

Experimental investigation of the effect of brick pattern on the structural response of masonry arches and barrel vaults

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2 **Experimental investigation of the effect of brick pattern on the**  
3 **structural response of masonry arches and barrel vaults**

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13 **Abstract.**

14 In this study, an experimental campaign is carried out on 1:5 in-scale models of arches and  
15 barrel vaults built with different brick patterns (radial and vertical), to investigate their structural  
16 behaviour under settlement of the supports. Models are built with cement blocks and lime  
17 mortar joints. The arch models are tested under opening settlement of one support, whereas  
18 vaults are tested under shear settlement of one abutment. The three-dimensional deformations  
19 of the structures are acquired by image and video recording, 3D-Digital Image Correlation  
20 (DIC), close-range photogrammetry and structured light scanner. The influence of the brick  
21 pattern is investigated through comparison of crack patterns, ultimate displacements and failure  
22 mechanisms.

23 **Keywords:** *in-scale model; masonry; arch; barrel vault; brick pattern; support settlement.*

24  
25 **1 Introduction**

26 For centuries, masonry represented the most employed construction technique in buildings,  
27 characterizing a great part of the western architectural heritage. Arches, and later vaults,  
28 represent the first overcome to the ancient trilithic system and for this reason they are two of  
29 the most used horizontal masonry structure typologies in historic buildings. As demonstrated  
30 by the recent seismic activity in the center of Italy, vaulted structures can respond to large  
31 support movements with the creation of plastic hinges with complex three-dimensional  
32 behaviour and cracking phenomena. However, the interpretation of the crack pattern is not

33 always straightforward, especially in three-dimensional vaulted structures, due to the great  
34 number of factors that influence the damage evolution. Among geometrical factors, recent  
35 numerical studies [1]-[11] have evidenced the key role of the brick pattern, namely the micro-  
36 geometry [12], on the global three-dimensional behaviour of vaulted structures. Despite the  
37 importance of this issue [8]-[10], there is a lack of experimental investigation on the topic.

38 Experimental tests have been widely used to study the stability of masonry arches and vaults  
39 by means of different experimental techniques, both quasi-static and dynamic. Because of the  
40 difficulties in performing full-scale tests on arches and vaults, experimental campaigns are  
41 usually performed on in-scale models, and only a very limited number of full-scale tests are  
42 available in the literature [13]-[15]. Small-scale models are less expensive and faster to be  
43 assembled, do not require significant building expertise, and allow to repeat several trials for  
44 the same test. Moreover, the use of reduced-scale models to simulate the structural behaviour  
45 of masonry constructions is also justified by Heyman's theory [16], since stability is a matter of  
46 geometry rather than material failure.

47 Since the strength of the materials of the models does not affect the behavior of curved  
48 structures, different materials, such as concrete, stainless steel, PVC, wood, and bricks, have  
49 been used for the blocks of small-scale arches and vaults, assembled either with mortar or dry  
50 joints.

51 The scope of experimental tests on in-scale models is to observe the structural response and  
52 collapse mechanism under different kinds of actions:

- 53 1. differential settlement of the abutments [17]-[34];
- 54 2. vertical external loads [22], [28],[29];
- 55 3. seismic action applied in quasi static regime, i.e., tilting plane, pulley systems, etc.  
56 [35]-[38];
- 57 4. seismic action applied in dynamic regime, i.e., shaking table tests [39]-[43].

58 Among the above-mentioned actions, differential settlements are one of the most recurrent  
59 causes of damage in masonry vaults, due to their high sensitivity to any small change in the  
60 boundary conditions. They are due not only to foundations settlements, but they can also  
61 develop during a seismic event. As a matter of fact, besides the dynamic response due to the  
62 acceleration of the vault's supports, a pseudo-static response is induced by the horizontal  
63 movement of the structures underneath (walls, columns) [26].

64 The present work aims to experimentally investigate the influence of the brick pattern on  
65 the in-plane shear response of barrel vaults. The shear test has been chosen since experimental  
66 campaigns devoted to pseudo-static response of masonry vaults to imposed shear displacements  
67 at the supports are quite scarce in literature [23], [24], [26]. In order develop a methodology  
68 that could be confidently applied to the test campaign on the barrel vaults, preliminary tests on  
69 a segmental arch subjected to a horizontal settlement of one support are carried out. This case  
70 study has been chosen since it is widely studied (e.g., [18], [19], [21], [22], [31]) and a great  
71 amount of data are available in literature for comparison and validation.

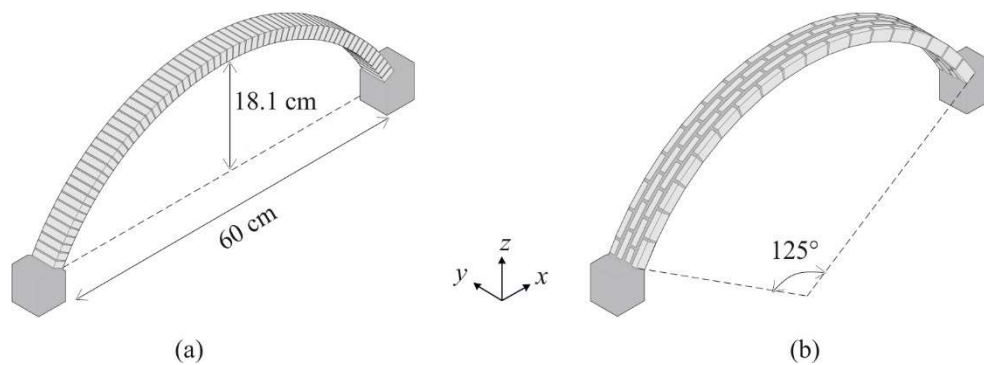
72 Two brick arrangements are considered: radial, with bed joints parallel to the spring lines,  
73 and vertical, with bed joints parallel to the head arches.

74 The paper develops through the following sections: Section 2 describes the geometry of the  
 75 case studies, i.e., of the arch and vault models; Section 3 is dedicated to the description of the  
 76 experimental set-up, in terms of testing devices, adopted materials and acquisition  
 77 methodologies; Section 4 presents the results of the experimental campaign on the segmental  
 78 arches and proposes a comparison with results from the literature; Section 5 discusses the  
 79 experimental tests on the barrel vaults built with different brick patterns; finally, conclusions  
 80 and perspectives are outlined in Section 6.

## 81 2 Geometry of the case studies

### 82 2.1 Segmental arch

83 The geometry of the segmental arch is described in Figure 1. The arch has a span length of  
 84 60 cm, a rise of 18.1 cm and an angle of embrace of  $125^\circ$ . The chosen dimensions mimic the  
 85 ones of the head arches of the 1:5 in-scale cross vault built at the University of Genova [23]. The  
 86 arch is made of blocks of dimensions  $9 \times 20 \times 40$  mm, which mimic in scale 1:5 the dimensions  
 87 of traditional masonry bricks.



88

89 Figure 1: geometry of the segmental arch in the radial (a) and vertical (b) configuration

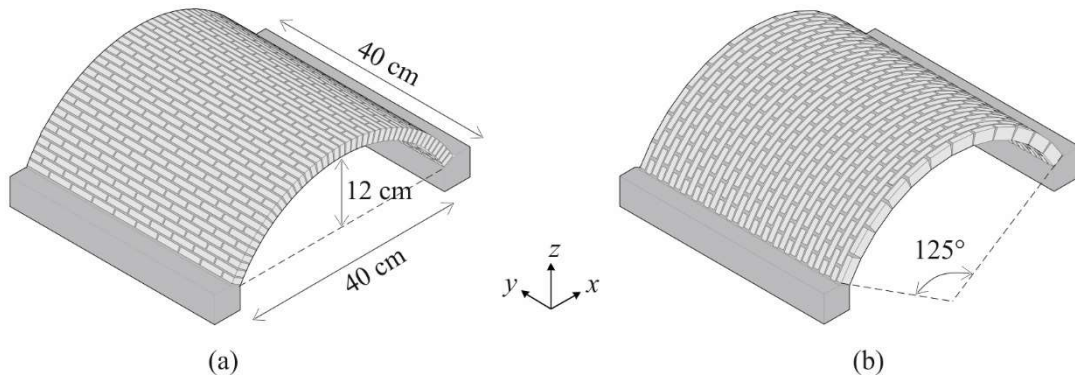
90 The bricks are arranged according to two patterns:

- 91 • a radial pattern (R), consisting in a single course of bricks (Figure 1a) disposed with the  
 92 longitudinal dimension normal to the arch plane; the bricks are laid vertically on their  
 93 short edge (rowlock orientation). With the use of this brick arrangement, the arch has a  
 94 single type of transversal bed joints, wedge-shaped, laid between the major faces of the  
 95 bricks. The final configuration of the arch models with radial pattern (denoted AR)  
 96 involves the presence of 65 cement-based bricks each and wedge-shaped mortar joints  
 97 with variable thicknesses between 1,3 mm and 1,9 mm.
- 98 • a vertical pattern (V), made of four parallel courses forming four parallel arches (Figure  
 99 1b), arranged so that both the arch thickness and the total arch depth are equal to the  
 100 ones of the radial arch. Due to the presence of multiple rows of bricks, the bed joints are  
 101 divided into two typologies: shorter transversal wedge-shaped joint, between each pair  
 102 of bricks laying on the same arch, with measures between 1 and 2.8 mm, and longer  
 103 longitudinal joint with rectangular cross-section, laying between each arch, with a

104 thickness of 5 mm. The configuration of the arches with vertical pattern (denoted AV)  
105 involves the presence of 74 cement-based bricks for each model organized in two  
106 couples of arches composed respectively of 18 and 19 bricks.

## 107 2.2 Barrel vault

108 The barrel vault has a square base: the net span of the vault is approximately 40 cm, the rise  
109 is about 12 cm, the length of the vault is 40 cm (Figure 2) and the angle of embrace is  $125^\circ$ .  
110 The rise-to-span ration is the same adopted for the arch model, but a smaller span has been  
111 preferred in order to reduce the number of bricks necessary to build the vault. The barrel vault  
112 is made of blocks of the same dimension as the arch blocks, arranged according to both radial  
113 (Figure 2a) and vertical pattern (Figure 2b). In the radial pattern, brick courses are laid normally  
114 with respect to the head arch plane, while the vertical pattern consists of adjacent arches with  
115 bed joints parallel to the head arch. In the following, the vault with radial and vertical pattern  
116 are referred to as VR and VV, respectively.

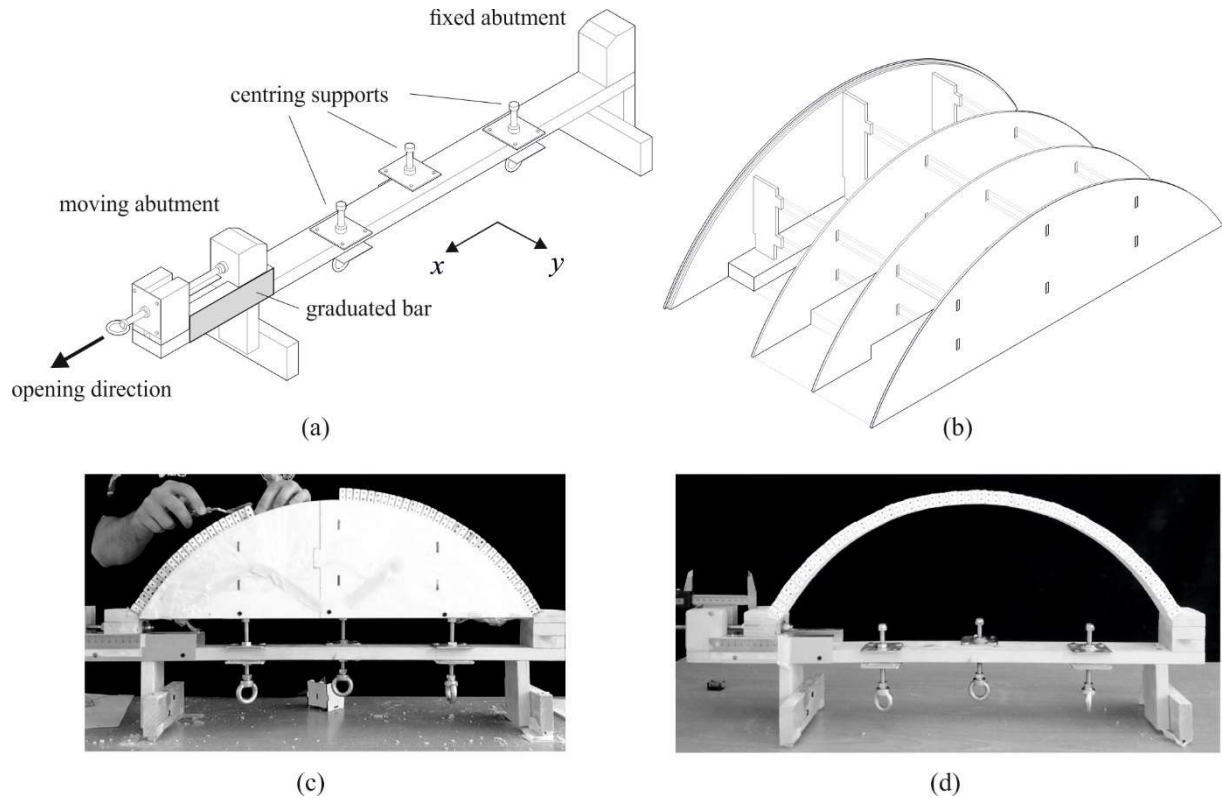


117 (a) (b)  
118 *Figure 2: geometry of the barrel vault in the radial (a) and vertical (b) configuration*

## 119 3 Experimental set-up

### 120 3.1 Testing devices

121 The testing device of the segmental arch was built in order to perform opening tests, i.e., to  
122 apply an imposed horizontal displacement in  $x$  direction at one of the abutments, while the other  
123 one remains fixed (Figure 3a). The centring is realized by a series of finnboard panels cut using  
124 CNC machines (Figure 3b). The lower surface of the centring is provided with three holes that  
125 fit into three threaded bars (centring supports in Figure 3a) attached to the testing device. These  
126 can be unscrewed in order to lower the centring after arch completion (Figure 3c) and to allow  
127 the removal of the centring (Figure 3d). Moreover, a digital calliper with a precision of a  
128 hundredths of a millimeter is installed at the moving abutment in order to measure the imposed  
129 displacement.



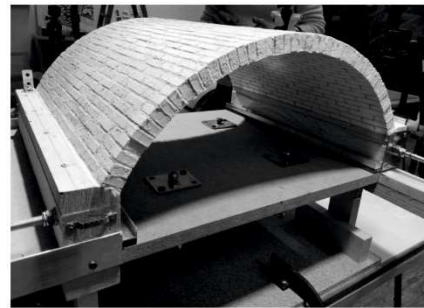
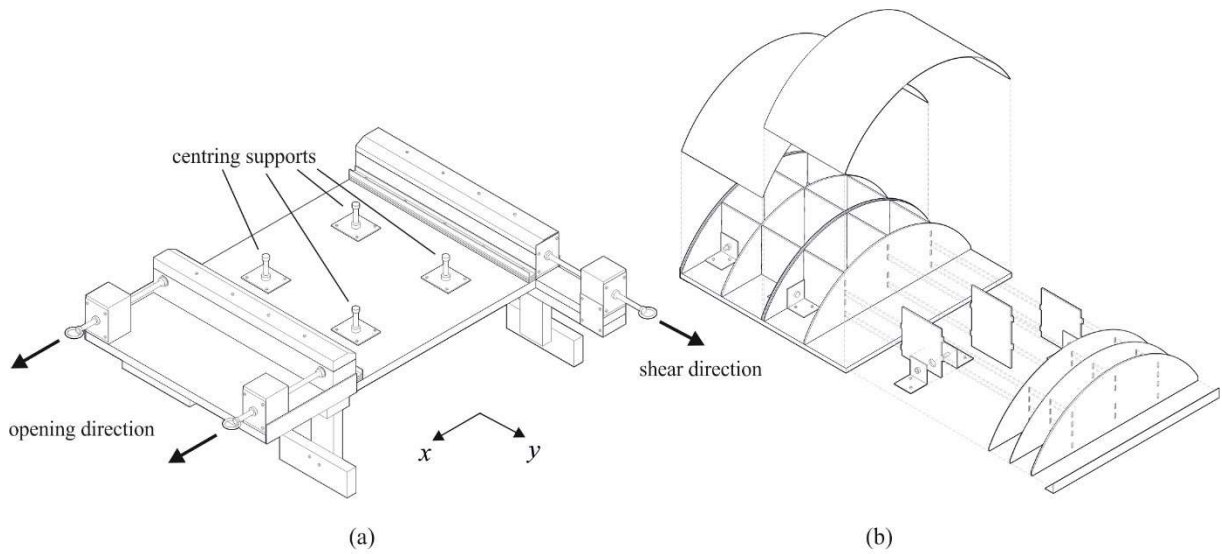
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131 *Figure 3: testing device of the segmental arch (a), axonometric exploded view of the centring (b), radial*  
 132 *arch during construction (c) and after centring removal (d)*

133 The testing device of the barrel vault was designed to allow both opening and shear tests to  
 134 be performed (Figure 4a). Specifically, one of the abutments is fixed in the  $x$  direction and  
 135 allowed to move in  $y$  direction, while the other abutment is fixed in the  $y$  direction and can be  
 136 moved in  $x$  direction. The centring is designed, similarly to the arch centring, with a rigid base  
 137 panel and an internal grid structure composed of several diaphragms (Figure 4b). Four threaded  
 138 bars support the base of the centring, which can be lowered by unscrewing the bars to allow the  
 139 centring removal after completion of the vault (Figure 4c-d).

140 The device is completed by a further equipment, used only during the construction of the  
 141 vault with vertical pattern. It consists of a boundary vertical panel, fixed at one of the vault  
 142 boundaries, against which successive brick courses make contrast by means of clamps (Figure  
 143 5). This solution avoids separation between subsequent courses and provides stability during  
 144 construction thanks to the pre-compression exerted by the clamps. The latter is intended to  
 145 replicate the construction procedure for real vaults with vertical pattern, in which parallel bricks  
 146 are tapped in order to provide bonding in the direction transversal to the arch planes.

147 Imposed settlements are monitored through a digital calliper, with a precision of a  
 148 hundredths of a millimeter, installed in correspondence of the moving abutment.



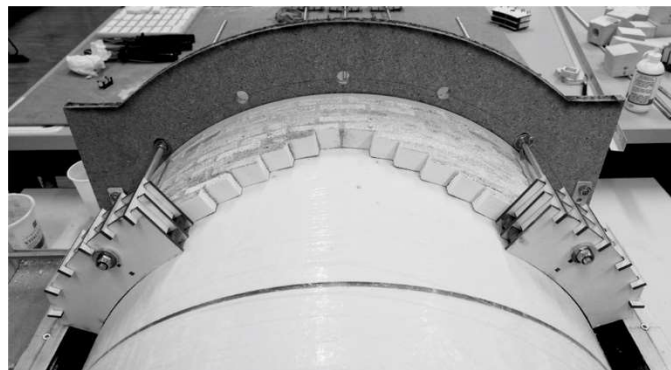
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Figure 4: testing device of the barrel vault (a), axonometric exploded view of the centring (b), radial vault during construction (c) and after centring removal (d)



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Figure 5: clamps adopted during the construction of the vault with vertical pattern.

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### 3.2 Materials

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157

The choice of materials was mainly dictated by the possibility to easily produce many units in a reduced amount of time and by the need to obtain a sufficient dimensional uniformity

158 between the blocks. According to these needs, two different materials were tested: wood and  
159 cement, respectively.

160 The idea to use wooden blocks was inspired by previous research on in-scale models of  
161 vaults, built with blocks and mortar [34]. Wooden blocks (Figure 6a) were obtained from 9  
162 mm-thick and 20 mm-deep spruce laths, manually cut in pieces of 40 mm. The obtained blocks  
163 were covered with a layer of enamel to reduce the absorption of water due to contact with wet  
164 mortar. This solution was subsequently discarded since it presented several drawbacks. Firstly,  
165 the hygroscopic behaviour of the spruce heavily altered the tests: despite the enamel treatment  
166 the blocks tended to swell while in contact with the mortar, due to the high ratio between the  
167 dimension of the joints and the bricks, modifying the whole geometry of the arch after drying.  
168 This drawback has not been reported in other studies ([24], [34]), probably due to the higher  
169 dimensions of the blocks. Moreover, the glaze-based (enamel) treatment altered the friction  
170 properties in the mortar-wooden block joints. Secondly, the low density of the spruce blocks  
171 made the arch quite unstable and heavily influenced by the vibrations derived from laboratory's  
172 activity carried out in the surroundings.

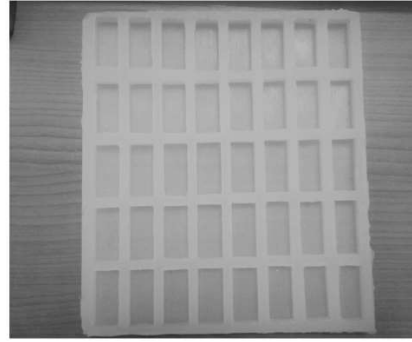


174 *Figure 6: wood (a) and cement (b) blocks*

175 To solve the abovementioned criticisms, cement blocks were fabricated. To this aim, a  
176 formwork made of bicomponent silicon rubber was built by using 40 wooden blocks to obtain  
177 the negative mould (Figure 7). This solution was chosen due to its reduced cost and ease of  
178 casting and stripping. Different mixes of sand, cement and water were tested, before choosing  
179 the one with the best performances in terms of regularity of the block surface and ease of  
180 compaction of the casted material to avoid air bubbles inside the blocks. The chosen mix is  
181 made of cement and water only, with 2:1 ratio. Stripping is made after 24 hours.



(a)



(b)

182

183

*Figure 7: Negative mould (a) and silicon rubber formwork (b)*

184 The mix adopted for mortar is the same used by D’Altri et al. [24] in a 1:12 in-scale model  
185 of a gothic barrel vault. It is composed of 3 parts of Silica sand and 1 part of superventilated  
186 hydrated lime and by the addition of PVA glue and water. The adopted Silica sand has a particle  
187 size distribution classified as G<sub>F</sub>85 according to UNI EN 12620 [44]. The PVA glue is added  
188 to improve workability and avoid fragmentation of the mixture. The quantity of water, not  
189 specified by the cited authors, was assumed equal to 1 part to obtain the required workability.  
190 The obtained mortar has weak cohesion, allowing cracks to open along the joints, as usually  
191 observed in historic masonry vaults.

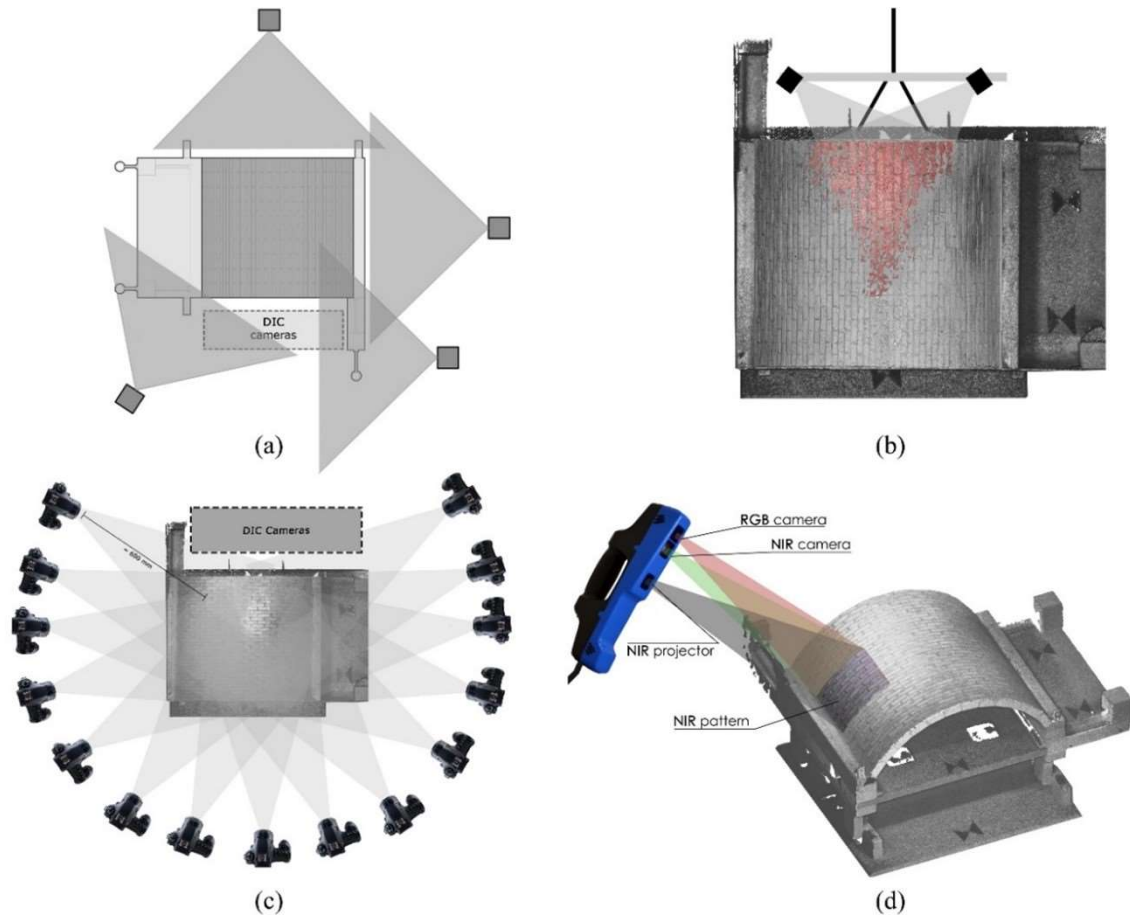
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### **3.3 Acquisition methodologies**

193 The acquisition and postprocessing phases of the campaign have been managed through the  
194 integration of four methodologies:

195

1. simple image and video acquisitions (Figure 8a) performed by four synchronized  
196 GoPro Hero 5 session cameras distributed around the vault model;
- 197 2. Digital Image Correlation (DIC) (Figure 8b), performed with the DIC system Q400  
198 from Dantec Dynamics A/S equipped with two convergent cameras;
- 199 3. close-range photogrammetry (Figure 8c) performed with a Canon EOS 60D camera  
200 and a Canon ef 24-105 mm f/4I lens;
- 201 4. range-based structured-light acquisition (Figure 8d) performed with a Stonex F6 SR  
202 scanner.



203

204 *Figure 8: Summary of the adopted acquisition methodologies: (a) GoPro Hero 5 session cameras, (b) DIC*  
 205 *cameras, (c) close-range photogrammetry, (d) range-based structured light scanning.*

206 The Digital Image Correlation (DIC) [45] is part of the image-based techniques. Basically,  
 207 DIC involves the comparison between a pair of stereoscopic images, taken as reference, with  
 208 other pairs of images of the deformed object [46]. Cross-correlation is used to estimate strain  
 209 and deformation of the tested object [45]. DIC works by tracking groups of pixels in the  
 210 compared images. To allow for the pixel detection, the model is first covered by a layer of  
 211 acrylic white paint and then by a black acrylic paint reproducing a texture of dots that act as  
 212 targets.

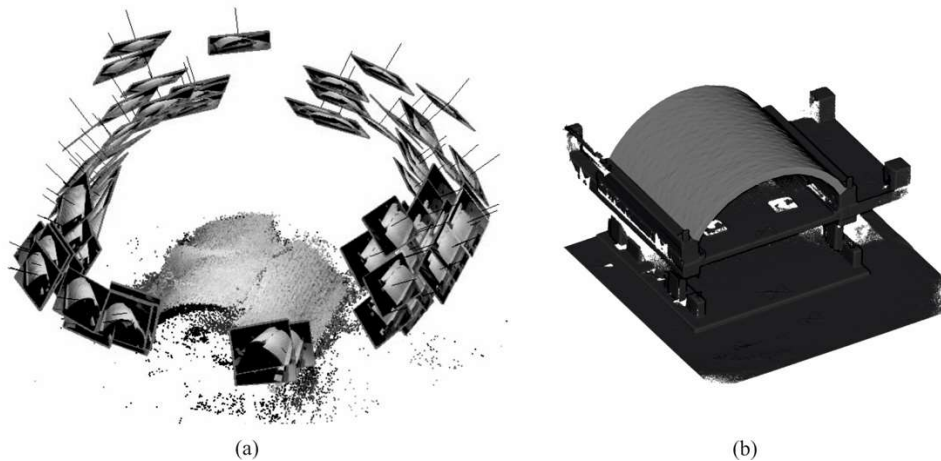
213 Close-range photogrammetry uses one or more photographs of an object from different  
 214 positions to derive its shape and location [47], through a three-dimensional reconstruction in  
 215 digital or graphical form, based on inverse perspective and descriptive geometry [48].

216 The use of structure-light scanners offers good solutions in the contactless acquisition of  
 217 small objects (magnitude  $< 1 \text{ m}^3$ ) [49][50]. These systems are based on the projection of specific  
 218 patterns on the objects's surface and the consequent acquisition through an offset camera: using  
 219 a principle similar to the triangulation is possible to estimate the position of physical points on  
 220 the object by recording the deformation of the pattern [51].

221 The video acquisition provides interesting information about the behaviour of the models:  
 222 videos are examined in slow motion and high-resolution frames are extracted to observe the

223 hinges evolution and the collapse mechanism. Close-range photogrammetry and structure-light  
224 scanners are adopted to obtain high-resolution 3D digital models of the structures in selected  
225 steps of the tests, used for metric documentation. The data processing of the close-range  
226 photogrammetry images is carried out to obtain dense point clouds comparable with the  
227 structured-light ones. The obtained three-dimensional point clouds (Figure 9) allow the  
228 extraction of orthophotos from the main planes of the in-scale models: these metric  
229 representations are extracted only from top and frontal views of the models, representing  
230 respectively the extrados and the head arch of the vaults, due to the impossibility to monitor the  
231 vault intrados. The obtained orthophotos are used to evaluate geometrical information such as  
232 the crack pattern and the magnitude of the structure's rotations. DIC is employed in this  
233 experimental campaign with the main objective of validating the results of image-based  
234 acquisition due to the fact that just a reduced portion of the vault is captured by the DIC cameras  
235 (Figure 8b).

236 The acquisitions are taken in different moments of the tests: a first one is done after the  
237 lowering of the centring, in the initial configuration of the model. The other acquisitions are  
238 taken during the imposition of the settlement. The tests are stopped to allow the acquisition  
239 procedures.

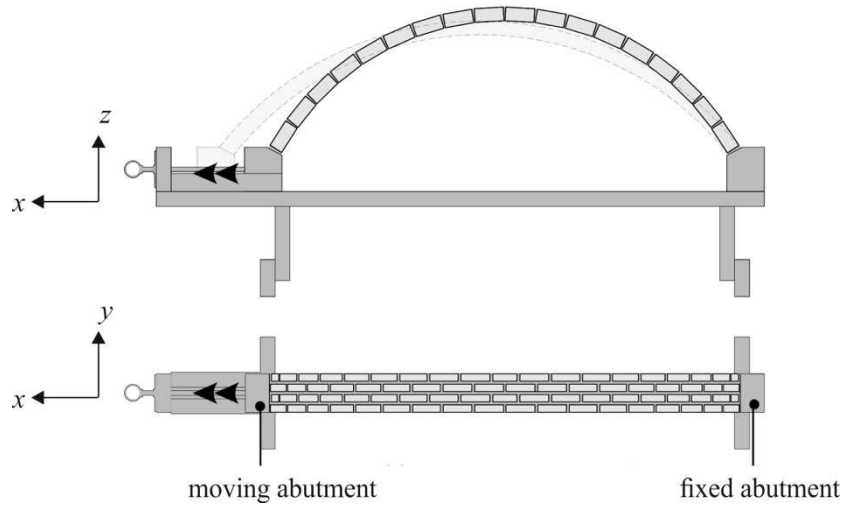


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241 *Figure 9: raw point cloud derived from close range photogrammetry (a) and final segmentation of the cloud*  
242 *(b).*

#### 243 **4 Results of tests on the segmental arch**

244 The experimental tests on the segmental arch were performed with the aim of developing a  
245 work methodology, that could be confidently applied on the subsequent test campaign on the  
246 barrel vaults. Specifically, these preliminary tests allowed to select the most proper materials  
247 and technique for building and assembling the blocks. The test involves the movement of one  
248 of the abutments along the longitudinal direction ( $x$ ) by twisting a threaded rod, while the other  
249 support is fixed to the testing device (Figure 10).



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*Figure 10: Schematic description of the opening displacement imposed to the arch models.*

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The movement of the abutment is constantly monitored with a digital calliper, so the ultimate displacement ( $u_u$ ) is recorded for each test. Images of the models are acquired at steps of 1 mm of imposed displacement, temporarily stopping the test. The photographic acquisition provides images of the model during the deformation, allowing to monitor the hinge opening during each step of imposed displacement. Moreover, the video acquisition allowed to capture the failure mechanisms of the models. In virtue of the bidimensional typology of the structures, all the data are extracted from the main vertical plane of the arches ( $x$ - $z$ ).

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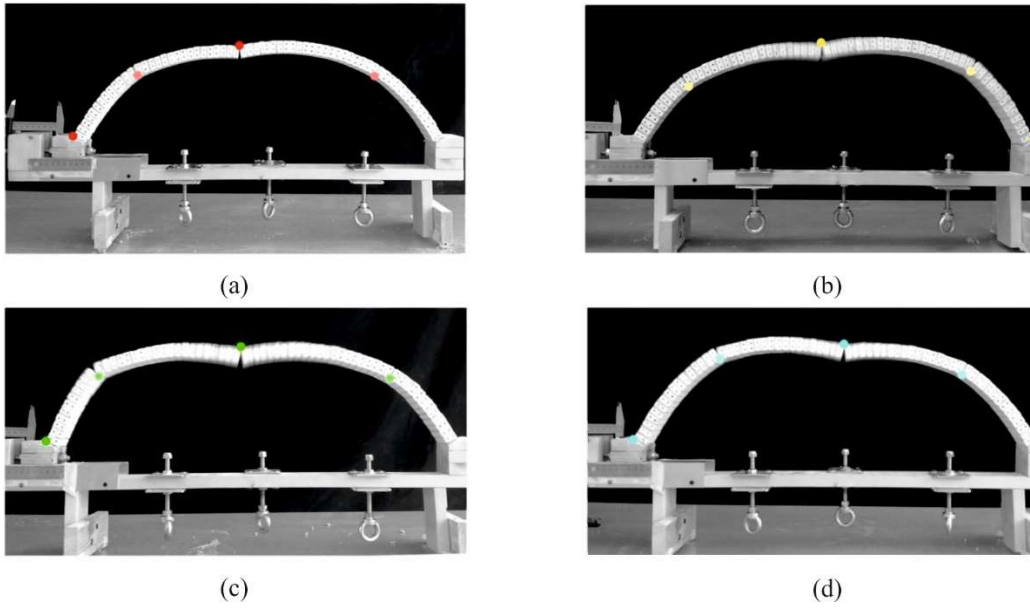
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The opening displacement imposed during the tests leads to the failure of the arch models, with the formation of cracks along the joints, assumable as hinges: the arch deformation during the test allows the shape accommodation through a maximum of three hinges, while the structure remains stable. The theoretical failure mechanism must appear with the formation of the other two hinges simultaneously, for a total of five, to transform the stable structure into a symmetric mechanism ([30],[21]). Despite this theoretical assumption, in reality little asymmetry in the arch construction can lead to imperfect asymmetrical mechanisms, triggered by the opening of just a fourth hinge ([16], [17], [19], [21], [22], [30]) as actually observed in the performed tests. The collapse mechanism is recorded, along with the hinge position (Figure 11 and Figure 12) and the value of ultimate displacement (Table 1).

*Table 1: ultimate displacements  $u_u$  [mm] on radial (AR) and vertical (AV).*

AR_1	AR_2	AR_3	AR_4	AR_5	AV_1	AV_2	AV_3
13.2	13.95	16.14	13.91	13.15	10.62	16.70	29.32

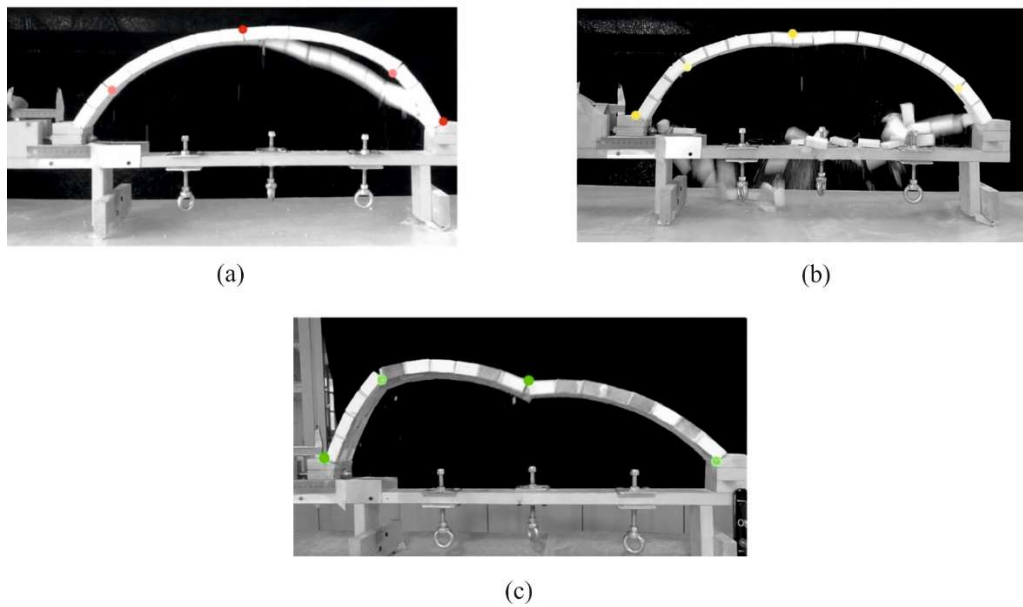
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*Figure 11: Collapse shapes and hinge position in AR\_2 (a), AR\_3 (b), AR\_4 (c) and AR\_5 (d).*

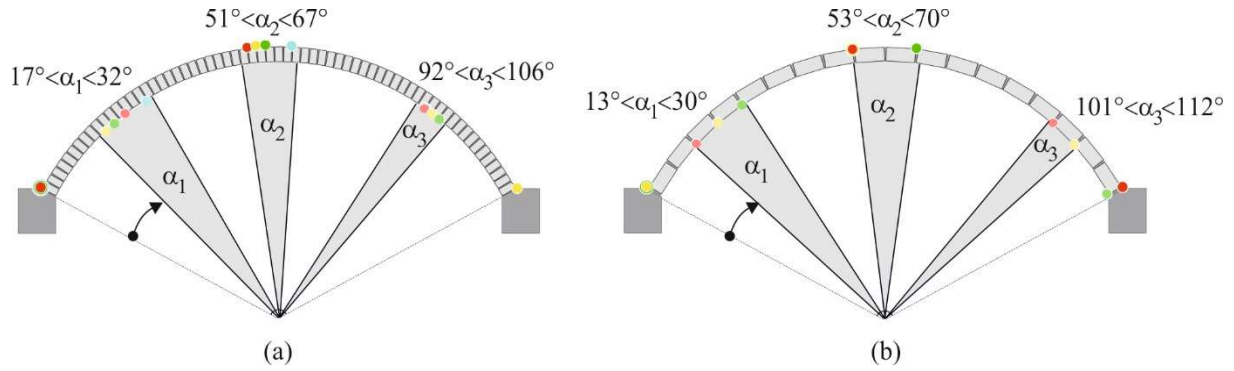


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*Figure 12: Collapse shapes and hinge position in AV\_1 (a), AV\_2 (b), AV\_3 (c).*

276 All the recorded collapse mechanisms are characterized by four hinges, with an alternation  
 277 in the position of the last one at the abutments, in accordance with the other experimental and  
 278 analytical investigations on this topic [30]. In particular, in the tests on AR\_1, AR\_3, AR\_4,  
 279 AV\_2, and AV\_3 models, the fourth hinge that induces collapse is located at the moving  
 280 abutment, whereas in the AR\_2 and AV\_1 models it is located at the fixed abutment. It is worth  
 281 noticing that, despite the different discretization of the arch geometry deriving from the two  
 282 different brick arrangements, the hinge positions fall into similar circular sectors (described by  
 283  $\alpha_1$ ,  $\alpha_2$ ,  $\alpha_3$ , as shown in Figure 13).  
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Figure 13: Range of angles in which the hinges develop in AR (a) and AV (b) models.

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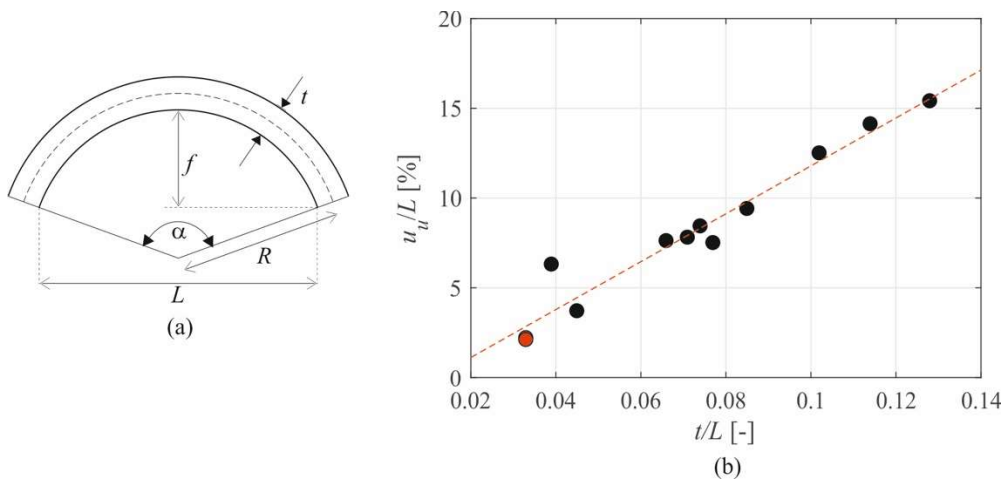
The performances of AR and AV models are quite different both in terms of ultimate displacements (Table 1) and of collapse shapes (Figure 11 and Figure 12). The ultimate displacements recorded in the AR models are not as dispersed as in the AV models. Moreover, the three AV models also show different behaviour at collapse. This variation can most likely be linked to the construction procedure: after the first trials with the vertical arrangement, it was noticed that the parallel arches separated at an early stage of imposed displacement, leading to differential collapse mechanisms of subsequent brick rows (Figure 12a). To avoid this issue, the construction process of the AV models was modified by imposing a small amount of pre-compression between the longitudinal mortar joints that bond the different arches together. As a result, the ultimate displacement has meaningfully increased in the two models tested after this variation (AV\_2 and AV\_3). The collapse mechanism also shows a variation after the change in the construction process, with the absence of differential failures of the successive arches (Figure 12cFigure 16).

Table 2: Comparison of experimental results on segmental radial arches subjected to opening settlement.

Authors	Blocks	Joints	$L$ [mm]	$t$ [mm]	$f$ [mm]	$R$ [mm]	$\alpha$ [°]	$t/L$ [-]	$t/R$ [-]	$u_u/L$ [%]
Romano, 2005 [33]	concrete	dry	908	60	348	500	150	0.066	0.120	7.61
			879	90	337	500	150	0.102	0.180	12.5
			814	60	235	500	120	0.074	0.120	8.43
			788	90	227	500	120	0.114	0.180	14.12
			910	90	455	500	180	0.099	0.180	7
Ochsendorf, 2006 [19]	cast concrete	dry	390	50	195	220	180	0.128	0.227	15.4
			709	50	297	385	160	0.071	0.130	7.8
Shapiro, 2012 [22]	3D printed	dry	313	24	100	185	130	0.077	0.130	7.5
			283	24	74	185	110	0.085	0.130	9.4
Alforno, 2020 [17]	timber	lime mortar	600	20	182	348	125	0.033	0.057	2.1
Masciotta, 2020 [21]	brick	lime mortar	1900	75	430	1301	97	0.039	0.058	6.3
Ferrero, 2022 [31]	composite material	dry	533	24	162	312	125	0.045	0.077	3.7
Present study	cement	lime mortar	600	20	182	348	125	0.033	0.057	2.2

301 The results obtained on the arches with radial pattern can be compared with the ones from  
 302 other similar experimental tests in the literature. Table 2 summarizes the main features of  
 303 experimental tests on segmental arches subjected to opening settlement (see Figure 14a for  
 304 explanation of the geometrical parameters reported in the table) along with the ultimate imposed  
 305 displacement, corresponding to the arch collapse, scaled with respect to the arch span length  
 306 ( $u_w/L$ ). For a better reading, Figure 14b plots  $u_w/L$  versus the thickness to span ratio  $t/L$ . Results  
 307 from the present study are represented by a red circle.

308 The graph in Figure 14b shows a quite perfect linear dependence of  $u_w/L$  on the thickness to  
 309 span ratio  $t/L$ , whichever the material adopted to build the blocks, whichever the angle of  
 310 embrace  $\alpha$  and for both cases of dry and mortar joints. The only outlier corresponds to the test  
 311 described in [21] and is due to the fact that, in that case, the arch was not subjected to its dead  
 312 load only, but two additional weights were positioned at the haunches to simulate the effect of  
 313 infill: in this case the stabilizing effect of the infill induces an increase of the displacement  
 314 capacity. The results obtained in the present experimental campaign are in perfect agreement  
 315 with the trend discussed above.

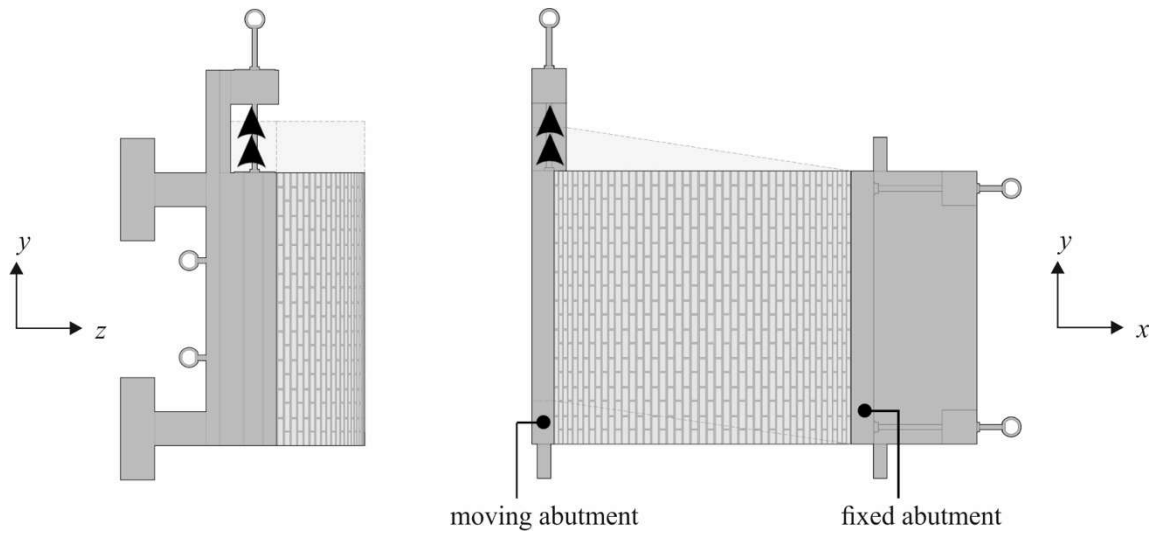


316

317 *Figure 14: Scheme of geometrical parameters (a) and ultimate displacement vs  $t/L$ .*

### 318 5 Results of tests on the barrel vaults

319 The vault models are tested under in-plane shear displacement imposed to one of the  
 320 abutments. Two models for each brick pattern are built and tested until collapse. The test is  
 321 performed by imposing the sliding of one support along the longitudinal direction  $y$ , (Figure  
 322 15) and the imposed displacement is constantly monitored through a digital calliper.



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Figure 15: Schematic description of the shear displacement imposed to the vault models.

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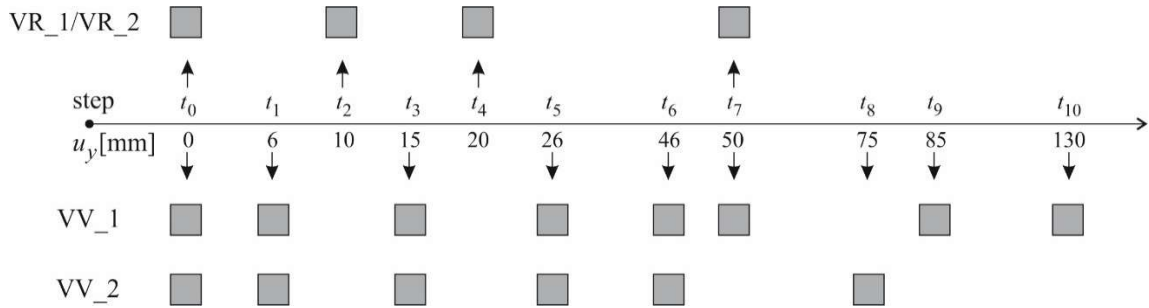
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The test is stopped to perform the acquisition of the deformed shapes, through close range photogrammetry and structured light, at selected imposed displacements to allow comparison between the different models. Moreover, the acquisition process is repeated every time a significant phenomenon, such as crack openings, rotations, local failure, occurs. Figure 16 reports a synoptic scheme of the acquisition steps as a function of the imposed displacement  $u_y$  for each vault. It is worth noting that the acquisition steps are coincident in the case of vaults with the same brick pattern, but not always coincident between VR and VV vaults, since they have not been set *a priori* but on the basis of the visible phenomena observed during the test.



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Figure 16: Synoptic scheme of the acquisition steps.

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In Figure 17 a selection of images of the failure, from the most representative perspective, is reported, while Table 3 summarises the ultimate displacement  $u_u$  reached in each test.

Table 3: ultimate displacements  $u_u$  [mm] of barrel vaults

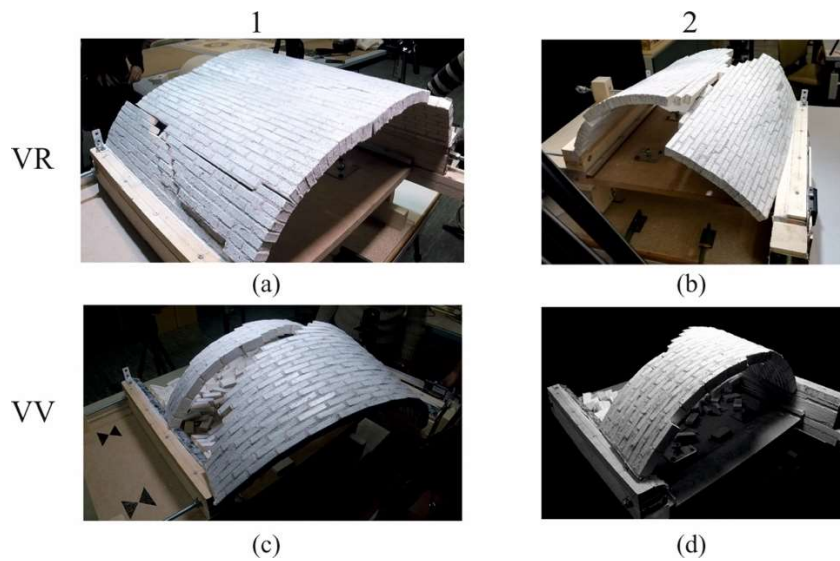
VR_1	VR_2	VV_1	VV_2
60.67	91.42	>150	93.77

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Differently from arches, vaults involve complex three-dimensional failure mechanisms.

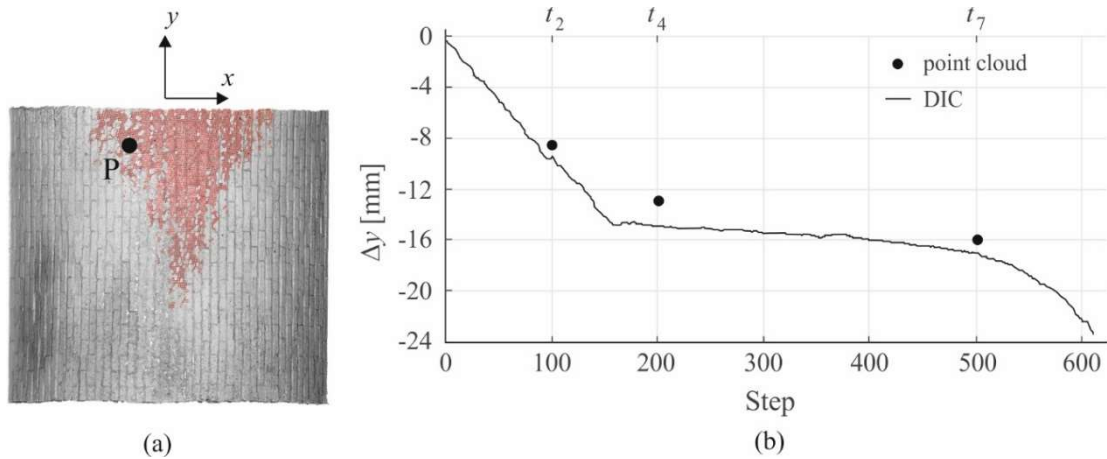
341 The VR models show shear cracks that run across the whole depth of the model following  
 342 the longitudinal joints. Some of these evolve into rotational hinges and trigger a global collapse  
 343 mechanism. However, the two models reach the collapse at quite different ultimate  
 344 displacements (Table 3). On the contrary, the VV models are characterized by the local collapse  
 345 of some arches near the heads of the vault and by the rigid rotation of the remaining portions.  
 346 The rigid rotation of the vault on the abutment is particularly evident in the VV\_1 model, which  
 347 reaches the end of displacement range (fixed at 150 mm) without a global failure. Local  
 348 collapses make it difficult to identify the displacement capacity in the VV vaults, therefore the  
 349 ultimate displacements reported in Table 3 should be carefully interpreted.



350

351 *Figure 17: collapse mechanisms of the tested models: VR\_1 (a), VR\_2 (b), VV\_1 (c) and VV\_2 (d)*

352 The reliability of the data obtained by the close-range photogrammetry is preliminarily  
 353 assessed by comparing the results obtained through point clouds with the results from the DIC.  
 354 The comparison is performed on VR\_1 vault by evaluating the y component of the displacement  
 355 vector  $\Delta y$  for a selected point P on the extrados (Figure 18a) at each acquisition step ( $t_2, t_4, t_7$   
 356 that correspond to steps 100, 200, 500 of the DIC acquisition process, respectively). Figure  
 357 18b plots the time history of  $\Delta y$  obtained through DIC and the instant values of  $\Delta y_i$  extracted  
 358 from point clouds comparison at the three selected acquisition steps, where  $\Delta y_i$  is given by the  
 359 distance between point P at steps  $t_i$  and  $t_0$  ( $i=2,4,7$ ). The comparison shows a shift of about 1-2  
 360 mm between the two data sets. This error is considered acceptable, considering the manual  
 361 selection of point P at the different steps.



362

(a)

(b)

363

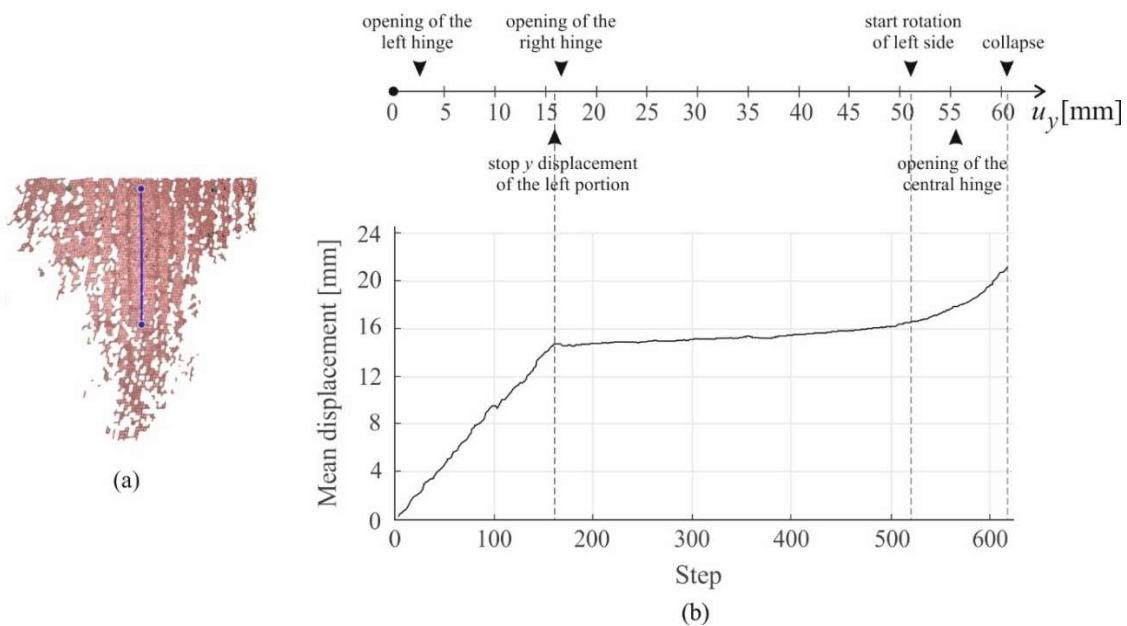
Figure 18: Position of point P on the vault extrados (a) and its displacement acquired through DIC and point cloud comparison

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A further comparison between data collected through different techniques is provided in Figure 19 for the VR\_1 vault, as an example. In particular, Figure 19 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 (Figure 19b top) with the time history of the mean displacement of a control linear strain-gauge (Figure 19a) recorded through DIC (Figure 19b bottom). This comparison shows a perfect match between phenomena recorded with different techniques. Specifically, the mean displacement linearly increases until  $u_y$  of about 16 mm, corresponding to the opening 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.

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(a)

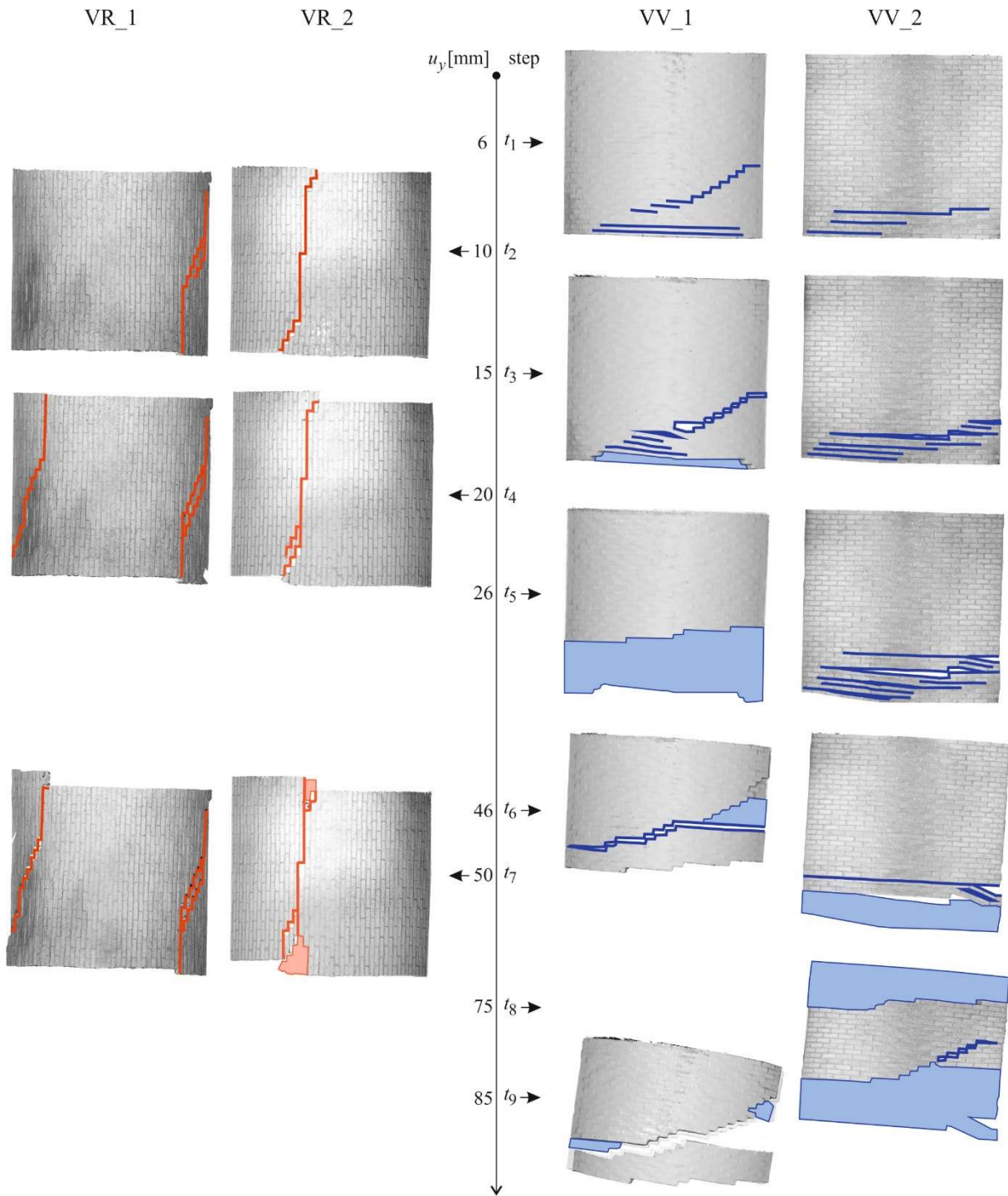
(b)

377

Figure 19: Position of the linear strain-gauge (a), time history of mean displacement of the linear strain-gauge on the VR\_1 vault (b)

378

379 Crack patterns are obtained by merging information from synchronized video acquisition,  
 380 dense point clouds and visible phenomena observed during the test development. They are  
 381 illustrated in Figure 20 on the orthophotos of the vault extrados for each acquisition step.  
 382 Collapsed portions of the vaults are highlighted by red or blue solid color.  
 383

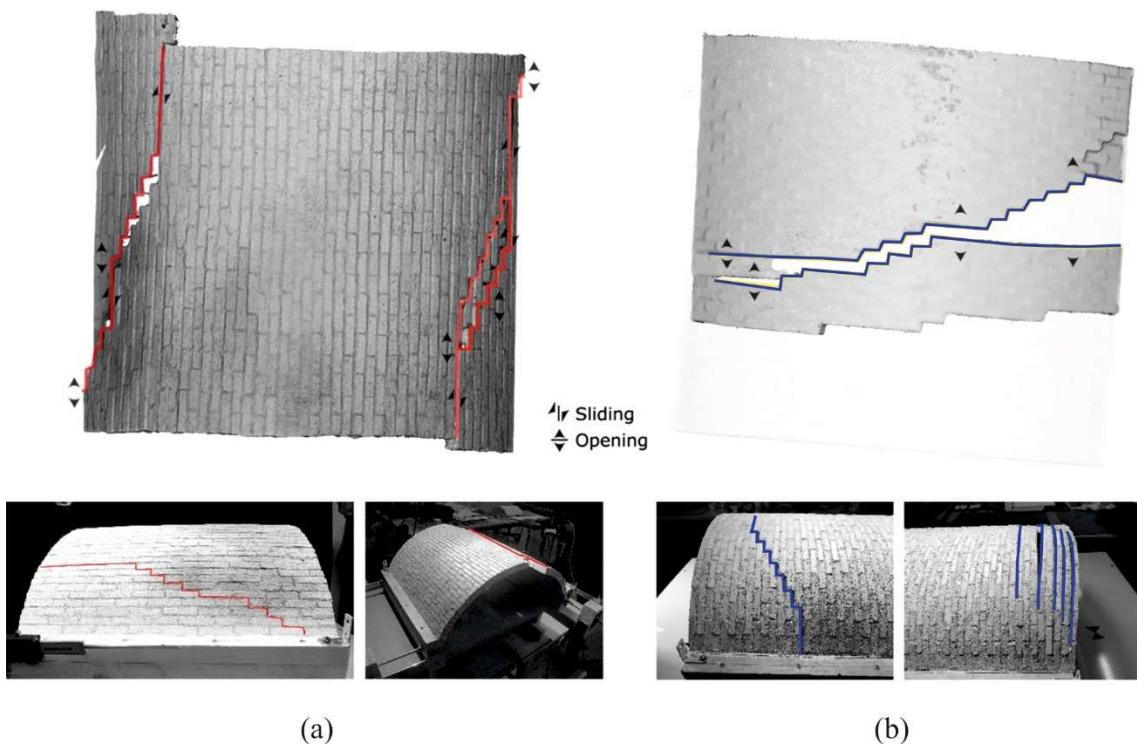


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Figure 20: Crack patterns in radial (VR) and vertical (VV) vaults.

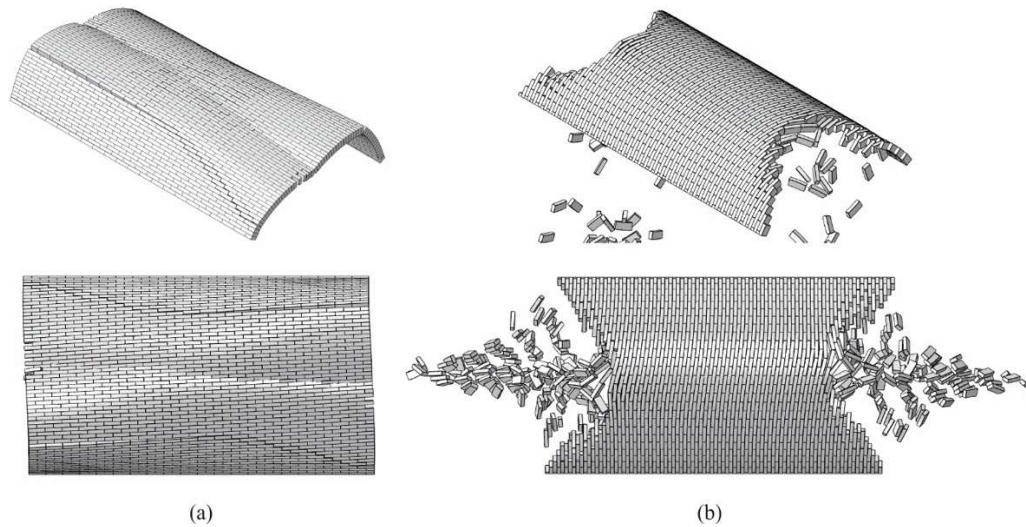
386 The critical analysis of the crack patterns experienced in the models reveals substantial  
 387 differences between the two brick arrangements. Characteristic crack patterns are summarized  
 388 in Figure 21, which compares VR\_1 and VV\_1 at step  $t_7$  ( $u_y = 50$  mm). In the VR models most  
 389 of the cracks occur along the longitudinal joints. These major cracks appear to be quite straight  
 390 along a single longitudinal joint or inclined involving multiple rows of bricks (Figure 20, left  
 391 side, Figure 21a). A similar crack pattern was obtained by D’Altri et al. [24] on a scaled model  
 392 of a pointed barrel vault built with a radial pattern. On the other hand, in the VV models the  
 393 major cracks occur in the radial joints, leading to the formation of separate portions of the  
 394 structure (Figure 20, right side, Figure 21b) that lead to local collapses of the portions near the  
 395 head arches. The major cracks can assume either straight or inclined directions also in VV  
 396 models, reasonably depending on construction issues. These results are in perfect agreement  
 397 with those reported by Alforno [52], where a numerical study on ideal barrel vaults subjected  
 398 to shear settlement of the abutments was performed (Figure 22): the radial vault collapses with  
 399 a four-hinge mechanism due to the formation of longitudinal and inclined cracks; the vertical  
 400 vault undergoes local collapses of the portions near the head arches (see [17] for a detailed  
 401 description of the adopted numerical approach, which is out of the scope of this paper). Even  
 402 though the geometry of the ideal barrel vault differs from the one object of the present study, it  
 403 is worth noting that also in the reported numerical investigation the vault with vertical brick  
 404 pattern showed a higher displacement capacity than the one with radial arrangement.



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Figure 21: Characteristic crack pattern of VR (a) and VV (b) vaults



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*Figure 22: Deformed shapes of radial (a) and vertical (b) barrel vaults according to Alforno [52]*

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Besides the described main differences in the crack pattern between vaults arranged with different brick apparatus, some differences occur between vaults arranged with the same brick laying technique, as clearly visible in Figure 20 for the VR\_1 and VR\_2 vaults. Specifically, the major crack position varies due to construction issue, i.e., to the impossibility to perfectly replicate the model construction. These construction imperfections are expected to be much greater in building in-scale models than real scale vaults. In the VR\_1 vault the two major cracks lead to the separation of the central portion, that starts rotating upon the sliding haunches; in the VR\_2 model, the major crack along the key joint causes sliding between the two separated portions, with consequent small local failures near the heads and the rigid rotation of the two haunches upon the abutment. This difference in the collapse mechanism induces quite different displacement capacity, being the ultimate displacement of the VR\_2 vault 50% higher than the one of the VR\_1 vault.

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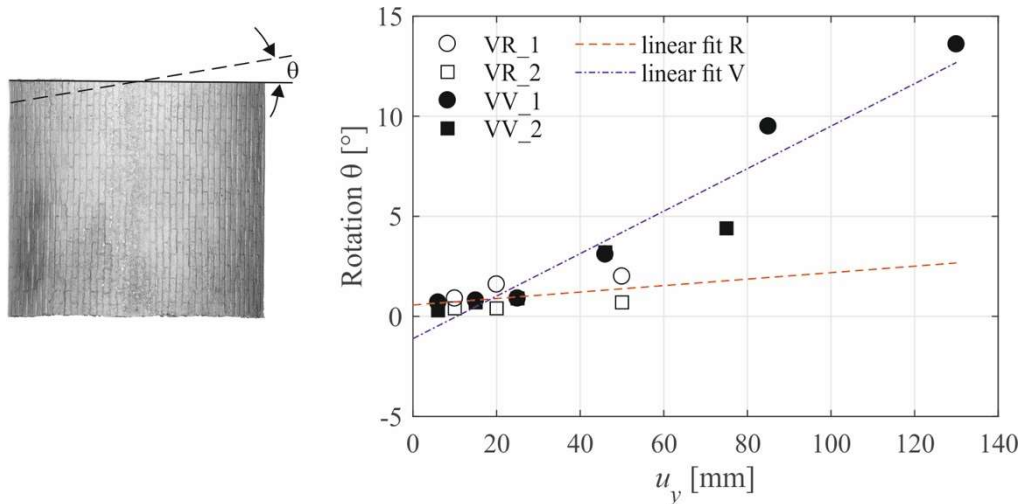
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Finally, rotations of the vault longitudinal axis with respect to the original configuration ( $t_0$ ) are measured and plotted in Figure 23 for all the analyzed specimens. Linear fits of the data for VR and VV vaults allows a general trend to be outlined. Specifically, the VR vaults experience lower rotations with respect to the VV vaults. This is due to the different crack patterns described above: in the VR vaults the longitudinal cracks foster sliding in  $y$  direction between separated portions of the vault; conversely, transversal cracks and subsequent local collapses in the VV vaults cause rotation of the remaining portion of the vault in the  $x$ - $y$  plane.



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*Figure 23: Rotation with respect to initial geometry versus imposed displacement*

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It is worth pointing out that the results of the present experimental campaign are not statistically relevant due to the small number of performed tests (two for each brick arrangement). The large scattering of the quantitative results is expected to decrease for a higher number of specimens. Therefore, in order to acquire reliable quantitative data necessary to confidently calibrate numerical models, the experimental campaign must be extended. Hence, the present work has to be intended as a first exploratory study which results can offer qualitative interpretation of the influence of the brick pattern on the collapse mode.

437

## 6 Conclusions

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This paper presents the results of an experimental campaign addressed to investigate the effect of brick pattern on the static behaviour of segmental arches and barrel vaults subjected to opening and shear settlement of the abutments. Two brick arrangements have been considered: radial, with bed joint perpendicular to the head arches, and vertical, with bed joints parallel to the head arch plane.

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Tests performed on arches with opening settlement of one support allow the following conclusions to be outlined:

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- Radial arches (AR) present collapse shapes and ultimate imposed settlement in line with other experimental data in the literature. Specifically, a linear relationship between the dimensionless ultimate displacement and the thickness to span ratio was found to hold for segmental arches subjected to their own weight, whichever the adopted materials and angle of embrace, with both dry and mortar joints;
- Vertical arches (AV) display ultimate displacement strongly dependent on the construction methodology. In particular, they can reach a significant higher displacement capacity (up to twice the one of AR) if pre-compression is applied between the longitudinal mortar joints that bond the different arches together.

Results of the tests on barrel vaults subjected to shear settlement of one support highlight the following issues:

- 456           • The crack pattern is strongly influenced by the brick arrangement. Radial vaults  
457 (VR) are characterized by major cracks along the longitudinal joints with consequent  
458 sliding of the separated portions of the vault in the direction of imposed settlement;  
459 vertical vaults (VV) show major cracks along the radial joints, with partial collapse  
460 of the head arches and rotation of the remaining part of the vault in the horizontal  
461 plane;
- 462           • Construction imperfections strongly influence the collapse shape and the  
463 displacement capacity, leading to different results for the vaults with same brick  
464 pattern;
- 465           • in general, the VV vaults under shear settlement display a higher ultimate  
466 displacement than the VR vaults. The same holds for AV arches under opening  
467 settlement in presence of transversal pre-compression.

468       To the Authors' knowledge, the described experimental campaign is the first specifically  
469 addressed to investigate the effect of the brick pattern. The obtained preliminary results  
470 qualitatively confirm previous findings of numerical studies described in [52] and the  
471 importance of this construction issue on the static behaviour of arches and vaults. A deeper  
472 knowledge of this topic can help in choosing the most proper strengthening technique in line  
473 with the "minimum intervention" approach recommended for historic constructions.

474       Future research will be addressed to extend and improve the experimental campaign so as  
475 to: overcome the discussed construction issues; provide physical-mechanical characterization  
476 of the adopted blocks and mortar; allow for higher level of repeatability of the tests; employ  
477 load cells to measure reaction forces; improve the acquisition methodologies in order to have a  
478 continuous monitoring of the displacement field of the entire surface of the vault. These future  
479 results can be used to validate numerical models, which can be subsequently confidently  
480 adopted to extend the investigation to other kinds of vaulted structures.

481

#### 482       **CRedit author contribution statement**

483       **Francesco Roselli:** Methodology, Validation, Investigation, Formal analysis, Visualization,  
484 Writing - Review & Editing. **Marco Alforno:** Conceptualization, Methodology, Validation,  
485 Formal analysis, Writing - Original Draft, Writing - Review & Editing, Supervision. **Amedeo**  
486 **Manuello:** Resources, Writing - Review & Editing. **Fiammetta Venuti:** Conceptualization,  
487 Methodology, Resources, Validation, Formal analysis, Visualization, Writing - Original Draft,  
488 Writing - Review & Editing, Supervision.

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