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SEISMIC PERFORMANCE OF MASONRY POINTED VAULTS – CASE STUDY OF ST. ANTHONY CHURCH IN BARBAN, ISTRIA

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Abstract

More than 140 churches with medieval wall paintings have been preserved in Istria, which are an essential part of Istrian cultural identity, and classify Istria as the region with the greatest density of this type of cultural heritage. In the last 25 years considerable effort has been put into the preservation and conservation of the wall paintings, but also in the restoration of the churches from the structural point of view. The most significant adverse effects on the frescoes are capillary humidity and cracks that occur as a result of the ground settlement. In this paper we will focus on small single-nave churches with pointed barrel vaults, which are characteristic for the Gothic period. As a case study, the seismic capacity of the church of St. Anthony in Barban will be studied. The interior of the church was entirely painted in the early 15th century. The church has a simple architecture: a rectangular ground plan, roof covered with slate tiles and a bell gable present at the front façade. The walls are built of regular stone blocks in lime mortar. We present results of the numerical analysis of the pointed vault due to seismic actions. The admissible failure mechanisms related to formation of plastic hinges are examined.

Keywords: stone masonry, single-nave church, pointed barrel vault, medieval wall paintings, seismic capacity

1. Introduction

Due to a combination of favourable historical circumstances a large number of churches with wall paintings has been preserved in Istria. So far, more than 140 sites [1] with wall paintings dating from the 8th until the end of the 16th century have been investigated and documented [2, 3]. The most prominent researcher and connoisseur of Istrian wall paintings was academician Branko Fučić, who made a great contribution to their discovery, valorisation and popularization.

The standard procedure for preparation of the wall substrate for a wall painting consisted of two steps: first a thick layer of coarse lime plaster was applied, which was then followed by a final fine plaster, applied only on that wall area that could be painted during one day. This fine plaster was then painted with inorganic pigments. As a rule, the purpose of the wall paintings in the Middle Ages was to educate the illiterate population, therefore they were full of hidden messages, stories and warnings. Some of these messages were successfully interpreted while some of them still remained unrevealed due to the passage of time. An exceptional historic record is also hidden in the drawings and graffiti, written in Glagolitic or Latin, cut with a sharp object on the wall paintings [4].

In this work we explore the dynamic response of single-nave churches with pointed barrel vaults that contain these valuable wall paintings. In total, about 15 churches of such characteristics have been preserved [3]. Commonly, these are small churches whose ground plan dimensions do not exceed 10 m, built from local limestone shaped into more or less regular blocks. The vault, on the other hand, is usually made of smaller and less processed units and is significantly thinner than the load-bearing walls. Vaults were originally covered with slate tiles – in some cases they were replaced with clay tiles. The walls were mostly plastered on the outside (except in cases when large regular stone blocks were used). Nowadays, due to deterioration this plaster is often no longer present.

As a case study, the seismic performance of the pointed vault in St. Anthony church in Barban will be studied.

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2. St. Anthony church in Barban

The church of St. Anthony in Barban is located in the immediate vicinity of the entrance gate and the walls of the former fortified castle (Fig. 1). It is a small single-nave Gothic building with rectangular ground plan (7,7 x 5,8 m) and a pointed barrel vault (Fig. 2), built at the turn of the 14^{th} to the 15^{th} century. Due to its preserved medieval frescoes the object is inscribed in the Croatian Register of Cultural Properties as a protected cultural heritage.

The walls are made of regular square stone blocks in lime mortar with very thin joints (not plastered on the outside). The thickness of the walls is 75-80 cm. On each façade a small narrow window is present; the front western façade also contains two square windows and a bell gable. Roof is covered with slate tiles (Fig. 1).

Figure 1. St. Anthony church in Barban: a) front view; b) Interior view.

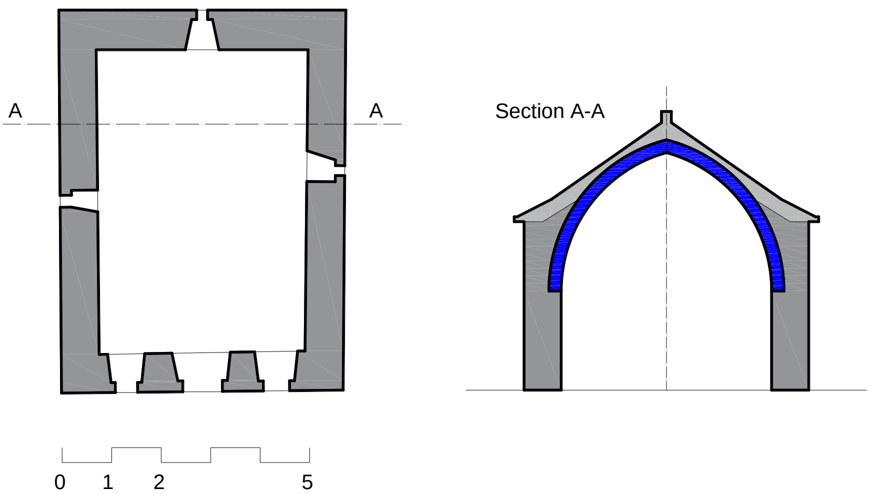

Figure 2. Ground plan and section A-A with marked pointed vault.

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The area around the church has been raised afterwards by more than one meter thus making a basin around the church (Fig. 1). The walls of the church are separated from the surrounding elevated terrain by a narrow space; only in front of the western (entrance) façade there is a flat stone-paved area, reached by stairs. Due to the raised terrain, during heavy rains rainwater overflows from the nearby road and parking lot, which is retained in the area in front of the church. In this way, the walls of the church are filled with capillary moisture, which damages the structure of the wall, as well as the wall paintings inside the church.

At the beginning of the 15th century its interior was painted with 15 scenes from the legend of St. Anthony the Abbot, the patron saint of the church, shown in two opposite bands on the north and the south wall. The western and the eastern walls were also painted with depiction of the Virgin Mary with the Child and images of various saints important to the local community. On all surfaces of the preserved wall paintings we can find incised numerous Glagolitic graffiti, depictions of architecture (fortified towns, bell towers and churches), figural drawings, depictions of ships and stylized ornaments (Fig. 3). The time of painting can be determined by the oldest graffiti, dated before 1429 [4].

Figure 3. a) Drawing of a ship; b) Glagolitic graffiti.

By studying archival photos and conservation and restoration reports [5], it was detected that the church was repaired on several occasions. The last significant interventions were carried out in the 1960s: the works consisted of repairing the roof covering, some plastering in the interior and retouching of the paintings. From 2005 till 2013 the Croatian Conservation Institute carried out the necessary preventive works in the interior and a complete replacement of the roof covering (Fig. 4), since more than 80 slate tiles were damaged and with each heavy rain the roof and the vault leaked, so that some parts of the vault paintings were irretrievably lost [7].

3. Horizontal capacity of the pointed barrel vault

Pointed arches and vaults give smaller values of thrust than circular arches and can be made thinner than circular arches for large angles of embrace [8], which is why they were especially exploited during the Gothic period. Pointed arches can sustain greater support displacements as well [8]. When pointed arches supported on buttresses are subjected to horizontal accelerations, they have in most cases bigger horizontal capacity than their circular counterparts [9], but this should be confirmed on a case-by-case basis.

Following the Heyman's assumptions that sliding failure cannot occur and that masonry has no tensile strength but infinite compressive strength limit analysis may be applied to masonry structures [10]. This means that the collapse of the structure does not occur due to exceeding of the masonry strength but due to loss of stability. The collapse of the masonry vault will therefore occur due to formation of sufficient number of plastic hinges and transformation of the system into a mechanism. The analysis of masonry arch structures is thus based entirely on the arch geometry.

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Figure 4. Extrados of the vault during the replacement of the roof tiles in 2008 [6].

Dynamic behaviour of pointed arches has been recently studied by Di Carlo et al. [11], Dimitri and Tornabene [9], Misseri and Rovero [12] and Zizi et al. [13]. Misseri et al. [14] performed an extensive experimental campaign on pointed arches under quasi-static horizontal loading, while Šćulac and Čeh [15] documented collapse mechanisms of a pointed arch tested on a shaking table.

Seismic capacity of buttressed masonry arches has been studied in detail in [16,17,18], although they focused only on semicircular or segmental arches (angle of embrace less than 180°). Seismic capacity of buttressed pointed arches is much less investigated. Two studies containing an extensive parametric investigation including various geometrical parameters were conducted by Dimitri and Tornabene [9] and Chisari et al. [19].

In this work the methodology proposed by Brandonisio et al. [17,18] for analysis of buttressed masonry arches under horizontal loads will be applied to the segmental pointed arch from St. Anthony church in Barban. The idealised geometry of the pointed arch supported by two walls (i.e. two buttresses) is shown in Fig. 5. A uniform arch thickness of 25 cm was assumed.

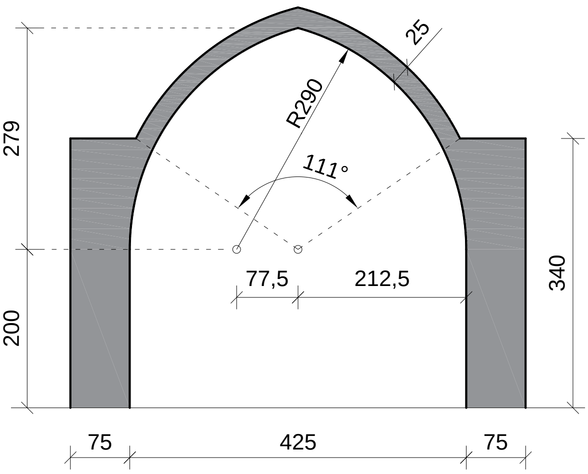

Figure 5. Idealised geometry of the pointed vault supported by two walls (buttresses).

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Figure 6 shows three physically admissible hinging mechanisms of the buttressed pointed vault subjected to gravity loading and constant horizontal ground accelerations, that are usually evaluated [18]. The system is divided into rigid bodies connected by four hinges occurring alternately at the extrados and intrados of the system. In the local mechanism (Fig. 6a) the four-hinge mechanism develops only within the vault. This commonly happens in case when the vault is slender while the buttresses are squat [16]. In the semi-global mechanism (Fig. 6b) one wall (buttress) is included into the hinging mechanism and a hinge develops at the bottom of the wall. Finally in the global mechanism (Fig. 6c) two hinges open at the bottom of the walls and both walls are included into the hinging mechanism. In any case, the seismic capacity significantly depends on the geometry of the vault and the buttresses and the load values, and there is no exact rule which mechanism will be relevant.

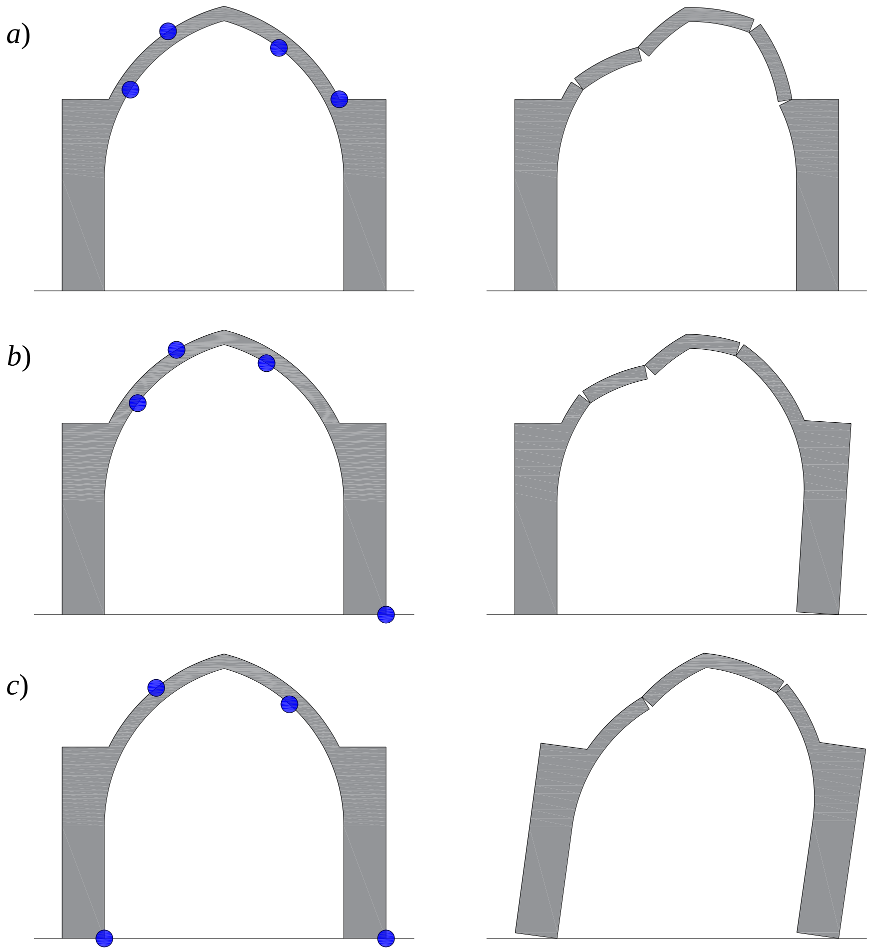

Figure 6. Collapse mechanisms: a) Local mechanism; b) Semi-global mechanism; c) Global mechanism.

Figure 7 presents the kinematics of the local mechanism (according to Fig. 6a) with the corresponding vertical and horizontal virtual displacements. The self-weight of the vault is applied as a vertical force W_i acting in the centre of mass of each rigid body i along with horizontal forces λW_i proportional to the self-weight of each rigid body i via horizontal load multiplier λ.

Applying the principle of virtual work and taking into account that the internal work is equal to zero (since we are dealing with rigid bodies) we obtain the following virtual work equation

$$\sum_{i=1}^{N} W_i \cdot \delta_{v,i} + \sum_{i=1}^{N} \lambda W_i \cdot \delta_{u,i} = 0 \quad (1)$$

where N is the number of rigid bodies, while $\delta_{u,i}$ and $\delta_{v,i}$ are horizontal and vertical virtual displacements of the rigid body i, respectively.

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The horizontal load multiplier λ may be obtained from (1) as

$$\lambda = -\frac{\sum_{i=1}^{N} W_i \cdot \delta_{v,i}}{\sum_{i=1}^{N} W_i \cdot \delta_{u,i}} \quad (2)$$

Solving the virtual work equation we obtain load multiplier λ equal to 0,39, i.e. ground acceleration equal to 0,39 g will cause the opening of four hinges in the vault and formation of the collapse mechanism.

The location of the hinges was found iterative in order to get the minimum value for λ. For acceleration acting to the right a hinge always forms at the extrados of the right springing (C_3). Note that the embrace angle is only 111°, so C_1 will also form at the left springing [9].

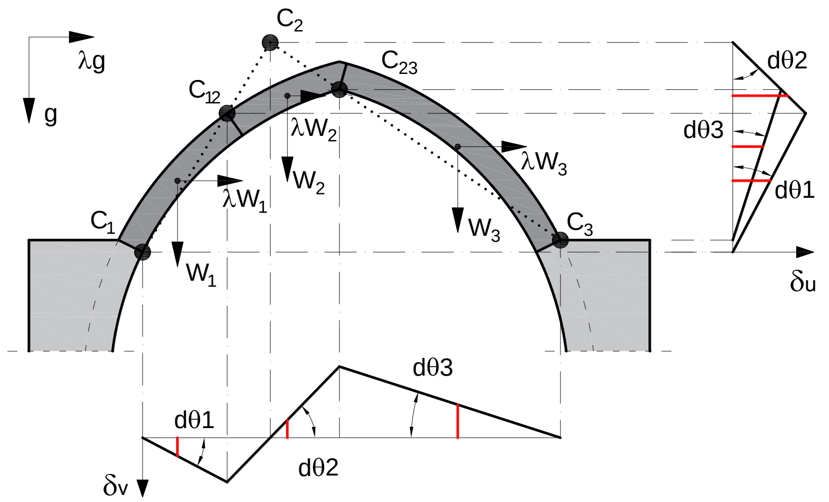

Figure 7. Formation of a local mechanism (hinges formed only in the vault)

Figure 8 presents the kinematics of the semi-global and global mechanism. Solving the virtual work equation we obtain load multiplier λ equal to 0,15 for semi-global and 0,19 for global mechanism.

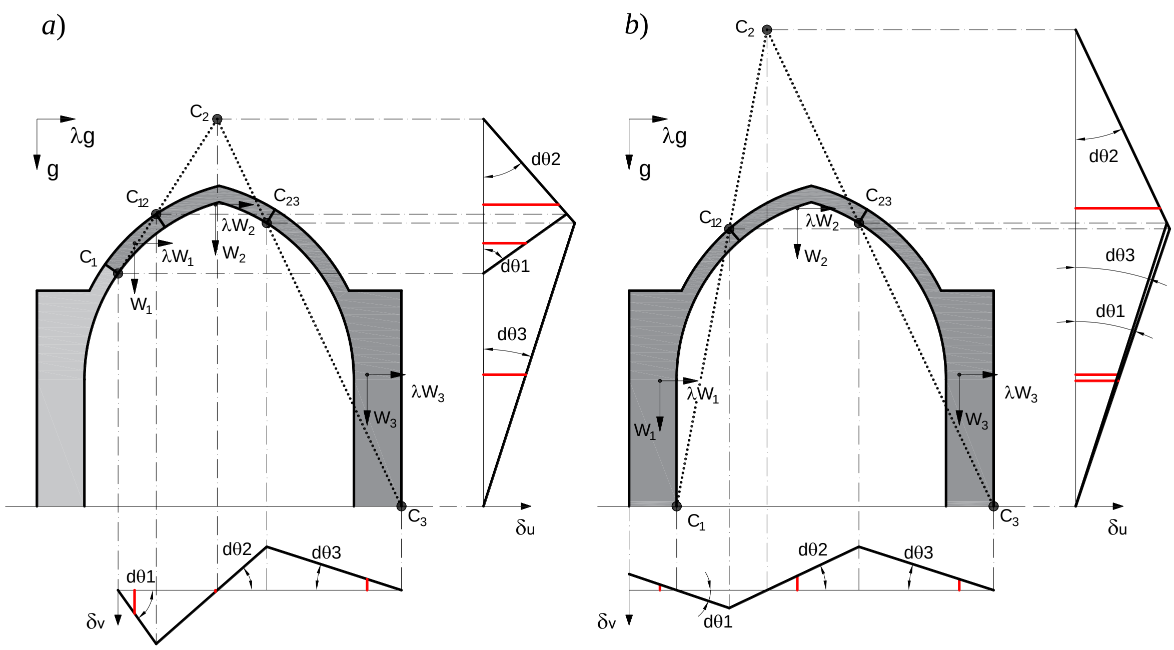

Figure 8. a) Semi-global mechanism; b) Global mechanism.

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These mechanisms are originally proposed for buttressed arches i.e. when the arch is supported on piers. In the building under consideration the buttresses (walls) are supported by transversal walls at a small distance, thus achieving a spatial behaviour of the building. Due to the good quality of transversal walls, appropriate connection of walls and box-like behaviour the semi-global and global mechanism would not be activated. The relevant mechanism is thus the local mechanism with load multiplier λ equal to 0,39.

The reference peak ground acceleration on type A ground for the location considered equals to 0,134 g for a reference return period of 475 years [20]. In combination with the importance factor equal to 1,2 (due to social and economic consequences of collapse attributed to importance class III) the design ground acceleration equals to 0,16 g. This means that the considered pointed vault has satisfactory seismic resistance. In case the seismic capacity of the vault would not be satisfactory, the only appropriate vault strengthening would include reinforcement at the extrados, since the intrados of the vault contains wall paintings.

The peak ground acceleration demand 0,16 g refers to systems at the ground level. It is assumed that this value is the same at the level of the vault springing, since the height of the walls is small. In case of mid-rise and high-rise buildings the acceleration amplification effect resulting from the response of the global system on which the vault rests should be considered.

The effect of infill at the connection with the walls (see Fig. 4) was not taken into account in the analysis. Since the infill has a favourable effect on the behaviour of the vault [21], the seismic capacity would be even higher.

4. Conclusions

In this work we studied the dynamic response of St. Anthony church in Barban with pointed barrel vault, which contains valuable wall paintings. The physically admissible hinging mechanisms of the pointed arch subjected to gravity loading and constant horizontal ground accelerations have been analysed. The collapse of the buttressed vault will occur due to formation of four plastic hinges occurring alternately at extrados and intrados and transformation of the system into a mechanism.

Due to the good quality of transversal walls, appropriate connection of walls and box-like behaviour the semi-global and global mechanism would not be activated. The relevant mechanism is the local mechanism, i.e. the four-hinge mechanism would form only in the vault. The considered vault has satisfactory seismic resistance.

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References

[1] Bistović, Ž. Wall paintings, https://istra.lzmk.hr/clanak.aspx?id=3092, (accessed September 21, 2022).

[2] Fučić, B. (1963): *Istrian frescoes (in Croatian)*. Zora, Zagreb.

[3] Bistrović, Ž. (2011): *Colourful trail of Istrian frescoes*. Istria County, Pula.

[4] Fučić, B. (1982): *Glagolitic Inscriptions (in Croatian)*. JAZU, Zagreb.

[5] Photo Archive of the Conservation Department in Rijeka, Ministry of Culture and Media - Republic of Croatia

[6] Author of photos: Serđo Tomišić, Kapitel d.o.o. (2008)

[7] Šaina, T. (2020): Restoration of frescoes in Barban churches, *The Parish Church of St. Nicholas in Barban*, Proceedings of the scientific conference in occasion of 310th anniversary of construction and consecration, Barban.

[8] Romano, A., Ochsendorf, J.A. (2010): The mechanics of gothic masonry arches, *International Journal of Architectural Heritage*, **4** (1), 59-82, doi: https://doi.org/10.1080/15583050902914660

[9] Dimitri, R., Tornabene, F. (2015): A parametric investigation of the seismic capacity for masonry arches and portals of different shapes, *Engineering Failure Analysis*, **52**, 1–34, doi: https://doi.org/10.1016/j.engfailanal.2015.02.021

[10] Heyman, J. (1982): *The masonry arch*, Ellis Horwood Limited.

[11] Di Carlo, F., Coccia, S., Piedigrossi M. (2017): Dynamics of masonry pointed arches under base motion, *International Journal of Masonry Research and Innovation*, **2** (4), 335-354, doi: https://doi.org/10.1504/IJMRI.2017.087447

[12] Misseri, G., Rovero, L. (2017): Parametric investigation on the dynamic behaviour of masonry pointed arches, *Archive of Applied Mechanics*, **87**, 385-404, doi: https://doi.org/10.1007/s00419-016-1199-4

[13] Zizi, M., Cacace, D., Rouhi, J., Lourenço, P.B., De Matteis, G. (2022): Automatic Procedures for the Safety Assessment of Stand-alone Masonry Arches, *International Journal of Architectural Heritage*, **16** (9), 1306-1324, doi: https://doi.org/10.1080/15583058.2021.1881655

[14] Misseri, G., DeJong, M.J., Rovero, L. (2018): Experimental and numerical investigation of the collapse of pointed masonry arches under quasi-static horizontal loading, *Engineering Structures*, **173**, 180-190, doi: https://doi.org/10.1016/j.engstruct.2018.06.009

[15] Šćulac, P., Čeh, N. (2023): Experimental test on a pointed arch model monitored by contactless optical system, *International Journal of Masonry Research and Innovation*, 1-16.

[16] Alexakis, H., Makris, N. (2017): Hinging Mechanisms of Masonry Single-Nave Barrel Vaults Subjected to Lateral and Gravity Loads, *Journal of Structural Engineering*, **143** (6), 04017026, doi: https://doi.org/10.1061/(ASCE)ST.1943-541X.0001762

[17] Brandonisio, G., Mele, E., De Luca, A. (2017): Limit analysis of masonry circular buttressed arches under horizontal loads, *Meccanica*, **52**, 2547-2565, doi: https://doi.org/10.1007/s11012-016-0609-6

[18] Brandonisio, G., Angelillo, M., De Luca, A. (2020): Seismic capacity of buttressed masonry arches, *Engineering Structures*, **215**, 110661, doi: https://doi.org/10.1016/j.engstruct.2020.110661

[19] Chisari, C., Cacace, D., De Matteis, G. (2021): Parametric investigation of the effectiveness of FRM-retrofitting in masonry buttressed arches, *Buildings*, 11, 406, doi: https://doi.org/10.3390/buildings11090406

[20] HRN EN 1998-1:2011/NA:2011 *Eurocode 8: Design of structures for earthquake resistance* **-** Part 1: General rules, seismic actions and rules for buildings -National Annex.

[21] Gago, A.S., Alfaiate, J., Lamas, A. (2011): The effect of the infill in arched structures: Analytical and numerical modelling, *Engineering Structures*, **33** (5), 1450–1458, doi: https://doi.org/10.1016/j.engstruct.2010.12.037