damper in tension and compression is the similar, due to the unique structural mechanism.

The results showed that the combination of steel and GFRP rods in dampers has favorable results in energy absorption and re-centering. Replacing the GFRP rods with steel rods in dampers is able to boost re-centering capability, although energy absorption is reduced

So, with this combination, both energy absorption and reversibility properties are well supplied. The results of the experimental test of a sample damper confirm numerical results, however, the difference in results in higher load cycles is greater.

The following are some of features of the introduced hybrid damper.

a) The construction of the damper is far from technical complexity, also due to the low cost and availability of steel and GFRP rods, the cost of construction of damper is reasonable and can be used as an economic damper.
b) Due to the special structure of the damper and the fact that the rods are only affected by traction, low diameter rods can be used in the damper.
c) The symmetry of the damper structure has caused the damper results to be symmetrical in tension and compression loading.

Based on the results of the analysis and testing and due to its reversibility and proper energy absorption, the introduced damper can be used as a passive control tool in structures.

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