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Original scientific paper

Efficiency of Buttress Form on the Out-of-plane Resistance of Masonry Walls Subjected to Vault Thrust

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Abstract: Many historical buildings are covered with vaults or domes. This study investigates the effectiveness of the buttress form on the lateral (out-of-plane) resistance of masonry walls subjected to the inclined vault thrust. For this purpose, a basic calculation model was created from an existing historical masonry building. Calculation models were obtained by adding buttresses which have various forms but equal volumes to this model. In addition to the most commonly rectangular, trapezoidal, and triangular buttresses, two-stepped, concave curvilinear, and semi-cylindrical buttresses were also considered. Nonlinear static analyses were performed on the models with Abaqus software. By considering one side (half) of the calculation models, inclined thrust force versus wall top section lateral displacement graphs were obtained, and the effectiveness of the buttress form on the lateral resistance of the building was determined. It has been observed that the structure has the highest out-of-plane resistance (5700 kN and 5431 kN) when supported by triangular and curvilinear concave buttresses, respectively, and the lowest resistance (1549 kN) when supported by semi-cylindrical buttresses. In the study, the effects of three parameters, depth, thickness and height of the buttress, on the lateral resistance of the building were also investigated by considering only the rectangular buttressed model. These parameters were found to have significant effects on the resistance as expected.

Keywords: buttress form; inclined thrust; lateral resistance; nonlinear static analysis; vault

1 INTRODUCTION

For most historic masonry buildings, the main load-bearing elements are vaults, domes, arches, walls, columns, buttresses, and foundations. When the structures built in ancient times are examined, it is seen that the high walls were supported with buttresses in most cases in order to safely carry the forces transferred from the vaults, domes and arches. Buttresses are also important and necessary for these structures to be resistant to earthquake and wind forces.

Buttresses are elements that are built to support walls in the perpendicular direction to their plane and stand like protrusions. They are divided into two groups as classical and flying buttresses. Classical buttresses are constantly interconnected with the wall throughout their height, and in some historical masonry structures they are along the entire wall height, and in some, they are up to a certain height of the wall. On the other hand, flying buttresses are arch-shaped and are in contact with the wall they support in a small area. These buttresses transmit the thrust they receive from the wall to a strong vertical buttress at their other end. Looking at the building-type historical masonry structures, it is seen that the classical buttresses are placed on the walls in three ways: on the outside, on the inside, and some part on the outside while the rest on the inside.

When the historical masonry architecture of the world is searched, a wide variety of buttresses are encountered, including rectangular, trapezoidal, stepped, combined, curvilinear, and special forms [1-4]. Some examples are given in Fig. 1.

Historical buildings have been examined in many ways until today [5-9]. Special studies have also been carried out on buttresses. Huerta [10, 11] investigated historical documents on the sizing principles of buttresses in buildings built in the Middle Ages and Renaissance periods. Heyman [12] examined various structural members in historic stone buildings, including buttresses. There are also studies on the determination of the overturning resistance of buttresses in vaulted structures [13-15].

a) Rectangular buttresses of the Kızıltepe Ulu Mosque (Mardin, Turkey) (Photo: Authors)

b) Trapezoidal buttresses of the Süleymaniye Mosque (Istanbul, Turkey) (Photo: Authors)

c) Stepped buttresses of the King's College Chapel (Cambridge, England) [1]

d) Triangular buttresses of the Eziran Cuma Mosque (Isfahan, Iran), [2]

e) Curvilinear concave buttresses of the Cuetzalan del Progreso Church (Progreso, Mexico), [3]

f) Semi-cylindrical buttresses of Zazadin Han (Konya, Turkey), [4]

Figure 1 Examples of buttresses at historical masonry buildings

García and Meli [16] found that despite the differences in size and other features of the churches built in Mexico in the 16th century, there are similarities in the proportions between some basic dimensions of structural elements such as buttresses and walls. De Lorenzis et al. [17] performed detailed failure analyses of trapezoidal and stepped masonry buttresses. The relative efficiencies of different buttress forms (trapezoidal, two-stepped, and three-stepped) with the same total volume were obtained and compared both analytically and numerically. There are also some studies on the behavior of masonry buildings under dynamic loads such as earthquakes and their failure mechanisms [18, 21]. Chávez and Peña [22] evaluated the effects of buttress and vault thickness on building behavior in their study on the structural analysis of typical Mexican temples. The study revealed that the strength of vaulted masonry structures depends on the buttresses' ability to withstand the load transmitted to them from the vaults. İzol et al. [23] studied the out-of-plane seismic resistance of high masonry walls with rectangular buttresses. In the study, calculations and comparisons were also made for both the current and without buttresses states of the Süleymaniye Mosque's Qibla wall. Marrs [24], in her master's thesis, used the applied element method to analyze the out-of-plane strength of masonry buttresses.

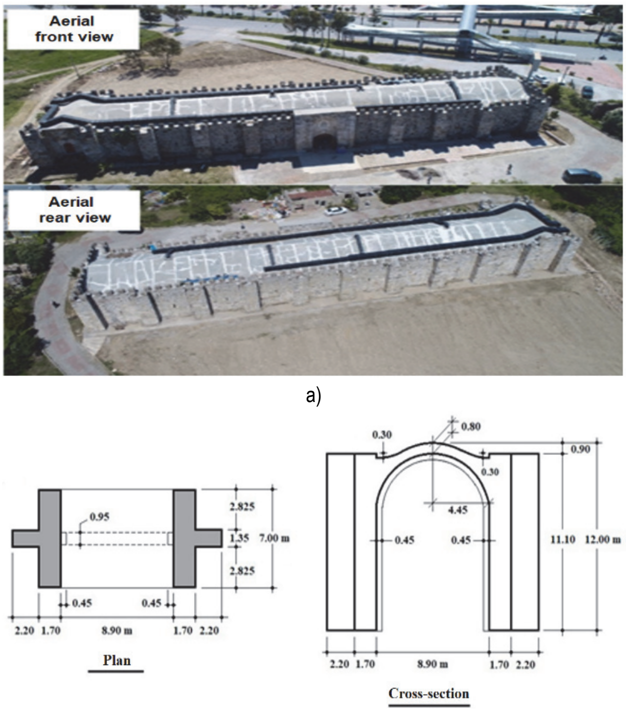
In the above-cited studies, only a few most common buttress forms were handled. Whereas, as it has been shown in Fig. 1, there are many other buttresses in the world's historical masonry architecture. Hence, investigation of the efficiency of various buttresses is important to see their contribution to the structures they belong to. Motivated from here, this study investigates and compares the efficiency of not only the most common buttresses but also some special ones, on the out-of-plane resistance of a masonry wall subjected to inclined vault thrust. In the study, in addition, the effects of the depth, thickness, and height of the buttress on the wall resistance are also investigated for the rectangular buttress case. Nonlinear static analyses were performed on the models with Abaqus software. By considering one-half of the calculation models, inclined thrust force versus wall top section lateral displacement graphs were obtained, and the efficiency of the buttress form on the lateral resistance of the structures was determined.

2 MATERIALS AND METHOD

2.1 The Basic Model and the Buttress Forms Used in the Analyses

In this study, the historical Şarapsa Han (Inn) located in the Alanya district of Antalya, Turkey was used as the sample structure [25]. As a stone masonry building, this structure was chosen because it has a simple plan and cross-section. Fig. 2 shows aerial front and rear views of the Han, and the plan and transverse elevation of the basic model used in the calculations obtained by slightly modifying the actual model of the structure. The model is one of the typical repeating slices of the structure. It consists of two pairs of walls and buttresses facing each other, and a piece of vault connecting them. Hereinafter, this model will be called the "basic model".

Various buttress forms were considered in order to see the effect of the buttress form on the out-of-plane resistance of the masonry walls under the influence of the inclined vault thrust. In this context, the most preferred buttress forms and three special buttress forms were considered. These buttresses are rectangular, triangular, trapezoidal, and two-stepped, concave curvilinear (second order parabola), and semi-cylindrical buttresses, as shown in Fig. 3.



a)

b)

Figure 2 a) Views of Şarapsa Han, b) Plan and cross-section of the basic model (drawings are not to scale)

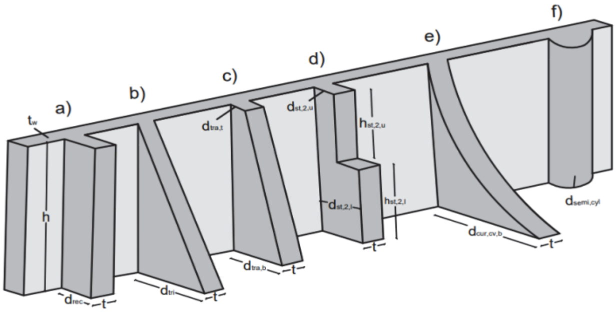


Figure 3 The buttress forms considered in the analyses: a) rectangular *b*., b) triangular *b*., c) trapezoidal *b*., d) two-stepped *b*., e) concave curvilinear *b*., and f) semi-cylindrical buttress

In order to use an equal amount of material in all buttresses, their volumes have been taken equally. Because only in this way, the comparison of the results to be obtained will be meaningful. The first buttress is rectangular buttress and its volume is $V_{\text{rec}} = t \times d_{\text{rec}} \times h = 1.35 \times 2.20 \times 11.10 \cong 33\ \text{m}^3$. This value has been taken as the constant volume value for all buttresses. In Fig. 3 there are some symbols regarding the geometrical properties of the buttresses and their explanations are given in Tab. 1. The perpendicular and parallel dimensions of a buttress to the wall are called "depth" and "thickness", respectively. The dimensions of the buttresses are presented in Tab. 2. It should be noted that the arrangements of trapezoidal, two-stepped, and curvilinear concave buttresses were completely made according to our preference, provided that the criteria of constant volume were adhered to. It is clear that an unlimited number of other designs can be made for these buttresses, of course.

Table 1 Symbols related to the geometrical features of the buttresses

Notation	Meaning
h	Height of wall and buttresses
t_w	The thickness of the wall
d_{rec}	Depth of rectangular buttress
d_{tri}	Base depth of the triangular buttress
$d_{tra,b}$	Base depth of the trapezoidal buttress
$d_{tra,t}$	Top depth of the trapezoidal buttress
$d_{st,2,u}$	Depth of the upper part of the two-stepped buttress
$d_{st,2,l}$	Depth of the lower part of the two-stepped buttress
$d_{cur,cv,b}$	Base depth of the curvilinear concave buttress
$d_{semi\ cyl}$	Depth (radius) of the semi-cylindrical buttress
$h_{st,2,u}$	Height of the upper part of the two-stepped buttress
$h_{st,2,l}$	Height of the lower part of the two-stepped buttress
t	The thickness of the buttress

Table 2 Dimensions of the considered buttresses

Buttress form	Dimensions (m)
Rectangular	$h = 11.10$, $t_{rec} = 1.35$, $d_{rec} = 2.20$
Triangular	$h = 11.10$, $t = 1.35$, $d_{tri} = 4.40$
Trapezoidal	$h = 11.10$, $t = 1.35$, $d_{tra,b} = 3.30$, $d_{tra,t} = 1.10$
Two-stepped	$h = 11.10$, $t = 1.35$, $d_{st,2,u} = 1.47$, $d_{st,2,l} = 2.93$, $h_{st,2,u} = 5.55$, $h_{st,2,l} = 5.55$
Curvilinear concave	$h = 11.10$, $t = 1.35$, $d_{cur,cv,b} = 6.60$
Semi-cylindrical	$h = 11.10$, $d_{semi\ cyl} = 1.375$

2.2 Models and Material Properties

In the structural analysis of both historical and contemporary masonry buildings, the modeling of masonry texture is an important issue. Three modeling approaches are used in the modeling. These are detailed micro modeling, simplified micro modeling, and macro modeling. Fig. 4 shows an illustration of these modelings. The mechanical properties of the mortar and masonry unit should be specified separately in the detailed micro-modeling. With this approach, it is assumed that cracks will form in the joint areas. Continuum elements are used in simplified micro-modeling to extend and represent units, while discontinuous elements are used to model mortar behavior and the unit-mortar interaction. Another frequently used modeling technique is macro modeling (homogenized material approach). This type of modeling involves making analyses without distinguishing between the units and the binder (mortar, etc.). In this modeling technique, the properties of the masonry unit and the mortar are combined and considered as a single homogeneous material. The values obtained from the homogenization process are the mechanical properties used in this modeling. Since it requires less time and computer memory, the macro modeling method is generally preferred for the calculation of large structures. Details of these modeling approaches can be found for example in Lourenço [26] and Işık et. al. [27].

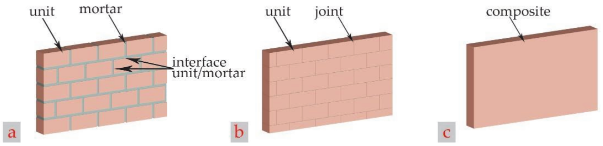


Figure 4 Modeling methods of masonry: (a) detailed micro modeling, (b) simplified micro modeling, (c) macro modeling [23]

In this study, the macro-modeling approach was used because this approach finds a middle way between simplicity and accuracy. There are various formulas in the literature for the computation of the modulus of elasticity and compressive strength of a masonry texture. For the analyses here the expressions in Tomaževič [28] have been used. In this reference, the following relationship is given for the compressive strength of the material:

$$f_c = K f_u^{0.65} f_m^{0.25} \tag{1}$$

Here, K can vary between 0.40 and 0.60 depending on the material and it is a constant (in MPa$^{0.10}$), f_u and f_m represent the compressive strength of the masonry unit and the mortar, respectively. In the mentioned reference it is stated that, in cases where there is no possibility of experimental work, the modulus of elasticity (E) might be taken in the range of $200f_c$ and $2000f_c$, and the tensile strength (f_t) can be taken in the range of $0.03f_c$ and $0.09f_c$. Moreover, it is emphasized that the values of $E > 1000f_c$ should be used with caution. $E = 750f_c$ ve $f_t = 0.06f_c$ expressions were adopted in this study. The Poisson's ratio of the homogenized material was taken as 0.20. The unit volume weight of the masonry material was calculated with the following expression:

$$\gamma = \varphi_u \gamma_u + \varphi_m \gamma_m + \varphi_v \gamma_v \tag{2}$$

Here, φ_u, φ_m, φ_v, ve γ_u, γ_m, γ_v indicate the volume fractions and unit weights of masonry unit, mortar, and voids, respectively. For an old historical stone masonry structure like Şarapsa Han, it can be said that the volume fractions of approximately 75%, 20%, and 5% for the masonry unit, mortar (including filling material), and voids, respectively, are reasonable values. As for the unit volume weight of the masonry unit and mortar, values in Korkmaz [29] were used for these. In his study, the unit volume weight of stone and mortar is given as 26.37 kN/m^3 and 17.95 kN/m^3. The elastic modulus of stone and mortar is given as 29635 MPa and 8333 MPa, and compressive strengths are given as 79.5 MPa and 11 MPa, respectively. By using these values and the above expressions, the material properties required for the texture of the structure were determined and shown in Tab. 3.

Table 3 Material properties used in calculations for the models

Unit volume weight, γ / kN/m^3	Poisson's ratio, ν	Compressive strength, f_c / MPa	Tensile strength, f_t / MPa	Modulus of elasticity, E / MPa
23.37	0.20	15.65	1	11738

In this paper, the finite element modeling of the basic model and other buttressed models was made with the Abaqus program [30]. The Concrete Damaged Plasticity (CDP) model in the Abaqus program was employed for nonlinear material definition. The CDP model is based on two main fracture mechanisms: crushing under compression and cracking in tension, as shown in Fig. 5. There are many studies in which the CDP model is used in nonlinear material definition [31, 32].

When unloading is made at any point of the softening branches of the stress-strain curves of the material, a decrease in the modulus of elasticity is observed due to the damage to the material. The decrease in the modulus of elasticity is characterized by two damage variables. These are the d_t and d_c (t denotes tension and c denotes compression) parameters. These parameters take values between 0 and 1. A value of zero represents the undamaged case, and a value of 1 represents the case of complete damage, that is, the case of complete loss of strength. In many studies mentioned above using the CDP model, the expression $d = 1 - \sigma / f$ has been used in the calculation of d_t and d_c parameters. The same expression was used in this study as well.

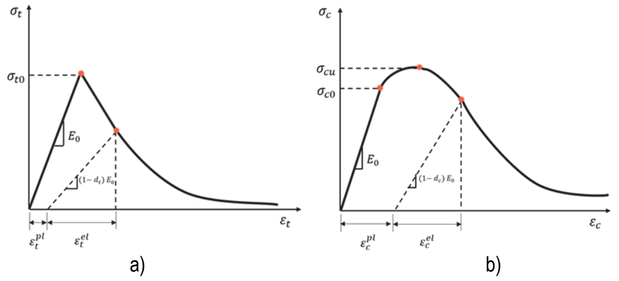


Figure 5 The behavior of masonry material under axial loading; a) in tension b) in pressure [27]

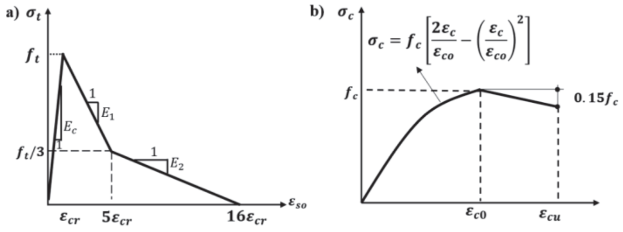


Figure 6 $\sigma - \varepsilon$ relations adopted for masonry texture a) in tension b) in compression

To represent the stress-strain curves of masonry material, Hognestad's [33] modified model was used in compression and Massicotte et. al.'s [34] model in tension, as shown in Fig. 6.

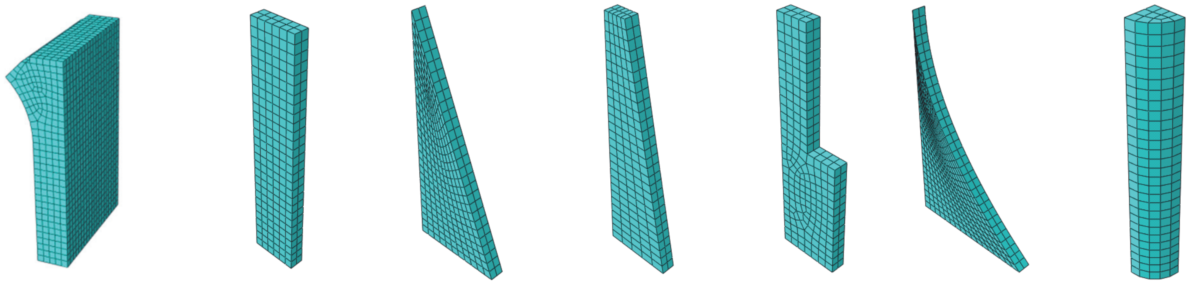
Other parameters (the ratio of initial equibiaxial to initial uniaxial compressive strength "f_{b0}/f_{c0}", the dilation angle "Ψ", the eccentricity "ϵ", the tensile to compressive meridians slope ratio "K_c", and the viscosity "μ") required to accurately simulate nonlinear behavior when using the CDP model are shown in Tab. 4. These values are taken in accordance with the values in the Abaqus user manual and the literature mentioned above.

Table 4 Concrete Damaged Plasticity Parameters used in the analyses

f_{b0}/f_{c0}	Ψ	ϵ	K_c	μ
1.16	10°	0.1	0.667	0.002

2.3 Finite Element Models and Analysis Method

While forming the finite element meshes of the models with Abaqus, the C3D8R element (8-node brick element) was used. It should be expressed that the final meshes were obtained by refining the initial meshes until stable results were obtained for each model. All degrees of freedom of the nodes in the base sections of the models were constrained, i.e. the base sections were taken as fixed. The finite element mesh of half of the basic model without buttresses, which is called the "plain model", and of each considered buttress is given in Fig. 7. Calculation models were formed by adding considered buttresses to the plain model.



a) Plain model: Number of elements: 3880, Number of nodes: 4914

b) Number of elements: 336, Number of nodes: 609

c) Number of elements: 566, Number of nodes: 954

d) Number of elements: 280, Number of nodes: 522

e) Number of elements: 356, Number of nodes: 645

f) Number of elements: 880, Number of nodes:1440

g) Number of elements: 308, Number of nodes:522

Figure 7 Finite element meshes, numbers of elements and nodes of half of the models a) Plain model b) rectangular buttress c) triangular buttress d) trapezoidal buttress e) two-stepped buttress f) concave curvilinear buttress g) semi-cylindrical buttress

In the study, firstly and mainly, the effect of buttress form on the masonry wall out-of-plane resistance under inclined force is investigated. For this purpose, the load transmitted from the vault to the models was considered as a single load while making calculations. Base shear force-control node displacement curves (pushover curves) were obtained for the models, each of which has a different form of the buttress. In all models, a node on the symmetry axis in the upper section of the wall was taken as the control node. Calculations were also made for the plain model which has no buttresses (Fig. 7a), and the "non-linear static analysis method" was adopted as the analysis method.

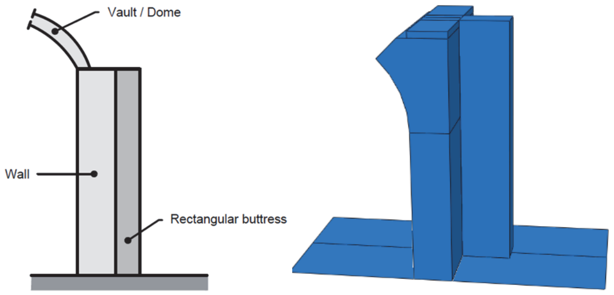


Figure 8 Schematic representation of a vaulted/domed masonry structure with walls supported by rectangular buttresses

By comparing and evaluating the pushover curves obtained by the analyses, the effect of buttress form on the out-of-plane resistance of the wall and thus the structure, was determined and discussed. In the study, secondly, the effect of buttress depth, thickness, and height on the wall resistance was investigated by considering only the rectangular buttressed model, as shown in Fig. 8.

3 ANALYSES AND RESULTS

In this section, in vaulted masonry structures, firstly the effects of the buttress form, and then considering only the rectangular buttress case, the effects of some geometrical parameters on the out-of-plane resistance of the walls are investigated.

3.1 Effects of Buttress Form

The obtained pushover curves for the models having the considered buttress forms are presented in Fig. 9. Maximum base shear force values of the models are given in Tab. 5. It is seen that models with triangular and curvilinear concave buttresses have significantly higher out-of-plane resistance than the models having buttresses in other forms. In the initial stages of their analysis, the triangular buttressed model showed slightly higher resistance than the curvilinear concave buttressed model, while the curvilinear concave buttressed model maintained its lateral resistance better in the middle and later stages of the analysis.

Among the other buttressed models, those with two-stepped and trapezoidal buttresses exhibited very close resistance and behavior. The rectangular buttressed model has slightly lower resistance than the two-stepped and trapezoidal buttressed models. Among all models, the semi-cylindrical buttressed one showed the lowest resistance. The plain model which has no buttress naturally exhibited the lowest resistance.

The analyses have clearly revealed how effective the buttress form is on the out-of-plane resistance of the walls in vaulted masonry structures. It is already known from the Strength of Materials that form has a significant effect on resistance to various effects. Here this fact manifests itself once again and especially for the masonry buttresses.

It should be noted that the designs of trapezoidal, two-stepped, and curvilinear concave buttresses were made according to our own choice, provided that they comply with the constant volume criterion. Therefore, if different designs are made for these buttresses, it is quite normal to obtain slightly different results from those obtained here.

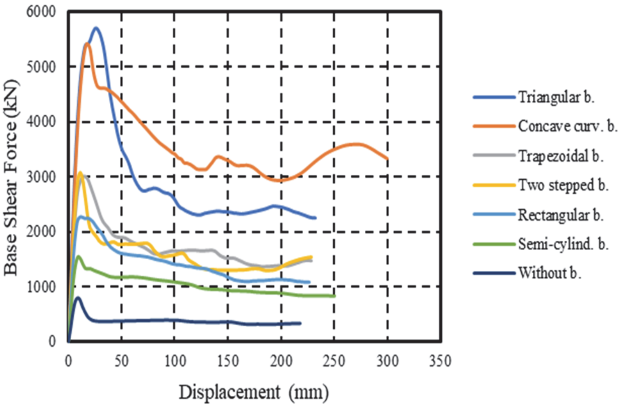


Figure 9 Pushover curves of the models with different buttress forms

Table 5 Collective comparison of the maximum base shear forces of the models

Buttress form	Max. base shear force, $R_{\max}$ / kN
Semi-cylindrical	1549
Rectangular	2277
Trapezoidal	3018
Two-stepped	3073
Curvilinear concave	5431
Triangular	5700

In Fig. 10, contour representations of the damage parameter for the models at the last stage of their analysis have been shown. From the figure, it can be clearly seen where the damage and thus the stresses are concentrated as the models reach the collapse.

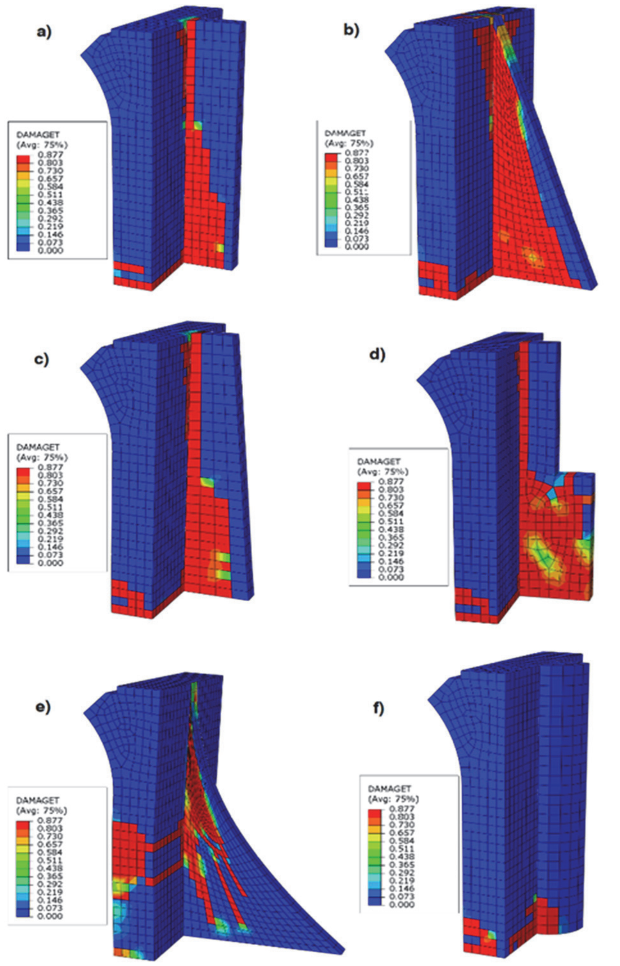


Figure 10 Contour representations of the damage parameter for the models a) rectangular buttressed model, b) triangular buttressed model, c) trapezoidal buttressed model, d) two-stepped buttressed model, e) concave curvilinear buttressed model, f) semi-cylindrical buttressed model

Before closing this section, it is useful to mention one more point. There are alternatives to the nonlinear static analysis method used here in determining the collapse loads of masonry structures. The limit analysis method is a reliable and practical method that stands out among these methods.

3.2 Effect of Buttress Depth

Here, for examining the effect of depth, thickness, and height of the buttress on the out-of-plane resistance of a masonry wall, only the rectangular buttressed model was considered. While examining the effect of one parameter, the others were held constant.

The effect of the depth (dimension perpendicular to the wall plane) of the buttress was investigated for $d = 0$, 1.1 m, 2.2 m, 3.3 m, and 4.4 m. The pushover curves of the models with buttresses at these depths are shown in Fig. 11. As can be seen from the curves, the resistance of the structure increases substantially as the depth of the buttress increases. According to the figure, for example, the lateral resistance at a buttress depth of 4.4 m is more than twice the resistance at a depth of 2.2 m. The results obtained are logical and expected since the increase in the buttress depth will increase the second moment of the area of the cross-section of the wall and buttress pair. And it is well known that this increase is related to the third power of the depth dimension. The fact that the walls are supported by deep buttresses in high historical buildings shows us that the builders of these structures have a good understanding of the effect of the depth of the buttresses on the lateral resistance of the structure. This further increases our respect and admiration for these builders.

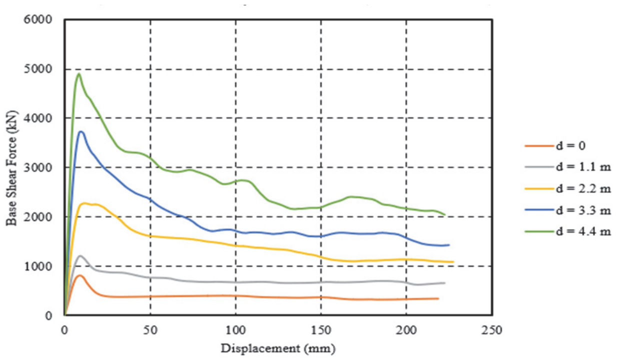


Figure 11 Pushover curves of the rectangular buttressed model for different buttress depths

3.3 Effect of Buttress Thickness

The effect of the thickness (dimension parallel to the wall plane) of the buttresses was examined for $0 \times t = 0$ m, $0.5 \times t = 0.675$ m, $1.0 \times t = 1.35$ m, $1.5 \times t = 2.025$ m and $2.0 \times t = 2.7$ m. The pushover curves of the models with buttresses of these thicknesses are presented in Fig. 12. As can be seen, the increase in thickness increases the lateral resistance of the structure. The reason for this is that the moment of inertia of the cross-section of the wall + buttress pair increases with the increase in the thickness of the buttress.

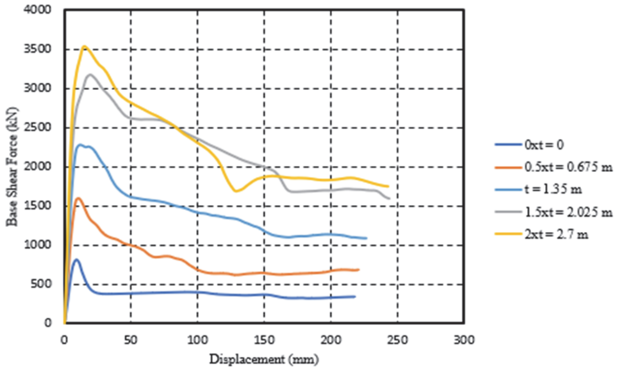


Figure 12 Pushover curves of the rectangular buttressed model for different buttress thicknesses

However, the increase in the moment of inertia here was not as effective as the increase in the buttress depth. Because, the moment of inertia of a rectangular section about an axis passing through its geometric center varies with the first power of the section dimension parallel to that axis, however, varies with the third power of the section dimension perpendicular to the axis. Therefore, to increase the out-of-plane resistance of a masonry wall, increasing the depth of the buttress supporting that wall is a much more effective solution than increasing the thickness of the buttress.

3.4 Effect of Buttress Height

In some historical masonry buildings, the buttresses have a lower height than the walls. The Kızıltepe (Mardin) Ulu Mosque in Fig. 1a is an example of such a structure. Here, the effect of the buttress heights in some ratios of the wall height, which is 11.1 m, on the resistance and behavior of the wall has been investigated. The values considered for the buttress height are $h = 0$, 2.22 m, 4.44 m, 6.66 m, 8.88 m, and 11.1 m, and the ratios of these values to the wall height are 0, 0.2, 0.4, 0.6, 0.8 and 1, respectively. The pushover curves obtained for the models having buttresses at these heights are shown in Fig. 13. The radical effect of the buttress height on the wall resistance is clearly seen. As the ratio of the height of the buttress to the height of the wall decreases, it is a natural and expected result that the support provided to the wall decreases. From the figure, it can also be seen that buttresses having a height of eighty or even sixty percent of the entire wall height are nearly as effective as the buttress at the entire wall height. Another remarkable point is that even a buttress with a height close to half the height of the wall (buttress having a height of $0.4h$) provides very good support to the structure.

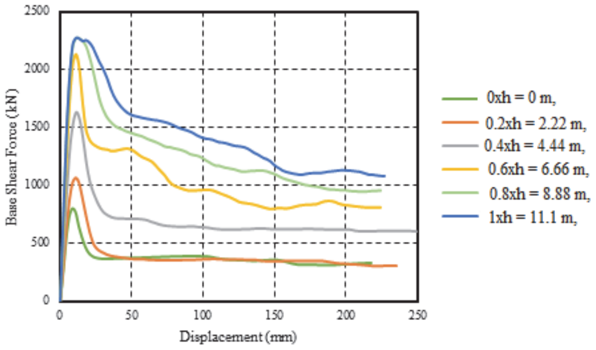


Figure 13 Pushover curves of the rectangular buttressed model for different buttress heights

Thus, parametric studies have shown that all three dimensions of a buttress significantly affect the level of contribution that the buttress gives to the wall it supports.

4 CONCLUSIONS

When examined, it is seen that many historic masonry buildings, especially those with high walls, mostly have buttresses. Therefore, it is indisputable that the importance of buttresses was well understood by those who designed and built these structures. In this study, the efficiency of buttress form on out-of-plane resistance of walls in vaulted structures was investigated. In addition, some parametric studies were carried out for the rectangular buttressed structures. The main results obtained from the study can be summarized as follows:

- Form of the buttresses significantly affects the out-of-plane resistance of the walls in the vaulted masonry structures. Among the buttresses of equal volume but different forms, triangular and concave curvilinear buttresses provide the highest support to the walls, while semi-cylindrical buttress offers the lowest contribution. The rectangular buttress, which is the most common buttress form in historical masonry buildings, lags behind first the triangular and concave curvilinear buttresses, and then the trapezoidal buttress in terms of supporting the walls against vault thrust. The efficiencies of trapezoidal and two-stepped buttresses are close to each other and higher than the rectangular buttress.
- Trapezoidal and two-stepped buttresses have been dimensioned by us, provided that they are of equal volume with others. If different dimension arrangements are made for these two buttresses, it is quite normal to get slightly different results from those obtained here.
- Analysis of the rectangular buttressed model showed that all three of the dimensions of a buttress (depth, thickness, and height) significantly affect the level of support that the buttress will provide to the wall.
- In this study, as analysis method, the nonlinear static analysis method has been adopted. The limit analysis method is another effective and practical method that can be used.

It is possible to extend the presented work to uniquely shaped buttresses and buttresses having weight towers.

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