Experimental and Numerical Study of Energy Dissipation Components of a New Metallic Damper Device

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Abstract

Purpose The novel metallic damper device for passive vibration control of structures, which is designed primarily for seismic protection of buildings, is described in this paper. It consists of the base plate, fixed into foundation, with two concentric cycles of vertical components and a middle steel activating plate anchored to the isolated structure. During an earthquake, the middle steel activating plate moves together with main structure causing bending of vertical components. Seismic energy is absorbed due to plastic deformation of the vertical components of the damper. The performance of various vertical components, the key elements of the novel damper is studied in this paper. The advantages of this type of damper reflect in its ability to adapt its own features depending on the intensity of the earthquake and that it has equivalent characteristics in every horizontal direction due to rotational symmetry.

Methods Sixteen experimental tests of the vertical components of the damper, were conducted to obtain their hysteretic behaviour. Numerical models using the finite element method and the Abaqus/Standard software were developed, validated and verified with experimentally obtained results.

Results The experimental results show significant energy absorption of the vertical components of the novel damper. Numerical models can be used in further research instead of expensive experimental tests.

Conclusions The vertical components of the novel damper possess extraordinary hysteretic performance. If the components of the energy dissipation device are properly designed for maximum displacements, the device is not expected to suffer heavy damage or total failure during earthquakes.

Keywords Metallic damper · Energy dissipation · Hysteretic behaviour · Experimental test · Finite element method · Cyclic load

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Introduction

The impacts of earthquakes are dominant in design of structures in seismic active areas. During the earthquakes, the damage of the structure can be caused, as well as the collapse of the structure. Human losses and huge material costs caused by earthquakes require permanent research in the field of seismic protection of the buildings in seismic active areas. The beginnings of the earthquake-resistant design of structures date from the early twentieth century. Movement of the ground in horizontal direction during the earthquake causes large deformation and damage of structures, therefore, the first ideas for the earthquake-resistant design of structures were related to the separation of the building from its foundation by a layer of sand and talc [1].

The contemporary systems of vibration control in buildings can be divided in passive, active, semi-active and hybrid systems [2, 3]. The passive systems of vibration control are popular because they do not require any source of external energy during operation. Within the passive systems for vibration control there are two groups of devices: seismic isolation devices and energy dissipation devices. The concept where the devices for passive vibration control were placed in foundations of buildings is recognized and widely accepted as a base isolation.

Different types of seismic isolation devices were developed and tested in the past, such as elastomeric bearings, lead-rubber bearings, combined bearings, sliding friction pendulum bearings etc. The main differences between these types of isolation devices are related to the used materials and the way they provide horizontal flexibility [4, 5]. Lately, experimental and analytical researches in the field of seismic isolators are directed towards improvement of the already mentioned types of seismic isolators and the removal of their flaws [6–9].

Systems for seismic isolation and energy absorption, besides implementation in building structures, are used for seismic protection of bridges, as well [10, 11]. Numerous experimental testing, numerical and analytical analysis are available in the literature and some latest can be found in [12–17].

Beside seismic vibration isolation, passive vibration systems have been improved to implement for control of low frequency micro-vibration of structures [18].

Seismic isolators usually do not possess the capacity of energy absorption, so application of the energy dissipation devices is necessary. Passive energy dissipation devices can be divided according to the method they dissipate energy in hysteretic devices, viscoelastic devices, re-centring devices, dynamic vibration absorbers etc. There are two groups of hysteretic devices, such as metallic dampers and friction dampers. Metallic dampers dissipate energy through inelastic deformation of material, while friction dampers dissipate energy through friction. The main advantages of metallic dampers are reflected in stable hysteretic behaviour, which rate is independent of loading rate. Constitutive models of metallic materials are well known and used in every day practice, so another advantage of these dampers is simple analytical prediction of the response and calculation of the amount of energy they can dissipate [19]. According to the geometry and the shape of deformation there are different groups of metallic dampers, such as torsional beam, flexural beam, cantilever plate, U-strip etc. Flexural beam dampers are usually constructed with rectangular or circular cantilever beams. These beams are dominantly subjected to bending deformation during earthquakes and they can be applied in the base isolation system due to their geometry. Detailed experimental testing of these metallic dampers proved that they have satisfactory hysteretic behaviour [20, 21]. Recent research in this field involved experimental testing of U-shaped dampers, analysing their reliability and seismic response of building models [22–24], as well as E-shaped dampers [25]. The scope of research covers experimental testing of hysteretic behaviour of dampers made of steel plates with different geometry [26, 27]. Also, pipe dampers were developed and tested [28–30]. Recently, a new type of metallic dampers called bar dampers, made of circular bars arranged in rectangular form between two plates, was proposed and experimentally tested. It is confirmed that this type of dampers possesses significant hysteretic behaviour [31, 32]. All mentioned metallic dampers were mainly used in the concept of the base isolation and in the region of column-beam joints. On the other hand, there are dampers which are used as bracings in the frame structures and the experimental and analytical research and upgrading of these types of dampers, as well as the response of the structure with dampers, are also a current topic of research [33–43]. Furthermore, there are investigations of the aluminium usage as a material for hysteretic devices [44, 45]. Also, algorithm for investigation of optimal location of metallic dampers to reduce seismic effects on the structure were proposed [46]. Continuous research in the field of metallic dampers has led to a huge number of papers dealing with various types of dampers, which have not been mentioned in this paper, and therefore readers are referred to the state-of-the-art paper [19].

In this paper, the new vertical multi-gap multi-level multidirectional seismic energy absorber is analysed (Fig. 1) for
the purpose of providing its application in seismic engineering practice. This concept of metallic hysteresis damper for passive seismic control is developed by the three authors within the frame of the innovation project Seismo-safe 2G3-GOSEB building system, which resulted in a registered patent [47].

The experimental testing of eight vertical components of that energy dissipation device, as the main parts, with a different size of the cross section, is presented in the paper. It is proved that vertical components possess significant hysteretic behaviour and can be used for seismic energy absorption. Numerical models of all eight vertical components using finite element method in software package Abaqus/Standard are developed, verified and validated with experimentally obtained results. The proposed numerical models can be used for further analyses of the energy dissipation device as a whole. In comparison with the similar devices applied so far, this one offers important advantages as it demonstrates a high level of success in proper reaction in all directions with maintaining its ability to adapt its own features depending on the intensity of the earthquake, providing safety upon the action of the moderate, strong until the strongest possible earthquakes.

Description of the New Energy Dissipation Device

The energy dissipation device consists of vertical elements which are fixed into a base plate. Vertical elements have circular cross section changeable along the height and they are located in two circles radially symmetric. The base plate is fixed into foundations. At the top of the vertical components of the device, there is a middle steel activating plate which is fixed by a hollow part to the upper steel plate anchored into upper isolated building. All elements of the energy dissipation device were made of steel S-15-30. Between middle steel activating plate and vertical components there are gaps (smaller gaps in the inner circle and larger gaps in the external circle of the vertical components).

During the earthquake, the middle steel activating plate, together with the upper isolated building, moves and creates a contact with the vertical components of the energy dissipation device. During the contact, the vertical components bend entering inelastic range of steel behaviour. By inelastic deformation of vertical components, the seismic energy is absorbed. Different gaps size between the middle steel
activating plate and inner vertical components and between the middle steel activating plate and external vertical components give the possibility of changing the stiffness of the energy dissipation device as a whole during the weak and strong earthquakes. During the weak earthquakes, when displacement of upper isolated structure is less than the gap between the middle steel activating plate and inner circle of the vertical components, the energy dissipation device is inactive. In the case of moderate earthquakes, the inner circle of vertical components will be activated to bend and provide adequate level of energy dissipation. Finally, during the most severe earthquake, both inner and external circle of vertical components go into inelastic deformations providing full seismic energy dissipation. Based on this, the new energy dissipation device has multi-level absorption potential. This is the first advantage of this device compared to the other dampers.

The second advantage of this energy dissipation device reflects in its multi-directional property. Namely, radial symmetric disposition of the vertical components provides the same physical and mechanical characteristics of device in all directions which is very important because it is not possible to predict the direction of earthquakes.

The third advantage of this device is a possibility to design the absorption device of desired mechanical characteristic because the vertical components may have different diameter of the circular cross section. The axonometry of proposed damper and geometry of base and middle steel activating plate are shown in Fig. 1a–c, while detailed description of vertical elements will be presented in the next chapter.

For seismic isolation of buildings, the energy dissipation device should be used in combination with seismic isolation devices (for example rubber bearings or friction pendulum systems). In order to prevent excessive displacements of the isolated structure, potential rocking of structure or the occurrence of unwanted torsional deformations of the structure, it is necessary to use displacement control devices. Preventing the unwanted displacements of the isolated structure ensures that the middle steel activating plate is in the designed position, whereby the operation of the energy dissipation device during the earthquake is as designed and expected. All three devices are mounted in seismic dilatation, which is a horizontal dilatation at the level of the foundation or above the rigid basement, which divides the structure into isolated superstructure and substructure (Fig. 1d). For the adequate functioning of the devices for base isolation of buildings, a rigid foundation structure should be designed, which would not have significant displacements or rotations during an earthquake. If large rotations of foundation would occur there would be a possibility of dislocation of the components of energy dissipation device, which would have undesirable impact on its functionality.

### Experimental Testing of Model Prototypes of Vertical Components of Energy Dissipation Devices

**Geometry of Vertical Energy Dissipation Components**

Different geometrical parameters of vertical components were analysed to obtain the way it influences hysteretic behaviour of vertical components. The vertical components are made of a ductile metal in the form of a moderately steep cut cone. According to the diameter of the cone base \(d_b\), there have been adopted a total of four options from which there have arisen four types of energy dissipation components. For each type of energy dissipation components, there have been designed vertical elements in two alternative variants of cones, i.e., with different diameters of the top \(d_t\), whereas the diameter of the element at the base has been kept the same. The different types of energy dissipation (ED) components have been designated as follows:

- **Energy dissipation components Type – 1:**
  - Prototype model – 1: ED – T1 – E1 \((d_b/d_t=32.0/25.6 \text{ mm})\)
  - Prototype model – 2: ED – T1 – E2 \((d_b/d_t=32.0/19.2 \text{ mm})\)

- **Energy dissipation components Type – 2:**
  - Prototype model – 1: ED – T2 – E1 \((d_b/d_t=28.0/22.4 \text{ mm})\)
  - Prototype model – 2: ED – T2 – E2 \((d_b/d_t=28.0/16.0 \text{ mm})\)

- **Energy dissipation components Type – 3:**
  - Prototype model – 1: ED – T3 – E1 \((d_b/d_t=24.0/19.2 \text{ mm})\)
  - Prototype model – 2: ED – T3 – E2 \((d_b/d_t=24.0/14.4 \text{ mm})\)

- **Energy dissipation components Type – 4:**
  - Prototype model – 1: ED – T4 – E1 \((d_b/d_t=20.0/16.0 \text{ mm})\)
  - Prototype model – 2: ED – T4 – E2 \((d_b/d_t=20.0/12.0 \text{ mm})\)

All the vertical components have the same height of the cone body of \(h_1=190 \text{ mm}\) and end with an identical
cylinder with a diameter \( d = 24.0 \) mm with a constant length of \( h_1 = 60.0 \) mm. This gives eight different vertical components in total (Fig. 2). With the described adapted geometry of the vertical components, there have been provided equivalent conditions for fixation into the base metal plate, while through the standard cylinder at the top of the vertical elements, there have been provided equivalent conditions for excitation (contact and activation) of all the components that were tested.

All these eight originally designed vertical energy dissipation components were experimentally tested for the purpose of defining their real hysteretic behaviour under the effect of horizontal cyclic loads with increasing displacement amplitudes. This provides very well-organized comparative analysis of the influence of geometrical parameters on the hysteretic behaviour of vertical components of the new metallic damper. Therefore, the results should be useful for the future practical application and design of new metallic damper with desired characteristics.

Selection of Suitable Properties of Implemented Material

For the manufacturing of the experimental model prototypes of the energy dissipation components, there has been selected a corresponding metal S-15-30 with the pronounced ductility and ability not to experience failure under a large number of iterated cyclic loads with large amplitudes of displacement. These properties of the selected material are expected to be proved by the experimental tests.

In the mechanical manufacturing of all the experimental prototype models, metal elements with hexagonal cross-section have been used. With such selection, conditions for elaboration of a hexagonal segment necessary for the fixation of the element to the base by screwing are created. In addition, the selected profile has been used as suitable for the manufacturing of all the remaining segments of the corresponding prototype models in accordance with their designed geometrical properties (Fig. 2).

The prototypes of vertical components of energy dissipation device are shown in Fig. 3.

Experimental Testing of Produced Model Prototypes of Vertical Components of Energy Dissipation Device

Within the frames of the experimental testing of the produced model prototypes of energy dissipation devices, an ample experimental program consisting of a total of 16 nonlinear experimental tests was realized since each individual component was tested twice as follows:

- Test-1, or the so-called original test, to obtain the hysteretic response under the initial conditions;
- Test-2, or the so-called repeated test, to get an insight into the hysteretic response of the model that has already been tested.

For the successful realization of the specific experimental program within the frames of these investigations, a specific experimental platform was created. The experimental platform was created of two global segments: rigid base structure to which the base cross-sections of the experimental model were fixed and a mobile lateral structure connected to a horizontal actuator applied for simulation of cyclic loads through simulated cyclic displacements with increasing amplitudes.

The initial position of the prototype and the characteristic deformed configuration under the applied considerable horizontal displacement are shown in Fig. 4.

Experimental Results Obtained for Tested Model Prototypes of Energy Dissipation Components

In the course of the experiments, in addition to acquisition by certain control channels, there were also successfully recorded measured values of the horizontal deformation at the top \( L_x \) as well as the corresponding values of the applied horizontal force \( F_x \).

By consistent processing of the obtained experimental data, hysteretic relationships were plotted for the original and repeated tests of all eight experimental models.

The recorded hysteretic relationships for the original tests of all eight tested vertical components of seismic energy dissipation device are shown in Figs. 5a, 6a, 7a, 8a, 9a, 10a, 11a and 12a. The recorded hysteretic relationships for the repeated tests of the same tested vertical components of the seismic energy dissipation device are presented in Figs. 5b, 6b, 7b, 8b, 9b, 10b, 11b and 12b.

From the presented experimental results in graphic form, i.e., in the form of the nonlinear hysteretic relationships for the original and the repeated tests of each experimental model prototype of energy dissipation devices, it can be concluded that there is a lot of similarity. It is worth to mention that the repeated tests were performed after the original tests, without the relaxation of hydraulic jack of the actuator, therefore the initial conditions for the repeated tests were zero displacement and non-zero force. Thus, the obtained hysteresis diagrams for the repeated tests should be shifted along force axis to annul residual force. Taking this into account, it can be concluded that hysteretic behaviour of all tested prototypes is stable and symmetric. In the Table 1, mean values of absolute values of maximal force in both directions for the original and repeated tests are shown. This way, it is proved that the designed innovative energy dissipation components
Fig. 2 Model prototypes of vertical components of energy dissipation device constructed for experimental testing (measures in mm): a ED-T1-E1; b ED-T1-E2; c ED-T2-E1; d ED-T2-E2; e ED-T3-E1; f ED-T3-E2; g ED-T4-E1; h ED-T4-E2
**Fig. 3** Model prototypes of vertical components of energy dissipation device constructed for experimental testing; *a* ED-T1-E1 to ED-T4-E1; *b* ED-T1-E2 to ED-T4-E2

**Fig. 4** View of experimental test set-up for testing of model prototypes of energy dissipation components under the simulated reversed cyclic loads with the increasing displacement amplitudes

**Fig. 5** Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T1-E1; *a* Original test; *b* Repeated test
Fig. 6  Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T1-E2; a Original test; b Repeated test

Fig. 7  Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T2-E1; a Original test; b Repeated test

Fig. 8  Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T2-E2; a Original test; b Repeated test
possess extraordinary nonlinear performances and do not suffer considerable degradation of performance and damage during the repeated tests.

From the general presentation of the obtained experimental results given above, it is clear that the presented experimental research confirmed the advanced features of the proposed energy dissipation devices for real practical applications.

Fig. 9 Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T3-E1; a Original test; b Repeated test

Fig. 10 Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T3-E2; a Original test; b Repeated test

Fig. 11 Recorded hysteretic model response under the simulated reversed cyclic loads for specimen ED-T4-E1; a Original test; b Repeated test
Numerical models of vertical components using the finite element method and the Abaqus/Standard software were developed. The detailed procedure of modelling is presented in this chapter. The main goal of the numerical analysis is to calibrate the finite element model of all types of vertical components of energy dissipation device. Numerical results are compared with the experimentally obtained results to validate and verify the proposed models. They can be used in the further research of the proposed damper instead of expensive experimental tests.
Geometry and Material Modelling

Geometry of the numerical models was created according to the physical models of the prototypes of vertical components of the energy dissipation device (Fig. 2). The threads for mounting and fixing the energy dissipation devices into experimental platform were not modelled because stress concentration in the thread’s region was not the subject of this analysis. Geometry of all models of the energy dissipation devices are shown in Fig. 13.

Cyclic displacements, that prototype is exposed to during the experiment, were applied by the mobile lateral structure connected to a horizontal actuator. The mobile lateral structure consists of two parts: flexible element and fixed element. Geometry of the mobile lateral structure of the test equipment is shown in Fig. 14a, b. The whole mobile lateral structure was not modelled because its stress–strain analysis was not the subject of this paper. One part of the mobile lateral structure in the region of contact with the prototype was modelled (Fig. 14c), and real behaviour in concordance with the experimental equipment was modelled with the suitable boundary conditions.

Energy dissipation devices were made of steel S-15-30. Module of elasticity of steel material is $E = 190$ GPa and Poisson’s ratio is $\nu = 0.30$ and with these parameters linear elastic behaviour of the material is described in numerical model. Yield stress of steel is $f_y = 430$ MPa, ultimate stress is $f_u = 745$ MPa and ultimate elongation is 16%. In the numerical analysis nonlinear behaviour of the material is modelled adopting bilinear kinematic hardening model with yield stress $f_y = 430$ MPa and tangent modulus $E_t = 6600$ MPa. Besides material nonlinearity, numerical analysis includes geometrical nonlinearity as well.

Boundary Conditions, Load and Contacts

At the surface of the part of vertical component that is fixed in experimental platform, displacement in three orthogonal directions were fixed and these boundary conditions represent clamping of the prototype. Lateral cyclic displacement in $x$ direction was subjected in the middle point of the two-parallel surface of the mobile structure, while the displacement in two other directions was fixed (Fig. 15). With these boundary conditions, the rotation of mobile lateral structure was allowed which is in accordance with the experimental set up. Magnitude of lateral displacement is adopted according to the experiment as much as possible (Fig. 16) taking into account that there were uncertainties and deviations during the experimental testing of the vertical components.
Interaction between the mobile lateral structure and energy dissipation device was modelled with a standard surface to surface contact. This type of contact transfers forces normal to the contact surfaces and the friction between two surfaces was analysed introducing friction coefficient 0.40. Two pairs of contact surfaces were defined on the appropriate sides with the concordance with the direction of the applied displacement through the analysis steps (Fig. 17). Pair of contact surfaces presented in the Fig. 17a is defined in the analysis steps where the displacement of mobile lateral structure is in positive x direction. The other pair of surfaces will not get in contact during the displacement in positive x direction which is the reason why contact surfaces are not defined on this side of the vertical components in those steps. Alternatively, in the analysis steps where the displacement of mobile lateral structure is in negative x direction adequate contact surfaces were defined (Fig. 17b). This way, by properly defining contact surfaces, the computational time is reduced compared to the case of defining contact surfaces all over the cylinder of the vertical components and mobile lateral structure.

**Finite Element Mesh**

The models of all types of vertical components of energy dissipation device were meshed with solid finite elements. Convergence of mesh was done on the model ED-T1-E1 and model ED-T4-E2 to obtain the optimal element type and mesh density. The number of the finite elements, i.e., the number of nodes, the application of the linear and quadratic shape functions, as well as the type of the integration to obtain the finite element stiffness matrix was varied in the mesh convergence analysis. As a subject of the comparative analysis, the force–displacement relation was adopted, as well as elastic and post-yield stiffness. The models were subjected to gradually increasing displacement of the mobile lateral structure. The results were also compared to the experimentally obtained values. All results are systematized in Fig. 18. In all analysed cases finite element mesh of the mobile lateral structure were the same, and only number of elements i.e., number of nodes of vertical component of energy dissipation device varied. Number of nodes/elements shown in Fig. 18 refer to mesh of vertical component. It can be concluded that the solid elements with 8 nodes and linear functions show much more stiff behaviour, especially in the case ED-T4-E2. With dominant bending deformation when solid elements with linear functions are applied, a large shear stiffness can occur, which is not realistic. This phenomenon is known as “shear locking”. This can be prevented by increasing the number of finite elements, using solid elements with 20 nodes and quadratic functions or using reduced integration [48, 49]. All these types of finite elements were used with different mesh size, while the results differ in less than 5% (Fig. 18). For the further analysis, a model with solid 8 nodes elements with linear shape functions and reduced integration, which consists of 4404 elements and 5020 nodes in case ED-T1-E1 and 4476 elements and 5140 nodes in case ED-T4-E2, has been chosen because it is more favourable, considering the calculation time and the required computer resources. Density of the finite element mesh in other types of vertical components of energy dissipation device was the same, but the number of nodes differs slightly because of the small changes in geometry. Finite element mesh of all analysed cases is shown in Fig. 19.

![Mesh convergence – force–displacement relation](image1)

**Fig. 18** Mesh convergence – force–displacement relation; a ED-T1-E1; b ED-T4-E2
Results and discussion

A nonlinear static analysis was performed with the displacement applied incrementally, where each analysis step was divided into 100–10,000 increments. Selected output data were displacements and forces (X-direction in numerical model). The force–displacement relationship was obtained and compared with the experimental results for all analysed cases of the energy dissipation components (Fig. 20). Experimentally and numerically obtained elastic and post-yield stiffnesses are compared as well. It can be concluded that the numerical results agree well with the experimental results analysing forward loading passes. Slightly deviation can be seen in backward loading passes, which is partly a consequence of the robustness and less sensitiveness of experimental equipment and residual forces in hydraulic jack of the actuator. Further research on this deviation should be done, but in general satisfactory numerical results were obtained in concordance to the experimental results. The proposed FEM model is verified and validated and can be used in further research instead of expensive experimental tests.

To obtain the influence of the steepness of the cone to the stress–strain relation in the vertical components of energy dissipation device, von Mises stress and plastic strains were analysed and based on that yield strength of all analysed vertical components of energy dissipation device were defined. Very important parameter for energy absorption is an area of hysteresis loop as a measure of the dissipated energy. For all analysed types of the vertical components of energy dissipation device (from ED-T1-E1 to ED-T4-E2) area of hysteresis loop was measured both for experimentally obtained results and numerical results in last loading – unloading loop. Results are shown in Table 2, as well as the difference between experimentally and numerically obtained results.

It can be concluded that numerical models give slightly higher values of absorbed energy than the experimentally obtained values. In most cases the difference between experiment and FEM results is less than 10%, except in the cases ED-T3-E2 and ED-T4-E1 where difference is less than 12%, which can be accepted as a correct agreement of numerical and experimental results.

Important parameter to evaluate performance of a metallic damper is cumulative dissipated energy vs cumulative displacement curve [50] and these curves are shown in Fig. 21 for all analysed vertical components of the proposed metallic damper. Moreover, comparative analysis of numerical and experimental results is present. Cumulative dissipated energy curves indicate that vertical components have significant damping, which is directly proportional to the diameters of the cone body of vertical components. Also, the dissipated energy monotonically increases as a function of the accumulative displacement. Comparing the results one can conclude that there is a reasonable agreement of the numerical and experimental results, taking into account that differences are less than 10%.

Other crucial parameters used to rate hysteretic dampers are effective stiffness (\(K_{\text{eff}}\)) and effective viscous damping ratio (\(\beta_{\text{eff}}\)) which is directly proportional to the total dissipated energy in each cycle i.e., an area of hysteresis loop.
Fig. 20  Force–displacement (hysteretic) diagrams—comparison of numerically and experimentally obtained results: a) ED-T1-E1; b) ED-T1-E2; c) ED-T2-E1; d) ED-T2-E2; e) ED-T3-E1; f) ED-T3-E2; g) ED-T4-E1; h) ED-T4-E2
Those parameters can be obtained for each cycle as:

\[
K_{\text{eff}} = \frac{|F_{\text{max}}| + |F_{\text{min}}|}{|D_{\text{max}}| + |D_{\text{min}}|},
\]

(1)

\[
\beta_{\text{eff}} = \frac{2E_{\text{loop}}}{\pi K_{\text{eff}}(|D_{\text{max}}| + |D_{\text{min}}|)^2},
\]

(2)

where \(F_{\text{max}}\) and \(F_{\text{min}}\) are maximal restoring forces and \(D_{\text{max}}\) and \(D_{\text{min}}\) maximal displacements in forward and backward loading passes of each loading cycle.

The effective stiffness and viscose damping ratio as a function of cumulative displacement for all analysed vertical components are shown in Figs. 22 and 23, respectively, for experimental as well as numerical results. It can be concluded that numerical analysis gives slightly lower effective stiffness and higher effective viscose damping ratio. The trends for both parameters are similar for the numerical and experimental results and reasonable agreement between the results can be noticed.

To define idealized force–displacement curve there is a need to define elastic stiffness \(K_e\), post-yield stiffness \(K_y\) and yield strength \(F_y\) (Fig. 24). Based on the data processing of the experimental and numerical results in forward

**Table 2** Area of hysteresis loops in last loading–unloading cycle as measure of absorbed energy

| Energy dissipation component | Absorbed energy |   |   |
|-----------------------------|-----------------|---|---|
|                            | Experiment [kNmm, J] | Numerical (FEM) [kNmm, J] | Difference [%] |
| ED-T1-E1                   | 1659.35          | 1798.54          | 8.39 |
| ED-T1-E2                   | 1336.09          | 1457.30          | 9.07 |
| ED-T2-E1                   | 1162.20          | 1170.49          | 0.71 |
| ED-T2-E2                   | 910.81           | 885.79           | 2.75 |
| ED-T3-E1                   | 693.45           | 710.18           | 2.41 |
| ED-T3-E2                   | 499.34           | 558.37           | 11.82 |
| ED-T4-E1                   | 341.49           | 377.23           | 10.47 |
| ED-T4-E2                   | 320.86           | 309.23           | 3.62 |
loading passes the elastic stiffness and post-yield stiffness, for all analysed prototypes of vertical components of the energy dissipation device, are systematized in Table 3. It can be concluded that the elastic stiffness is proportional to the diameter of the cone base and top which is the expected result. Comparing the results of the post-yield stiffness, it can be concluded that in the case of the same diameter in the cone base and for a different diameter at the cone top (for example cases ED-T1-E1 and ED-T1-E2) larger post-yield stiffness is in the case of the larger diameter of the cone top. When comparing the post-yield stiffness of the models ED-T1-E2 and ED-T2-E1, for example, it can be seen that the post-yield stiffness is about the same, or even greater in the case of ED-T2-E1 which have a smaller diameter of the cone base compared to ED-T1-E2. This is the consequence of the different steepness of the cone in compared cases, which

Table 3 Elastic and post-yield stiffness of vertical components – comparative analysis of experimental and numerical results

| Energy dissipation device | Elastic stiffness Ke | Post-yield stiffness Ky |
|--------------------------|---------------------|------------------------|
|                          | Experiment [kN/mm]  | Numerical (FEM) [kN/mm]| Difference [%] | Experiment [kN/mm] | Numerical (FEM) [kN/mm] | Difference [%] |
| ED-T1-E1                 | 1.9882              | 1.9844                  | 0.19          | 0.1096              | 0.1036                  | 5.79          |
| ED-T1-E2                 | 1.4353              | 1.4372                  | 0.13          | 0.0606              | 0.0619                  | 2.15          |
| ED-T2-E1                 | 1.2224              | 1.1832                  | 3.31          | 0.0655              | 0.0634                  | 3.31          |
| ED-T2-E2                 | 0.8131              | 0.7987                  | 1.80          | 0.0362              | 0.0342                  | 5.85          |
| ED-T3-E1                 | 0.6623              | 0.6498                  | 1.92          | 0.0383              | 0.0364                  | 5.22          |
| ED-T3-E2                 | 0.4493              | 0.4646                  | 3.41          | 0.0218              | 0.0221                  | 1.38          |
| ED-T4-E1                 | 0.3081              | 0.3174                  | 3.02          | 0.0242              | 0.0234                  | 3.42          |
| ED-T4-E2                 | 0.2189              | 0.2267                  | 3.56          | 0.0120              | 0.0119                  | 1.09          |

Fig. 25 Stress–strain distribution ED-T1-E1: a plastic strain, force 6.91 kN; b von Mises stress, force 6.91 kN; c plastic strain, force 15.59 kN; d von Mises stress, force 15.59 kN
leads to different development of the plasticized zone across the cone body of the vertical components. This phenomenon will be explained in the following text where stress–strain analysis is discussed.

The influence of the cone body steepness on the stress–strain state of the vertical components will be analysed based on the distribution of plastic strains. Figure 25a and b show the plastic strains and von Mises stresses at the moment corresponding to the beginning of the plasticization of the steel material of the model ED-T1-E1, where the corresponding force is 6.91 kN. Figure 25c and d show the plastic strains and von Mises stresses in the same model, but at the maximal analysed force of 15.59 kN. It is concluded that the fibres in the nut zone are plasticized first, where von Mises stresses at that time are approximately equal to the yield stress of the steel material. With a further force increase, the plasticized zone expands towards the free end of the vertical component of the energy dissipation device, where the von Mises stress at the maximal analysed force is about 710 MPa, which is slightly less than the ultimate capacity of the steel material. Figure 26 shows the distribution of plastic strains at the beginning of plasticization of the steel material and at the maximal analysed force in the vertical component for the rest of the analysed models (ED-T1-E2 to ED-T4-E2). Comparing the alternative variants of the cone (E1 and E2) of all analysed models (ED-T1 to ED-T4), it is noticed that when the cone is steeper (E2) the plasticization of the steel material occurs at the cross section along the body of the vertical component of the energy dissipation device, while in the case of milder cones (E1) the fibres in the nut zone are plasticized first. Based on the forces that lead to plasticization of steel material and maximal analysed forces at equivalent displacements of the vertical components, it can be concluded that with a decrease in the diameter of the cone base and top there is a decrease in the plasticization force and bearing capacity of the vertical component. In the idealized model of the force–displacement dependence of the vertical component (Fig. 24), the force leading to the plasticization of the steel material (Figs. 25 and 26) can be adopted as yield strength. Finally, all parameters for defining idealized force–displacement relationship of all analysed prototypes of vertical components were defined.

Conclusions

The paper presents a new metallic damper for passive vibration control of structures called vertical multi-gap multi-level multi-directional seismic energy absorber. The proposed device absorbs energy through plastic deformation of the material which vertical components are made of. Experimental testing of eight different vertical components of the energy dissipation device was conducted. The tests consist of the original test and the repeated test done for all eight prototypes. The aim of the original test was to determine hysteretic behaviour of the prototypes and the aim of the repeated test was to get an insight into the hysteretic response of the model that has already suffered plastic deformation. Numerical models using the finite element method and the software Abaqus/Standard were developed in accordance with the physical characteristics of the prototypes and the procedure of modelling was explained in detail. The numerical results show good agreement with the experimentally obtained results. Based on all of the above, general conclusions can be summarized:

1. The vertical components of proposed innovative seismic energy dissipation device are expected to possess extraordinary performance since the hysteretic diagrams are very wide, stable and have significant area which represents dissipated energy.

2. With the repeated experimental tests, it is confirmed that the vertical components of seismic energy dissipation device neither experience degradation of the characteristics of the resisting force, nor the damage.

3. If the components of the energy dissipation device are successfully designed for maximum displacements, the device is not expected to suffer heavy damage or total failure during repeated earthquakes.

4. The proposed numerical finite element model is validated and verified. The numerical results are in a good correlation with the experimentally obtained results from the aspect of dissipated energy (area of cyclic loop) and elastic and post-yield stiffness. The proposed numerical model can be used in the analysis of the vertical component of the energy dissipation device with the variation of its geometry and mechanical characteristics of the material. The numerical model can also replace expensive experimental tests for the research of the energy dissipation devices.

5. The rate of the diameter change of cone body of the vertical components of the energy dissipation device affects the distribution of the plastic strains. Namely, in the case of the steeper cone (larger rate of diameter change) the plasticization of steel begins in the cross section along the body of the vertical component, while in the case of the milder cone (smaller rate of diameter change) the plasticization of steel begins in the zone of the nut.

This paper is the beginning of the research of the performance of a new metallic damper. Taking into account that novel metallic damper possesses rotational symmetry, it is expected to have the same performance in all horizontal directions. Moreover, the middle steel activating plate...
Fig. 26 Plastic strain distribution: a ED-T1-E2, force 6.07 kN and 11.92 kN; b ED-T2-E1, force 4.74 kN and 10.10 kN; c ED-T2-E2, force 3.85 kN and 7.29 kN; d ED-T3-E1, force 2.96 kN and 6.14 kN; e ED-T3-E2, force 2.59 kN and 4.74 kN; f ED-T4-E1, force 1.74 kN and 3.41 kN; g ED-T4-E2, force 1.47 kN and 2.66 kN
simultaneously transfers a displacement from upper isolated structure to all vertical components along one vertical tangent of the upper cylinder of the vertical components. Based on that it is expected that the hysteretic performance of the novel metallic damper is proportional to the hysteretic performances of the vertical components and their number. Our focus in further research will be on determination of the hysteretic behaviour of the whole assembly of the metallic damper and to prove the expected results previously mentioned. In this regard, the principles of the herein presented numerical model will be used for numerical investigation of the whole assembly of the metallic damper. The main goal will be to prove that with the proper choice of the geometrical characteristics of the vertical components, the metallic damper can be designed with characteristics appropriate for the expected earthquake.

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Code Availability Not applicable.

Declarations

Conflict of Interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

Ethical Approval All parts of this research and manuscript are done in accordance with the rules of good scientific practice.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

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