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Technical note

COMPARATIVE NUMERICAL ANALYSIS OF DIFFERENT STRENGTHENING SYSTEMS OF HISTORICAL BRICK ARCHES

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The article presents a comparative numerical analysis of various ways to strengthen historical brick arches. Five ways of strengthening brick arches with steel tie-rods have been proposed. Two of these involve the use of braces wrapped around pillars supporting the arch connected with a tie-rod; the other two ways involve the use of the tie-rods with welded metal sheets of different sizes; the latter involves the use of a tie-rod glued with the use of an epoxy adhesive. The collected data were compared with the reference model of the arch left without any interference. The results make it possible to evaluate the effectiveness of the methods by comparing displacements in the vertical and horizontal direction and stresses. The article indicates the direction of proper planning and design of the arch strengthening in brick structures in historical buildings.

Key words: historical buildings, brick arches, tie-rod, modal analysis, FEM.

1. Introduction

The analysis of historical buildings' components is an extremely complex issue. Lack of documentation, the variety of materials used over the centuries, and damages result in the stability assessment of the structure being problematic. Among the issues associated with the historical buildings, an important role is played by commonly used structural arched elements. The performance of these structures was described in an article by Pałkowski [1]. An increasing importance is put to strengthening and repair of historical structures conducted non-invasively or with as limited interference in the historical structure as possible. Methods for strengthening shown in the existing arched structures can be found, inter alia, in the works of Rzeszotarski *et al*. [2], Jasieńko and Rapp [3]. The strengthening of domes was described by Jasieńko and Raszczuk [4], and Collini *et al*. [5], while of arched lintels by Orłowicz and Nowak [6].

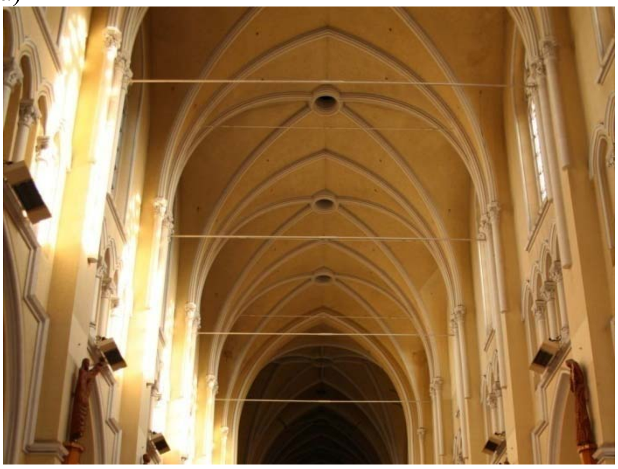
The paper aims at getting acquainted with the phenomenon of the tie-rod usage in the arched elements of historical objects. They are one of the commonly used methods of stabilizing the arches. Their popularity can be observed even nowadays. Exemplary methods of using steel tie-rods were described by Ural *et al*. [7] and Pisani [8] while tie-rods mounted by glue were elaborated on by Matkowski [9]. The arches strengthened by using tie-rods subjected to dynamic loads, are presented in the work of Calderini *et al.* [10].

2. Brick arches as a construction form of historical buildings

It is widely known that the arched structures allow to achieve large spans. They were popular already in the Middle Ages. They owe the popularity at that time to the limited knowledge on the material transferring tensile forces. Therefore, attempts were made to construct elements transferring only compressive forces. To this day, arched constructions can be found in historical religious buildings, bridges, museums, palaces, manor houses and other facilities where space plays a significant role. Due to the poorer knowledge on the materials, such arches were usually made of bricks of parameters characteristic for the era and area.

The arches can be divided according to their shape to circular, elliptical or parabolic. Examples of arched elements are shown in Fig1. Properly made arches are characterized by a pressure line designated for the actual load in the arch's core corresponding to its geometry. The fulfillment of the above condition ensured the structure's durability and enabled its proper performance for many years. A scheme of the arched element shown in Fig.2 is subjected to the numerical analysis described in the article.

a)



b)

c)

Fig.1. Examples of tie-rod usage in brick arched structures: a) The Cathedral Basilica of the Holy Family in Częstochowa, b) the cloisters of the Wawel Royal Castle, c) the cloisters of the Castle in Lidzbark Warmiński.

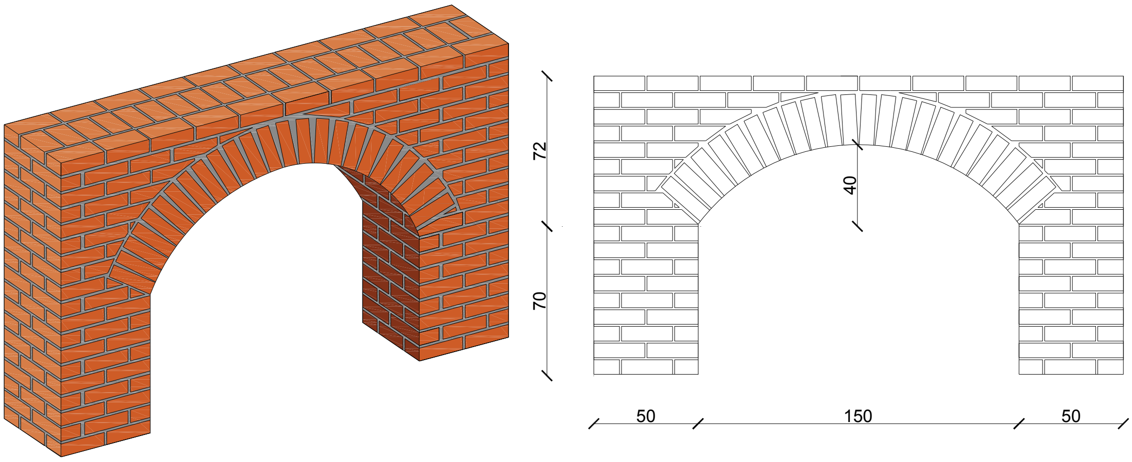


Fig.2. Scheme of the arched element for the numerical analysis.

3. The use of the tie-rods in the structural arched elements

The damages of arches in historical objects caused by exceeding the load capacity, fatigue of the materials' structure or exceptional external forces create the need of improving their technical condition. Typical damages of arched elements include scratches and cracks. No intervention quickly leads to a total destruction of the element, hence the actions improving their conditions should be taken. In case of historical buildings non-destructive and non-invasive methods are used. Among these methods, partial or total rebuilding and injections are mainly used for brick structures. In arched structures, due to the nature of their work, tie-rods are used. It is the most popular form of strengthening brick arched structures. These element, more or less slender, aim at stabilizing the building or its part, through fastening two or more walls, elements together, and limiting their free and independent movement. The method of using tie-rods has already been known for a few hundred years, nevertheless even currently it is not undermined and used been nowadays. The first tie-rods in the arched elements were used as early as in the Middle Ages [11]. However, they had a form of wooden beams. Today, steel tie-rods are commonly used. The tie-rods are mounted at the base of the arch as the elements limiting the bends caused by gravity, construction's age or environmental effects. The correct performance of the tie-rod is associated with the introduction and maintenance of a suitable prestressing force. The value of this force must be properly selected, depending on the wall's compressive strength. The force should induce a state of the arch's tension that opposes the external loads acting on the arch. An inaccurate force selection may negatively affect the construction performance causing the appearance of additional scratches. It is crucial to take into consideration the difference of thermal deformations of the brick wall and steel, the wall creep, and steel relaxation. Therefore, while selecting the method for improving the arched structure condition several factors should be taken into account. Among them, the wall compressive strength, the Young's modulus, the degree of the wall heterogenity and its geometry can be identified. Having decided to use the tie-rods, the tests and calculations should be performed in order to decide how to anchor the tie-rod, to determine its diameter and the steel to be used, and to establish the prestressing force. An important issue is the proper transfer of the force from the-tie rod to the masonry structure. In historical buildings, where the wall is characterized by a high heterogeneity, the surface must be sufficiently large, since the brick walls poorly transfer point compressive stresses.

The most popular ways to mount steel tie-rods are shown in Fig.3. The schemes became a basis to perform, numerical analyzes for different ways of strengthening arched constructions. The classic method of assembling the tie-rods is to use the pressure element in the form of steel sheets. In recent years, glued tie-rods have become very popular due to their increasingly better properties of used adhesives and speed of implementation. This method renders it possible to preserve without any interference (drilling) one side of the wall which in case of historical elements (polychrome or other wall decorations) significantly increases the value of the conducted works.

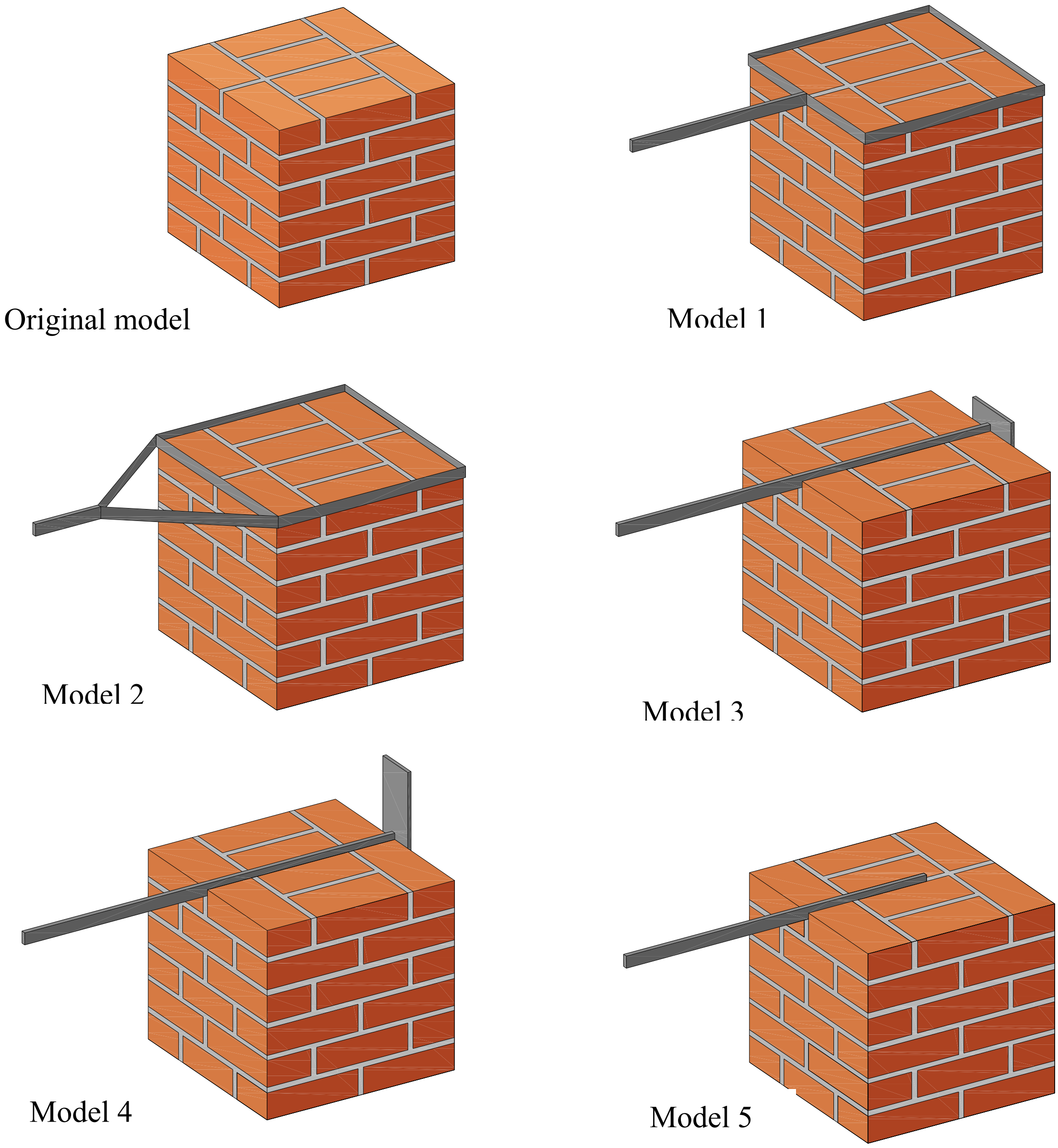
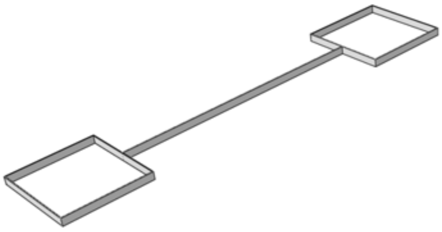
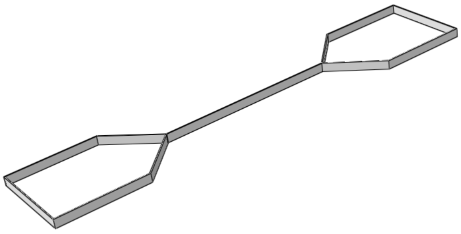
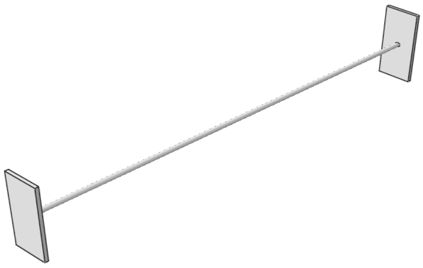


Fig.3. The proposed schemes to strengthen brick arched structures.

4. Numerical analysis

A comparative numerical analysis was made for the brick arch with a span of *1.5 m* and *0.4 m* heigh. The arch, made of solid brick, was based on the 0.5 x $0.5\ m^2$ square section pillars. The vertical load was applied to the upper arch surface, in the middle of its span. Three-dimensional models were made for five different ways of strengthening. For comparison, the results are juxtaposed with a model left without any interference. The numerical analysis was conducted on the basis of the finite element method (FEM) in the Abaqus software. The discretization was made using solid elements, eight-node, with three degrees of freedom in each node.

Table 1. Description of the proposed strengthening systems.

	Strengthening's scheme	Strengthening's description
Model 1		-flat bar with a thickness of *5 mm* and a width of *5 cm*
Model 2		- flat bar with a thickness of *5 mm* and a width of *5 cm*
Model 3		- bar with a diameter of 3 cm - pressure metal sheets with dimensions of 10x10 $cm^2$and a thickness of 2cm
Model 4		-bar with a diameter of *3 cm* - pressure metal sheets with dimensions of *10x20* cm^2 and a thickness of *2cm*
Model 5		- bar with a diameter of *3 cm* glued with epoxy adhesive

To conduct the analysis, the materials in accordance with Tab.2 were used. The table includes values of the Young's modulus [E], the density [ρ] and the Poisson's ratio [ν].The brick arch was treated as a homogeneous material, excluding the division to the brick and mortar. The non-linear nature of the wall performance was represented by the elastic-plastic material described by the Mises criterion.

Table 2. Material data for the numerical models.

	E [MPa]	ρ [kg/m^3]	ν
Masonry	*3700*	*1500*	*0,2*
Tie-rod	*200 000*	*7850*	*0,33*
Epoxy adhesive	*12 500*	*1150*	*0,34*

Five schemes to strengthen the brick arch were proposed (Tab.1). The first two involve the use of perimeter braces around the pillars supporting the arch. The braces are made of flat bars with a width of *5 cm* and a thickness of *5 mm*. The brace in the first case surrounds the pillar and is welded to the tie-rod. The second brace surrounds the pillar from three sides and comes with a flat bar pointing at an *45°*in the tie bar. In the next two proposed ways of strengthening bars with a diameter of *3 cm* are used. At the ends of the bars, the pressure metal sheets with dimensions *10 x 10* $cm^2$and *10 x 20* cm^2respectively for the first and second scheme were welded. The last way strengthening included gluing the bar binding the arch with an epoxy adhesive. The glued bar, as in the two previous cases, had a diameter of *3 cm* and is based on a pillar over a length of *25 cm*.

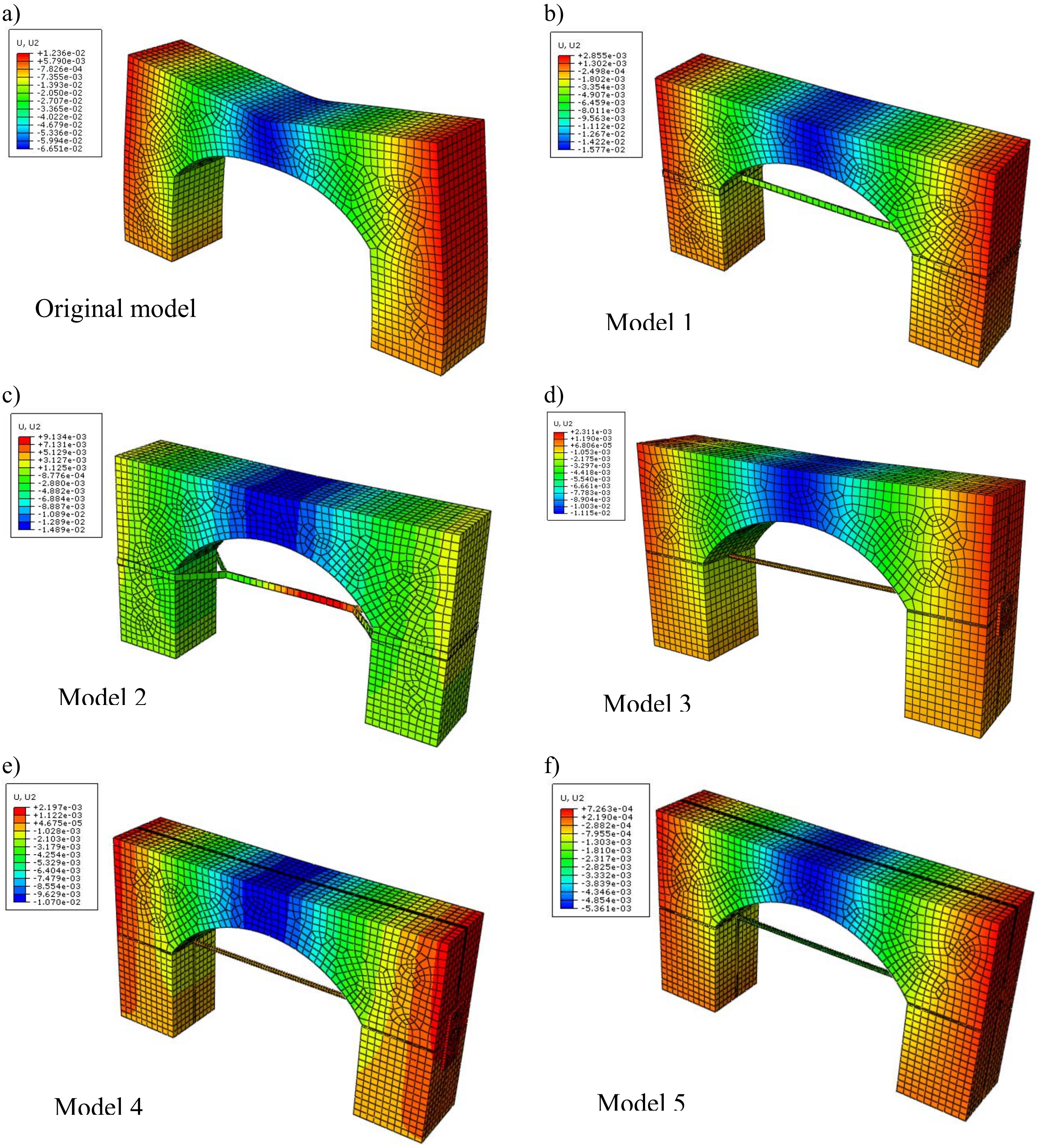


Fig.4. Maps of vertical displacements of the brick arch for different strengthening schemes.

The used strengthenings aim at protecting the structure from excessive deformation, which consequently can even lead to the object's failure. The vertical deformations were measured at the midpoint of the bottom arch surface. They represent the maximum values of vertical displacements. Figures 4 and 5, respectively, show the vertical displacement maps and a graph of the displacement at the aforesaid point. The largest displacements were observed in the reference arch (*6.65 cm*). The proposed strengthenings reduce their value up to *0.53 cm*. The methods that include the use of braces reduce the displacements to about *1.5 cm*, whereas the methods that include the use of the tie rods with the pressure elements to about *1.0 cm*. The juxtaposition of the vertical and horizontal displacements is presented in Tab.3. The horizontal displacements of the reference arch equal as much as *12 cm*. Large horizontal displacements are also observed in the case of using perimeter braces surrounding the column from 4 sides. The best method of limiting both the vertical and horizontal displacements proved to be the method of gluing the tie rod with an epoxy adhesive.

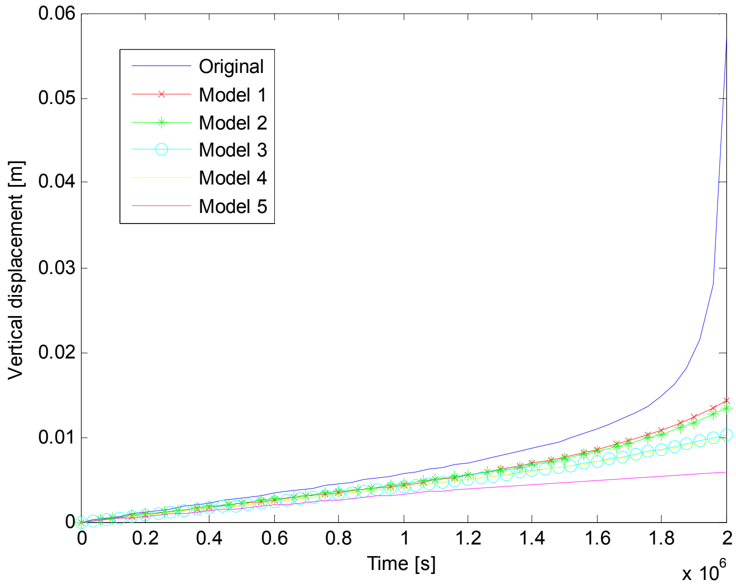


Fig.5. Graph of vertical displacements at the center of the arch.

Table 3. Juxtaposition of the vertical and horizontal displacements for different schemes of strengthening.

Model	Vertical displacement in midpoint of the arch [*cm*]	Max. horizontal displacement [*cm*]
Model without strengthening	*6.65*	*12.00*
Model 1	*1.58*	*8.29*
Model 2	*1.49*	*1.38*
Model 3	*1.12*	*2.53*
Model 4	*1.07*	*1.56*
Model 5	*0.53*	*0.59*

The schemes for the brick arch stresses for various methods of strengthening are summarized in Fig.6. Each of them demonstrates the significant stresses at the point of the force application and the center of the bottom arch surface. The stresses in the reference model have large stress values in the support areas, while the stresses of strengthened arches are to a large extent transferred to the prestressing elements. In the model with the glued tie rod, the stresses are accumulated at the place of gluing. The perimeter braces and welded metal sheet in models 1-4, transmit large stresses to the outer side of the pillars.

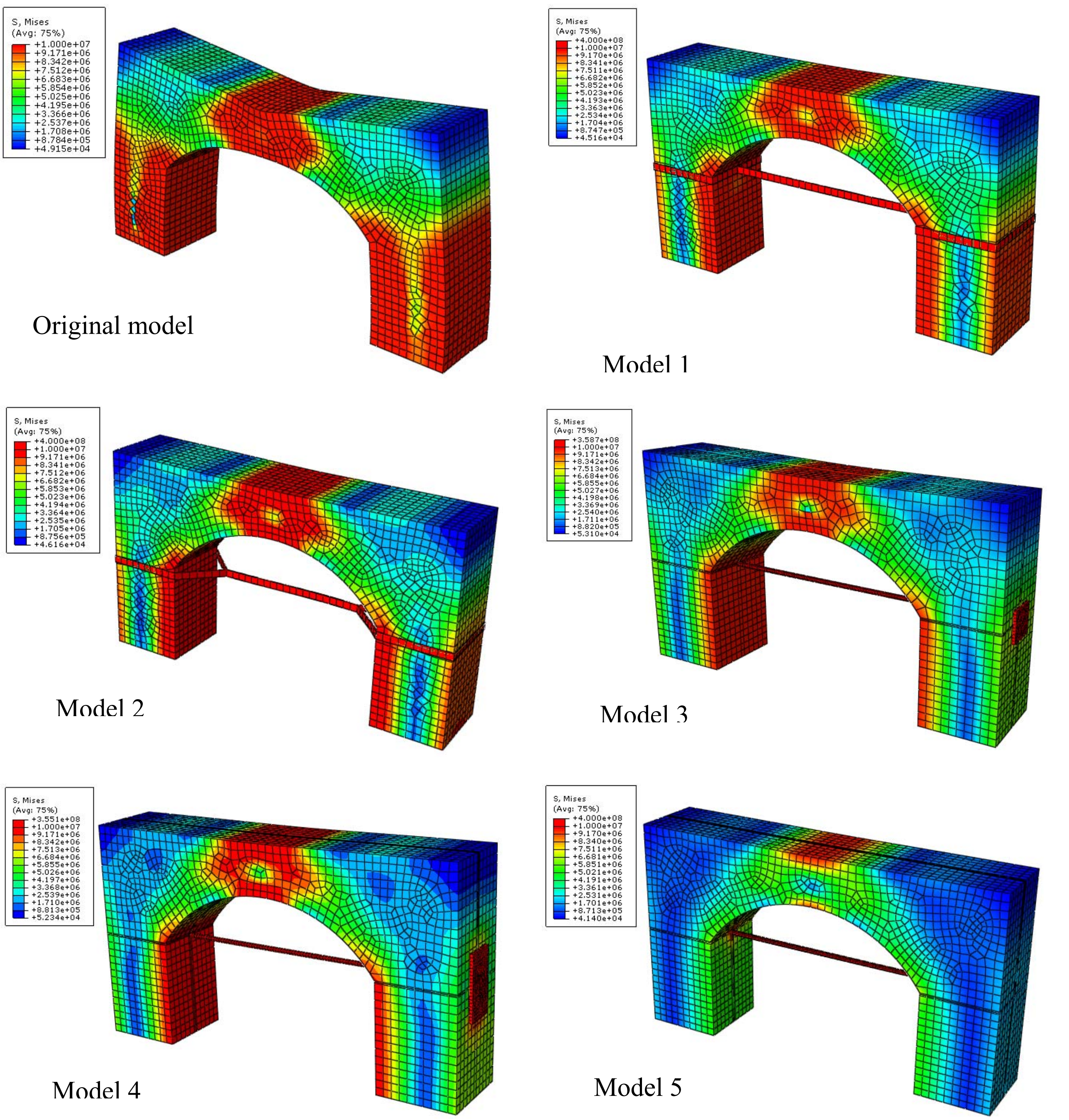


Fig.6. Maps of stresses for the brick arch for different strengthening schemes.

5. Conclusions

In the article, a comparative numerical analysis of various ways to strengthen the brick arches and used mainly in historical buildings is described. The calculations covered the assessment of the use of five different ways of strengthening. The results were compared with the reference arch, left without any strengthening. The effects of strengthening are shown in the form of horizontal and vertical displacements, and stresses. A strong emphasis was put on vertical displacements registered at the midpoint of the arch, that correspond to the maximum displacements of the structure. The analysis allowed making the following conclusions:

- strengthening the brick arches with steel fastening elements gives extremely good results due to a reduction of expansion forces,
- the slightest deformations, both vertical and horizontal, are observed for the tie-rods glued with an epoxy adhesive,
- the use of the perimeter braces surrounding the pillar from the four sides (Model 1) connected with the tie-rod is not correct due to a slight influence on the horizontal deformations,
- the use of braces surrounding the pillar from the three sides and coming through a flat bar at an angle of *45*°to a tie-rod gives better results than a brace surrounding a pillar from 4 sides (horizontal displacements),
- the use of larger pressure sheets (Model 2-3) does not have much impact on the vertical deformation, however, the impact on the horizontal deformations is noticed,
- the stresses in the brick arches with braces are largely transferred to the compressing element,
- the use of the glued tie-rods significantly reduces the stress for the arch itself,
- the stress distribution in the case of using braces and tie-rods with welded metal sheets is similar, however, the use of braces transfers the stresses to the outer part of the arch to a greater extent.

The topics related to the objects of historical and cultural heritage are becoming increasingly popular. Historical buildings are exceptionally important for their historical information, hence each of them requires an individual approach. The need for the design and planning of works aiming at ensuring the stability of historical buildings is increasing. Incorrect execution of brick arch strengthening, so frequently used in historical buildings, can cause irreversible consequences, and even lead to a collapse. Therefore, work on these issues will be continued in further studies and numerical analyzes.

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