Prethodno priopćenje/Preliminary communication
Primljen/Received: 03. 10. 2019.
Prihvaćen/Accepted: 03. 12. 2019.

ANALYSIS OF MASONRY WALLS STRENGTHENED WITH MECHANICAL DAMPERS

Emir Buljubašić, M.Sc.
Facjulty of Civil Engineering Sarajevo, Student, emir.buljubasic1@gmail.com
Goran Simonović, Ph.D.
Faculty of Civil Engineering Sarajevo, goran.simonovic@gf.unsa.ba

Abstract: The paper gives an overview of the characteristics of masonry walls, bricks and mortar, with reference to the mechanical characteristics of the walls. The focus was placed on unreinforced masonry walls (URM) and their earthquake behavior. Empirical and experimental data were used. The results of the numerical analysis of a single unreinforced masonrywall, obtained through the use of two modern software packages, ABAQUS and SAP2000, are in good agreement with the experiments conducted at the Faculty of Civil Engineering, University of Sarajevo. After the verification of the results, the masonry walls strengthened by applying mechanical dampers without and with a metal frame were analyzed.

Key words: Unreinforced masonry walls (URM), earthquake, seismic loads, strengthening of masonry walls, mechanical dampers, passive dampers, metal frames, energy dissipation devices, seismic isolation, expirimental testing of masonry walls, numerical analysis of masonry walls

ANALIZA OJAČANJA ZIDANIH ZIDOVA MEHANIČKIM DAMPERIMA

Sažetak: U radu je dan pregled karakteristika komponenata zidanih zidova, zidnih elemenata i maltera, s osvrtom na mehaničke karakteristike zidova. Poseban naglasak je stavljen na ne armirane zidane zidove i njihovo ponašanje uslijed potresa. Korišteni su empirijski i eksperimentalni podaci. Dobiveni rezultati za pojedinačni zid, koji su dobiveni kroz upotrebu dva suvremena programska paketa, ABAQUS i SAP2000, se dosta dobro slažu sa eksperimentima, koji su provedeni na Građevinskom fakultetu Univerziteta u Sarajevu. Nakon verifikacije rezultata numeričkih ispitivanja analizirana su ojačanja zidanih zidova apliciranjem mehaničkih dampera bez i s okvirom.

Ključne riječi: Ne armirani zidani zidovi, potres, seizmičko djelovanje, ojačanje zidanih zidova, mehanički damperi, pasivni damperi, metalni okvir, uređaji za disipaciju energije, seizmička izolacija, eksperimentalno ispitivanje zidanih zidova, numerička analiza zidanih zidova

1. Introduction

An earthquake is a natural phenomenon whose impact must certainly be taken into account when designing and constructing buildings. It has long been known that strong earthquakes can produce catastrophic consequences, enormous damage, and especially loss of human life. That is why earthquake protection is a very important task in modern urbanized society (Hrasnica M., "Aseizmičko građenje" [1]).

Bosnia and Herzegovina is located in an area of high seismic activity and earthquakes from the recent past have shown that unreinforced masonry structures are very vulnerable to and at high risk of the occurrence of stronger earthquakes. During the earthquake action, masonry does not have the ability to dissipate or to consume the energy through inelastic deformations [2].

Application of energy dissipation devices, seismic dampers, has begun in recent decades. Over time, dampers have been continuously developed and enhanced, from simple passive mechanical dampers that dissipated energy based on friction or through metal flow to active energy dissipation systems that can recognize system vibrations using various types of sensors and timely respond to them.

Dampers are used in various fields of construction where seismic resistance of structures need to be improved. The use of mechanical dampers can help improve the dynamic properties of structures during an earthquake by modifying the characteristics of structural response. The primary reason for using energy dissipation devices in structures is to reduce the displacement and damage caused by excessive structural deformation. The displacement reduction is achieved by adding rigidity and/or energy dissipation (damping) to the structure of the building. By using passive energy dissipator systems, we can achieve a response reduction of two to three times if they do not add rigidity and more than that in the case of additional rigidity. It should be emphasized that these systems reduce forces in the structure while it operates in the elastic region [3].

In order to prevent new damage to existing masonry structures, we will analyze the possibility of strengthening existing masonry walls by using passive mechanical dampers, where the paper focuses on increasing rigidity of the system.

2. Material and geometric characteristics of unreinforced masonry walls

Characteristics of masonry wall components, as well as of masonry walls as a whole, were tested in the laboratory of the Institute for Materials and Structures of the Faculty of Civil Engineering Sarajevo in Sarajevo [4, 5, 6, 7, 8]. This paper briefly outlines the test procedures and uses the test results of esteemed professors to create numerical models.

2.1. Material and geometric characteristics of wall elements

Experimental tests were conducted on samples of solid clay bricks sized 250/120/65mm (length/width/height).

2.1.1. Testing the compressive strength of the wall element

Compressive strength tests of wall elements were carried out according to national standards and European standards [5]. According to national standards, the mean compressive strength of $f_{b,c}$ = 29.9 N/mm^2 was obtained. Based on these regulations, bricks can be classified as M20, with a characteristic compressive strength of 20 N/mm^2 [5].

According to European standards (EN 772-1: 2011), the samples whose surfaces were treated by sanding had a mean compressive strength value of bricks of $f_{b,c}$ = 53.9 N/mm^2, while the brick samples to which a surface layer of mortar was applied had a mean compressive strength value of the wall element of $f_{b,c}$ = 47.1 N/mm^2 [5].

2.1.2. Testing the tensile strength of the wall element

Since standard tests that should be applied when determining tensile strength of a wall element were not defined, the tensile strength test of solid clay bricks was carried out in two ways [5], namely:

a) By the Brazilian test
b) By indirectly determining the bending tensile strength

When examining the tensile strength of the wall element by the Brazilian test, nine cylindrical samples were made with dimensions: base/height = 54mm/ 50mm, and tests were performed. The obtained average tensile strength of solid bricks was $f_{b,t}$ = 3.75N/mm^2 with a coefficient of variation of 14% [5,6].

Nine samples of solid brick blocks sized 250/120/65 (length/width/height), [5,6] were subjected to indirect method of determining tensile strength, and the average tensile strength value of solid bricks was $f_{b,t}$ = 5.2 N/mm^2. The coefficient of variation was very high at 40%. [5].

Visual inspection confirmed very irregular failure surfaces related to bending test, unlike the Brazilian test in which the samples had a rather smooth failure surface. For this reason, as well as due to the smaller coefficient of variation, the tensile strength value of bricks adopted for numerical analysis was: $f_{b,t}$ = 3.75 N/mm^2 [5,6].

2.2. Material characteristics of mortar

The mortar used in the experimental study was handmade lime-cement mortar with a ratio of ingredients: lime:cement:sand = 1:0.5:4. The lime-cement mortar used for construction of the test samples is with the selected composition in order to obtain a compressive strength of mortar of about 2.5 N/mm^2, which is typical of most existing masonry structures. The test is performed on prisms of dimensions 160 mm / 40 mm / 40 mm [5].

2.2.1. Testing the compressive strength of mortar

Testing compressive strength of mortar is prescribed in EN 1015-11:1999 - Part 11, which is related to the determination of bending and compressive strength of hardened mortar. The average compressive strength of the mortar during testing at the Institute for Materials and Structures of the Faculty of Civil Engineering Sarajevo was $f_{m,c}$ = 2.3 N/mm^2 with a coefficient of variation of 14%. Therefore, the tested mortar samples belong to the M2 mortar type, with the minimum compressive strength of mortar of 2.0 N/mm^2 [5].

2.2.2. Testing the tensile strength of mortar

The tensile strength test is performed indirectly, that is, tensile strength is measured with sample bending. The sample is placed in a press and the maximum load is measured until the sample fails. The average tensile strength of the mortar during testing was $f_{m,t}$ = 1.3 N/mm^2 with a coefficient of variation of 20% [5].

2.3. Mechanical characteristics of unreinforced masonry

2.3.1. Experimental testing of masonry compressive strength and modulus of elasticity

In order to obtain as realistic characteristics of the material for numerical analysis as possible, tests were performed in compliance with the European standard (CEN-EN 1052-1) on six prismatic samples of masonry. Dimensions of the samples made of solid bricks and lime-cement mortar (specified in the previous sections) are 51.4/64.6/12cm (l/w/h). Horizontal and vertical joints are 1.4cm thick on average. Solid clay bricks with a compressive strength of approx. 30 N/mm^2 and dimensions 250/120/65mm, immersed in water prior to placement, were used. [6] (Hrasnica et al. 2014).

Compressive strength is defined as the ratio of the vertical load to the initial prism area, regardless of the fact that joints are not ideally filled. The average compressive strength was 6.48 N/mm^2 with a coefficient of variation of 36%, while the average value of the modulus of elasticity was 4024 N/mm^2 with a coefficient of variation of 46% [6].

2.3.2. Determining the modulus of elasticity of the material empirically

Due to the lack of test data related to stress-strain relationships, as well as the modulus of elasticity of solid clay brick and lime-cement mortar, we will use empirical formulae to determine and idealize the values necessary for numerical calculation [9, 10, 11].

To assess the modulus of elasticity of clay bricks (E_b), (Kaushik, Rai, & Jain, 2007) [9] recommend a range of values dependent on the compressive strength of bricks (f_b). The given interval of the modulus of elasticity for clay bricks is given by (1):

$$150 \cdot f_b \leq E_b \leq 500 \cdot f_b. \tag{1}$$

To assess the modulus of elasticity (E_m) of lime-cement mortar, (Kaushik, Rai, & Jain, 2007) recommend a range of values (2) depending on the compressive strength of mortar (f_m). The given interval of modulus of elasticity for lime-cement mortar is:

$$100 \cdot f_m \leq E_m \leq 400 \cdot f_m. \tag{2}$$

Assuming that it is a very good material for the empirical determination of the modulus of elasticity, we will use the maximum limit values of empirical formulas (1) and (2). Substituting the experimentally obtained compressive strength values of wall blocks (f_b=29.00 N/mm^2) and mortar (f_c=2.30 N/mm^2) into the above formulas yields the empirical values of the modulus of elasticity of wall blocks ($E_{b,EMP}$=14500N/mm^2) and mortar ($E_{m,EMP}$=920N/mm^2).

In order to control the experimentally obtained value of the modulus of elasticity of masonry using the empirically obtained values of the modulus of elasticity of masonry blocks and mortar, we will use the empirical formula for determining the equivalent elastic modulus of masonry given by equations (3), (4) and (5).

It is important to note that the equivalent modulus of elasticity is a function of the physical and mechanical characteristics of bricks and mortar for the linear and elastic behavior of masonry walls (Francis et al., 1971) [12], and is given by equation (3):

$$\frac{1}{E_M}=\frac{\delta_b}{E_b}+\frac{\delta_m}{E_m}+2\cdot\delta_m\cdot\delta_b\cdot\frac{\nu_b\cdot E_m-\nu_m\cdot E_b}{\delta_m\cdot(1-\nu_b)\cdot E_m+\delta b\cdot(1-\nu_m)\cdot E_b}\cdot\left(\frac{\nu_m}{E_m^2}+\frac{\nu_b}{E_b^2}\right), \tag{3}$$

$$\delta_m=\frac{t_m}{(t_m+t_b)}, \tag{4}$$

$$\delta_b=\frac{t_b}{(t_m+t_b)}, \tag{5}$$

where:

E_M - is the modulus of elasticity of masonry;
t_m ; t_b - are the thickness of mortar and thickness of bricks (height of bricks);
E_m ; E_b - are the modulus of elasticity of mortar and modulus of elasticity of wall blocks (bricks);
v_m ; v_b - are the Poisson's ratio of mortar and Poisson's ratio of wall block (brick)

The value of the modulus of elasticity determined experimentally is E_M = 4024 N/mm^2. In addition to the known thicknesses of materials (t_m = 14mm; t_b = 65 mm), and the assumed Poisson's ratio (v_m = v_b = 0.2), substituting into formulae (3), (4) and (5), yields the masonry modulus of elasticity value of $E_{M,EMP}$ = 4010 N/mm^2, and it is approximately equal to the value obtained experimentally.

Based on the test results, it can be concluded that the modulus of elasticity is considerably lower than the recommendations given in EC6 (6). However, according to some authors (Tomaževič, 2009), the modulus of elasticity may vary within the value limits in formula (7) [6].

Table 1. Experimentally and empirically obtained values of the modulus of elasticity of masonry

Moduli of elasticity according to	Formulae	Values of moduli of elasticity of masonry [N/mm^2]
Experimentally	-	4024
EC6	$1000 \cdot f_k$ (6)	6480
Tomašević	$100 \cdot f_k \leq E_M \leq 1000 \cdot f_k$ (7)	$648 \leq E_M \leq 6480$
Francis	(3)	4010

2.3.3. Testing the shear strength of masonry

The behavior of masonry walls subjected to horizontal loads largely depends on the interaction between the wall elements and the mortar, or the characteristics of the contact (interface) between them. Testing their interface is of great importance because the contact surface between the wall element and mortar is usually the weakest element of the composite, i.e. because it combines the characteristics of brittle high-strength bricks with mortar, which has a much lower strength but much more pronounced ductility [4, 5, 6, 7].

The shear strength is determined according to EN 1052-3: 2001. The experimentally obtained values of the parameters required for numerical analysis are: cohesion, c=150kPa, and internal friction angle φ = 37°. It should be noted that all samples failed along the joint [5].

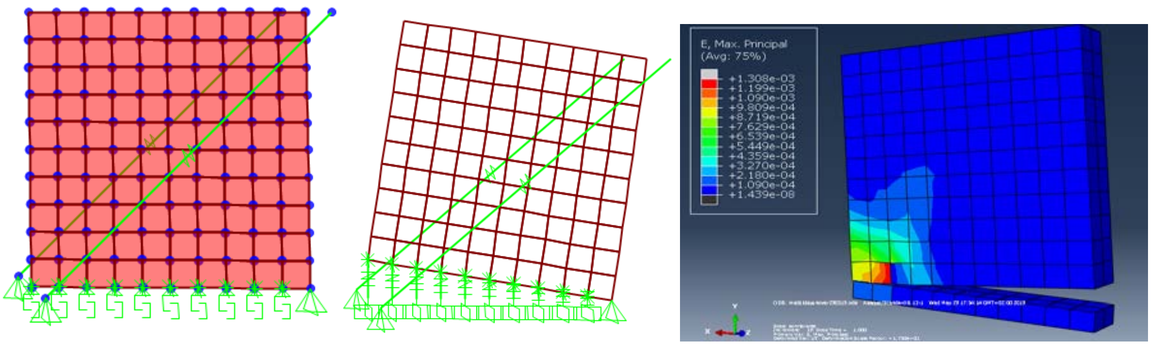
3. Numerical modeling of masonry walls strengthened with mechanical dampers

Numerical macro models of the masonry wall that was tested in the laboratory for materials and structures of the Faculty of Civil Engineering in Sarajevo are made [4, 5, 6, 7, 8].

Macro modeling allows larger finite elements (coarser discretization) because the heterogeneous masonry wall is approximated by a single material and the discretization is independent of the brick pattern. It also reduces the number of unknown quantities in the system, that is, it significantly speeds up the calculation of the structure. This model is appropriate for the analysis of real masonry structures in practice. This type of modeling is most preferable when a trade-off between accuracy and efficiency is needed [13].

3.1. Macro modeling of masonry walls

In the software package SAP2000, the masonry wall is modeled at the macro level as a homogeneous and elastic material using "plane stress" elements. The dimensions of the masonry wall are 103/103/25cm, and the material characteristics are given in Table 2. The wall was previously subjected to a vertical pressure of σ_o=0.4 kN/mm^2. Link elements, specifically gap elements ("compression only"), were used for the contact surface of the wall with base [14]. We assumed that the tensile strength of the masonry wall was equal to zero ($f_{t,b}$=0), and we limited the link elements so that they take loads only for the direction perpendicular to the ground. The compressive rigidity of the gap elements is exceptionally high (k = 10,000 kN/m) so that they can take all vertical loads. The value of opening of the gap element is set so as to start opening with the lowest tensile force, that is, the wall separates from the contact surface. To take horizontal loads, a fixed support is placed in a wall corner to allow horizontal force to be taken and to allow the wall to rotate as a rigid body about one point. The global size of finite elements is 100mm.



a) b) c)

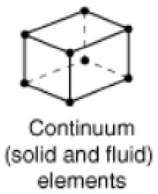
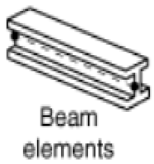
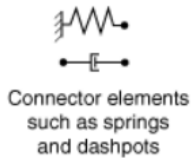
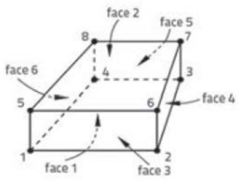
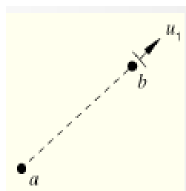
Figure 1. a) Wall strengthened with mechanical damper, b) Overturning of the wall strengthened with mechanical damper - SAP2000, c) Overturning of masonry wall - ABAQUS

In the software package ABAQUS, masonry wall is also modeled at the macro level. The wall model consists of three parts, specifically:

a) Concrete base (length/height/width = 103/10 /25cm)
b) Masonry wall (length/height/width = 103/103/25cm)
c) Concrete beam (length/height/width = 103/25 /45cm)

All these elements are modeled as 3D deformable finite elements. The characteristics of the individual elements are shown in Table 2. The masonry wall is modeled as linearly elastic and is used to simulate the mechanism of wall failure by overturning (Figure 1.c).

Table 2. Material characteristics of numerical models and description of finite elements - ABAQUS

Elements		Masonry wall	Concrete base	Concrete beam	Metal frame	Mechanical damper
Bulk density [Tonnes/mm^3]		1.85E-9	2.50E-09	2.50E-09	7.70E-09	-
Modulus of elasticity [N/mm^2]		4024.00	31635.00	31635.00	210000	-
Poisson's ratio		0.2	0.2	0.2	0.25	-
Type of element		C3D8R: linear volume finite element with eight nodes (hexagonal)			B31: linear beam finite element with two nodes in space	Connector
Group		Three-dimensional stress			Beam	Translational type-axial
Finite element	Type					
	Selected					

When overturning, the wall will rotate as a rigid body and detach at the first joint (Figure 1.b), so that the focus of the paper is on the wall-base interaction. The global size of finite elements is 100mm. The upper edge of the wall is free and subjected to a vertical load of σ_o=0.4 kN/mm^2. The top plate is slightly wider than the wall so that mechanical dampers could be subsequently installed. Movement of the upper plate is restricted to perpendicular to the wall direction. The wall top and the upper plates are ideally connected through the "Interaction" function by "tie" elements using the "surface to surface" discretization method. The wall-base connection is modeled so that the joint opens when the transverse force increases. Assuming that the mortar in the joint takes only compressive forces, the assigned contact properties are defined in the tangential and normal direction with respect to the contact plane. Through friction, defined by the “tangential behavior”, the given contact resists the transverse force. Also, in order to transfer normal forces and at the same time prevent the elements from penetrating through each other, we assigned the "normal behavior" to the connection with "Hard contact" option.

3.2. Modeling of metal frame

To model the metal frame, we used class S235 steel with the liquid limit of fy = 235N/mm^2; the dimensions of the frame are h/l=103/103 cm. HOP 60x60x4 hollow sections were used for beams and columns.

We used frame elements for their modeling in the SAP2000 software package, while the metal frames in ABAQUS were modeled using two-node linear beam finite elements in space "B31". The global size of finite elements in the ABAQUS software package is 50mm.

3.3. Modeling of mechanical dampers

Mechanical dampers are modeled by link elements with boundary forces and boundary displacements with the assumption that the entire diagonal is a single element, although in reality a mechanical damper is installed on an additional element because it is relatively small in size. The mechanical properties of dampers depend on the damper manufacturer's specifications. Type "Multi-Linear elastic" axial links were used for modeling in SAP2000, while in ABAQUS they were modeled by "Connector" elements. The selected element type is "translational basic axial elements", which allows connection and movement in the direction of the line connecting the given points. Figure 2 shows the behavior of the mechanical damper.

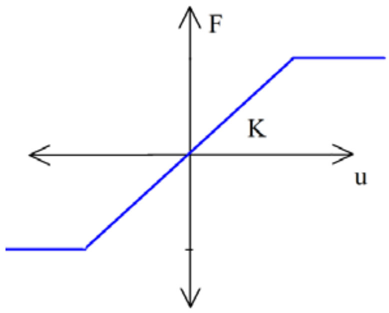


Figure 2. Behavior of the mechanical damper

In further text, hysteretic metal dampers will be used and marked as MD“X”kN“Y”mm, where: “X” is the limit bearing capacity of the damper in [kN] and “Y” is the limit displacement in [mm], which are defined by the mechanical damper manufacturer's specifications.

3.4. Modeling of masonry walls strengthened with mechanical damper with and without the use of metal frames

The numerical model of the strengthened wall was obtained by combining the above elements with already defined characteristics. The dimensions of all elements as well as the size of finite elements are kept as stated above. The mechanical dampers and the frame are at a distance of 20 cm from the masonry wall.

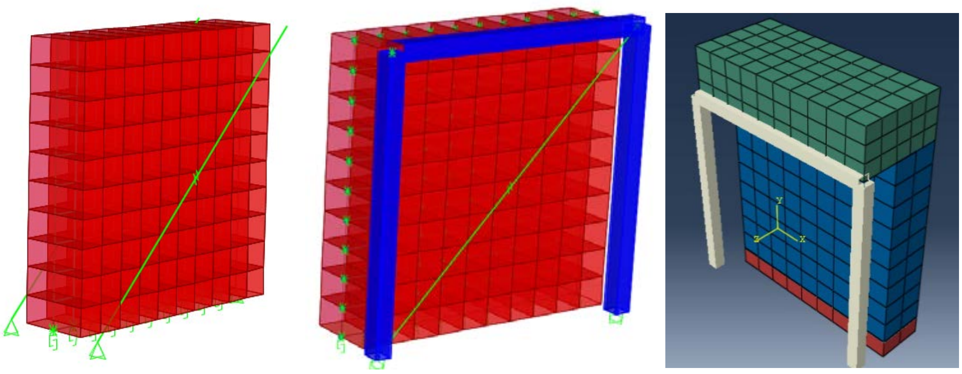


Figure 3. Numerical models of masonry wall reinforced with mechanical dampers without metal frame (a) and with metal frame in SAP2000 (b) and ABAQUS (c)

In the software package SAP2000, displacement of the lower end of damper is prevented, while the upper end is connected by "constrain" elements to the upper surface of the wall to follow the behavior of the wall. Models of masonry wall strengthened with mechanical damper with and without metal frame are shown in Figure 3.

As stated above in the software package ABAQUS, the connection of the wall top and the upper plate is made using the "tie" elements, which linked these two elements with the master-slave connection as one whole. To connect the metal frame to the concrete plate, we also used "tie" elements, but this time the discretization method was "Node to Surface" to connect the "beam" element to the edge of the 3D deformable element. The bottom of the upper plate (master surface) is connected ideally to the top of the frame beam (slave surface).

4. Verification of the numerical model

Verification of the numerical results will be carried out based on the results of small-scale wall tests [8] conducted in the laboratory of the Institute for Materials and Structures of the Faculty of Civil Engineering Sarajevo.

Samples of reduced-size unreinforced masonry walls of dimensions l/w/h = 103/103/25cm were made [8]. The wall was constructed without reinforcement and tested under the action of the vertical force V = 100 kN or under the mean vertical stress σ = 0.4 N/mm^2. The wall rotated as a rigid body without the occurrence of diagonal cracks [8]. The capacity curves obtained by the nonlinear static pushover analysis in the software packages SAP2000 and ABAQUS showed good agreement with the hysteresis curve obtained experimentally Figure 4.

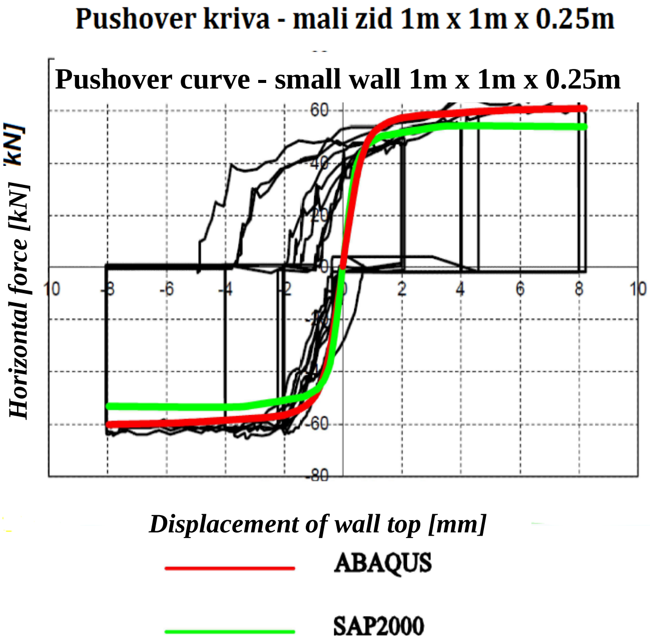


Figure 4. Comparison of the capacity curves of experimental results [8] and numerical models

5. Pushover analysis of masonry walls strengthened with mechanical dampers

On earlier models of reduced-size masonry walls (103x103x25cm) with already known characteristics, mechanical dampers were added on both sides at a distance of 20 cm from the wall. The capacity curves obtained by the pushover analysis are shown in Figure 5.

Examining the results of the pushover analysis, it can be observed that the direct use of mechanical dampers on the masonry wall did not bring a significant change in the transverse resistance of the wall. The dampers did not prevent the wall from overturning (Figure 1.b). Also, due to the overturning of the wall, the mechanical damper is displaced from its initial axis, making its efficiency questionable. Using dampers of higher rigidity we can observe a slight increase in the capacity curve.

6. Strengthening of masonry walls with combination of metal frame and mechanical dampers

As we have seen earlier the effect of mechanical dampers as reinforcement of masonry walls is very small in the case of direct installation or without additional elements for placement.

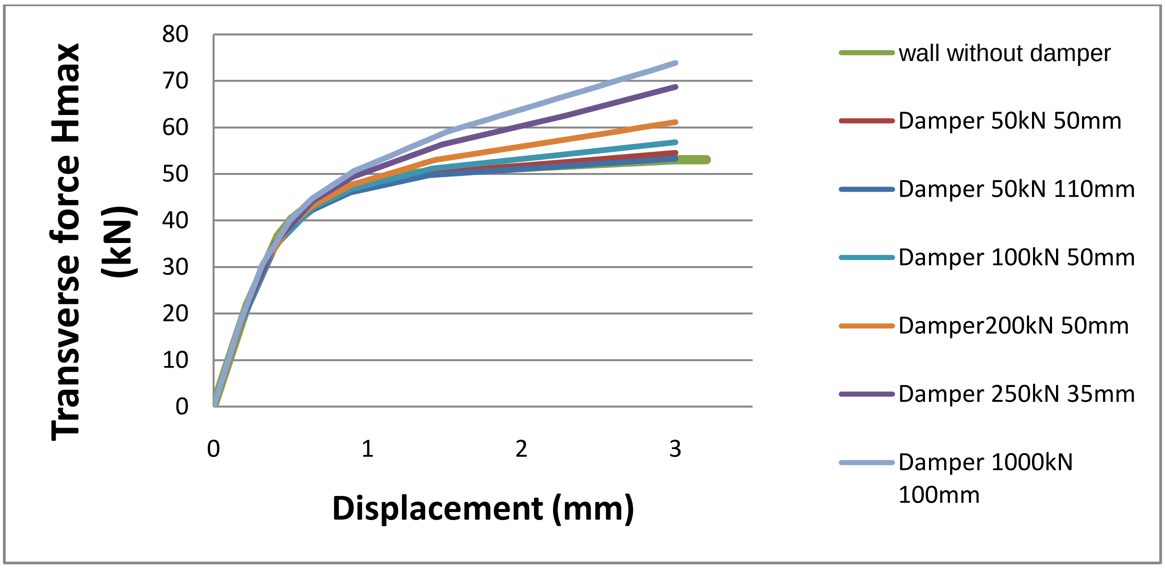


Figure 5. The capacity curves of masonry wall strengthened with mechanical dampers without frames

In order to increase the effectiveness of mechanical dampers in strengthening of masonry walls, we used an additional metal frame as described above. Its function is to take transverse forces resulting from seismic action and to take the bending moment of the wall by decomposing it into a couple of forces that will be taken by metal frame poles. Since masonry walls are very vulnerable to the seismic effects, the idea is to transfer that effect to another element, in this case the metal frame (Figure 6). Although it is impossible to completely transfer the effect to another element when reinforcing an existing wall, it is possible to reduce it and relieve the existing element. Strengthened masonry walls will act as a single whole. The metal frame will be directly near the wall and participate in taking the load. The transverse force that occurs will be transferred over the frame beam that is fixed by anchors to the ceiling, through the poles and the mechanical damper to the support. The bending moment will be transferred through the couple of forces to the frame piles so that pressure will occur in one pile and tension will occur in the other. It is also important to note that the behaviour of the entire system, in this case the metal frame strengthened with mechanical dampers, depends on the behavior of the individual components of the frame and the mechanical damper. The behavior of the strengthened system should be approximately equal to the sum of nonlinear responses of the metal frame and the damper at the same displacement [15].

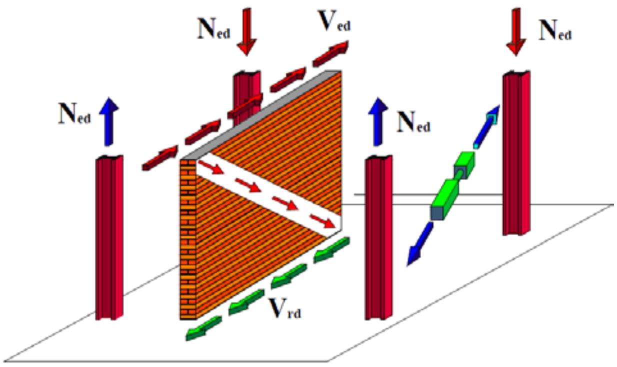


Figure 6. Illustration of the planned distribution of loads in the strengthened wall

The rigidity of the strengthened system, ko, should be equal to the sum of the rigidity of the metal frame, k_s, and of the mechanical damper k_{damp} for the same value of displacement d_x (Figure 7). As the displacement increases, the intensities of forces in piles will also increase. As described earlier, the behavior of the frame will depend on the behavior of the mechanical damper. The behavior of the strengthened masonry wall should be approximately equal to the sum of the nonlinear behavior diagrams of individual elements of the strengthened wall at the same displacement (Figure 7) [15].

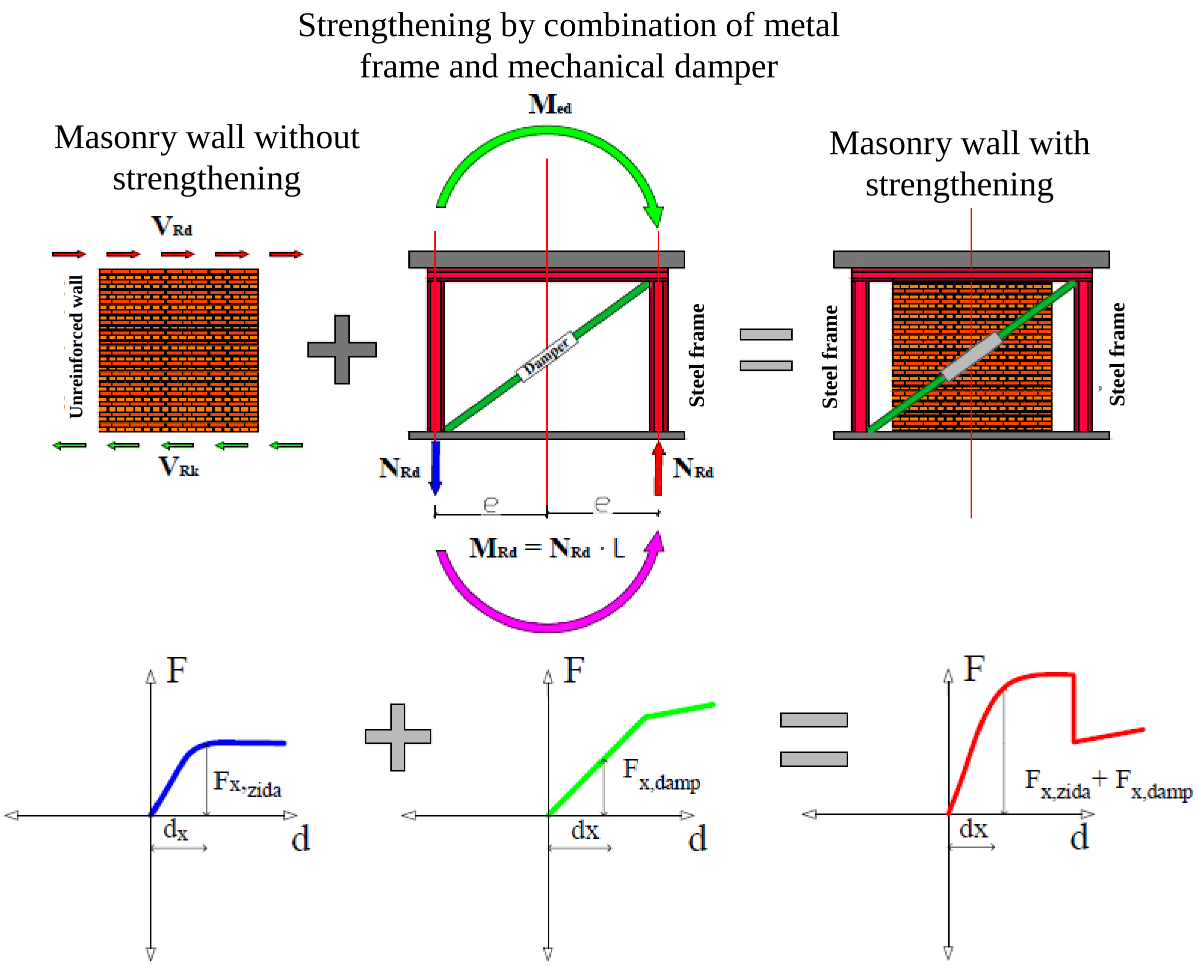


Figure 7. The behavior of the model shown as the sum of transverse forces of the wall and metal frame strengthened with mechanical damper at the same displacement

7. Pushover analysis of masonry walls strengthened with combination of metal frame and mechanical dampers

Results of the pushover analysis on the model of masonry wall strengthened with mechanical dampers and a metal frame are shown in Figure 8.

If we consider the capacity curves (Figure 8), we can see an increase in the resistance to transverse force compared to the results of the pushover analysis for the case of the masonry wall strengthened directly by a damper (Figure 5). The increase in resistance to transverse force is explained by the addition of a metal frame. This increase remains approximately the same for different specifications of mechanical dampers, thus raising the question of the effect of a mechanical damper in the entire system. During the testing, we could see that the resistance of the metal frame to transverse forces can be increased by up to 70% by correctly selecting the rigidity of the damper and by placing it diagonally in the unreinforced metal frame. If the difference in rigidity between the mechanical dampers and the metal frame was much greater, plasticization of the pole occurred at lower forces, while the global displacement of the frame top reduced by approximately 20%.

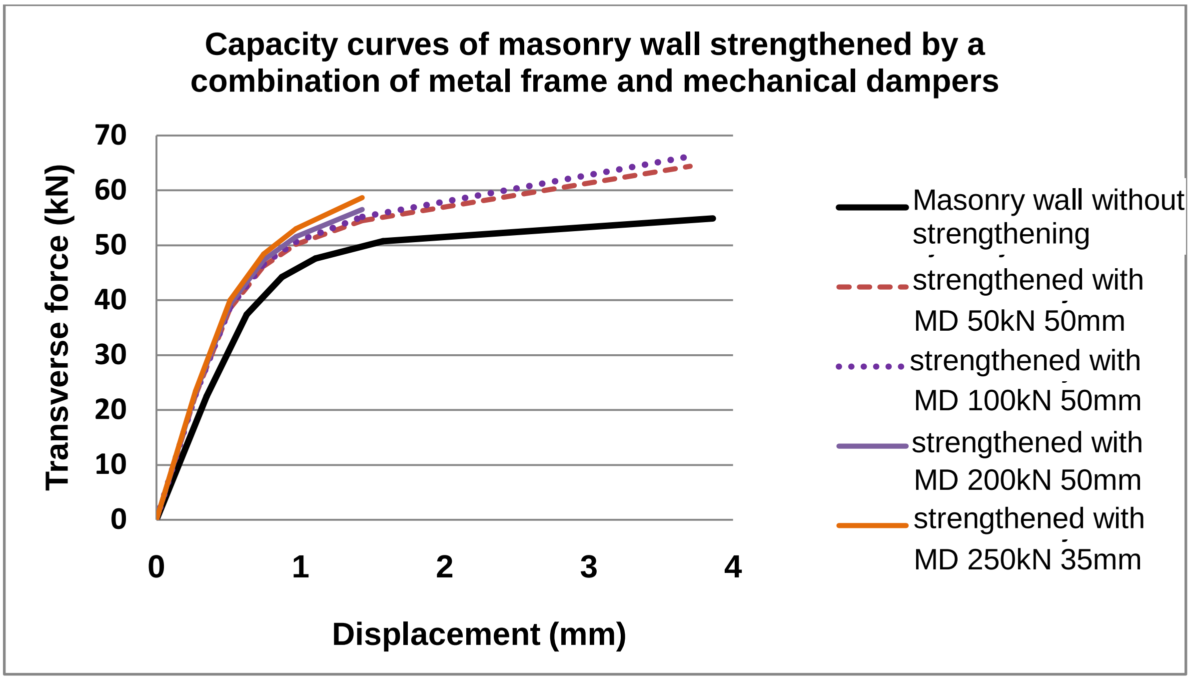


Figure 8. Capacity curves of the masonry wall strengthened by a combination of mechanical dampers and a metal frame - SAP2000

8. Dynamic analysis of masonry walls with and without strengthening

As an additional control, we performed a dynamic nonlinear analysis of masonry walls without strengthening to verify if the masonry wall really overturns and then performed the same analysis for masonry walls reinforced with mechanical dampers with and without frame. The dynamic analysis was carried out in the software package ABAQUS, displacements of the top of the wall were imposed at certain time intervals. The specified load program is shown in Figure 9.

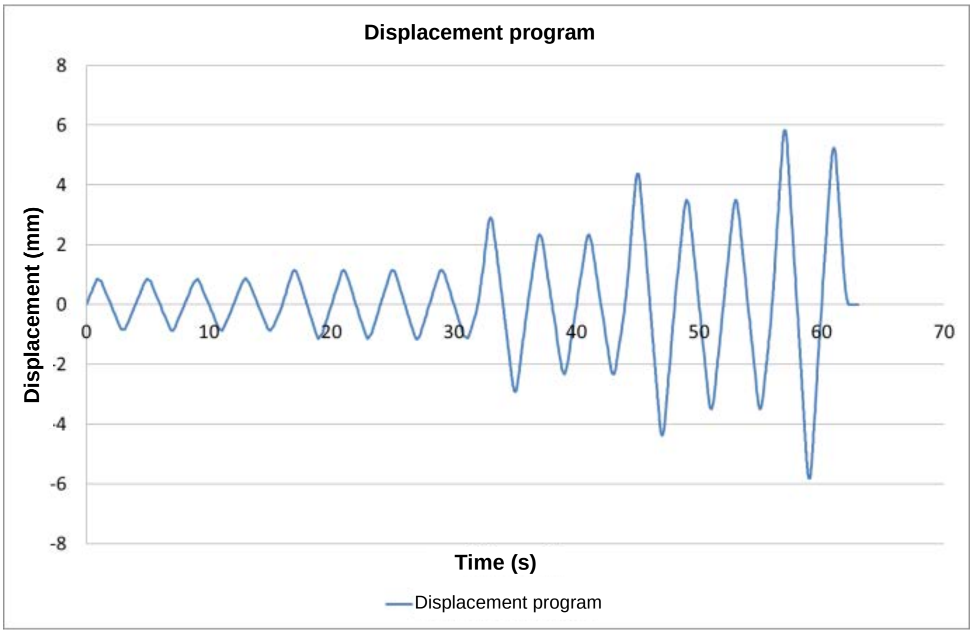


Figure 9. The load program - ABAQUS

The obtained hysteresis curves of the individual masonry wall strengthening cases are shown in Figure 10. The shape of the hysteresis curve of the masonry wall without strengthening is typical of a wall failure due to bending or overturning (Rocking).

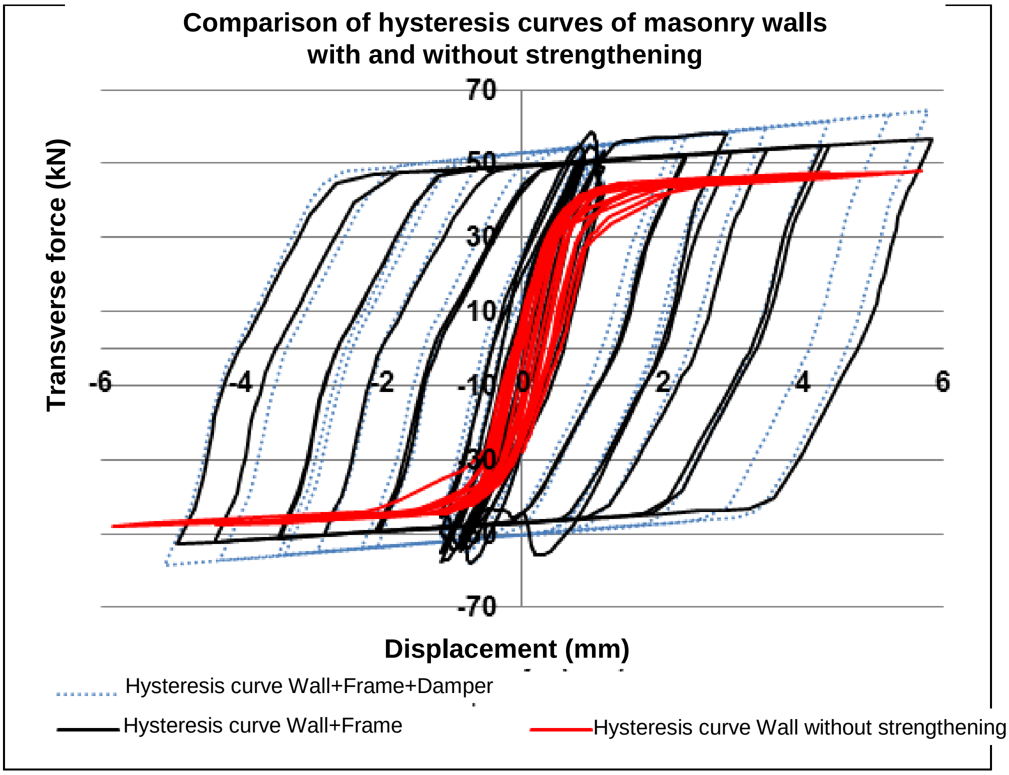


Figure 10. Hysteresis curves of masonry wall with and without strengthening

This analysis again found the small influence of mechanical dampers, i.e., the increase of the system resistance to transverse force mainly comes from the effect of the metal frame. This analysis confirms the previous statements on the use of mechanical dampers being questionable in strengthening masonry walls.

9. Recapitulation

When analyzing the masonry wall strengthening with mechanical dampers, we established that the effect of direct installation of dampers is very small. In order to increase the efficiency of strengthening using mechanical dampers, we added a metal frame intended to take the transverse force and bending moment due to seismic actions and thus to relieve the masonry wall which has a low resistance to these actions. Table 3 shows an overview of the obtained strengthening analysis results.

The effectiveness of masonry wall reinforcement with mechanical dampers with an emphasis on increasing the stiffness of the element is shown in Figure 11. The displacements at failure for direct strengthening of masonry wall with dampers are almost identical, which indicates that failure occurs even with the use of strengthening in the case of boundary displacement. We can also see the effects of different specifications of dampers. As the rigidity of the damper increases, the global resistance of the system to transverse forces increases proportionally, but the utilization of the damper also decreases as the displacements of the global system decrease. When applying an additional metal frame, the strengthening effects increase by an average of 10% compared to direct strengthening by dampers.

Table 3. Overview of analysis results of the masonry wall with and without strengthening

Type of strengthening	Elements	Mechanical damper			Limit values at failure of the element		Percentage increase in transverse bearing capacity with reinforcement	Percentage utilization of mechanical dampers at failure
		Name (MD)	Specifications					
			Boundary force	Boundary displacement	Transverse force	Displacement		
			[kN]	[mm]	[kN]	[mm]	[%]	[%]
Without strengthening	Masonry wall		-	-	54.21	3.87	-	-
	Metal frame		-	-	18.71	8.92	-	-
Element strengthened with mechanical dampers	Masonry wall	50kN50mm	50	50	57.39	4.07	5.87	5.76
		100kN50mm	100	50	59.61	3.82	9.96	2.70
		200kN50mm	200	50	65.55	3.87	20.92	1.37
		250kN35mm	250	35	74.85	3.89	38.07	1.10
	Metal frame	50kN50mm	50	50	22.96	8.86	22.72	12.50
		100kN50mm	100	50	27.11	8.80	44.91	6.21
		200kN50mm	200	50	31.42	7.75	67.91	2.73
		250kN35mm	250	35	29.01	5.22	55.04	1.47
Combination of masonry wall, metal frame and mechanical damper		50kN50mm	50	50	64.41	3.70	18.81	5.23
		100kN50mm	100	50	66.22	3.70	22.15	2.62
		200kN50mm	200	50	56.54	1.43	4.29	0.50
		250kN35mm	250	35	58.67	1.43	8.23	0.40

With the use of higher-rigidity mechanical dampers, the transverse resistance of the global system increases and the system displacements decrease, but also the axial force increases in the strengthened diagonal, which can cause metal to flow, or poles to fail in corners if they are poorly dimensioned. Also, the negative effect of the combination of high-rigidity dampers and frames of low resistance to transverse forces can be observed in Figure 11. Displacements of the system will be reduced almost by half, but when plasticization of the pole foot occurs, the entire system will fail, so attention should be paid to that when dimensioning frame elements.

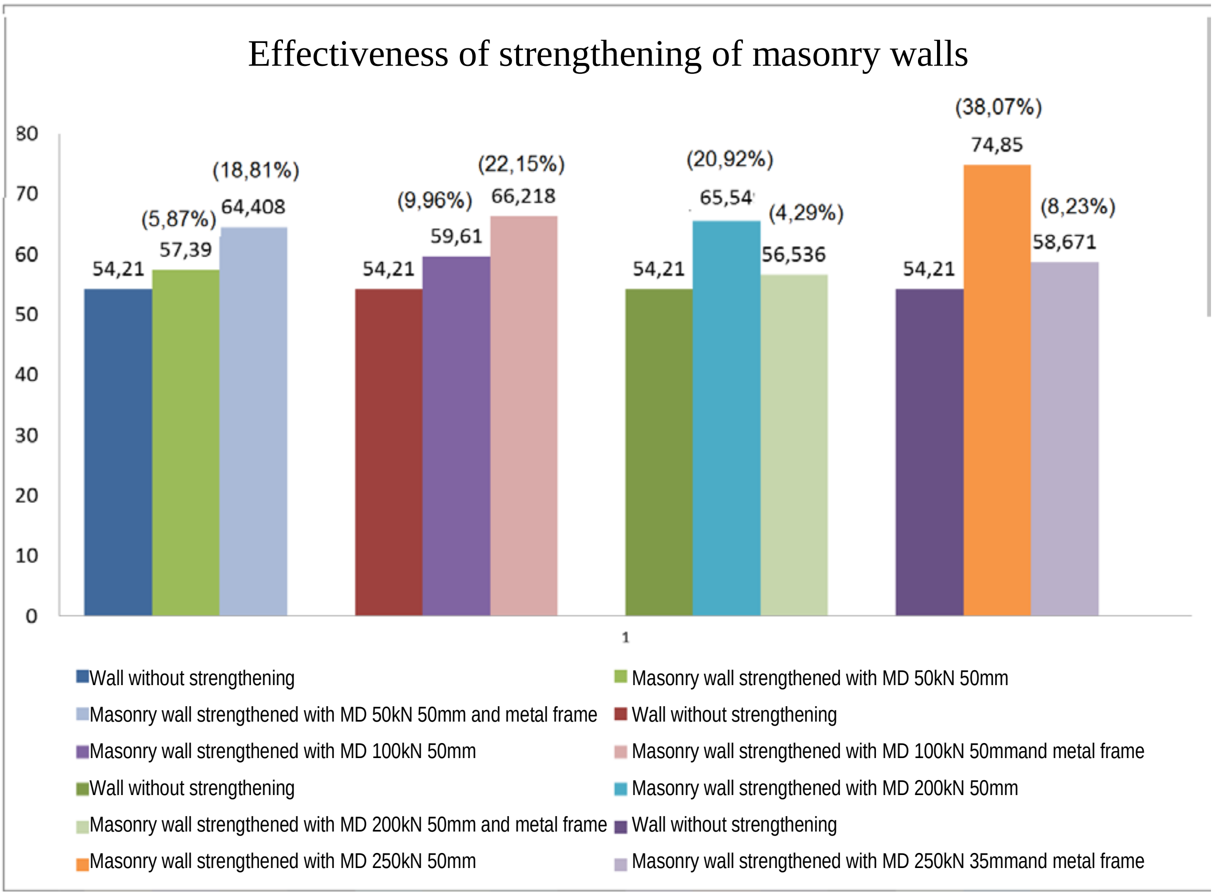


Figure 11. Effectiveness of masonry walls strengthening with mechanical dampers with and without frame

10. Conclusion

The presented paper shows an analysis of the strengthening of masonry walls using mechanical dampers. The focus of the paper is placed on the effect of increasing system rigidity when strengthening masonry walls with mechanical dampers. The mechanical characteristics of the materials were obtained experimentally in the laboratory of the Institute for Materials and Structures of the Faculty of Civil Engineering Sarajevo [4, 5, 6, 7] and were used in developing the numerical model of masonry walls.

The numerical model of the masonry wall presented in this paper is at the macro modeling level, that is, the wall elements and mortar are modeled as homogenized material, so that in the beginning we idealized the actual behavior of the structure, but the results are good enough to perform the analysis. Failure of the wall or of any element rarely occurs for one reason only, but it is a complex process resulting from the action of multiple factors that ultimately lead to failure. The selected masonry wall of known material and geometric characteristics with the dimensions ratio h:l = 1:1 is modeled for failure of the contact between the wall and the base, after which overturning (rocking) of the wall will occur. After verifying the results of the numerical model, we carried out strengthening of the masonry wall.

For the masonry wall, strengthened by a diagonally installed mechanical damper, we will contribute to increased bearing capacity of the transverse force by taking a part of the tensile force with the damper that will be formed perpendicular to the pressed diagonal of the wall resulting from seismic action. Numerical analysis showed that direct strengthening of masonry walls using mechanical dampers did not have a significant effect unless dampers with high rigidity were used.

In order to increase the effectiveness of mechanical dampers, we applied a combined method of strengthening where we installed a metal frame in addition to dampers. The idea is to split the bending moment resulting from seismic action into couple of forces that will be taken by frame poles. The intention of the metal frame is also to take a part of the transverse force in order to enable the masonry wall to fulfil its primary purpose, which is to take the vertical load in its plane. This method of strengthening showed a greater effectiveness in relation to the independent strengthening by mechanical dampers. However, a detailed analysis showed that the positive effects of this strengthening method were mainly related to the addition of the metal frame, while mechanical dampers contributed less to relieving the wall from these effects.

Finally, the analyses have shown that walls are quite rigid structural elements, without pronounced ductility, which makes questionable their coupling with dampers which are markedly ductile, because failure occurs in the wall before dampers are activated. Through future papers, analyses should be extended to other types of walls and dampers before making a general conclusion.

11. References

1. Hrasnica M.: *Aseizmičko građenje*, Građevinski fakultet Univerzitet Sarajevo, Sarajevo, 2012.
2. Zbornik radova - 3. Simpozij doktorskog studija građevinarstva, Građevinski fakultet Sveučilišta u Zagrebu, 2017.
3. Sučević P.: *Protupotresna izolacija građevina*, Magistarski rad, Građevinski fakultet Zagreb, nepoznata godina izdavanja.
4. Hrasnica M., Biberkić F., Medić S.: *In-Plane Behavior of Plain and Strengthened Solid Brick Masonry Walls*, Key Engineering Materials, Juli 2017.
5. Hrasnica M., Medić S., Ademović N.: *Cyclic shear tests on URM and strengthened masonry walls and its modelling*, Conference Paper, Second European Conference on Earthquake Engineering and Seismology, August 2014.
6. Hrasnica M., Medić S., Biberkić F.: *Experimental testing of Solid Brick Masonry Walls*, 16th European Conference on Earthquake Engineering, Juni 2018.
7. Hrasnica M., Medić S.: *Finite element modeling of experimentally tested solid brick masonry walls*, 16th European Conference on Earthquake Engineering, Juni 2018.
8. Medić S.: *Eksperimentalna i numerička analiza zidova od pune opeke izloženih utjecaju potresa*, Doktorski rad, Građevinski fakultet Univerzitet Sarajevo, 2018.
9. Kaushik H.B., Rai D.C., Jain S.K., Asce M.: *Stress-Strain Characteristics of Clay Brick Masonry under Uniaxial Compression*, Journal of materials in Civil Engineering © ASCE, September 2007.
10. Nwofor T.: *Experimental determination of the Mechanical properties of Clay Brick Masonry*, Canadian Journal on Environmental, Construction and Civil Engineering Vol.3, No. 3, 2012.
11. Barraza J.A.C.: *Numerical Model for Nonlinear Analysis of Masonry Walls*, doktorski rad, Fakultät für Bauingenieurwesen der Rheinisch-Westfälischen Technischen Hochschule Aachen Aachen, 2012.
12. Arash S.: *Mechanical properties of masonry samples for theoretical modeling*, 15th International Brick and BlockMasonry Conference, Florianópolis – Brazil, 2012.
13. Hrasnica M., Medić S.: *Modeling Strategies for Masonry Structures*, Advanced Technologies, Systems, and Applications II, str. 633-644, 2018.
14. Sap2000, CSI Analysis Reference Manual, Computers and Structures, Inc., Berkley, California, USA, 2003.

15. Simonović V., Šahinagic-Isović M., Selimotic M., Simonović G.: *Numerical analysis of seismic resistance of masonry buildings using passive dampers*, 16th European Conference on Earthquake Engineering, Juni 2018.