Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2023) 2434-2443

ECCOMAS
Proceedia

COMPDYN 2023
9th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Athens, Greece, 12-14 June 2023

INFLUENCE OF THE DISPLACEMENT OF THE SUPPORTS ON THE COLLAPSE BEHAVIOR OF MASONRY SEMI-CIRCULAR ARCHES

S. Coccia[1] **and F. Di Carlo**[2]

[1] University of Rome "Tor Vergata"
Via del Politecnico 1, 00133, Rome, Italy
e-mail: coccia@ing.uniroma2.it

[2] University of Rome "Tor Vergata"
Via del Politecnico 1, 00133, Rome, Italy
e-mail: di.carlo@ing.uniroma2.it

Abstract

Displacements of the supports affecting masonry arch systems and vaulted structures can determine a condition of collapse because of gradual changes in geometry. The paper presents an experimental study for the evaluation of the magnitude of the horizontal displacements of the supports that can be sustained by the masonry structure subjected to its self-weight before collapse. To this aim, both the arch prototypes and testing machine have been designed ad-hoc and realized by means of the use of the 3D printing technique. Two semi-circular configurations of the arch have been studied. The first one is a 1:2 scale version of the arch system studied by Ochsendorf in 2002 and characterized by a mean radius of 110 mm, a number of voussoir equal to 16 and a thickness-mean radius ratio equal to 0.23. The second configuration, defined by the same values of mean radius and number of voussoirs and by a higher thickness-mean radius ratio, equal to 0.3, has been set to investigate the effect of the slenderness on the behavior of the arch. The effect of the displacement of the supports on the stability the arch has been investigated in terms of collapse mechanism, evolution of the position of the hinges and ultimate displacement capacity. A comparison of the experimental outcomes has been also performed with numerical results obtained with a tool previously developed by the same authors in the framework of the rigid in compression no tension model for the masonry material and based on the approach of the kinematical theorem of the collapse state.

Keywords: Masonry arch, experimental tests, support displacement, collapse state.

ISSN:2623-3347 © 2023 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2023.
doi: 10.7712/120123.10572.20870

1 INTRODUCTION

The masonry arch is a structural element widely adopted to create a space and withstand overlying loads. Different shapes can be adopted, among which circular, pointed, segmental or elliptical ones. Many works available in literature address the topic of the static behaviour of the masonry arch (see for example [1, 2]). In recent decades, some of them investigate the behaviour of arches subjected to movements of the supports. The spreading of the supports can be caused by various reasons, such as foundation settlement, column and wall tilting, construction defects, soil heterogeneity, subsidence or landslides. These phenomena usually occur gradually over time and are not related to the stability of the arch, but they become worrisome when accompanied by large deformations. However, if these phenomena are not solved autonomously, the progression of the movements of the supports can lead the structure in an unstable mechanism with a consequent collapse. Various authors study the response of masonry arches using analytical and numerical models, such as the ones based on the finite element (FEM) [3] and discrete element (DEM) [4] approaches. Analytical studies were developed to determine the positions of the three hinges at the incipient support displacement [1] and at the collapse state [5-8]. In the first case, the assumption of small displacements is used, while in the second, the occurrence of large displacements and the progressive changes in the geometry of the arch are both considered.

This paper presents the results of experimental tests performed to evaluate the magnitude of the horizontal displacement of the supports that a masonry arch subjected to the self-weight can withstand before reaching a collapse condition. In particular, a polylactic acid (PLA) in-scale model of the arch, composed by dry assembled ashlars, is realized by using the 3D printing technique. Similar tests are also performed by other authors, by using different materials for the realization of the voussoirs of the arch, such as concrete [5], bricks [9], autoclaved concrete [10] or a two-component composite material [11]. The choice of this type of technique allows to reduce the cost and the realization time of the model, ensuring a good test repeatability. For the same reasons, this experimental method has already been successfully adopted in other recent research to evaluate the collapse state of masonry structures [12-16]. Nevertheless, it has not been used to study the problem of the displacement of the supports.

2 EXPERIMENTAL SURVEY

An experimental survey for the computation of the magnitude of the displacements that cause the collapse of circular arches subjected to dead loads has been planned and conducted at the University of Rome “Tor Vergata”. The experimental tests are based on the outcomes of a numerical tool previously developed by the same authors and described in detail in [17]. Both arches and testing machine have been accurately designed and realized using the 3D printing technique. A PLA filament has been used, as shown in Figure 1.

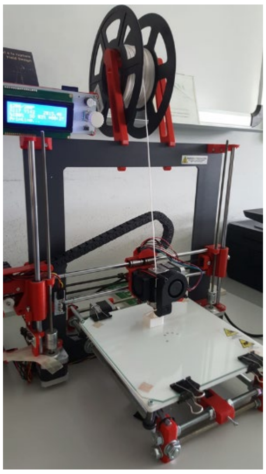


Figure 1: 3D printing process.

With reference to the arch model, two different geometries have been considered, identified by a thickness to mean radius ratio equal to 0.23 and 0.3. Each arch has been designed as an assemblage of sixteen voussoirs, each one disconnected by the others and having the possibility to only rotate around the two edges of its transversal section. Each voussoir has been realized as a box aiming to reduce the time required for the printing process. The boxes are constituted by two elements, a hollow box and a cover, sliding through a suitable groove realized in the walls of the box (Figure 2a). The various boxes have been filled with spherical lead ball to increase the weight of the single voussoir, equal to about 30 g. In order to avoid sliding failures, the different voussoirs have been connected to each other by means of strips of tape. As shown in Figure 2b, an x-shaped configuration has been adopted for the connection system, to allow both opening and closure of the hinges located at the intrados or extrados of the arch, but simultaneously avoiding sliding between two adjacent voussoirs.

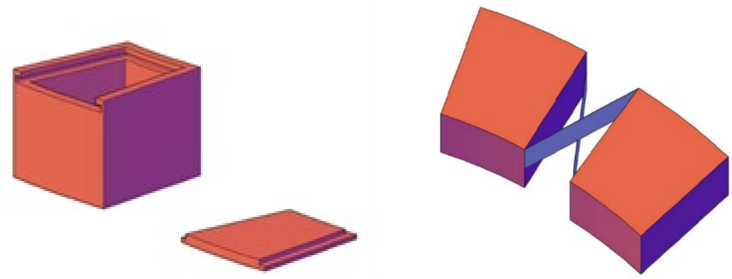


Figure 2: Detail of the a) boxes and b) connection system.

The testing machine has been properly designed in order to apply a displacement at one of the two springing of the arch, in any direction. Furthermore, the magnitude of the displacement can be gradually increased. The test set-up, shown in Figure 3a, is composed by different parts, most of which realized with the 3D printing. The PLA and steel parts are shown with red and grey colours, respectively. A view of the testing machine is shown in Figure 3b. The left springing of the arch rests on a fixed wooden support, while the right one lies on the moving system. Two plain round steel bars are placed along the vertical direction at about 210 mm to each other, connected to a wooden structure through locking devices. A slotted guide is fixed on the vertical wooden panel, to enforce the direction of the displacement. Another slotted guide, joining the two vertical steel plain bars, allows to constantly keep the springing of the arch in a horizontal position, for any direction of the imposed displacement. This guide can move at the same time along the vertical and horizontal directions, to apply a generic displacement to the right springing of the arch, avoiding the occurrence of a rotation. A special element, which can be inserted inside both slotted guides, allows to hold the right springing of the arch. This element is provided with two prismatic blocks which, sliding into the horizontal guide connecting the two steel bars, allow to maintain its stability avoiding rotations. Furthermore, one of the two blocks is long enough to reach the slotted guide fixed to the vertical wooden panel and features a circular shape end to move along the guide directing the displacement of the arch. The displacement is imposed by means of a threaded rod connected to one end to the right prismatic block of the resting element and to the other to a block fixed to the wooden vertical panel or to the horizontal guide, in case of inclined or horizontal displacement, respectively. The threaded bar is held in place through a spring and the screwing of a nut allows to impose the displacement. The testing machine is completed by a knob, useful to screw the nut more easily. Furthermore, a goniometer and a ruler are placed on the vertical wooden panel, to facilitate the measurements of the angle of inclination and magnitude of the imposed displacement.

Figure 3: Testing machine: a) scheme and b) view.

3 EXPERIMENTAL RESULTS

With the aim to investigate the collapse mechanisms of arches subjected to a spreading of the supports, two geometrical configurations are examined. Figure 4 shows the geometry of the arch identified through the mean radius R_m, the thickness t, the clear span L and the angle of the position of the generic hinge β_i. A first series of tests involves an arch characterized by a ratio t/R_m equal to about 0.23 and sixteen voussoirs of about 11.25°, with R_m equal to 110 mm and t equal to 25 mm (Figure 5a). The test has been repeated three times, obtaining the values of the collapse displacement δu reported in Table 1, together with the positions of the hinges at the collapse state. Figures 5b,c,d show the evolution of the second experimental test for different values of the displacement of the supports up to collapse. The first visible hinge is formed at the extrados in the crown (Figure 5b). Two hinges also occur at the intrados, symmetrically, between the third and fourth voussoir from the springing of the arch. A collapse with a symmetrical five-hinge mechanism occurs in all tests (Figure 5d). It is worth to highlight that the position of the hinges does not change with increasing values of the displacement.

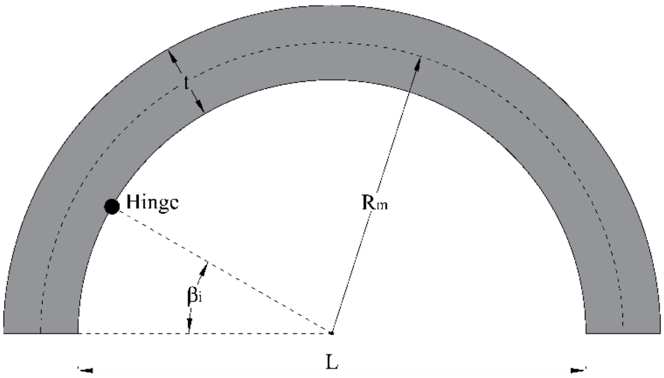


Figure 4: Scheme of the experimental arch.

Test	Hinge positions β_i [°]	δu [mm]	$\delta u/L$ [%]
1	0-33.75-90-146.25-180	28	14.38
2	0-33.75-90-146.25-180	29	14.89
3	0-33.75-90-146.25-180	31	15.92

Table 1: Results of the experimental tests (t/R_m=0.23).

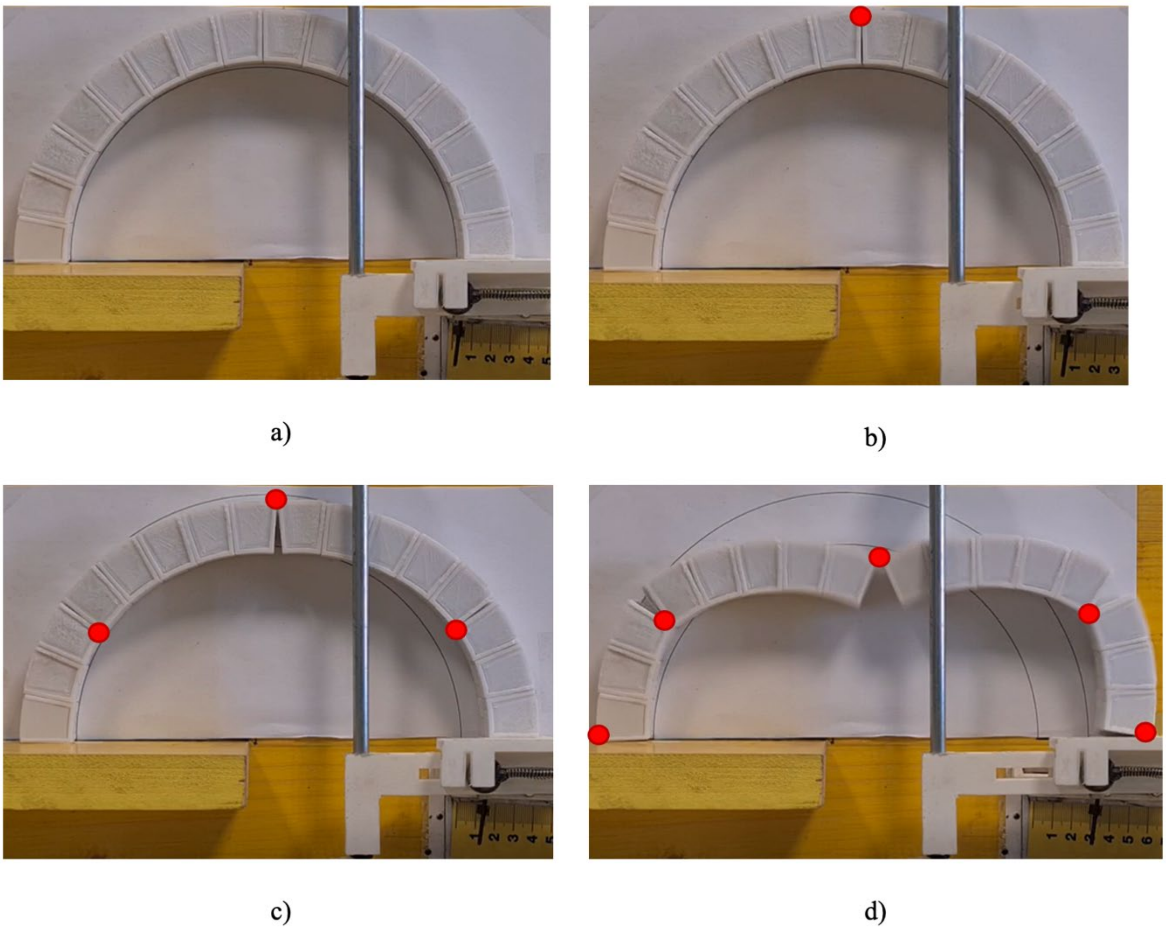


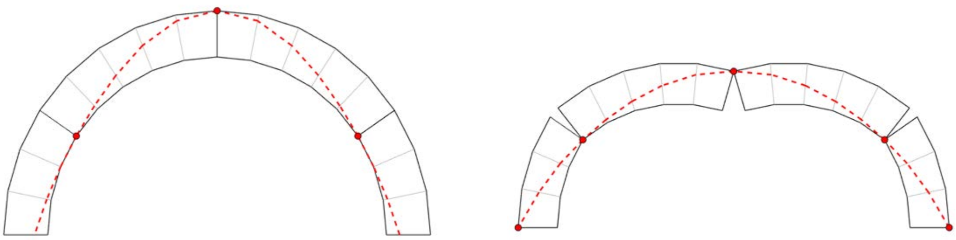
Figure 5. Evolution of the second experimental test: a) δ=0mm, b) δ=3mm, c) δ=10mm e d) $\delta=\delta u$=29mm.

The obtained results are compared in Table 2 with the outcomes of an experimental survey performed by Ochsendorf [5] on an arch having the same geometrical characteristics. It can be noted that the results obtained in the two experimental surveys are basically comparable. In the same table, the experimental results are also compared with the ones obtained with the analytical modelling previously developed and proposed by the same authors and reported in [17].

Experimental			Analytical
Test n.	This paper	Test performed by [5]	Modeling proposed by [17]
1	14.38%	15.4%	16.84%
2	14.89%		
3	15.92%		

Table 2: % span increase just before the collapse *($\delta u/L$)*: comparison between experimental and analytical results

Furthermore, Figure 6 shows the line of pressure and the corresponding position of the hinges in the undeformed configuration and in a configuration close to the collapse displacement of the supports.



a) b)

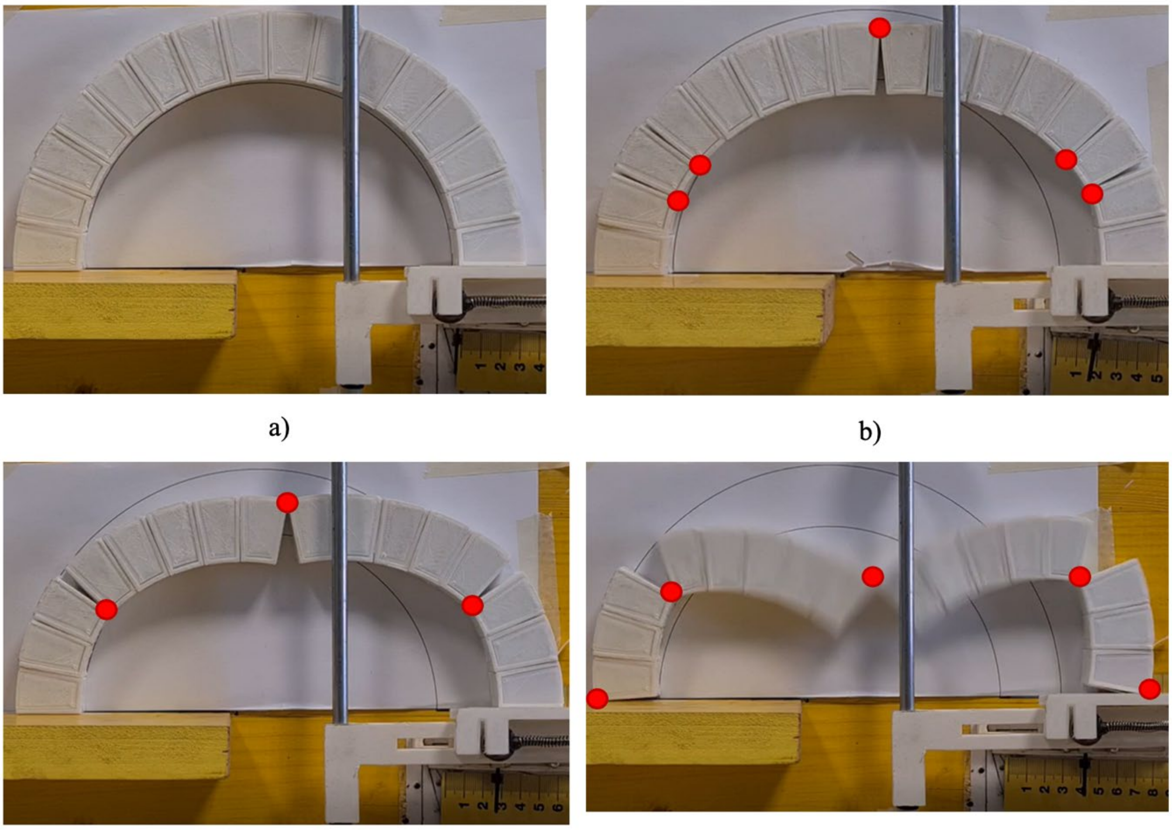
Figure 6: Analytical results in the a) undeformed configuration, b) configuration close to the collapse displacement.

The second series of tests concerns an arch with a ratio t/R_m equal to 0.3. The position of the hinge remains symmetrical during the execution of the text, but it changes for a support displacement equal to 15 mm. In particular, the position of the intrados hinges changes from 22.5°-157.5° to 33.75°-146.25°. Table 3 shows the value of the collapse displacement and the corresponding positions of the hinges at collapse.

Hinge positions in the undeformed configuration [°]	Hinge positions at the collapse displacement β_i [°]	δu [mm]	$\delta u/L$ [%]
22.5-90-157.5	0-33.75-90-146.25-180	42	14.38

Table 3: Results of the experimental tests (t/R_m=0.3)

Similarly to the previous geometry of the arch, Figures 7b, c, d show the evolution of the experimental test for different values of the displacement of the supports up to collapse.



a) b) c) d)

Figure 7. Evolution of the experimental test: a) δ=0mm, b) δ=15mm, c) δ=25mm e d) δ=δu=42mm.

The obtained experimental results are compared in Table 4 with the analytical ones. The observed difference of the collapse displacement is due to the fact that in the analytical modeling the position of the hinges at the intrados changes only for a support displacement of 62 mm, causing a collapse for alignment of the hinges.

Experimental	Analytical	
	Hinge positions at the intrados	
	22.5°- 157.5°	33.75° - 146.25°
22.46%	33.15%	25.56%

Table 4: % span increase just before the collapse (du/L): comparison between experimental and analytical results

In fact, as shown in Figure 8a, at this point the line of pressure results to be tangent in other two points at the intrados of the arch, with a consequent change of the position of the hinges. In this new configuration, the collapse is achieved for the alignment of the hinges (Figure 8b).

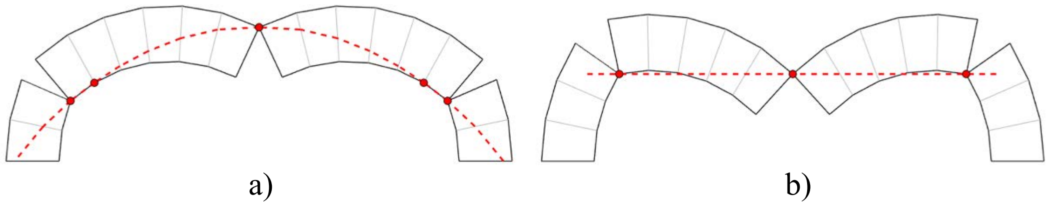


Figure 8. Deformed configuration: a) change of the position of the hinges; b) collapse mechanism.

It is worth to underline that, if the position of the hinges at the intrados is set in the analytical procedure according to the experimental outcomes, the collapse of the arch occurs with the same symmetrical five-hinge mechanism found in the experimental test, for a support displacement equal to 47.8 mm (Figure 9a and Table 4). The reason of the change of the position of the hinges at the intrados found in the experimental test for a displacement of 15 mm can be probably due to imperfections and inaccuracies of the physical models, with respect to the ideal geometry implemented in the analytical model. In fact, as shown in Figure 9b, the line of pressure in the undeformed configuration is very close to the position of the new hinges.

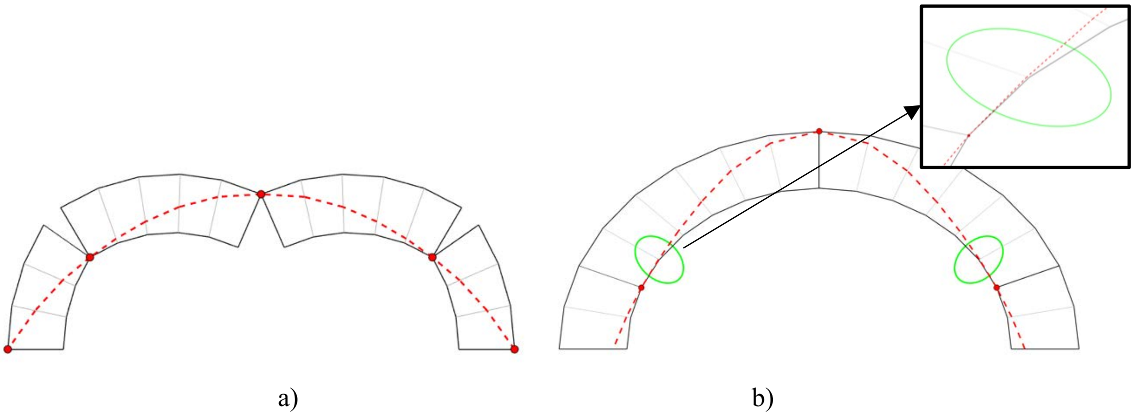


Figure 9. a) Analytical collapse mechanism according to the experimental layout of the hinges; b) detail of the line of pressure.

4 CONCLUSION

The paper presents the results of an experimental survey performed to investigate the collapse condition of masonry arches subjected to self-weight and to a displacement of the springings. Two geometrical configurations have been studied, based on a thickness to mean radius ratio equal to 0.23 and 0.3, respectively. Both the arch prototypes and testing machine have been designed ad-hoc and realized by means of the use of the 3D printing technique. The obtained results have been compared with those evaluated by means of a numerical tool previously developed by the same authors, in the framework of the rigid in compression no tension model for the masonry material and based on the approach of the kinematical theorem of the collapse state. With reference to the first geometry, a comparison is made also with a further experimental investigation available in literature. In this case, a good agreement between experimental and analytical results is found, both in terms of collapse displacement and layout of the hinges at collapse. With reference to the second analyzed geometry, a difference in the evaluation of the collapse displacement is found, due to the different layout of the hinges at the collapse state observed in the experimental tests, with respect to the analytical one. In fact, it is noted that the analytical displacement value tends to the experimental one if the experimental layout of the hinges is set in the analytical model, highlighting the importance of accounting for the presence of imperfections and inaccuracies of the physical models, with respect to the ideal geometry of the arch. Finally, in all performed tests, the analytical model overestimates the real displacement capacity of the arch.

REFERENCES

[1] M. Como, Statics of historic masonry constructions. *Springer International Publishing Switzerland*, 2017.

[2] J. Heyman, The stone skeleton. *International Journal of solids and structures,* **2**(2), 249-279, 1966.

[3] C. Ferrero, C. Calderini, P. Roca, Effect of joint deformability on the experimental and numerical response of dry-joint masonry arches subjected to large support displacements. *Engineering Structures*, **275**, Part A, 2023.

[4] T. Forgács, V. Sarhosis, K. Bagi, Minimum thickness of semi-circular skewed masonry arches. *Engineering Structures*, **140**, 3177-336, 2017.

[5] J. Ochsendorf, The masonry arch on spreading supports. *Structural Engineer*, **84**(2), 29-35, 2006.

[6] F. Di Carlo, S. Coccia, Z. Rinaldi, Collapse load of a masonry arch after actual displacements of the supports. *Archive of Applied Mechanics*, **88**, 1545–1558, 2018.

[7] F. Di Carlo, S. Coccia, Collapse state of elliptical masonry arches after finite displacements of the supports. *Engineering Failure Analysis*, **114**, 2020.

[8] S. Galassi, P. Zampieri, A new automatic procedure for nonlinear analysis of masonry arches subjected to large support movements. *Engineering Structures*, **276**, 2023.

[9] P. Zampieri, F. Faleschini, M. Zanini, N. Simoncello, Collapse mechanisms of masonry arches with settled springing, *Engineering Structures*, **156**, 363-374, 2018.

[10] S. Galassi, G. Misseri, L. Rovero, G. Tempesta, Capacity assessment of masonry arches on moving supports in large displacements: Numerical model and experimental validation. *Engineering Failure Analysis*, **129**, 2021.

[11] C. Ferrero, M. Rossi, P. Roca, C. Calderini, Experimental and numerical analysis of a scaled dry-joint arch on moving supports. *International Journal of Masonry Research and Innovation*, **6**(4), 405-421, 2021.

[12] C. Calderini, S. Lagomarsino, M. Rossi, G. De Canio, M. Mongelli, I. Roselli, Shaking table tests of an arch-pillars system and design of strengthening by the use of tie-rods. *Bulletin of Earthquake Engineering*, **13**(1), 279–297, 2015.

[13] A. Gaetani, P. Lourenço, G. Monti, M. Moroni, Shaking table tests and numerical analyses on a scaled dry-joint arch undergoing windowed sine pulses. *Bulletin of Earthquake Engineering,* **15**, 4939-4961, 2017.

[14] A. Quinonez, J. Zessin, A. Nutzel, J. Ochsendorf, Small-Scale Models for Testing Masonry Structures. *Advanced Materials Research,* **133-134**, 497-502, 2010.

[15] M. Rossi, C. Calderini, S. Lagomarsino, Experimental testing of the seismic in- plane displacement capacity of masonry cross vaults through a scale model. *Bulletin of Earthquake Engineering*, **14**(1), 261–281, 2016.

[16] D. Foti, V. Vacca, I. Facchini, DEM modeling and experimental analysis of the static behavior of a dry-joints masonry cross vaults. *Construction and Building Materials*, **170**, 111-120, 2018.

[17] S. Coccia, F. Di Carlo, Z. Rinaldi, Collapse displacements for a mechanism of spreading-induced. *International Journal of Advanced Structural Engineering*, **7**, 307–320, 2015.