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PASSIVE SEISMIC PROTECTION IN RC STRUCTURES WITH SOFT GROUND FLOOR

By

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Abstract

The increasingly common design of reinforced concrete (RC) structures with soft stories in seismically active areas requires a more detailed calculation approach and the introduction of special seismic solutions. A soft story refers to an open ground floor space, while the upper floors are masonry. Regarding earthquake effects, the most unfavorable and at the same time the most common variant is the construction of "soft stories" on the ground floor of buildings.

The paper presents the principle of nonlinear static analysis, based on the application of the N2 method as a representative nonlinear static method supported by Eurocode 8. A nonlinear static analysis model of two RC structures with a soft story is shown, where the impact of masonry infill is considered. In one model, metal-yielding dampers, specifically the DC90 SYSTEM, are used on the ground floor as a special type of passive seismic protection. The results of the nonlinear static analysis are then presented in the form of a pushover curve, displacement diagrams, relative story displacements, and the distribution scheme of plastic hinges, all with the aim of evaluating the efficiency of metal-yielding dampers.

The general conclusion that emerges from the presented results of the numerical investigation is that the DC90 SYSTEM has a significant impact on improving the seismic performance of RC frame structures with a soft story. By applying this passive seismic protection system, inter-story drifts on the ground floor are reduced, the overall displacement of the building is decreased, and the soft story mechanism transforms into a more favorable beam failure mechanism. Considering the market price of this type of damper, it can be concluded that the initial investment in seismic protection is significantly lower than the cost of repairing a damaged building after a moderate earthquake, while the contribution to preventing the collapse of the structure during strong earthquakes and preserving human lives is invaluable.

Keywords: *Nonlinear analysis, "pushover" curve, N2 method, masonry infill, "soft ground floor", metal dumpers*

1. INTRODUCTION

Great attention is paid to seismic protection in the world, because experience has shown that the destruction during strong earthquakes can have catastrophic proportions, with the real possibility of a large number of human casualties. In countries located in seismically active areas, seismic protection of facilities is regulated by appropriate technical regulations [15]. Respecting the valid technical regulations in the design of the structure adopted by a large number of assumptions.. In addition to a number of assumptions about the characteristics of earthquakes, as well as other types of loads, the most common assumption that is introduced in modeling, is to ignore the influence of non-structural parts of the structure, ie. filling of frame structures. However, during the effects of an earthquake, the influence of the masonry infill of the RC frame has a great influence on the very response of the structure, affecting its load-bearing capacity, ductility and rigidity. The reason why it is necessary to pay special attention to this phenomenon and analyze it in more detail, is that most objects in seismically active areas of this type, RC frame structure is filled with non-reinforced masonry infill.

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Experiences of past earthquakes unequivocally indicate one of the more critical subsystems of this type, and that is multi-storey reinforced concrete buildings with "soft" storeys. [21]. Different reinforcement techniques of this type of construction were investigated, both locally and globally. Ground floor pillars were reinforced, ie their ductility was increased by additional transverse reinforcement, steel cladding, additional ground floor trusses were made with steel joints, less weight and less rigidity were used for floors above the soft ground, and all this did not give satisfactory final results. All of the above techniques succeed to some extent in improving the seismic performance of reinforced concrete structures with a soft ground, but to a certain extent. Further improvement of these performances with relatively small financial investments can be achieved by a special system of passive seismic protection, whose work is based on additional damping, i.e. dissipation of seismic energy.

In this paper was investigated, the efficiency of dampers based on metal expansion, in improving the seismic performance of the RC frame structure with a soft ground. The specific system we have applied for passive seismic protection is the DC 90 System, a patent of a domestic company from Belgrade, which has found its application around the world as a very practical, economical, reliable seismic protection system.

Figure 1. Collapse of structures due to the soft ground effect (left) dampers with acceptable structural and aesthetic requirements (right)

2. NONLINEAR MODELING OF STRUCTURE

The lack of the current concept of seismic design and application of linear static methods of structural analysis is reflected in the fact that based on the conducted calculation there is no insight into the extent of damage to the supporting structure. Experience from earthquakes indicates that this design does not provide a uniform risk because different structures may have different behavior and very different degrees of damage during the same earthquake [15].

In general, methods of analysis of structures for seismic actions can be divided into static and dynamic, and models of structures into linear and nonlinear. Accordingly, four combinations of these analyzes are possible. Nonlinear static (pushover) analysis stands out as a compromise solution between the accuracy and complexity of the calculation [14]. This analysis generally determines the relationship between the total shear force and the horizontal displacement of the top of the building in the form of the so-called. "pushover" curves or blood capacity. The main principle of the pushhover method is the gradual application of a horizontal load on the structure, from the zero value to the point of required displacement or the point of capacity (bearing capacity), where the points of relaxation of the structure are registered, Fig. 2a. [11]. It is necessary that the required displacement is less than the total load capacity. Simplified, the entire calculation process, pushover analysis requires the determination of three key elements: the capacity curve, the demand curve (demand) and the target point of performance (performance point) [3].

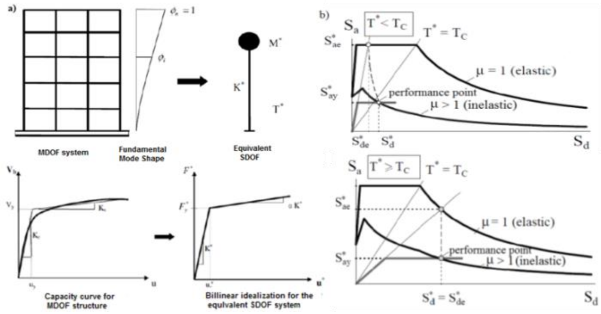

Figure 2. a) The concept of transformation of MDOF system into equivalent SDOF system, b) graphical representation of determining the target displacement of equivalent

SDOF system

Depending on the method of determining the demand curve and the point of targeted displacement, there are several conventional pushover calculation methods. The method that has found its application in Eurocode 8 is the N2 method, first introduced by Fajfar et al. (1988) as an alternative to the CSM (Capacity Spectrum Method) method. It is based on converting the response of a MDOF (multi degree of freedom) system with a multiple degree of freedom response system, a single degree of freedom (SDOF) system and combining a design capacity curve and an inelastic spectrum of requirements. What distinguishes the N2 method is the possibility of graphical representation, analytically determined values, where the characteristic points and the philosophy of calculation can be seen relatively clearly. Fig. 2b shows the elastic and inelastic spectra of requirements and idealized diagrams of the capacity of the structure in AD (acceleration-displacement) format [9], [15].

Nonlinearity is introduced into the calculation through plastic joints, which are defined in predetermined places, mainly concentrated at the ends of pillars or beams, using an appropriate law of plastic behavior or a more advanced model of fibrous cross section. Concentrated joints of the force and moment type are brittle-plastic joints. For each degree of freedom of force (normal or shear force) the law of plastic force and displacement can be defined. Also, for each degree of freedom of moment (bending moment and torsion moment), the law of plasticity of moment and rotation can be defined. For that degree of freedom for which the appropriate law of plasticity has not been adopted, it is considered that in that case all changes in stress and deformation behave according to the law of elasticity [18]. With the SAP2000 software package, it is possible to define the characteristics of different types of joints. The theoretical foundations on which the work of the program is based are given in the FEMA

*Corresponding Author: Nazim MANIĆ

regulations. In our case, we use bending joints (M) for the beams, while we use axial-bending (P-M) joints for the column [12].

It has been observed that a frame structure under seismic action behaves better when it can be ensured that plastic joints are formed in the beam and not in the columns (weak beam / strong column mechanism) and if the shear capacity is greater than the shear corresponding to the maximum possible load capacity bending [17]. In order for them to be realized, it is necessary to choose during the design that the ratio of the sum of the load-bearing moments of the bending of the columns to the sum of the load-bearing moments of the beams, in common nodes, is not less than 1.30. [7]. A specific mechanism of breakage that can potentially occur in multi-storey buildings is the "soft" ground floor mechanism. Eurocode 8 specifically emphasizes and prohibits the formation of such a mechanism. In that case, the angle of rotation of the mechanism θ is significantly increased, and thus the required local ductility at the ends of the columns is increased. As can be seen from Fig. 3a, the case of forced displacement d_m is much more unfavorable, when it is predominantly achieved only by deformation of the ground floor.

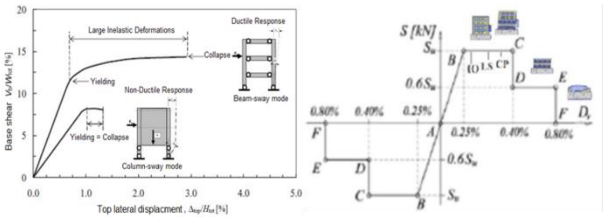

Figure 3. Capacity curves of characteristic fracture mechanisms (left), idealized diagram of force-displacement of masonry infill according to FEMA recommendations (right)

In nonlinear analysis, the state of the structure can be defined based on the state of the plastic joints of the structure itself. The basic parameters for understanding and controlling the seismic response of a structure are stiffness, bearing capacity and ductility [6].

We distinguish between the two broadest approaches to modeling structures, and thus masonry fillings, namely detailed modeling, i.e. micro approach and macro approach, i.e. application of simplified models [1]. The research is focused on the development of different models of interchangeable diagonals by which the filling is introduced into the calculation. European regulations do not recognize masonry infill in frame structures in this way, over the replacement diagonal, but the impact of the infill is taken into account by reducing its own vibration period. Accordingly, for the purposes of this paper, we will use the American regulations FEMA, which deals in detail with this topic. Based on its work on instructions and procedures for modeling masonry infill, according to FEMA regulations, the SAP2000 software package has the ability to model the equivalent rod via a "link" element, in this case a link type PlASTIC (WEN). It can be used to define the stiffness and yield strength, if you want insight into the nonlinear behavior of the wall. The yield strength of the wall, on the force-relative displacement diagram, represents point B in Fig 3b.. [20]. For the purposes of our study, we will use the experimental results of testing the lateral durability of the masonry infill of Professor Miha Tomažević, which can be found in [22], [13]. In fact, masonry walls made of Ytong block (autoclaved aerated concrete block) were examined, according to the CIB, as one of the typical representatives of masonry infill of relatively lower rigidity and infill that is increasingly used in our area [23].

The design of structures according to modern regulations with acceptable damage to the structure in the event of a project earthquake, requires primarily checking the assumed degree and mechanism of damage, and often the need to strengthen the structure is determined. Passive control systems are characterized by operation without the need for an external power source, they are inherently stable, they have an effective effect in both major and minor earthquakes. They are relatively easy to design and construct, and require relatively low installation and maintenance costs, so these devices can be cost-effective compared to other construction management methods [4].

The DC90 system is a special type of metal dumpers developed in Serbia, whose work is based on stretching a special metal inside the muffler itself. It consists of steel plates, which usually have a relatively low yield strength, and the entire cross section is surrounded by a rigid steel pipe. They are used for masonry, reinforced concrete and steel skeletal structures, and are also used on bridge structures. The buckle can be visible or built into the wall mass. The stiffener consists of a steel diagonal with an installed damper, which is adequately anchored in the nodes of the RC frame. All works related to this system are supported by European standards [19].

The selection of a dumper of appropriate stiffness is a function of the type of earthquake, the stiffness of the masonry infill and the general performance of the structure itself. It should be noted that this type of dumper works on the principle of metal hysteresis with displacement control and has a large reserve of plasticity of the material (post-collapse capacity) even after degradation of the structure, when it does not receive tensile load. As the damper yields, the stiffness decreases and energy is wasted due to the inelastic hysterical response. The hysterical behavior of the damper can be represented by various mathematical models that describe the yielding behavior of the metal. One example is the Bouc-Ven model. Similar to masonry, we will model dumpers via a diagonal link element, type PLASTIC (WEN), but an important difference occurs in effective damping and postelastic stiffness, which in this case is different from 0. To define the basic parameter of the dumper, most often a bilinear hysteresis diagram model is used. Fig. 4 shows one such diagram, where k_{d0}, F_{dy}, α_d, and Δ_{dy} are the initial stiffness, tensile strength, coefficient of postelastic stiffness, and deformation at the elongation limit of the metal damper, respectively [24].

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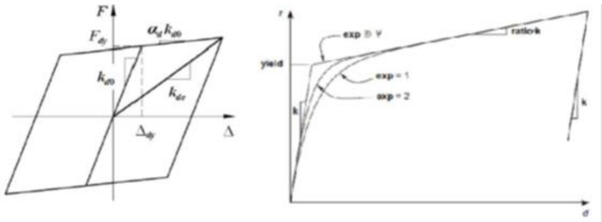


Figure 4. Idealized bilinear hysteresis force diagram-relative displacement of a metal damper (left) and characteristic diagram of the plasticity model according to Wen (right)

The characteristics of the dumper are adopted on the basis of the connection of force and displacement of the installed dumper, with the accompanying elements:

$$F_y = k_{d0}\Delta_{yd} = SRk_s\left(1+\frac{1}{B/D}\right)\Delta_{yd} \qquad (1)$$

wherein:

$k_s = 1/\delta_s$ - the stiffness of the RC structure in the horizontal direction at the place of installation of the dumper,

Δ_{yd} -yielddisplacement,

$B/D = k_b/k_d$ - the ratio of the stiffness of the metal diagonals and the stiffness of the dumper systemitself,

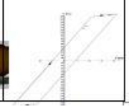
$SR = k_{bd}/k_s$ - the ratio of the stiffness of the overall damping device and the floor stiffness of the structure [16].

Adopting the characteristics of dumpers and their optimization is very complex and requires a problem. This complexity is reflected in the iterativeness and reversibility of the problem itself, in which a large number of possible combinations appear. More advanced algorithms for adopting relevant parameters are still being developed. In the literature [2], [26], [5], one can come across a whole spectrum of different adopted relevant values of metal damper parameters, and for the needs of our work we will adopt unequivocal, final values. The recommended displacements at the yield limit Δ_y are in the range from 0.0014H to 0.0020H, which also corresponds to interstorey drifts, where no major damage to non-structural elements is expected. Increasing the stiffness ratio B / D has a relatively small contribution to reducing the inelastic response of the structure. Therefore, the recommended value of this ratio is 2, primarily for the purpose of providing sufficient rigidity for the needs of proper operation of the metal damper. The recommended value of SR is 2, because parametric studies have shown that a relatively large value of SR gives unfavorable relations between the inelasticity of the design response and the cost price of dissipation devices [26]. Based on these recommendations and tests performed in the laboratories of the innovation center "SYSTEM DC 90" and the Military Technical Institute VTI in Belgrade, we adopt a coefficient of postelastic stiffness of 5%. Based on the adopted values, other characteristic values of masonry infill can be calculated [5], [18]:

$\delta_s = 9.15\cdot 10^{-6}$, $k_s = 109.30\,kN/m$, $\Delta_{yd} = 7.00mm$, $k_{d0} = 327.90kN$, $F_y = 2295.08kN$

Based on these results and the offer of metal dumpers from the company SISTEM DC 90, which are already used, and which have been experimentally tested, we finally adopt a dumper type "Kruševac" Sistema DC 90. The characteristics of this dump are closest to the calculated values of the optimal dump.

Table 1. Technical characteristics of the DC 90 SYSTEM Damper [18]

Type	Characteristics					Image	Hysteresis diagram
"Kruševac"	V=1600kN, D=216-10mm, L=600mm						
	A [cm²]	ΔA [cm²]	F_y [kN]	F_u [kN]	Δ [cm²]		
	78,41	12,50	1581,89	2310,34	1-21		

3. NUMERICAL ANALYSIS

In this paper, RC frames of soft ground, DCM ductility, without and with metal dumpers are analyzed. Model 1 is an RC frame with a soft ground floor, and Model 2 is an RC frame with a soft ground floor and metal dumpers. Frames are adopted as regular in height. It is assumed that the observed frame was isolated, as the middle frame of a multi-storey structure, with a grid control distance of 5 m and a slab thickness of 16 cm.

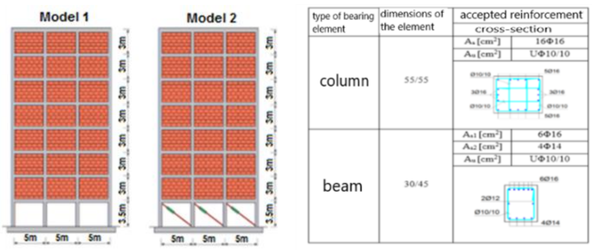


Figure 5. Sketch of adopted models with data of dimensioned structural elements

The elastic response spectrum for horizontal seismic action was taken according to Eurocode 8: type of elastic response 1, type of soil B, design acceleration of the substrate $a_g = 0.2g$ and significance factor $\gamma_I = 1$. When dimensioning the structural elements, reinforcement B500B and concrete grade C25 / 30 were used. The cross-sectional dimensions of the columns are 55/55 cm, and the beam 30/45 cm, with the proviso that we neglected the cooperation between the slab and the beam. The normalized axial force in the columns ν_d is 0.47, which satisfies the required condition to be less than 0.65 for DCM ductility class structures. Reinforcement in beams and columns was determined on the basis of preliminary analysis, where seismic influences were determined by applying multimodal analysis and all local conditions of DCM ductility class were met. After the adopted reinforcement, the characteristics of plastic joints (force-deformation curves) according to FEMA 356 were defined depending on the type of element (beam, column ...) and the

*Corresponding Author: Nazim MANIĆ

type of deformation (bending, shear ...). Applied infill of Ytong block of strength class 6, 62.5/25/30cm (length/height/thickness), in mortar of nominal strength M10, shear modulus G = 330000 kN/m^2 and ratio of shear modulus and modulus of elasticity of masonry infill G/E = 0.11 .

After defining all the necessary input data, a nonlinear static analysis of the multi-storey structure was performed, with the software package SAP2000v15. Two horizontal load distributions, modal and uniform, were adopted in the calculation, whereby for both analyzes, the initially adopted shape of the load was kept constant during the entire analysis. Based on the conducted "pushover" analysis, the force-displacement dependence was determined for the whole structure, Fig. 6.

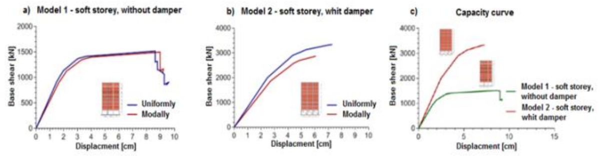


Figure 6. a) Model 1 capacity curve diagram, for uniform and modal load distribution b) Model 2 capacity curve diagram, for uniform and modal load distribution c) Capacity curve of both models

Based on the shown capacity curves, for two forms of lateral load, it can be seen that higher values of total horizontal force at the base of the RC frame are obtained with even distribution of lateral forces in relation to modal distribution, and higher values of frame top displacement are obtained for modal distribution. The number of plastic joints also depends on the shape of the lateral load, so that in the case of the applied modal distribution of lateral forces, the number of formed plastic joints is higher.

To better compare the behavior of the considered models and analyze the interrelationship, we will show the pushover curves for both models on a common diagram. It should be noted that the pushover curves are shown in Fig. 6c envelope curves formed due to the action of two different forms of horizontal load.

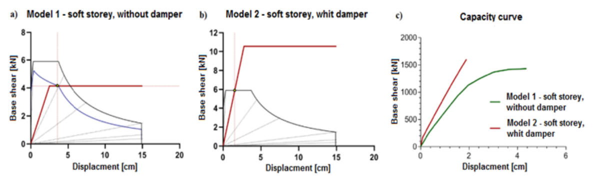


Figure 7. a) Model 1 idealized capacity curve diagram, with elastic and inelastic spectrum of requirements b) Model 2 idealized capacity curve diagram, with elastic spectrum of requirements c) capacity curve envelope diagram of both models, for target displacement

Fig. 7c shows a diagram with envelopes of the capacity curve for both models, based on a specific target displacement, Fig. 7a and 7b. The values of the total horizontal force at the base and the corresponding displacements for Model 1 are 1431.15kN and 4.38cm, for Model 2 1601.97kN and 1.89cm. In percentage terms, the forces increased by 11% and the displacements decreased by 57%. The change in the stiffness of the structure can be clearly seen from the diagram, due to the use of a dumper on the ground floor of the RC structure. With the change of the stiffness of the structure, the periods of oscillation T_1 = 0.62s, T_2 = 0.51s also change, and this change can be noticed with the increase of the total seismic force acting on the structure.

The first thing that can be noticed is the elastic response of the second model. Whether an elastic or inelastic response will occur depends on the intensity of the earthquake and the characteristics of the structure. In general, without attempting to quantify the degree of inelastic response, at the qualitative level it is accepted that an inelastic response is expected during medium to strong ground movements for most conventional structures. In our case, it is a relatively weaker earthquake, applied to the structure, which was additionally reinforced with metal dumpers and thus significantly increased its rigidity, so the elastic response of the construction of the first model is expected.

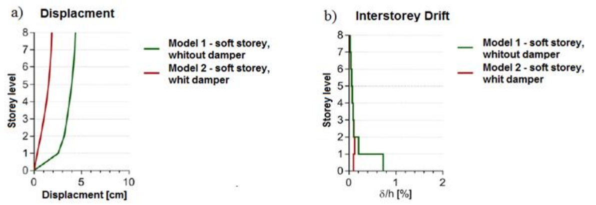


Figure 8. a) Diagram of floor movements of both models b) diagram of relative floor movements of both models

Lateral displacement and interstorey relative displacement are deformations that are most often used as a parameter of damage. We can say that the construction has a soft ground floor, if the lateral stiffness of the soft floor is less than 70% of the stiffness of the floor above or 80% of the average stiffness of the three upper floors. And a structure with an extreme soft ground floor is categorized if the lateral stiffness of the soft floor is less than 60% of the stiffness of the floor above or 70% of the average stiffness of the three upper floors [21]. We notice that the largest interstorey displacements are in the lower floors of the structure, which was expected in the first model on the first floor (ground floor) 0.73%, while in the second model the values of interstorey displacements are significantly lower and on the ground floor is 0.10%. According to the recommendations of FEMA 356, these values are within the allowed limits (up to 2%), but with the first model on the ground floor, certain damage to the non-bearing and load-bearing elements of the structure can be expected [10]. Second-order effects are not taken into account in any model, because the condition that the sensitivity coefficient of the interstorey relative horizontal displacement is less than 0.1 is met for all constructions. We can also conclude that the first models do not meet the usability limit state according to Eurocode 8, i.e. the condition of limiting the relative floor displacement of 0.5%, for buildings that have non-bearing elements of brittle materials that are attached to the structure, and which are obtained on the basis of the results for the ultimate load-bearing capacity [8].

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The assessment of the plastic mechanism and the distribution of structural damage is given through the cross-sectional scheme in which the values of bending moments at yielding are reached, i.e. in which the cross-sectional plasticization is started, Fig. 8. Beams and columns the levels of available plasticizations are given from the side, according to the FEMA regulations. Note that only the final schemes of frame plasticization are shown.

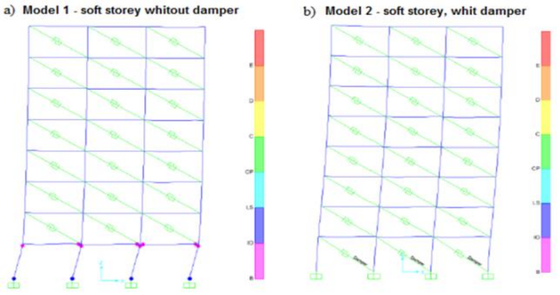

Figure 9. Deformation of the system and the arrangement of the formation of plastic joints of both models

For the considered seismic effect, nonlinear deformations occur in the structure, whereby plasticization occurs in the ground floor columns and at the ends of only some beams in the first model. When the level of deformation reached, which corresponds to the target displacement d_t, a complete plastic mechanism was not formed in any model. This indicates that the structures have sufficient deformation capacity to withstand an earthquake of a given strength without collapsing. The formation of plastic joints in the cross sections of the pillars is not expected given the capacitive sizing, but this response occurs in the first model and indicates a higher sensitivity of the frame, the possible fracture of the structure due to the formation of a soft floor. This model represents a construction of reduced stability. Loads are concentrated on the ground floor, so it is recommended in Eurocode 8 that the ground floor columns be additionally reinforced with transverse reinforcement along their entire height. The second model does not have a single plastic joint, which indicates that it is a relatively rigid structure, which due to the action of a given earthquake exhibits the characteristics of elastic behavior. However, additional attention should be paid to the increase in the ductility of the RC frame in which the dumper is installed, and especially to the nodal points, where the dumpers are anchored.

4. CONCLUSION

The design of reinforced concrete frame structures, taking into account the infill as a structural element, leads to a more realistic prediction of the behavior of the structure, exposed to earthquakes. Observing the positive and negative effects of masonry infill, we can conclude that the existence, type and position of the infill can have a significant impact on the stability and load-bearing capacity of the entire structure. This can best be seen in the case of soft ground structural systems.

More precisely, the omission of the masonry infill on the ground floor represents one of the greatest dangers to the stability of the structure, because in that way the performance of the structure is significantly weakened. Most of the total displacement occurs on the ground floor, while the rest of the structure behaves rigidly. However, such cases are very common in practice, primarily for architectural reasons, but we must keep in mind that in that case we consciously make a weak point in the construction in the most demanding place.

Very often, the negative effects, omissions of the masonry infill on the ground floor, cannot be remedied by standard constructive measures, such as increasing the ductility of the columns or the use of masonry infill of relatively lower rigidity, which was the case in this paper. In that case, it goes a step further and as an alternative solution is sought in the application of passive seismic protection, most often dumpers, whose work is based on the stretching of steel, which is characterized by economy, ease of application, reliability and efficiency.

In this paper, the efficiency of application of the metal dumper of the DC90 System is investigated. The general conclusion that clearly emerges from the presented results of the numerical test is that, the DC90 system, has a significant impact on the improvement of the seismic performance of RC frame structures with soft ground. By using this system of passive seismic protection, the interstorey drifts on the ground floor are reduced, the total displacement of the structure is reduced, and the soft ground mechanism is transformed into a much more favorable fracture beam mechanism. Taking into account the market price of this type of dumper, we can conclude that the initial investments in seismic protection are significantly lower than the cost of repairing the damaged structure after an earthquake of relatively medium strength.

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