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Investigating Energy Absorption Accessible by Plastic Deformation of a Seismic Damper Using Artificial Neural Network

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Abstract

In this study a seismic damper of high-rise structures is analyzed parametrically using artificial neural network (ANN). The input data for ANN model was generated using experimentally validated finite element (FE) analyses. The study investigates the amount of the absorbed energy dissipated by the plastic deformation of the tubes involved in the damper. The network used in this study computes the absorbed energy of the damping system in terms of three different variables including diameter ratio, the thickness and the diameter of the outer tube. To train the network, 90% of the FE results are utilized as input, and the capability of the network is examined by the rest 10% of data. It is shown that the trained neural structure can estimate the energy dissipation with an error less than 2%. According to the results, it is observed that despite the diameter, increasing in the thickness of the outer tube improves the energy absorption measurably. The results also show that the model with the diameter ratio of 1.6, as a critical design parameter, reflects the optimum absorbed energy among all cases.

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Keywords: Energy absorption capacity; hysteresis effect; parametric study; artificial neural network.

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1. Introduction

According to today's need in improving the safety of high-rise structures, damping of the dynamic energy imposed by earthquakes is top on the agenda. In this respect, mitigating the effects of the vibration of the structures through energy absorption mechanisms, should be performed by additional devices like seismic dampers (Balendra 1991).

To dissipate the energy some new dampers have recently been introduced, in each of which the absorption mechanism was mainly based on the plastic deformation of the metallic material. It leads to the fact that when a material is subjected to the cycles of loading and unloading, some energy is dissipated which is called hysteresis effect. Some studies have been done in order to improve the practicability of the damping systems using the expansion of the hysteresis loops drawn during the loading of the system (Rezai et al. 1999). For instance, Maleki and Mahjoubi (2013) studied a new design of the dual-pipe damper to improve the amount of absorbed energy. They put the hybrid system inside the bracing system and utilized the bending capability of the tubes to dissipate the energy. Their system improved the ductility and the energy dissipation capacity notably. Similarly, Boostani et al. (2018) utilized the tubes inside a bracing system where the energy absorption capacity was improved measurably. They also found out that the hybrid systems can absorb the dynamic energy of the earthquakes with high Richter very effectively.

In another research performed by Hashemi and Moaddab (2017) about the hybrid structural dampers, the stiffness of the damper can change in terms of the earthquake intensity which lead to a more practical mechanism. Likewise, in another hybrid system introduced by Maleki and Mahjoubi (2014) with two nested tubes, the gap was filled with two different metals. The energy dissipation of this mechanism includes the plastic deformation of the tubes and the energy dissipated to overcome the friction between the internal and external tubes. They optimized the design to find the most suitable parameters of the tubes in the damping system.

Present study is to accomplish a huge domain of dimensional investigations on a hybrid seismic damper in order to design more practical damping mechanism. In this regard, ANN technique with MATLAB is utilized to optimize three different parameters of the damping system in order to achieve the optimum absorbed energy. The Input set of data for ANN is extracted from experimentally validated FE simulations in ABAQUS performed with a parametric study using Python scripting.

2. Numerical investigation

2.1. Model definition

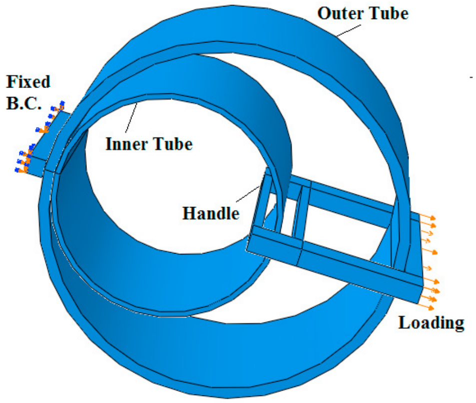
The present study consists of two tubes with different sizes, one inside another, at which the smaller inner tube will be engaged in deformation when the applied displacement upon the structure rises notably. This is because this hybrid system is designed to be engaged in two different stages where the outer tube is responsible for the earthquakes of low intensities and both tubes are involved at earthquakes of high intensities. This application of the damper reduces the manufacturing and repairing costs in case of minor earthquakes. In addition, it enhances the energy absorption capacity compared to the other common dampers with the same dimension. The results obtained by artificial neural network technique are utilized to investigate the dimensional effects of the tubes on the amount of dissipated energy through plastic deformation. It is worth noting that only the thickness and the diameter of the outer tube and the diameter ratio are changed for any new analysis. Furthermore, the ratio of the outer tube thickness to that of inner tube was kept equal to two for all studies.

2.2. Validation and simulations

To validate the FE simulations of this study, an experimental work carried out by Alavighi (2017) was utilized to verify the accuracy of the numerical solutions. Then, 1000 case studies were simulated in a commercial finite element package, ABAQUS, through a parametric study with Python scripting. Figure 1a shows the sample under tension-compression testing. The experiment was carried out on a sample manufactured as two steel tubes of different sizes connected to each other by a handle. It includes two tubes with 6 and 12 mm in thicknesses and with

∅ 265 and ∅ 400 in diameters as the inner and outer parts. In addition, two symmetrical gaps between the handle and two sides of the inner tube were taken as 15 mm in the study. The size of the gap is calculated according to SAC (FEMA-355D, 2000) to set the appropriate time of the engagement for the inner tube. The Young's modulus and Poisson's ratio of the steel were taken as 200 GPa and 0.3, respectively. Plastic properties of the material, true stress and corresponding true plastic strain, were summarized in Table 1. Figures 2a and 2b indicate a comparison between experimental and corresponding numerical results. The experimental work was carried out under displacement-controlled loading condition for the sake of simplicity. But in the numerical investigations, the loading pattern of SAC (FEMA-355D, 2000) was utilized, at which the increase in the drift angle (θ) was changed to increase in the displacements accordingly (see Fig. 3).

(a)

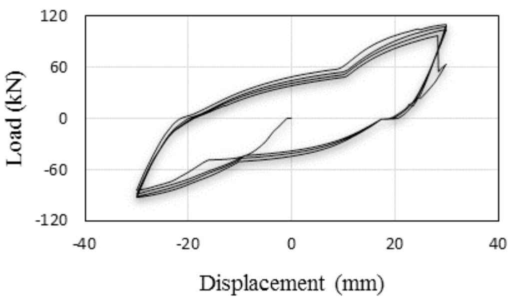


(b)

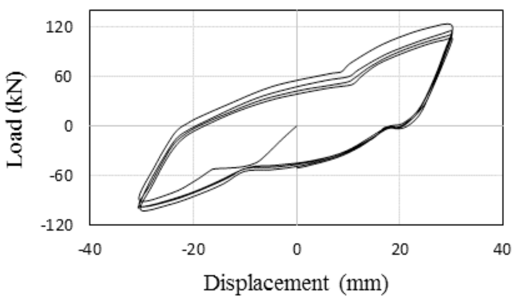
Fig. 1. The structure of the system. a) Experimental setup (Alavighi, 2017), b) A general configuration used in the numerical simulations indicating the components of the structures along with the boundary conditions.

Table 1. Plastic properties of the material used.

Property	Quantity					
True stress (MPa)	300	320	340	365	385	390
True plastic strain (mm/mm)	0	0.001	0.008	0.048	0.148	0.248

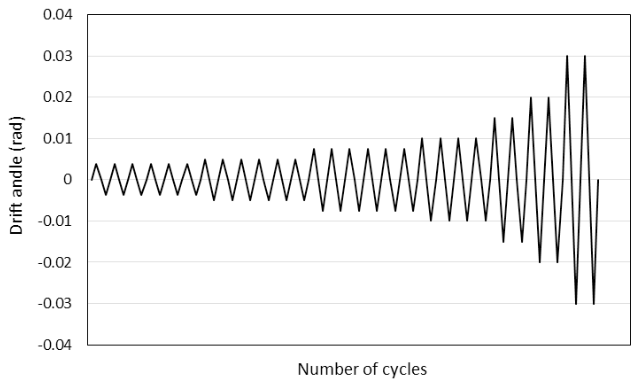


(a)



(b)

Fig. 2 Validation of the numerical study. a) Experimental outputs, b) Numerical results for the setup. The loading condition for validation was displacement-controlled.



Loading step	Drift angle (rad)	Number of cycles	Imposed displacement* (mm)
1	0.00375	6	3.75
2	0.005	6	5
3	0.0075	6	7.5
4	0.01	4	10
5	0.015	2	15
6	0.02	2	20
7	0.03	2	30

* The amount of imposed displacement is calculated according to the system dimensions.

Fig. 3 Standard cyclic loading pattern in accord with SAC, (FEMA-355D, 2000).

The effects of three different parameters on the amount of absorbed energy were investigated accordingly. For this purpose, 10 different values of three parameters were employed in order to prepare 1000 case studies as input data for the ANN model. Such huge amounts of input data were extracted through parametric study with the help of Python scripting in ABAQUS finite element package. In these analyses, the diameter ratio, the thickness and the diameter of the outer tube were considered in the ranges of 1.4 to 1.7, 8 to 14 mm and Ø375 to Ø435 mm, respectively.

The half-cycle plastic response of the material is proposed in Table 1. To simulate a loading-unloading conditions in ABAQUS, the plastic behavior of the material was modeled using isotropic J_2 flow theorem with half cycle combined hardening (Smith, 2009). A penalty contact algorithm along with Coulomb friction model with a coefficient of 0.1 were utilized in the analyses. To mesh the model, 8-node brick reduced integration elements (C3D8R) were utilized. Mesh sensitivity study was carried out and the element size of 5×5×5 mm was employed for the critical regions. As boundary conditions, one side of the system was fully fixed while the other side was connected to the handle and loaded (see Fig. 1b).

3. Artificial neural network

Artificial neural network (ANN) concept has been adopted from biological neural networks. ANN is very powerful method which can assist the prediction of results in many sophisticated engineering problems especially when the trend of the changes in the outputs is not fully defined.

An ANN model generally consists of several layers, however, the simplest one includes three compulsory layers; that is input, hidden and output layers. Neurons of each layer are the computing units of the corresponding layer, which are accountable for information processing in order to prepare the most preferable results. Every layer of each network can include different numbers of neurons given that how much the network is complicated. Numbers of the neurons should be obtained by trial and error method to estimate the closest results with a predefined desirable error between the test and predicted data. Linking between the layers of an ANN model is made through weights indicated in Fig.4.

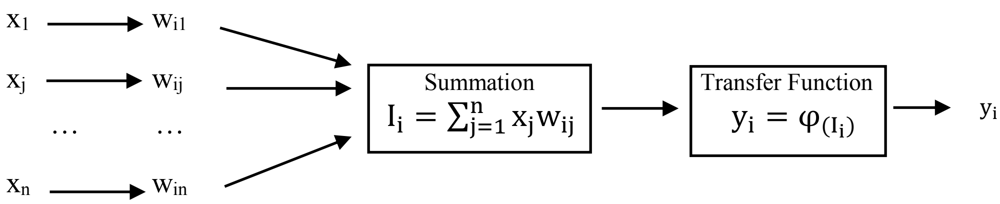


Fig. 4. Block diagram of the processing procedure in a neuron, Haykin (1998).

where x, w, y signify the inputs, weights and output, respectively. Furthermore, φ refers to transfer function which transforms the summations into the outputs Haykin (1998).

The network constructed in this study was trained with some pairs of data obtained from several FE analyses. The ANN model was prepared using MATLAB environment with a structure of 3-7-3-1 neurons in the input, two hidden and output layers, respectively. The input layer with three neurons receives information about diameter ratio, the thickness and the diameter of the outer tube. Fig.5 shows the configuration of the ANN model used in this study. The ANN model here is based on the Feed-forward back-propagation algorithm utilized in a four-layer network. Moreover, the Levenberg-Marquardt (LM) back propagation algorithm was defined as learning method Apalak (2006). According to some trial models and subsequent outcomes, it was found out that the tangent sigmoid transfer function used in the hidden layers and the logistic sigmoid transfer function utilized in the output layer produced the best results. In addition, to reach the most accurate results, mean square error (MSE) performance function was utilized between the predicted network outputs and the desirable results, Apalak (2007). In this study, 1000 pairs of numerical data obtained from a parametric study. From this set, 90% of data were assigned as input data to train the network. Likewise, 10% of data were randomly chosen to be utilized as the test patterns in order to check the accuracy of the predicted output.

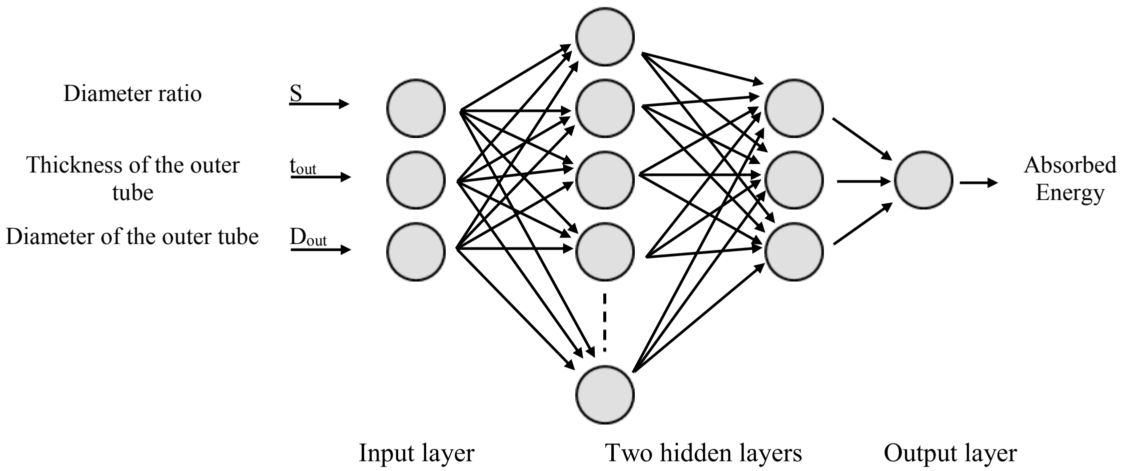


Fig. 5. Configuration of the ANN model used in this study.

4. Results and discussion

In this work, a hybrid seismic mechanism was investigated. The hybrid system was designed to decrease the cost of manufacturing and repairing without decreasing the energy dissipation capacity of the damper. ANN method was employed to study the effects of three different parameters on the energy absorption capacity of the damping system. FEM analyses were utilized to prepare the input data for ANN and the experimental data were utilized to validate the FE results. Finally, the optimum values of those three parameters were determined to guarantee the highest energy absorption for the system.

4.1. Dimensional effects by ANN

The ANN technique utilized in this study provides a wide domain of investigations in terms of three different variables. The outputs of the ANN demonstrate a very appropriate prediction with an error less than 2%. The dimensional effects of the system were studied by plotting some 3D diagrams represented in Fig. 6. Given the plots, the mutual effects of each set of two-dimensional variables on the amount of the absorbed energy can be drawn. The trend by which the parameters affect the dissipated energy can also be indicated. According to the first two diagrams of the figure, it can be concluded that changing the diameter ratio from 1.4 to 1.6, will cause imperceptible change in the amount of absorbed energy. On the other hand, increasing the thickness of the outer tube or decreasing the outer tube diameter will improve the absorbed energy capacity. In the third diagram where the outer tube diameter is fixed, the absorbed energy can be improved by increasing the thickness while it is almost insensitive to the diameter ratio. Likewise, Fig. 6d indicates that in the models with the same thicknesses, those of lesser outer tube diameter can absorb the energy more effectively.

The negligible effect of the diameter ratio on the amount of dissipated energy was also investigated in Fig. 7. However, it can be concluded that the designs with S=1.6 are more feasible ones having optimal dissipated energy.

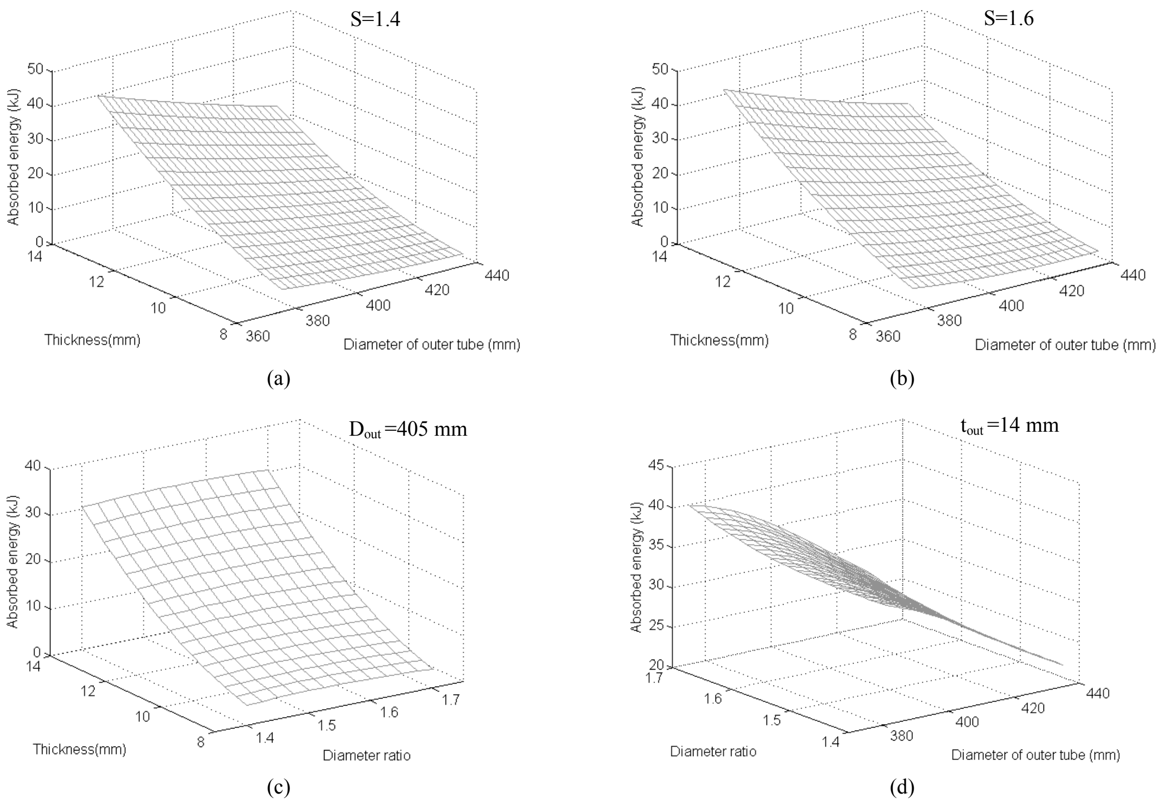


Fig. 6 Coupled effects of dimensional variations of different case studies on the amount of absorbed energy; a) S=1.4, b) S=1.6, c) D_{out}=405 mm and d) t_{out}=14 mm.

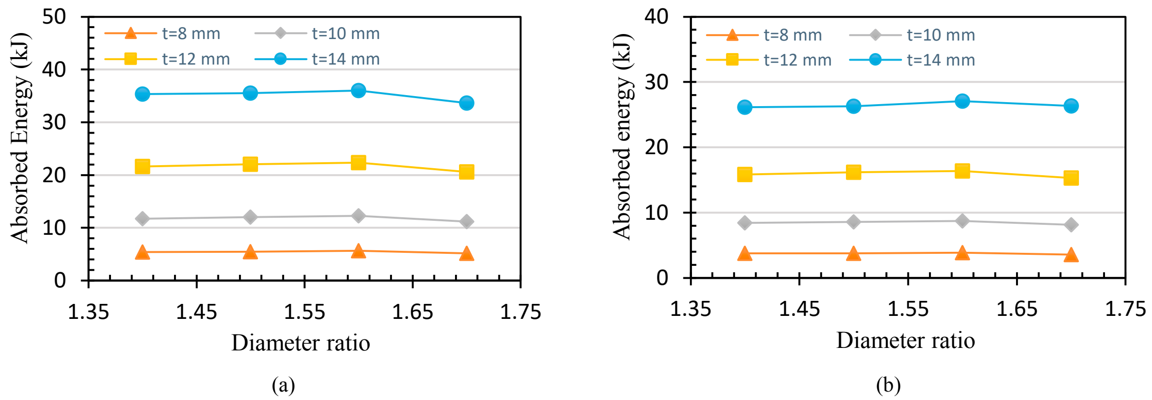
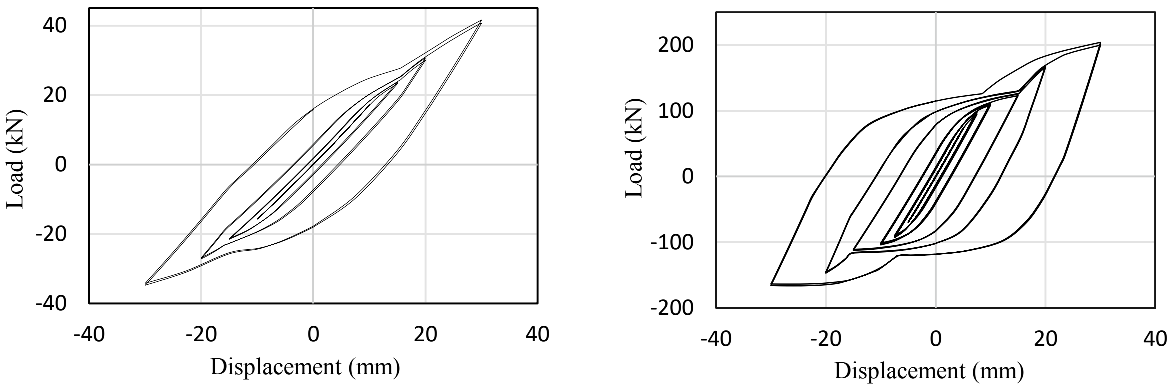


Fig. 7. Comparisons between the amounts of absorbed energy in terms of the diameter ratio and the thickness of the outer tube, a) D=390 mm, b) D=420 mm.

4.2. Model efficiency

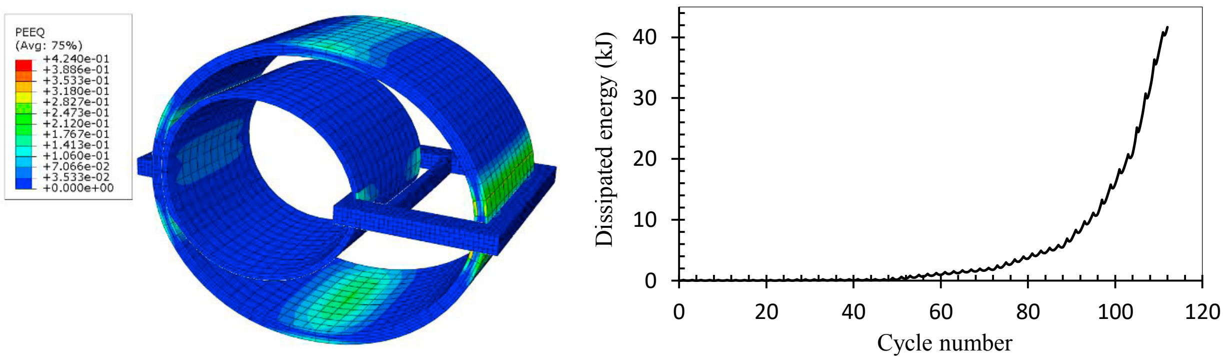
In order to survey the subsequent influence of the parameters, the load-displacement curves of two different models were plotted to evaluate the hysteresis effects. It was observed that the expansion of the hysteresis loops is directly related to the augmentations in the amount of absorbed energy. The load-displacement curves of the least and the greatest values for the absorbed energy were plotted in Fig. 8. It is found out that the absorbed energy for Ø375 and $t = 14$ mm is 13 times larger than that for Ø435 and $t = 8$ mm. At the same time, the percentage of the expansion in the hysteresis loop is almost consonant with the increase in the energy augmentation. Moreover, it is shown that the amount of applied load starts to rise suddenly in some points, at which the inner tube is engaged in the system because the amount of applied displacement is greater than the length of the gap between the handle and inner tube (see Fig.9a). In such points the load experienced by the system rises and the amount of absorbed energy increases consequently.



(a) (b)

Fig. 8. Comparison between the load-displacement curves of two different models.

Figure 9a depicts a contour of the equivalent plastic strain in a chosen model at which the locations for high plastic deformation are traceable. In addition, the energy dissipated by the plastic deformation of the chosen model was indicated in Fig. 9b. It is evident that the amount of absorbed energy is not high enough during the earlier stages while a minor earthquake might take place, but it rises rapidly after some steps of loading according to the displacement pattern reported previously.



(a) (b)

Fig. 9. a) Equivalent plastic strain contour for a chosen model, and b) Corresponding curve representing the dissipated energy.

Feasibility of the new system is another characteristic of the proposed mechanism owing to the possibility of the replacement of the outer tube in case of minor earthquakes. In this regard, there will be no need to replace the damper with a new one which is the case for the conventional dampers.

5. Conclusion

This work utilized a parametric FE study along with ANN method in order to survey the energy absorption capacity of a modified seismic damper. In addition, the improvement in the energy absorption capacity was investigated considering three different parameters of the system. It was shown that the dimensional variations affect the amount of absorbed energy which may attributed to the expansion or the contraction of the hysteresis load-displacement loops. It was found out that the increase in the tube thicknesses along with the reduction of the tube diameters improve the amount of absorbed energy. Moreover, the absorbed energy is maximized while the diameter ratio is $S = 1.6$ which is extracted as the optimal value. This research supplies a vast domain of survey in terms of three important parameters of the damper which enables the designer to propose new structures.

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