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NUMERICAL ANALYSIS OF AN INNOVATIVE ENERGY DISSIPATION DEVICE

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Abstract

Application of systems for passive vibration control is an efficient way for seismic protection of structures. Systems for passive vibration control consist of seismic isolation devices and energy dissipation devices. Base isolation of structures is a concept where devices for passive vibration control are placed in foundations of buildings. Various energy dissipation devices have been developed and tested so far, while metallic dampers represent a significant class. Those devices dissipate energy through the yield of metal material which they are made of. The metallic dampers have often been used because of their main advantages reflected in stable hysteretic behavior and well-known models for analytical prediction of the dissipated energy and structural response. Most of the metallic dampers have been developed for application in the beam-column joints or in the bracing system. The innovative energy dissipation device named multi-gap multi-level multi-directional seismic energy absorber, intended for the application in the horizontal seismic dilatation in the system of base isolation, has been developed recently by the group of the authors among whom is one of the authors of this paper. The main parts of the absorber are vertical components with linearly changeable circular cross-section. Due to the lateral displacements of the isolated structure the vertical components bend and energy dissipation is provided by yielding of the steel material they are made of. According to the previous experimental and numerical study of the absorber's vertical components, three-dimensional finite element model of the absorber has been developed and presented in this paper. The aim of the numerical analysis is to determine mechanical properties of the absorber based on the lateral force-displacement diagram. Furthermore, a simplified numerical model using one-dimensional beam finite elements has been proposed. The performance of the absorber has been determined using the available semi-analytical solution for elastoplastic deflection of non-prismatic cantilever beams previously developed by the first author as well. The obtained results have been compared and it has been concluded that all three modelling approaches provide reliable mechanical properties of the absorber necessary for dynamic analysis of structures in engineering practice.

Keywords: Metallic damper, finite element method, elastoplastic bending, lateral force-displacement relationship.

1. Introduction

Traditional design of structures in seismic areas demands ensuring sufficient ductility of the structure so that it dissipates seismic energy through inelastic deformations dominantly in the beam-column joints. On the other hand, systems of vibration control have been developed in the last few decades, whereby they are classified into passive, active, semi-active and hybrid systems (Spencer and Nagarajaiah 2003; Saaed et al. 2015). The advantage of the passive vibration control systems is that they do not require external energy for operation. Seismic isolation devices and energy dissipation devices are two main parts of the passive vibration control systems. The base isolation concept implies the application of these devices mounted in the seismic dilatation in the level of the building foundations.

Seismic isolation devices have high stiffness in the vertical direction to transfer gravity loads, but relatively low stiffness in the horizontal directions. Consequently, the application of these devices increases the natural period and changes the response of the structure during the earthquake. By increasing the natural period of the structure, the value of mass acceleration decreases, and thus the intensity of seismic forces in the structure is reduced. Based on the used materials and operation mode to provide horizontal flexibility, there are different types of seismic isolation devices: elastomeric bearings, sliding bearings and combined bearings (Kelly 1986; Naeim and Kelly 1999; Higashino and Okamoto 2006; Zorić 2023).

Application of the energy dissipation devices provides additional damping in the structural system. Passive energy dissipation devices can be classified into hysteretic devices, viscoelastic devices, re-centering devices, phase transformation dampers and dynamic vibration absorbers (Saaed et al. 2015, Zorić 2023). Metallic dampers are hysteretic devices which dissipate energy through inelastic deformation of steel material they are made of. They are characterized by stable hysteretic behavior; therefore they have found wide application in practice. A large number of different types of these devices have been developed so far (Zorić 2023; Javanmardi et al. 2020) with the primary application in the bracing systems of the frame structures or in the beam-column joint regions.

The innovative energy dissipation device named multi-gap multi-level multi-directional seismic energy absorber, intended for the application in the horizontal seismic dilatation in the system of base isolation, has been developed, tested and patented recently by the group of the authors among whom is one of the authors of this paper (Zlatkov et al. 2022; Projektinženjering tim et al. 2018). The main parts of the absorber are vertical components with linearly changeable circular cross-section, radially symmetrically positioned in two concentric circles and fixed into base plate (Fig. 1). The device is anchored to the substructure via base anchors. The middle activating plate is located at the top of the vertical components, whereby it is connected to the superstructure by a central hollow part and the upper plate anchored into upper isolated building. Due to the lateral displacements of the isolated superstructure, the middle activating plate comes into contact with the vertical components, whereby the vertical components bend and, when yield of steel material occurs, energy dissipation is provided. Between the middle activating plate and vertical components there are smaller gaps in the inner circle and larger gaps in the outer circle of the vertical components. Different gap sizes provide different stiffness of the device under various lateral displacements of a superstructure during weak and strong earthquakes. Hence, the innovative energy dissipation device has multi-level absorption potential, which is its advantage over the other dampers (Zorić 2023; Zlatkov et al. 2022).

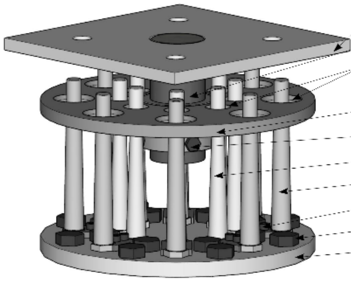


Fig. 1. Geometry and components of the innovative energy dissipation device

The experimental testing of the vertical components of the innovative energy dissipation device has been previously conducted and the numerical model of vertical components based on the finite element method and software Abaqus/Standard has been previously validated according to the experimental results (Zlatkov et al. 2022). According to this research, three-dimensional finite element model of the absorber has been developed (Zorić 2023) and presented in this paper. A simplified numerical model using one-dimensional beam finite elements has been proposed as well. Finally, the performance of the absorber is determined using the previously developed semi-analytical solution for elastoplastic deflection of non-prismatic cantilever beams with linearly changeable circular cross-section (Zorić et al. 2022). The aim of the numerical analyses is to determine mechanical properties of the absorber based on the lateral force-displacement diagram, as well as to reveal the advantages and disadvantages of those three numerical modelling approaches.

2. Geometry and material properties of the innovative energy dissipation device

The detailed geometric characteristics of the base plate and middle activating plate of the analyzed energy dissipation device are presented in Fig. 2a, b, while the geometry of the vertical components is presented in Fig. 2c. The vertical components are in the form of a moderately steep cut cone with the diameter of the cone base 32 mm and the diameter of the cone top 25.6 mm. The height of the cone body of the vertical components is 190 mm. The vertical components end with the cylinder with the diameter 24 mm and with the length of 60 mm, through which displacements of the isolated superstructure and middle activating plate are transmitted. At the bottom of the vertical component there is a screw nut and the cylinder with the metric thread for its fixation into the base plate. A gap between the middle activating plate and the inner and the outer circle of the vertical components is 5 mm and 18 mm, respectively. It is worth mentioning that the contribution of the central hollow part, upper plate, anchors, bolts and fasteners, as well as holes, to the mechanical properties of the innovative energy dissipation device is negligible, so these parts are not modeled in numerical analyses.

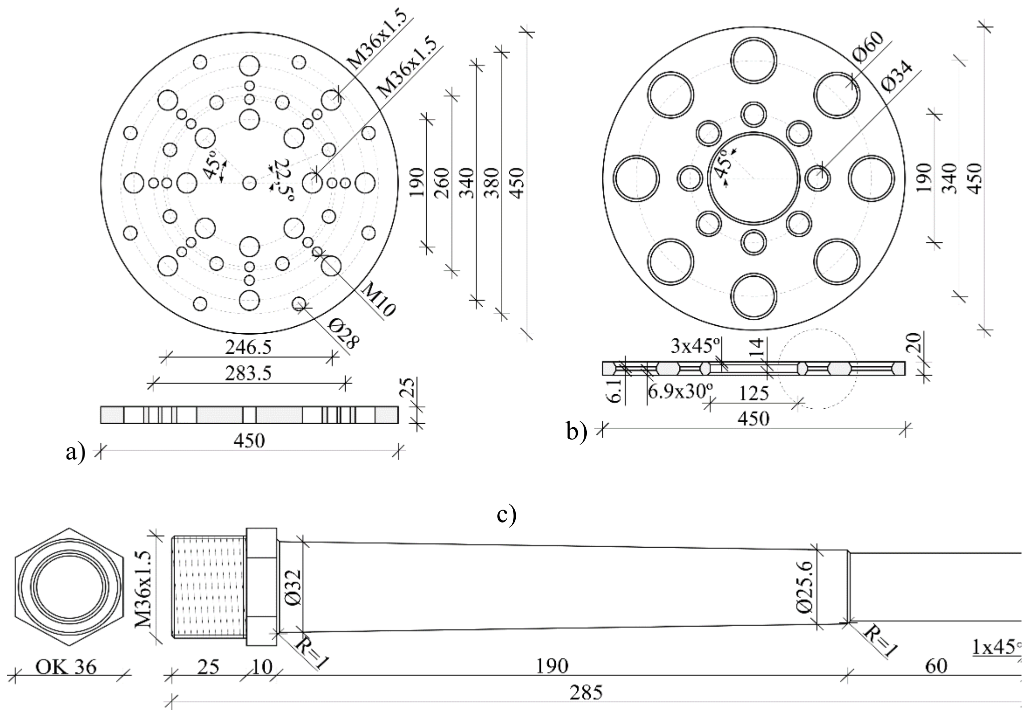


Fig. 2. Geometry of the components of the innovative energy dissipation device: a) base plate, b) middle activating plate, c) vertical component (measures in mm)

The innovative energy dissipation device is made of steel C45 (Zorić 2023; Zlatkov et al. 2022). In all numerical models, steel material behavior is defined using bilinear material model. The linear elastic branch is defined with the modulus of elasticity E = 190 GPa and the Poisson's ratio ν = 0.30, while plastic behavior is defined with the yield stress f_y = 430 MPa and the tangent modulus E_t = 6600 MPa, which corresponds to the ultimate stress f_u = 745 MPa and the corresponding strain ε_u = 5%.

3. Numerical analysis of the performance of the innovative energy dissipation device

Mechanical properties of the innovative energy dissipation device have been defined by analyzing force-displacement relationship obtained by developed three-dimensional finite element model and simplified one-dimensional beam finite element model using Abaqus/Standard software. The analysis has been performed using the semi-analytical solution for elastoplastic deflection of non-prismatic cantilever beams presented in Zorić et al. (2022) as well, taking into account that vertical components can be idealized as cantilever beams. Details of these numerical models are presented in this section.

3.1 Three-dimensional finite element model

Based on the geometry of individual components of the assembly of the innovative energy dissipation device (Fig. 2), the geometry of the numerical models has been defined (Fig. 3). Appropriate boundary conditions need to be defined to adequately simulate the behavior of the absorber. The base plate is anchored to the substructure, therefore, in the numerical model displacements in three orthogonal directions of the bottom surface of the base plate are fixed (Fig. 3). The lateral displacements of the isolated superstructure are transferred to the central opening of the middle activating plate. The performance of the absorber is determined for monotonically increasing displacement up to a value of 45 mm defined at the inner surface of the mentioned central opening. It is necessary to prevent rotations of the isolated superstructure for the proper functioning of the energy dissipator. Therefore, it can be considered that there is no rotation of the middle activating plate, which is modeled by fixed displacements of the inner surface of central opening in the *y* and *z* directions of the global coordinate system (Fig. 3).

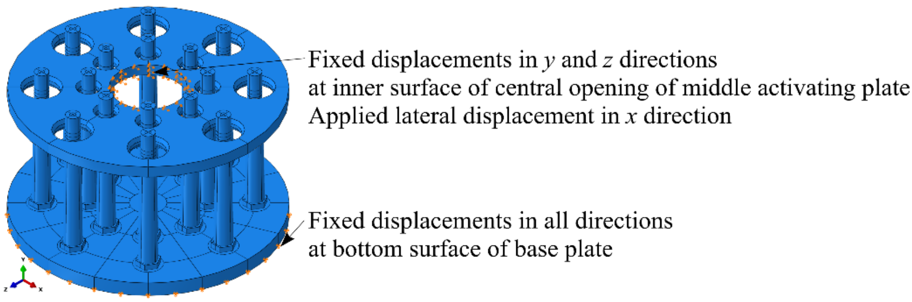


Fig. 3. Geometry of the three-dimensional numerical model, boundary conditions and load

Interaction of the middle activating plate and vertical components is modelled with a standard surface to surface contact (Abaqus Theory Manual 2011). This type of contact transfers forces normal to the contact surfaces. The friction between two surfaces is analyzed as well, where the friction coefficient is 0.40. Two pairs of contact surfaces are defined on the appropriate sides matching with the direction of the applied displacement at each vertical component and the corresponding opening in the middle activating plate (Fig. 4).

The aim of the numerical analysis is not to determine the stress-strain state in the metric thread, so it is not modeled, but the connection between the cylinder with metric thread and the base plate is modeled as an ideal connection without slippage. This is achieved by introducing the constraint that the displacements of the finite element nodes on the surfaces of the cylinders with the metric thread and the inner cylindrical surfaces of the holes in the base plate are equal (Fig. 5).

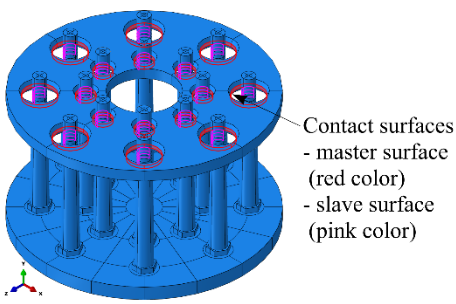


Fig. 4. Interaction of the middle activating plate and vertical components

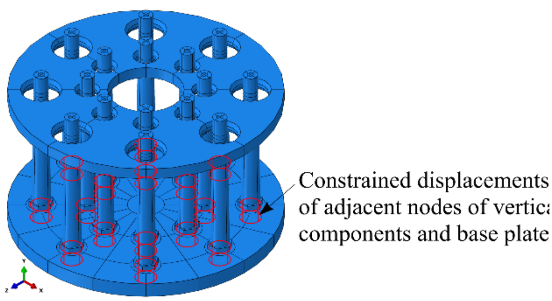


Fig. 5. Interaction of the vertical components and base plate

The model is meshed with solid eight nodes' elements with three degrees of freedom per node, with linear shape functions and reduced integration (C3D8R) (Abaqus Theory Manual 2011). Approximate global size of finite elements is 15 mm, while the circle shapes are divided into twenty-four segments except for larger openings in the middle activating plate which are divided into thirty-two segments. With such adopted mesh density model has 71211 elements and 85788 nodes. The finite element mesh is shown in Fig. 6. Besides material nonlinearity, numerical analysis includes geometrical nonlinearity as well.

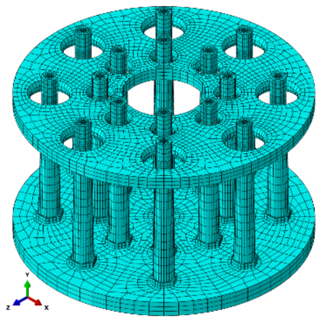


Fig. 6. Finite element mesh

3.2 One-dimensional finite element model

In the simplified one-dimensional finite element model only one vertical component is analyzed as cantilever beam. The cone body of the vertical component has linearly changeable cross-section. In this model, the cone body is approximated with nine segments with constant cross-section with an average diameter. The first eight segments are of length of 20 mm, and the last segment is of length of 30 mm (overall 190 mm which is the length of cone body). It is assumed that the vertical component of the innovative energy dissipation device is clamped at the bottom side of the cone body (Fig. 7). The displacement is applied at the height of the middle activating plate, which is at 40 mm below the top of the cylindrical end of the vertical component (Fig. 7). The model is meshed with beam finite elements with three nodes and six degrees of freedom per node (B32) (Abaqus Theory Manual 2011). Every segment is divided into four finite elements, which provides model with 44 elements and 99 nodes. It is worth mentioning that the displacements of the nodes of adjacent segments are constrained to be equal, which ensures continuity of the vertical component. This numerical model includes material and geometrical nonlinearity, as it is included in the previous model.

Fig. 7. Geometry of the one-dimensional numerical model, boundary condition and load

Overall lateral force due to the lateral displacement in the innovative energy dissipation device is equal to the sum of the lateral forces in single vertical components (Zorić 2023). While the lateral displacement of the middle activating plate is smaller than the size of the gap between it and the vertical component, there is no lateral force. Therefore, responses of the vertical components in the inner and the outer circles are analyzed from the moment of their contact with the middle activating plate. So, the intensity of the subjected lateral displacement is obtained subtracting the gap size from the analyzed lateral displacement of the middle activating plate (45 mm, see Section 3.1). Based on this, the vertical component of the inner circle is subjected to the lateral displacement of 40 mm, while the vertical component of the outer circle is subjected to the lateral displacement of 27 mm. According to such modeling procedure, the obtained lateral force-displacement diagram for single vertical component is shifted for the value of the gap size. This is done for the vertical component in the inner, as well as in the outer circle. Finally, by summarizing results over all vertical components, the lateral force-displacement relationship for the whole innovative energy dissipation device is obtained.

3.3 Semi-analytical solution

The semi-analytical solution for elastoplastic deflection of non-prismatic cantilever beams with linearly changeable circular cross-section has been previously developed and presented in Zorić et al (2022). The solution has been validated to provide satisfactory results compared to the experimental results of single vertical components of the innovative energy dissipation device (Zorić et al. 2022). In order to use this solution, the vertical component should be idealized as cantilever beam. It is assumed that the vertical component is clamped at the level of the middle plane of the nut and that the free end is at the middle activating plate because it does not constrain displacements and rotations of the vertical component. The part of the cylinder between the load application zone and the free end does not contribute to the performance of the vertical components. By neglecting the top cylinder cross-section, the vertical component can be considered as a cantilever beam with linearly changeable cross-section, as shown in Fig. 8.

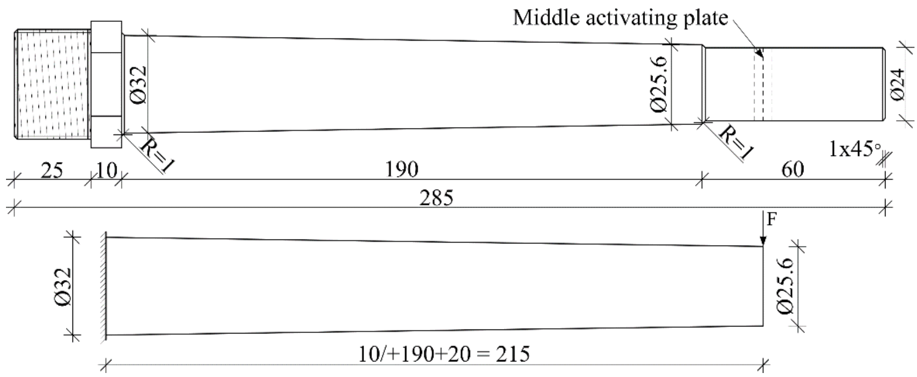


Fig. 8. Mathematical model of the vertical component for semi-analytical solution (measures in mm)

Bernoulli-Euler formula has been used to define elastic branch in the lateral force-displacement diagram. By incremental increase of plasticized part of the critical cross-section, using derived expression for bending moment in the function of a plasticized part of a cross-section and static equilibrium, the corresponding discrete values of lateral force have been calculated. For the discrete value of lateral force, the values of curvature have been defined in equidistant segments of the plasticized region of the beam. After approximation of the curvature function in the plasticized region and solving the beam deflection differential equation, with application of the Bernoulli-Euler formula in elastic region of the beam and appropriate boundary and continuity conditions, discrete values of the lateral displacements of the cantilever vertical component have been obtained (Zorić et al. 2022). Pairs of discrete values of force and displacement of the free end of the cantilever beam define plastic branch in the lateral force-displacement diagram for single vertical component. Summarizing results over all vertical components, as previously explained in Section 3.2, the lateral force-displacement relationship for the whole innovative energy dissipation device is defined.

4. Results and discussion

The main result of defining mechanical properties of the innovative energy dissipation device is the lateral force-displacement relationship. The results of all three numerical modelling approaches are presented and compared in Figure 9a. It can be concluded that there is a good correlation of the results in the qualitative manner, as well as that three-dimensional model gives slightly higher force intensity compared to the other two numerical models.

There are five phases in the response of the innovative energy dissipation device. In the first phase, when the displacement of the middle activating plate is less than the gap between it and the inner circle of the vertical components, the absorber is inactive (there is no lateral force). With displacement increasing, the contact of the middle activating plate and the vertical components in the inner circle occurs, causing bending and the lateral force in the energy dissipator. This represents the second phase of the response of the energy dissipator, when the steel material is in the elastic regime. After the plasticization of the vertical components in the inner circle, the absorber is in the third phase. The fourth phase of the energy dissipator begins with the activation of the vertical components in the outer circle (displacement of the middle activating plate is greater than the gap between it and the outer circle of the vertical components). In this phase, the vertical components in the outer circle are in the elastic regime, while the plasticization of the vertical components in the inner circle increases. Finally, the fifth phase is characterized by plasticization of all vertical components, when the device provides full dissipation potential. This result confirms multi-level absorption potential of the device, and the response can be idealized with multilinear function (Fig. 9b).

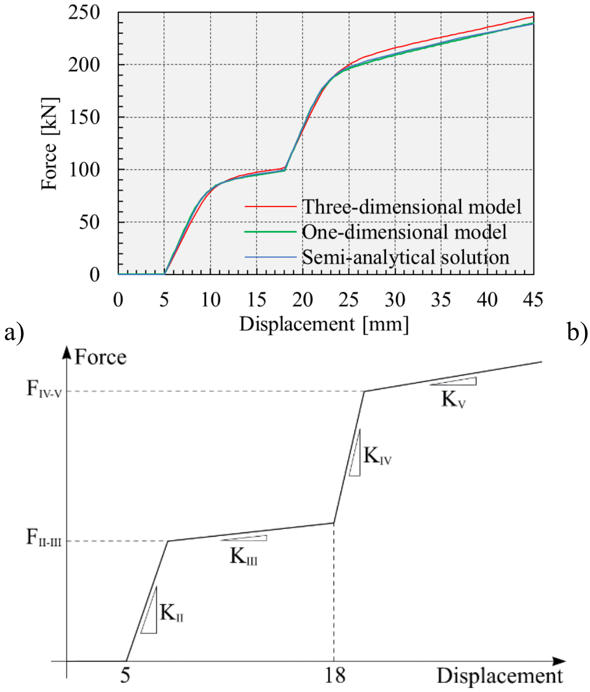


Fig. 9. Lateral force-displacement relationship for the innovative energy dissipation device: a) numerical results, b) idealized multilinear function

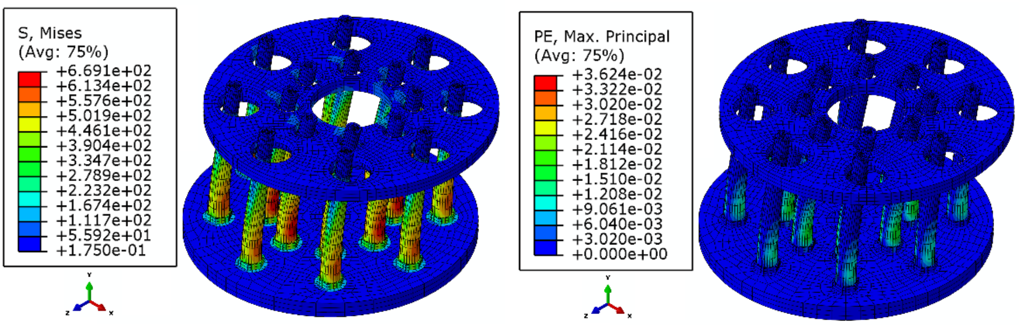
Based on the force-displacement diagrams, the stiffness values of the analyzed energy dissipator from the second to the fifth response phase (K_{II}, K_{III}, K_{IV}, K_V) are systematized in Table 1, as well as the shear forces at the transition from the second to the third (F_{II-III}) and at the transition from the fourth to the fifth phase (F_{IV-V}). The absorber stiffness in the first phase is equal to zero considering that the device is inactive in that phase. The differences of the results are around 5-10%, which confirms reliability of all three proposed numerical models. These parameters define the idealized multilinear response of the analyzed energy dissipator under monotonically increasing load (Fig. 9b) for application in the engineering practices.

Properties	Three-dimensional model	One-dimensional model	Semi-analytical solution
K_{II} [kN/mm]	17.189	18.200	17.980
K_{III} [kN/mm]	1.392	1.285	1.298
K_{IV} [kN/mm]	18.118	19.397	19.277
K_V [kN/mm]	2.005	1.999	1.926
F_{II-III} [kN]	90.721	88.338	89.060
F_{IV-V} [kN]	202.951	195.612	193.264

Table 1. Comparative analysis of the numerical results of the mechanical properties of the innovative energy dissipation device

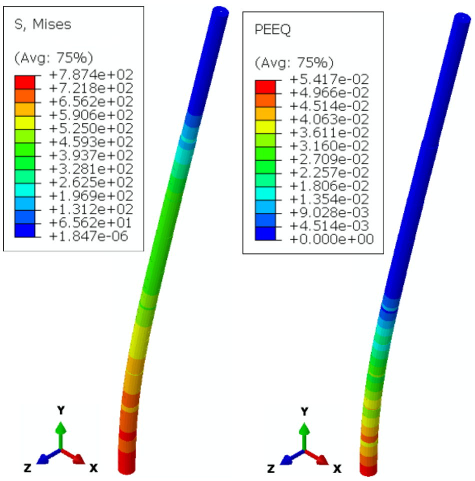
Besides the lateral force-displacement relationship, stress-strain state of the innovative energy dissipation device has been analyzed as well. Distribution of the von Mises stresses and maximal principal plastic strains obtained by three-dimensional numerical model are presented in Fig. 10. The maximal stresses occur in the nut zone of the vertical components and plasticization of the material starts in this region. The plasticization zone expands toward the free end due to the increase of lateral displacement of the middle activating plate. Slightly lower stress is in the vertical components in the outer circle, which is a consequence of the larger gap size and their smaller bending deflection compared to the vertical components in the inner circle.

The von Mises stresses and plastic strains obtained by one-dimensional numerical model for the vertical components in the inner and in the outer circle are presented in Fig. 11 and Fig. 12, respectively. The stress-strain state is similar in the qualitative manner compared to the three-dimensional numerical model results. However, higher values of stresses and plastic strains are obtained by the simplified one-dimensional model. It should be mentioned that the simplified model provides stresses higher than ultimate stress of steel material. This is a consequence of approximation of the cone body with nine segments with constant averaged diameter cross-section. Therefore, in the simplified one-dimensional numerical model the diameter at the nut zone is smaller than the real one, providing higher values of stresses and strains. Taking this into account, it can be concluded that one-dimensional model provides satisfying results regarding the lateral force-displacement relationship and mechanical properties of the innovative energy dissipation device, but does not provide accurate stress-strain analysis.



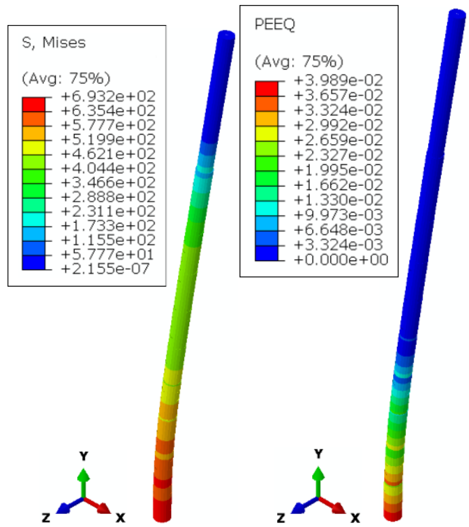
(a) (b)

Fig. 10. Stress-strain state of the three-dimensional numerical model of the innovative energy dissipation device: a) von Mises stresses, b) maximal principal plastic strains



(a) (b)

Fig. 11. Stress-strain state of the one-dimensional numerical model of the vertical component in the inner circle: a) von Mises stresses, b) plastic strains



(a) (b)

Fig. 12. Stress-strain state of the one-dimensional numerical model of the vertical component in the outer circle: a) von Mises stresses, b) plastic strains

The maximal stress and plastic strain at the clamped end of the vertical component in the inner circle obtained using the semi-analytical solution are 691.745 MPa and 0.03966, respectively. Those results confirm validity of the semi-analytical solution considering that maximal stress differs less than 5% and plastic strain differs less than 10% relative to the three-dimensional numerical model results.

The simplified one-dimensional numerical model and semi-analytical solution are favorable regarding the computer resources and time, providing satisfying results of the mechanical properties of the innovative energy dissipation device. On the other hand, from the aspect of stress-strain analysis of the vertical components, simplified one-dimensional numerical model is not accurate and the semi-analytical model has an advantage. Finally, the stress concertation in the zone of the contact of the middle activating plate and the vertical component cannot be analyzed using the semi-analytical solution, therefore, in the case of that problem the sophisticated three-dimensional numerical model is favorable.

4. Conclusions

Numerical analysis of the innovative energy dissipation device is presented in this paper. The sophisticated three-dimensional numerical model and the simplified one-dimensional numerical model of the energy dissipator have been proposed. Numerical analyses have been performed in order to analyze the mechanical properties and stress-strain state of the innovative energy dissipation device. Performances of the absorber have been analyzed using the previously developed semi-analytical solution as well. Based on the presented results, the following conclusions can be drawn:

- all three numerical modelling approaches provide satisfying results regarding the lateral force-displacement relationship and mechanical properties of the innovative energy dissipation device;
- there are five phases in the response of the innovative energy dissipation device which confirms its multi-level absorption potential;
- the lateral force-displacement diagram of the innovative energy dissipation device can be idealized with multilinear diagram defining the stiffnesses of the device in different phases, as well as defining the shear forces at the transition from one phase to another;
- the semi-analytical solution and simplified one-dimensional numerical model are favorable regarding the computer resources and time;
- the one-dimensional numerical model is not suitable for stress-strain analysis of the vertical components of the innovative energy dissipation device, so the semi-analytical solution has the advantage over this simplified numerical approach and,
- the advantage of the three-dimensional numerical model in relation to other two models is that it provides a complete analysis of the innovative energy dissipation device, whereby different phenomena, such as stress concentration in the zone of abrupt geometry change and contact stress between the middle activating plate and the vertical components.

Further research should cover numerical analysis of the innovative energy dissipation device with varying of geometry and material characteristics. Conducting a comprehensive experimental test of the innovative energy dissipation devices would be important to additionally validate numerical models.

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