Static behaviour of in scale masonry vaults under imposed settlement of the supports

Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)

Static behaviour of in scale masonry vaults under imposed settlement of the supports

F. Roselli, M. Alforno & F. Venuti
Politecnico di Torino, Department of Architecture and Design, Torino, Italy

A.M. Bertetto
Politecnico di Torino, Department of Structural, Geotechnical and Building Engineering, Torino, Italy

ABSTRACT: The European architectural heritage is heavily characterized by the use of unreinforced masonry spatial structures, like vaults, which represent vulnerable elements in historical buildings. In recent years, the use of in-scale models to investigate the structural behaviour of vaults has largely increased in scientific research. In-scale models allow to overcome the difficulty of performing destructive tests on real structures and allow to investigate the complex three-dimensional failure mechanisms derived by different kinds of load, including the settlement of the supports. In this study, an experimental campaign is carried out on 1:5 in-scale models of barrel vaults with different brick laying techniques, to investigate their structural behaviour un-der settlement of the supports. Two brick patterns are tested: radial and vertical, with bed joints respectively orthogonal and parallel to the head arch plane. Models are built with cement blocks and low cohesion mortar, to simulate the typical historic masonry behaviour. Two tests for each brick arrangement are carried out on the models, which are tested under shear settlement, involving the movement of one abutment normally to the head arch plane. The acquisition process involves image and video recording, while a constant monitoring with the 3D-Digital Image Correlation (DIC) is performed to measure the three-dimensional deformations of the structures. The acquired information allowed to obtain, for each test, crack patterns, ultimate displacements and failure mechanisms. Comparison of the results highlights different behaviour between the vaults built with the two brick arrangements, in terms of different typical crack phenomena leading to different, local or global, failures. The results of the research could help practitioners dealing with interventions on architectural heritage to properly interpret the collapse mechanisms on existing vaults and could be used, in future work, in the validation of numerical models for brick vault analysis.

1 INTRODUCTION

Masonry vaults heavily characterize the European architectural heritage, with a great diffusion along various centuries, before the growth of the modern construction techniques. Such a long period of utilization has as a result a great variety in the vaults typologies, shapes, materials and construction techniques. Due to this great diffusion in historical buildings, vaults still represent one of the most vulnerable elements in the building system. As demonstrated by the recent seismic activity in the centre of Italy, the vaulted structures can respond to high movements of their support with the creation of plastic hinges that lead to new static determined states with complex three-dimensional behaviour and cracking phenomena. These phenomena are typically related to the

DOI 10.1201/9781003308867-37

form-resistant nature of the vaults, deriving from the overall geometry of the structures. Nevertheless, this macro-geometry can be realized with the aforementioned great variety in the construction techniques, with different results.

In recent years, a few studies have focused on the importance of the brick patterns, namely, the micro-geometry (Alforno et al. 2020a), in the global three-dimensional behaviour of vaulted structures (Alforno et al. 2019, 2020b; Baratta & Corbi 2012; Barbieri et al. 2004; Boni et al. 2021; Calderini & Lagomarsino 2004;; ;oraboschi 2014;; Wendland 2007). The topic of the brick pattern has a great tradition in the treatises of the past centuries (;hoisy 1883; Curioni 1870), with a focus on construction issues, and very poor attention to its reflection on the structural behaviour of the whole elements. Today, in virtue of the new available scientific knowledge and methodologies, the evaluation of the brick pattern influence on the global structural behaviour of the vaults offers good possibilities for research.

The form-resistant nature of vaulted structures allows studying their behaviour by evaluating the geometry changes through physical in-scale models, without taking into account forces and material resistances, as demonstrated by the long tradition of models used in structural design (Brunelleschi, Gaudì, Frei Otto, etc.). The spread in technologies offers new possibilities for researchers in the usage of physical models and in the management of the acquired data: in recent years many experimental campaigns have been carried out involving various vault typologies (Calvo Barentin et al. 2017; D'Altri et al. 2019; Rossi et al. 2016), and monitoring systems (Digital Image Correlation (Manuello & Riberi 2021)).

The present work aims to experimentally investigate the influence of the brick pattern in the structural behaviour of in-scale barrel masonry vaults under imposed settlements of the supports. The collected data could be used in future work to validate numerical models (Eslami et al. 2012;; Ferrero et al. 2021; Milani et al. 2016).

In Section 2, the case study and experimental set up are described. Section 3 is focused on the acquisition methodologies employed in the experimental campaign. Results are presented in Section 4, while conclusions and perspectives are outlined in Section 5.

2 DESCRIPTION OF THE CASE STUDY AND EXPERIMENTAL SET UP

The adopted case study is a 1:5 model of a barrel vault with a square base: the net span of the vault is approximately 40 cm, the rise is about 12 cm, and the length of the vault is 40 cm (Figure 2). The barrel vault is made of blocks of dimensions 9 × 20 × 40 mm, which mimic in scale 1:5 the dimensions of classic masonry bricks.

The bricks are arranged according to two patterns:

- a radial pattern (R), composed of multiple rows of rowlock oriented bricks, placed orthogonal to the main vertical plane of the vault (Figures 1a and 2a);
- a vertical pattern (V), where the bricks are laid in rows parallel to the main vertical plane of the structure (Figures 1b and 2b).

The experimental set up of the barrel vault was designed to allow both opening and shear tests to be performed (Figure 2). Specifically, one of the abutments is fixed in the x direction and allowed to move in y direction (simple shear mechanism), while the other abutment is fixed in the y direction and can be moved in x direction (opening mechanism). Four pins support the centring, and the slab where they are fixed can be lowered to allow the centring removal after completion of the vault.

The setup is completed by a further device, used only during the construction of the vault with vertical pattern. It consists of a boundary vertical panel, fixed at one of the vault boundaries, against which successive brick courses make contrast by means of clamps. This solution avoids out-of-plane rotation of the new courses and provides stability during construction thanks to the pre-compression exerted by the clamps.

Imposed settlements are measured by a digital calliper installed in correspondence of the moving abutment.

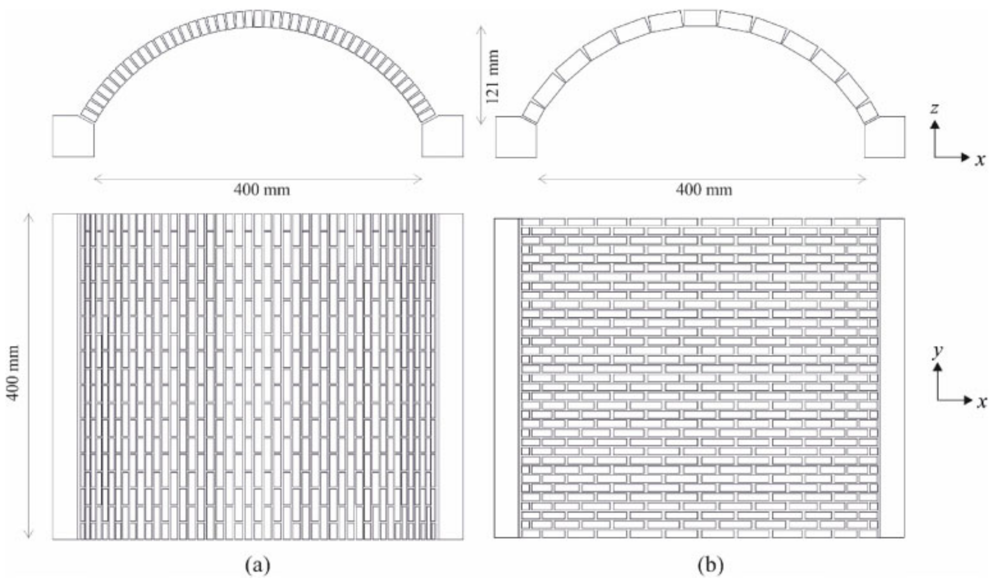

Figure 1. Geometry of the barrel vault in the radial (a) and vertical (b) configuration.

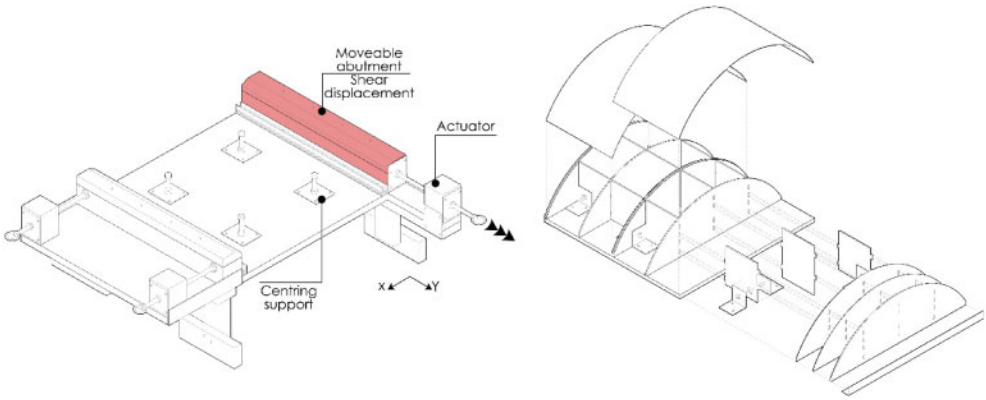

Figure 2. Experimental set up of the barrel vault: testing device and detail of the centring.

The choice of materials to fabricate blocks was mainly dictated by the possibility to easily produce many units in a reduced time and with low cost, and by the need to obtain a sufficient dimensional uniformity between the blocks. According to these needs, cement blocks were fabricated with a formwork made of bicomponent silicon rubber. This solution was chosen due to its reduced cost and ease of casting and stripping. The chosen mix is made of cement and water only, with 2:1 ratio. Stripping is made after 24 hours.

The mix adopted for mortar is the same used by D'Altri et al. (2019) in a 1:12 in-scale model of a gothic barrel vault. It is composed of 3 parts of Silica sand, 1 part of lime, 1 part of water and by the addition of PVA glue and water. The obtained mortar has weak cohesion, allowing cracks to open along the joints, according to the classical Heyman's theory.

All the built models (Figure 3) are composed of 450 bricks with a similar global mortar quantity. A total of 4 models, two for each arrangement, are tested under shear displacement.

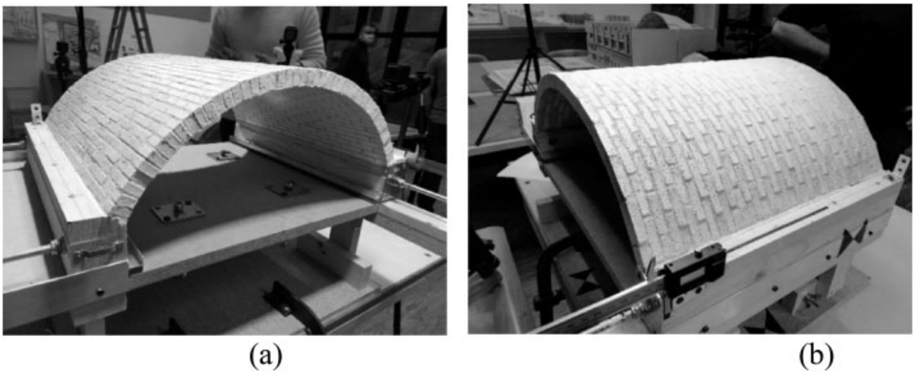

Figure 3. The built model in the radial (a) and vertical (b) configuration.

3 ACQUISITION METHODOLOGIES

During the tests, the direct observation of the phenomena occurred to the structures is accompanied by the acquisition of relevant data. These acquisitions are performed with contactless solutions to avoid alterations of the test proceeding. A constant video acquisition is performed by four synchronized GoPro Hero 5 session cameras distributed around the vault models (Figure 4a) with the aims of relating the cracking phenomena with the imposed displacement, monitored with

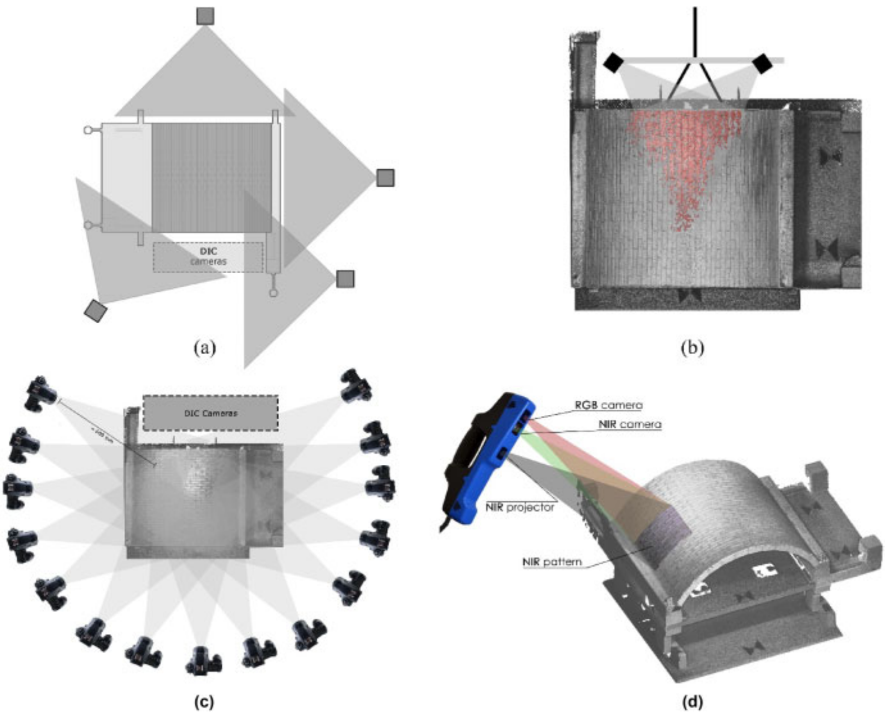

Figure 4. Summary of the adopted acquisition methodologies: (a) GoPro Hero 5 session cameras, (b) DIC cameras, (c) close-range photogrammetry, (d) range-based structured light scanning.

a digital calliper, and capturing the collapse mechanism of the structures. Due to the destructive nature of the tests, three-dimensional data of the models are acquired in several steps of the imposed displacement in order to manage the spatial data of the structures after their failure. Image-based close-range photogrammetry (Figure 4c) and range-based structured light scanning (Figure 4d) solutions are used with these aims, because of their common use in literature in the data acquisition for moveable heritage (Patrucco et al. 2019). At the end of the process, the result obtained is a series of three-dimensional dense point-clouds with an estimated error of about 1 mm. Furthermore, Digital Image Correlation (DIC) is performed, on a little portion of the models (corresponding with the key voussoirs of the vaults) (Figure 4b), for monitoring the three-dimensional deformations of the structures. The data are acquired, as couples of stereoscopic images, by steps of 0.1 mm of imposed displacement. The result obtained is a series of quadrangular meshes with a submillimeter estimated error.

4 EXPERIMENTAL RESULTS

The high-speed and high-resolution cameras provide images of the collapse mechanisms of the tested models. In Figure 5 a selection of images of the failure, from the most representative perspective, is reported. Differently from arches, vaults involve complex three-dimensional failure mechanisms. The latter are quite different for vaults with different brick pattern, but also between vaults with the same brick arrangement.

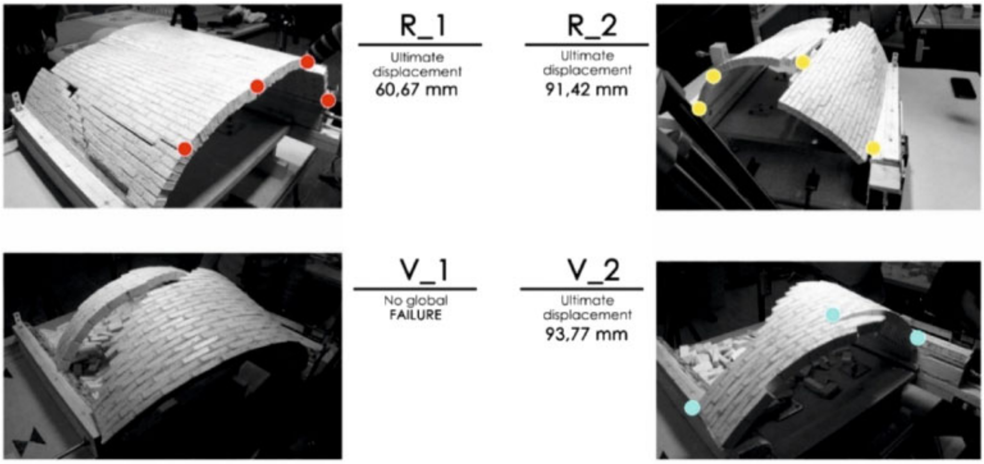

Figure 5. Collapse mechanisms of the tested models.

The R models show a four-hinge mechanism, even though they reach the collapse at quite different ultimate displacements (60.67 mm in R_1 and 91.42 mm in R_2). The hinges run across the whole depth of the model following the longitudinal joints, with two of them placed at the abutment interface and one in the proximity of the key bricks. On the contrary, the V models show a different behaviour, characterized by the local collapse of some arches and by the rigid rotation of the separated portions of the vault. The rigid rotation of the vault on the abutment is particularly evident in the V_1 model, which reaches the end of displacement range (fixed at 150 mm) without a global failure. The V_2 model collapses at 93.77 mm of imposed displacement with a three-hinge mechanism, developed among the arches still in compression, with the slipping of the structure from one of the abutments.

The critical analyses of the crack patterns experienced in the models reveal substantial differences between the two bricks patterns (Figure 6). In the R models most of the cracks are represented by fractures occurring along the longitudinal joints. These major cracks appear to be quite straight

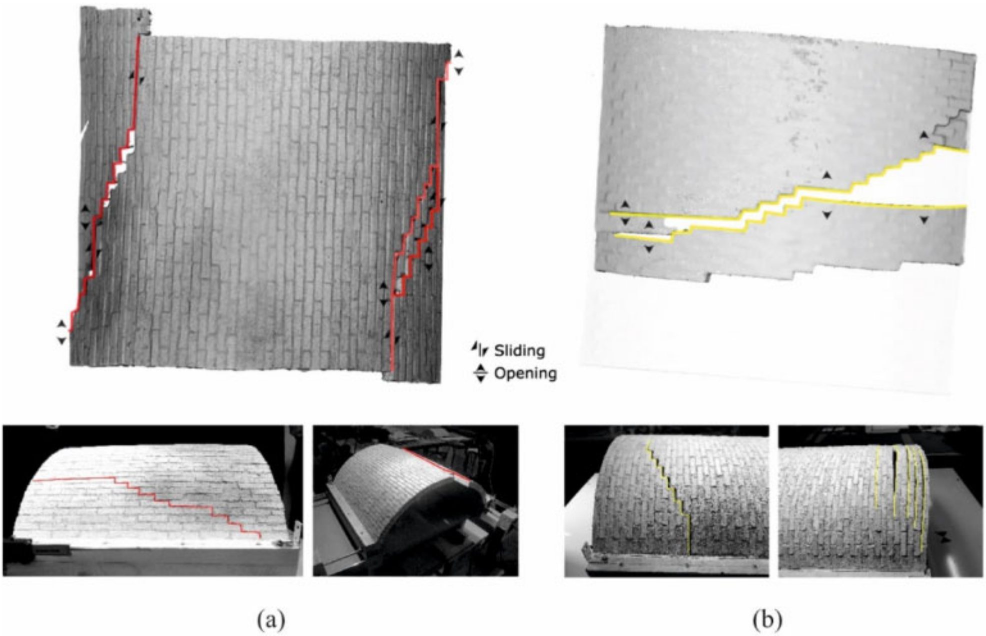

Figure 6. Crack pattern of R (a) and V (b) vaults.

along a single longitudinal joint or inclined involving multiple rows of bricks (Figure 6a). On the other hand, in the V models the major cracks occur in the radial joints, leading to the formation of separate portions of the structure (Figure 6b) that lead to local collapses. Also in V models, the major cracks can assume either straight or inclined directions, reasonably depending on construction issues.

Besides the described main differences in the crack pattern between vaults arranged with different brick patterns, some minor differences occur between vaults arranged with the same pattern, as clearly visible in Figure 7 for the R_1 and R_2 vaults. Specifically, the major crack position varies due to construction issue, i.e., to the impossibility to perfectly replicate the model construction. In the R_1 vault the two major cracks lead to the separation of the central portion, that starts rotating upon the sliding haunches; in the R_2 model, the major crack along the top of the vaults extrados

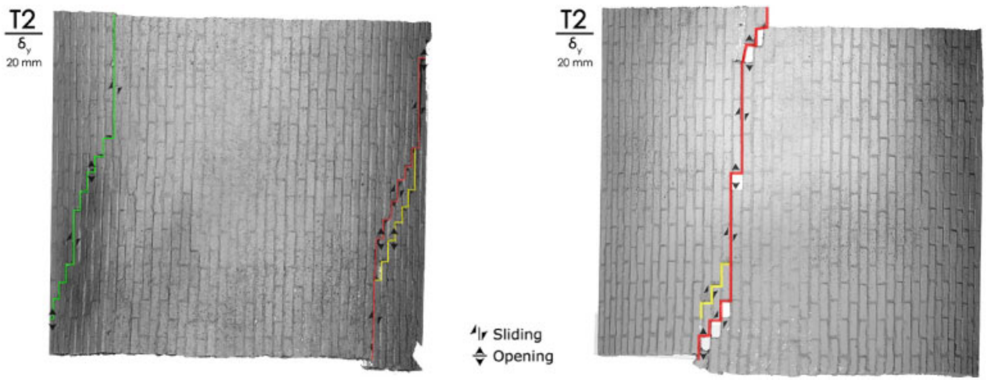

Figure 7. Crack pattern of R_1 (a) and R_2 (b) vaults for imposed displacement of 20 mm.

leads to a major sliding between the two portions, which cause small local failures near the heads and the rigid rotation of the two haunches upon the abutment, while the contact surface between them is reducing. This difference in the collapse mechanism induces quite different displacement capacity, being the ultimate displacement of the R_2 vault 50% higher than the one of the R_1 vault.

A deeper insight into the phenomena observed and recorded on each vault during the tests is provided in Figure 8 for the R_1 vault, as an example. In particular, Figure 8 compares the macroscopic visible phenomena reconstructed by direct observation, video acquisition and three-dimensional data managing of the range-based and image-based acquisition techniques at different stages of imposed displacement (Figure 8c top) to the mean displacement of a control linear strain-gauge (Figure 8b, corresponding with the key voussoirs of the vault) versus imposed displacement recorded through DIC (Figure 8c bottom). This comparison shows how the mean displacement linearly increases until the step (about 16 mm) corresponding to the reduction in the axial displacement (y) of the central portion of the vault and to the development of the inclined longitudinal crack that separates the right haunch portion. Then, the mean displacement remains almost constant and start increasing again in correspondence of the step (about 51 mm) when the structure starts rotating until collapse.

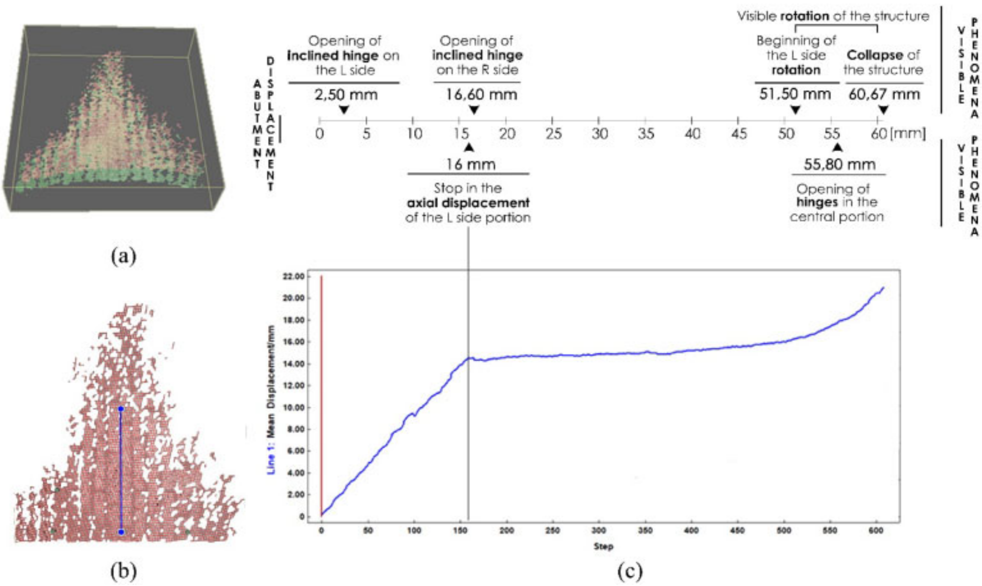

Figure 8. DIC cameras' field of view at step 0 (red) and 244 (green) of the imposed displacement (a), position of the linear strain-gauge (b), time history of mean displacement of the linear strain-gauge on the R1 vault (c).

5 CONCLUSIONS

In conclusion, the experimental campaign carried out in the present work has demonstrated the influence of the brick pattern on the structural behaviour of masonry barrel vaults under shear settlements of the abutments. The research has assessed two different typologies of characteristic cracks between models with radial and vertical arrangements of the bricks. These crack phenomena present common features but different directions and implications on the global behaviour of the structures also in terms of collapse (with the presence of 3 or 4 hinges mechanisms). The recognition of their nature can help practitioners and scholars to understand the shear nature of the displacement on real vaults. Moreover, the experimental tests have revealed the influence of the construction imperfections on the global behaviour of the masonry vaults: as previously reported, the formation of similar longitudinal cracks with different positions in both R models lead to different ultimate displacements and different implications on the structure stability. This difference must be related to the manual nature of the brickwork and the difficulty in the construction of perfectly similar mortar joints.

The results of the research also suggest the good interaction between different data acquisition and managing techniques: close-range photogrammetry and range-based structured light scanning, already consolidated in the fields of the moveable heritage, demonstrate a good integration with data provided with DIC methodology, in constant growth in the engineering field (Shao & He, 2021). The present work has obtained a good agreement between the DIC analysis results, and the visible phenomena recollected during the experimental tests, demonstrating the good possibilities of DIC monitoring on masonry construction. The use of 3D DIC with more relevant coverage of in-scale masonry vaults models (major ranges, use of multiple cameras) can lead to a properly deep knowledge and management of the three-dimensional deformation of the masonry vaults.

ACKNOWLEDGEMENTS

F. Chiabrando, G. Sammartano and G. Patrucco (Politecnico di Torino, Department of Architecture and Design) are greatly acknowledged for the photogrammetric and laser scanner survey of the models as well as for the support in postprocessing of data.

REFERENCES

Alforno, M., Monaco, A., Venuti, F. and Calderini, C., 2020a. Validation of simplified micro-models for the static analysis of masonry arches and vaults, International Journal of Architectural Heritage, 1–17, DOI: 10.1080/15583058.2020.1808911

Alforno, M., Venuti F., and Monaco, A. 2020b. The structural effects of micro-geometry on masonry vaults, Nexus Network Journal, 22: 1237–1258

Baratta, A. and Corbi, O. 2012. The static behavior of historical vaults and cupolas. Journal of Heritage Conservation, 32: 65–81.

Barbieri, A., Carloni, C. and Di Tommaso, A. 2004. Masonry orthotropic vaults in historical construction: the herring-bone pattern. In Proceedings of the 4th International Conference on Arch Bridges ARCH 04 (Barcelona, Spain).

Boni, C., D. Ferretti and E. Lenticchia. 2021. Effects of Brick Pattern on the Static Behavior of Masonry Vaults, International Journal of Architectural Heritage, DOI: 10.1080/15583058.2021.1874565.

Calderini, C. and Lagomarsino, S. 2004. The effect of the masonry pattern on the global behaviour of vaults. In Proceedings of the 4th International Conference on Structural Analysis of Historical Constructions (Padova, Italy).

Calvo Barentin, C., T. Van Mele and P. Block. 2017. Robotically controlled scale-model testing of masonry vault collapse, Meccanica, 53(7): 1917–1929.

Choisy, A. 1883. L'art de batir chez les Byzantines. Société anonyme de publications périodiques, Paris.

Curioni, G. 1870. L'arte di Fabbricare. Costruzioni civili, stradali, idrauliche. Negro, Torino.

D'Altri, A.M., De Miranda, S., Castellazzi, G., Sarhosis, V., Hudson, J. and Theodossopoulos, D. 2019. Historic barrel vaults undergoing differential settlements, International Journal of Architectural Heritage, DOI:10.1080/15583058.2019.1596332

Eslami, A., H.R. Ronagh, S.S. Mahini and R. Morshed. 2012. Experimental investigation and nonlinear FE analysis of historical masonry buildings – A case study, Construction and Building mMaterials, 35:251–260

Ferrero, C., M. Rossi, P. Roca and C. Calderini. 2021. Experimental and numerical analysis of a scaled dry-joint arch on moving supports, International Journal of Masonry Research and Innovation, 10.1504/IJMRI.2021.10035577

Foraboschi, P. 2014. Resisting system and failure modes of masonry domes, Engineering Failure Analysis, 44: 315–337.

Manuello, A., Riberi, F., 2021. Form-finding of pierced vaults and digital fabrication of scaled prototype. Curved and Layer. Struct. 2021; 8:1–15.

Milani, G., M. Rossi, C. Calderini and S. Lagomarsino. 2016. Tilting plane tests on a small-scale masonry cross vault: Experimental results and numerical simulations through a heterogeneous approach. Engineering Structures, 123: 300–312.

Patrucco G., Rinaudo, F., Spreafico, A. 2019. A New Handheld Scanner For 3d Survey Of Small Artifacts: The Stonex F6, in The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLII-2/W15, 2019 27th CIPA International Symposium "Documenting the past for a better future", Ávila, Spain.

Rossi, M., C. Calderini and S. Lagomarsino. 2016. Experimental testing of the seismic in-plane displacement capacity of masonry cross vaults through a scale model. Bulletin of Earthquake Engineering, 14: 261–281

Shao X.X., He X.Y., 2021, Real-time 3D Digital Image Correlation for Large Deformation and Rotation Measurements Based on a Deformation Transfer Scheme, in Experimental Mechanics.

Wendland, D. 2007. Traditional vault construction without formwork: masonry pattern and vault shape in the historical technical literature and in experimental studies. International Journal of Architectural Heritage, 1(4): 311–365