

# Strengthening of Masonry Rings With Composite Materials

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## Research article

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# Abstract

The paper presents the results of experimental testing of six masonry rings built to technical scale and strengthened with CFRP strips and sheets and also with an FRCM system with PBO, glass, basalt and carbon fibres. The rings were subjected to tensile loads induced by four hydraulic jacks. The assumption is that the masonry rings are a representative simplification of domes, especially their structural support. Both single layered domes and ribbed domes are exposed to tensile stress in up to one third of their height.

During the tests, the following information was collected: loads, displacements, strains of composites and failure modes. In some cases, an initial prestressing of reinforcements was carried out. Recommendations and limitations related to the use of the materials tested for reinforcing round, masonry structures under tensile stresses are discussed. The criterion for choosing the best solution was not only based on comparing the tensile strength of the reinforcement but also its stiffness. A strengthening efficiency index is proposed. The assessment of strengthening effectiveness was carried out, taking into account also heritage building conservation standards.

## 1 Introduction

Dome structures are to be found all over the world, and their symbolism has inspired many cultures. The great number of domes and their variety of form has encouraged many researchers to study domes from the point of view of architecture, construction, art, religion and philosophy. Today, many dome structures for many reasons require special attention from heritage building conservation and engineering design points of view.

Domes include the vaults and also the beam and shell structures, which converge at the highest point located above the center of gravity of the projection. In the case of brick and stone historical vaults, it is possible to distinguish rotary domes with a two-curved surface and polygonal domes made of interpenetrating cylindrical surfaces. From an engineering point of view, it is very significant that the geometrical arrangement of vault elements can be formulated in accordance with the theory of elasticity and plasticity. During static and strength analyses, spatial structures are often reduced to basic elements such as beams, columns or frames. Brick constructions with curved geometry are usually simplified to an arch, which can be treated as a representative element for describing the static work of the entire structure. For a certain group of building structures, a representative simplified element can be subjected to experimental testing, theoretical analyses and numerical simulations. A case in point is the strengthening ring under tensile load, which is subject to possible bending and shearing.

For straightforward cases of spherical and polygonal domes, there are formal analytical solutions that, are easy to interpret when a membrane state of stress is assumed. This assumption is only valid when the stress state is torque-free, the thickness of the shell is small in relation to the other dimensions, and the central surface is continuously curved. In the membrane state, the normal stresses from axial forces

and stresses tangential to the central surface occur. At this point, it can be stated unequivocally that in most domes, the static solution indicates the presence of tensile stress in the lower latitudinal bands regardless of their specific geometry. This stress state leads to the visible failure mode of domes as depicted in figure 1.

The most problematic part of dome construction is the support zone. This is why the research programme focused on examining this zone and proposing solutions to problems, which are also acceptable from a heritage conservation point of view. For this reason, the supporting zone research was simplified to focus on the masonry ring.

Traditional strengthening techniques, like reinforced concrete or steel elements, enable increased load capacity, rigidity and durability of the existing structure, but they are typically labour-intensive, often irreversible and questionable from an aesthetic point of view. To minimize the cross-sectional sizes of reinforcing materials, composites based on high-strength fibres, mainly carbon, aramid, glass, basalt and steel are used [3]. An important advantage of using composite materials is an undemanding adaptation to curved and rough surfaces. In the literature, there are numerous examples of reinforcements that have been applied to many different types of structural components, but examples of circumferential reinforcements of domes or cylindrical structures are relatively scarce, especially when it comes to reinforcements using composite materials. A good example of the use of composites for the conservation of historic structures is the dome of the Bane Bashi Mosque [4], where clamp strips and perimeter rods made of CFRP have been applied. The strengthening design was based on experience gained at a similar site - the Mustafa Pasha mosque in Skopje and on the basis of this an analogous strengthening system was adopted. The dome's shell was reinforced using CFRP rings and arches, whereas the dome's support drum was strengthened with CFRP rods glued with epoxy resin. Research on the static behaviour of the domes and cylindrical structures reinforced with composite materials is still ongoing, which may be the reason why their application in historical monuments is relatively scarce. An extensive research programme focused on the static behaviour of masonry vaults and domes reinforced with CFRP tapes, which have been joined to the structure using epoxy resin has been presented by Paolo Foraboschi, [1]. Another research programme of note is the programme implemented at Wrocław University of Science and Technology in Department of Building Structures, which is concerned with, inter alia, reinforcing brick arches with FRCM and CFRP systems [2]. In these cases, a load capacity increase of over 350% has been recorded. Due to numerous advantages, the application of composites and other modern materials is clearly increasing in conservation of historic building structures.

## 2 Experimental Research Programme

In domes and cylindrical structures, it is possible to distinguish in an experimental model, a latitudinal band in the form of a ring loaded from the inside.

The main goal of the research was to assess the effectiveness of peripheral strengthening using various techniques. For this purpose, 6 models (R1, R5, R6, R7, R8 and R9) of masonry rings were made, with

loading applied from the inside by means of a dedicated hydraulic system. A complex stress state was induced using a 4-point loading scheme. Six different composite systems were used to strengthen the rings. The parameters of: geometry, construction materials, loading system and measuring instrumentation were the same for all six models.

## 2.1 Geometry and static scheme of the models

An example of a model prepared for experimental testing is presented in figure 2. Critical dimensions, measuring instrumentation and loading system are described below.

Models of masonry rings were built to a technical scale with geometrical parameters as detailed below

- axial diameter of the ring:  $d = 300$  cm,
- internal radius:  $r_i = 133.25$  cm,
- outer radius:  $r_e = 166.75$  cm,
- cross section:  $A = 250 \times 335$  mm =  $83\,750$  mm<sup>2</sup>,
- height:  $h = 25$  cm.

The right brick bonds were selected to achieve maximum cross-sectional attachment and to minimize joint thickness. The joints between the bricks had a thickness in the range:  $5 \div 20$  mm. Using appropriate brick elements, a repeatable bond was obtained. Thus the rings had 8 symmetrical axes. Stable temperature conditions prevailed in the laboratory hall during preparation and testing of the models with the air temperature in the range of  $18 \div 22^\circ\text{C}$ , and air humidity ranging between  $45\% \div 55\%$ .

The models were built on a base covered with PE foil to minimize the influence of friction. The friction coefficient of the brick substrate against the base had been calculated on the basis of a ramp test, yielding a value equal to  $\mu = 0.43$ .

Figure 3 shows a diagram of the test stand, along with the arrangement of the sensors. The “F1” and “F2” detectors are strain gauges that register pressure on the structure. “P” detectors registered pressure in the loading system. Additionally a pressure gauge was installed at the hydraulic pump. Meters marked with the letter “d” were inductive displacement sensors (LVDT) recording the change in the diameter of the ring. The symbol “u” denotes inductive displacement sensors (LVDT) recording displacements of masonry structure points.

The design of the ring loading system was purposefully light and mobile. Its central part was made of a steel body composed of four double-acting hydraulic jacks with a stroke of 50 mm and a maximum working pressure of 20 MPa. The system ensured concentrated forces of 150 kN on each pressure unit were obtained and transmitted to the model through 6 elastomer discs.

The loading system transmitted force into four points (points 1, 2, 3, 4). This loading pattern resulted in a complex (unfavorable) stress state in the circumferential direction. The static solution of the ring (internal

forces) is presented in figure 4. The resulting state of stress in the structure was designed to simulate the unfavorable forces occurring in the support zones of domes, which result from disturbances in support continuity (pendentives, pillars, columns).

### 2.3 Bricks, mortar and masonry properties

One of the objectives of the research was to determine the material characteristics of the masonry, from which the rings models were made. This is why the bending and compression strength of the bricks and mortar was tested, and why the compression and shear strength of the masonry fragments was examined.

The compressive strength tests of the bricks were carried out in accordance with standard PN-EN 772-1 [13]. The mean value was equal to 11.75 MPa, standard deviation was 2.88 MPa and a coefficient of variation was calculated at 24.5%. A lime mortar with a grain size of 0 ÷ 2 mm was used in the construction of the models. The mortar was characterized by a high plasticity, low shrinkage (due to the longer setting time) and high adhesion to the substrate. These features are also characteristic for historical mortars. Bending and compression strength tests were carried out on 18 samples, 14, 21 and 28 days after forming, in accordance with the procedure described in PN-EN 1015 standard, [11]. The average value for the compressive and shear strength of the lime mortar is similar to the results obtained in testing of historical mortars by Matysek, [9] and Domasłowski et al. [10], which confirms the validity of its use in reconstructions and experimental testing of historic structures.

In addition to tests of individual materials, an examination was carried out of the entire structure of masonry elements. The value of the average compressive strength of the brickwork was converted into a characteristic value, and then compared to the characteristic value calculated according to the Eurocode formula (taking into account specific parts of the masonry). The experimental value was found to be more than three times higher. Table 1 summarizes the key results of all the tests conducted.

### 2.4 Strengthening methods

The following systems were used to strengthen the rings:

- R1: single CFRP strip attached to the masonry by a two-component epoxy composition;
- R5: single layered carbon fibre wrap on epoxy resin;
- R6: two layers of glass fibre mesh embedded in a mineral matrix;
- R7: four layers of B-FRCM system based on basalt fibre mesh embedded in a mineral matrix;
- R8: three layers of carbon fibre mesh embedded in a mineral matrix;
- R9: three layers of P.B.O. fibre mesh embedded in a mineral matrix.

Figure 5 shows all the reinforcing materials used. Most of them were covered additionally with a top layer of matrix. Table 2 summarizes the mechanical properties of the reinforcing materials. The data are based on the technical sheets of the individual products.

## 3 Results And Discussion

The results of the experimental testing are presented in relation to three different aspects and in the form of a synthesis.

### 3.1 Force-displacement relation

Ring deformation analysis (figure 6) shows that the R1 and R8 models had the greatest stiffness, whereas a slightly worse result was obtained for the R9 model. The lowest rigidity was demonstrated by the R6 model, which was confirmed by the lowest  $K_{EA}$  value. The values obtained for the R5 and R7 models were in-between the extremes, which in the case of the R5 ring is surprising. This could be explained by the strengthening technology used and the possibility of slip between the mat and epoxy resin.

### 3.2 Load carrying capacity

Due to the diversity of reinforcing materials used, the stiffness of strengthening materials under axial tension  $K_{EA}$  and the tensile strength  $R_u$  were adopted as the parameters for comparative analysis. The highest tensile strength was recorded for the carbon fibre strip (used in the R1 model) and the CFRP wrap (used in the R5 model), and the lowest load capacity was recorded for the double glass mesh in the G-FRCM system (used in the R6 model). In this phase of research, the rings were loaded right up to their destruction. A comparison of the maximum values of destructive forces provides an estimate of the effectiveness of the reinforcement system used in relation to increasing the load capacity after reinforcement (figure 7).

As expected, the highest load capacity was obtained in the R1 model reinforced with carbon fibre strip, and the lowest in the case of the R6 model reinforced with glass fibres mesh. The result achieved using PBO-FRCM nets should be noted.

### 3.3 Assessment of strengthening effectiveness

According to conservation doctrines, strengthening historical objects should strive to achieve the intended strengthening effects with the smallest possible cross-section of added elements. For this reason, a quantitative assessment of reinforcement effectiveness was carried out as part of the comparative analysis of the experimental results obtained from all the ring models. This involved calculating the EF factor, which is the quotient of the ultimate force for the ring after reinforcement  $F_{max}$  [N] and the stiffness of the reinforcing materials under tensile strength  $K_{EA}$  [N]:

$$EF = \frac{F_{max}}{K_{EA}} \quad (1)$$

Based on the calculations of the EF factor (1), it can be concluded that reinforcements using FRCM systems are the most beneficial, especially P.B.O fibre nets (table 3). The R1 model revealed the best stiffness and the highest carrying load capacity.

## 4 Conclusions

1. It is possible to create a complex, unfavorable stress state that simulates the forces occurring in the bases of domes using the loading system for the ring as proposed in this paper.
2. The use of contemporary materials (bricks, mortars) to create models simulating historical structures is possible, provided that their parameters are strictly controlled.
3. Based on the results obtained from experimental testing of the rings, it is possible to estimate the increase in the load capacity of the structure after reinforcement, which in turn allows the number of reinforcing elements to be minimised while ensuring maximum diffusion surface and minimal interference with the historical substance.
4. The R1 ring, which was reinforced with a single CFRP strip, recorded the greatest load capacity. The weakest reinforcement was recorded for the double glass fibre mesh in the FRCM system - model R6.
5. Adopting the EF indicator as the criterion for assessing the effectiveness of reinforcement, it can be concluded that the application of the following methods should be considered in the structural maintenance of historical buildings: PBO mesh reinforcement in the PBO-FRCM system, carbon mesh reinforcement in the C-FRCM system and also basalt reinforcement in the B-FRCM system.

## Declarations

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### Authors' contributions

JJ: Research concept, main assumptions. KR: Principal investigator, analysis of the results. PF: Analysis and development of results and editing. KK: State of art summary and editing. ŁB: consultation and selection of instrumentation. All authors read and approved the final manuscript.

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### Availability of data and materials

The datasets used and analysed during the current study are available from the corresponding author on reasonable request. The materials are described in experimental sections.

## Competing interests

The authors declare that they have no competing interests.

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## Tables

**Table 1:** Mechanical properties of bricks, mortar, and masonry

brick compressive strength	$f_{c,b} = 11.75 \text{ MPa}$
mortar compressive strength	$f_{c,m} = 5.76 \text{ MPa}$
mortar tensile strength	$f_{x,m} = 1.34 \text{ MPa}$
compressive strength	$f_c = 15.47 \text{ MPa}$
Young's modulus	$E = 2.21 \text{ GPa}$
plastic deformation (under compression)	$\varepsilon_{c,pl} = 0.70\%$
limit deformation (under compression)	$\varepsilon_{c,max} = 0.94\%$
shear strength	$f_v = 0.121 \text{ MPa}$

**Table 2:** Values of compressive and shear strength for masonry elements

Model	Material	Cross-section	$e$	$A_{re}$	$E$	$K_{EA}$	$f_u$	$R_u$
		[mm]	[-]	[mm <sup>2</sup> ]	[GPa]	[MN]	[MPa]	[kN]
R1	CFRP strips	1.4 x 60	1	84.0	170	14.28	2 600	218.4
R5	Carbon Fibre Fabric	0.440 x 120	1	52.8	242	12.78	3 800	200.6
R6	Glass fibres net	0.024 x 200	2	9.6	72	0.69	1 250	12.0
R7	Basalt fibres net	0.039 x 150	4	23.6	89	2.10	1 538	36.3
R8	Carbon fibre net	0.047 x 200	3	28.2	103	2.90	1 031	29.1
R9	P.B.O fibre net	0.046 x 200	3	27.6	95	2.62	1 664	45.9

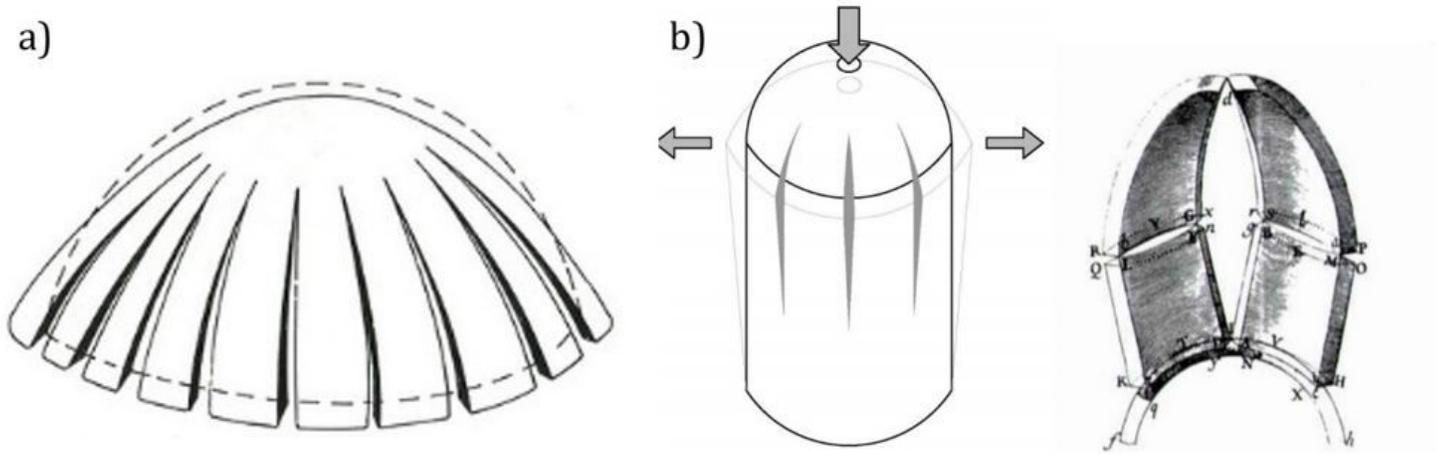
where:

- $e$  - the number of reinforcing elements at the height of the ring,
- $A_{re} = e \cdot A_r$  - total cross-sectional area of the reinforcement,
- $K_{EA} = E \cdot A_{re}$  - stiffness of the reinforcement during tension,
- $R_u = f_u \cdot A_{re}$  - tensile strength capacity of the reinforcement

**Table 3:** Comparison of strengthening effectiveness

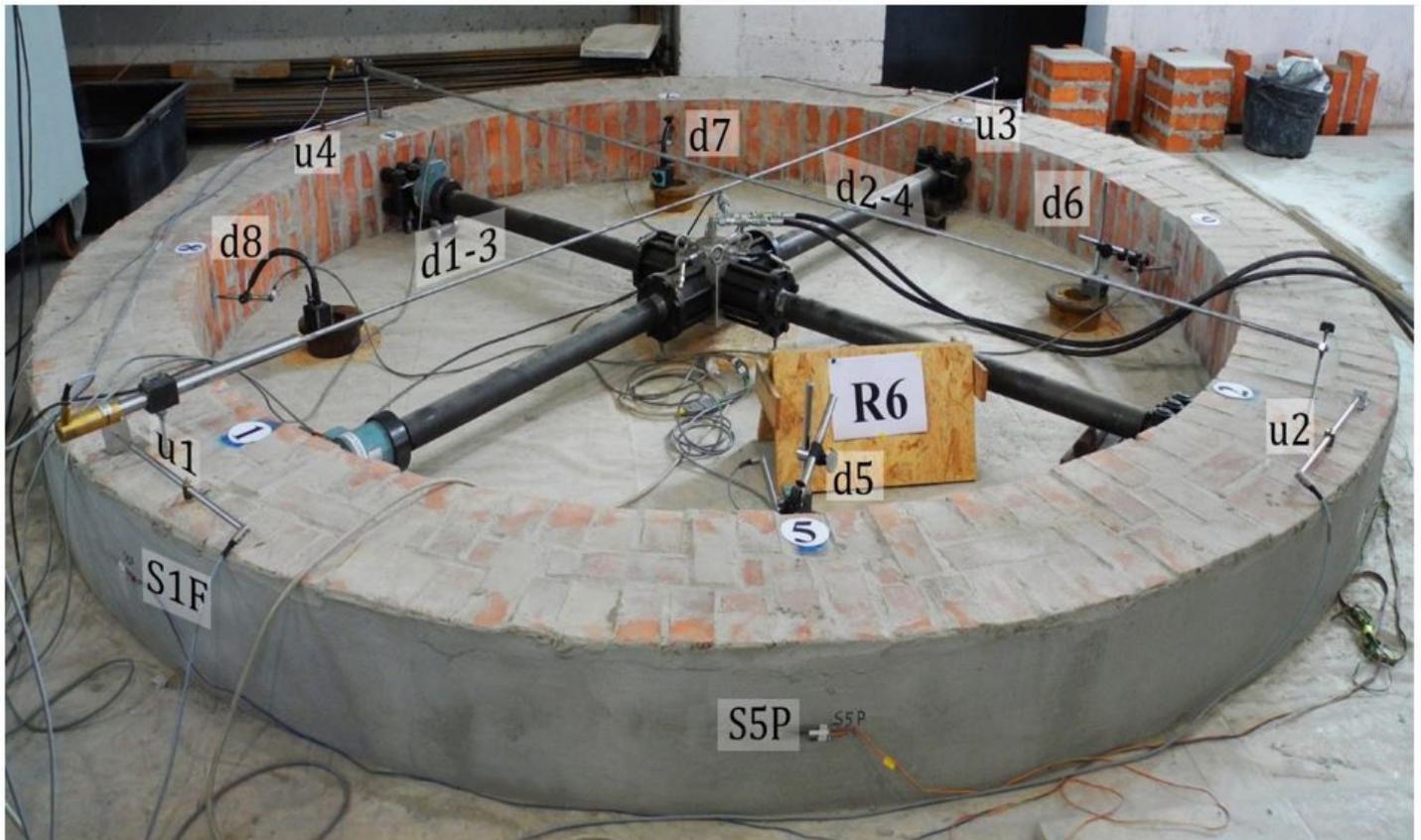
Ring Coefficient	R1	R5	R6	R7	R8	R9
EF factor	4.2	1.8	9.5	12.9	14.0	21.1
Destructive force [MPa]	60.54	22.77	6.57	27.09	40.56	55.25

## Figures



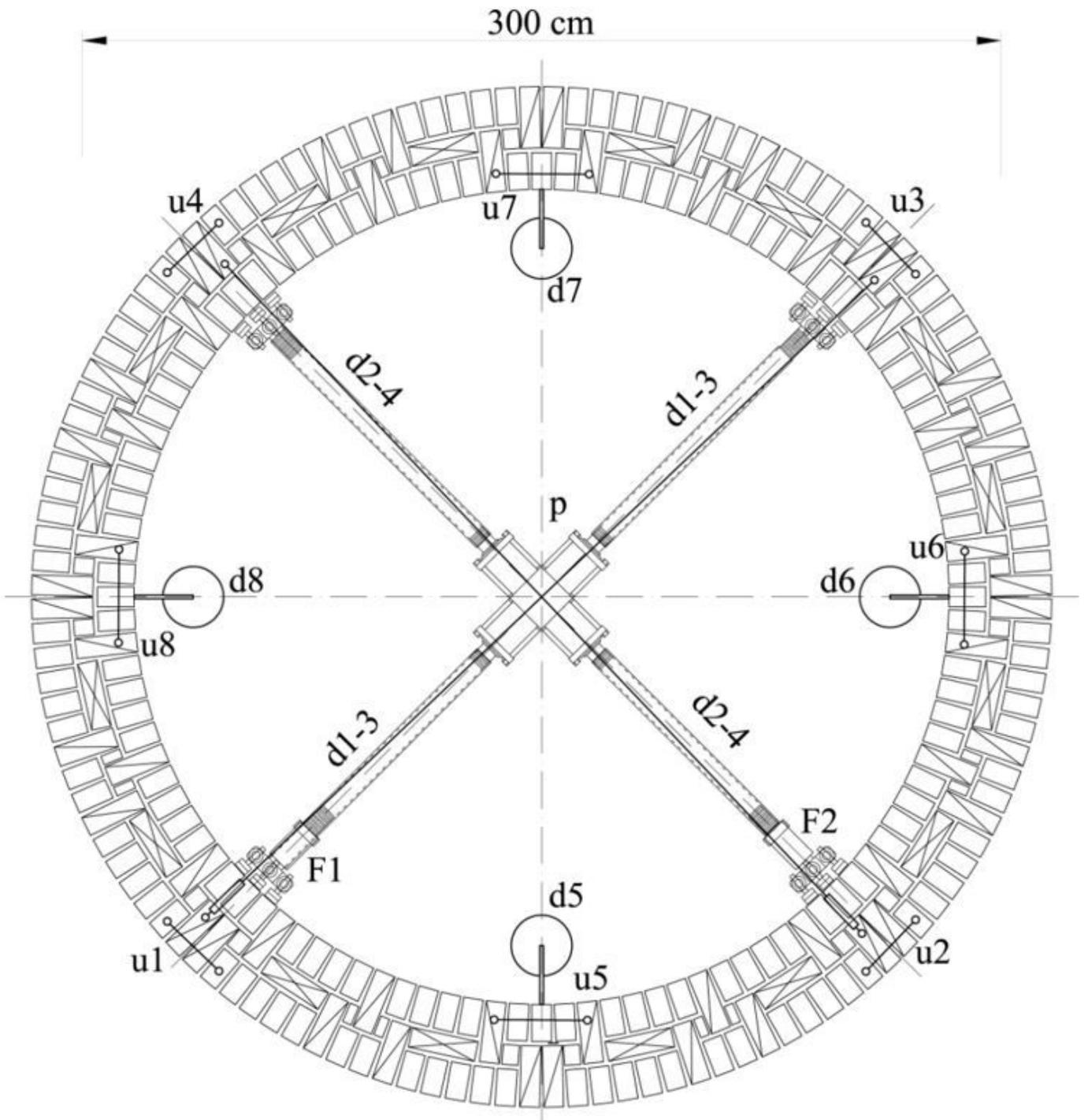
**Figure 1**

The failure mode of domes: a) separation of arches [6], [8] b) vertical cracks, [7]



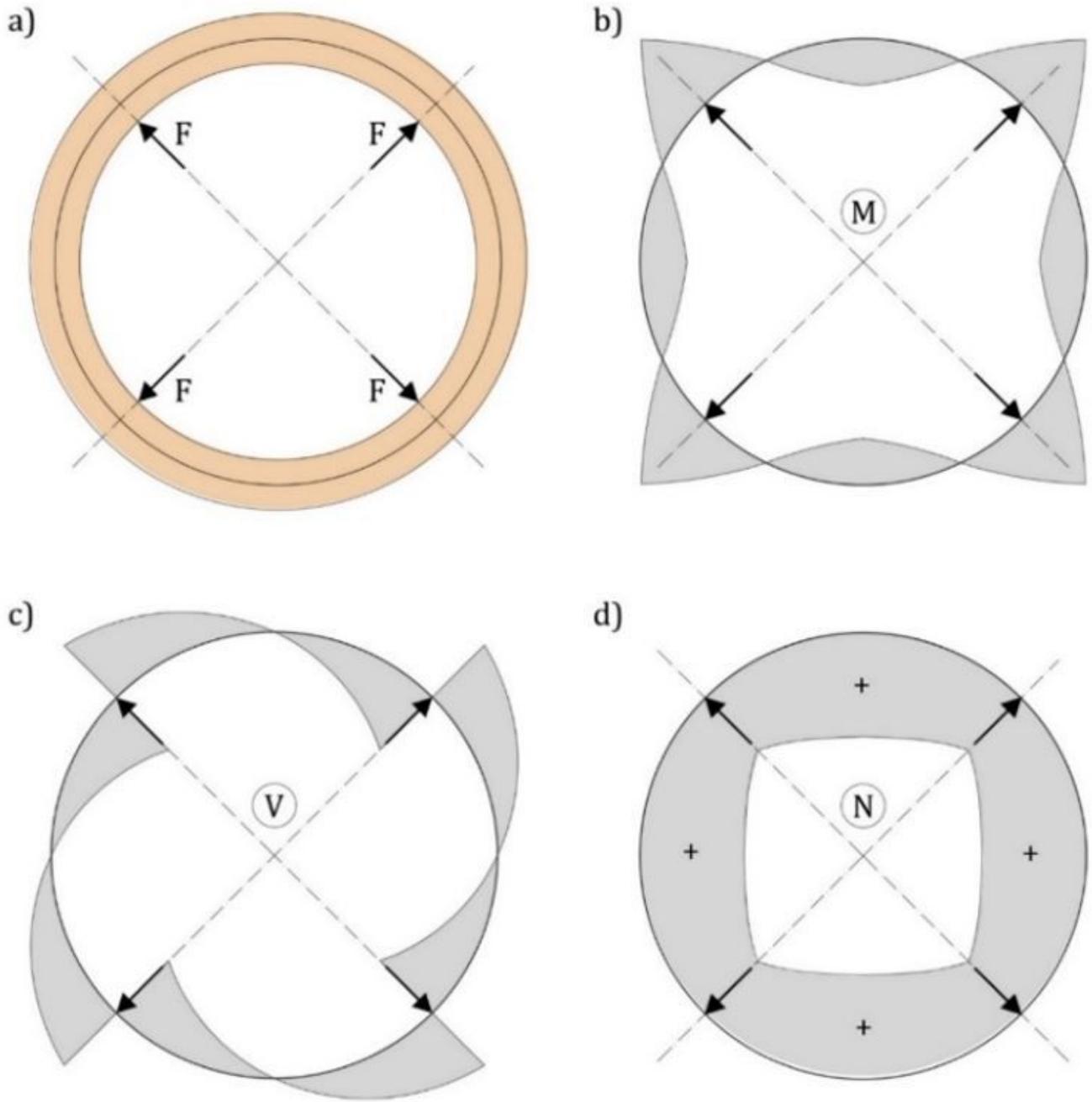
**Figure 2**

Model R6 prepared for experimental testing



**Figure 3**

Arrangement of the measuring instrumentation and the loading system - description in the text



**Figure 4**

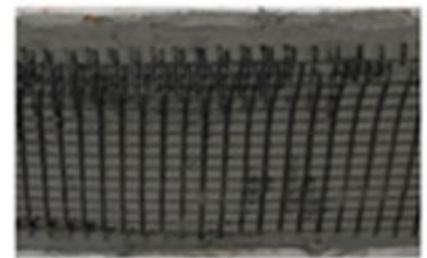
The static solution of the ring, a) static scheme b) bending moments, c) shear forces, d) tensile forces



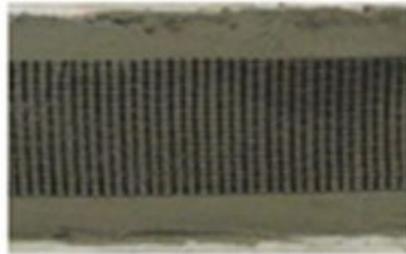
**R1** CFRP strip



**R5** C-FRP wrap



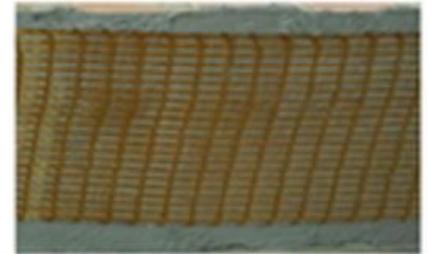
**R6** G-FRCM mesh



**R7** B-FRCM mesh



**R8** FRCM mesh



**R9** PBO-FRCM mesh

**Figure 5**

Six different types of strengthening

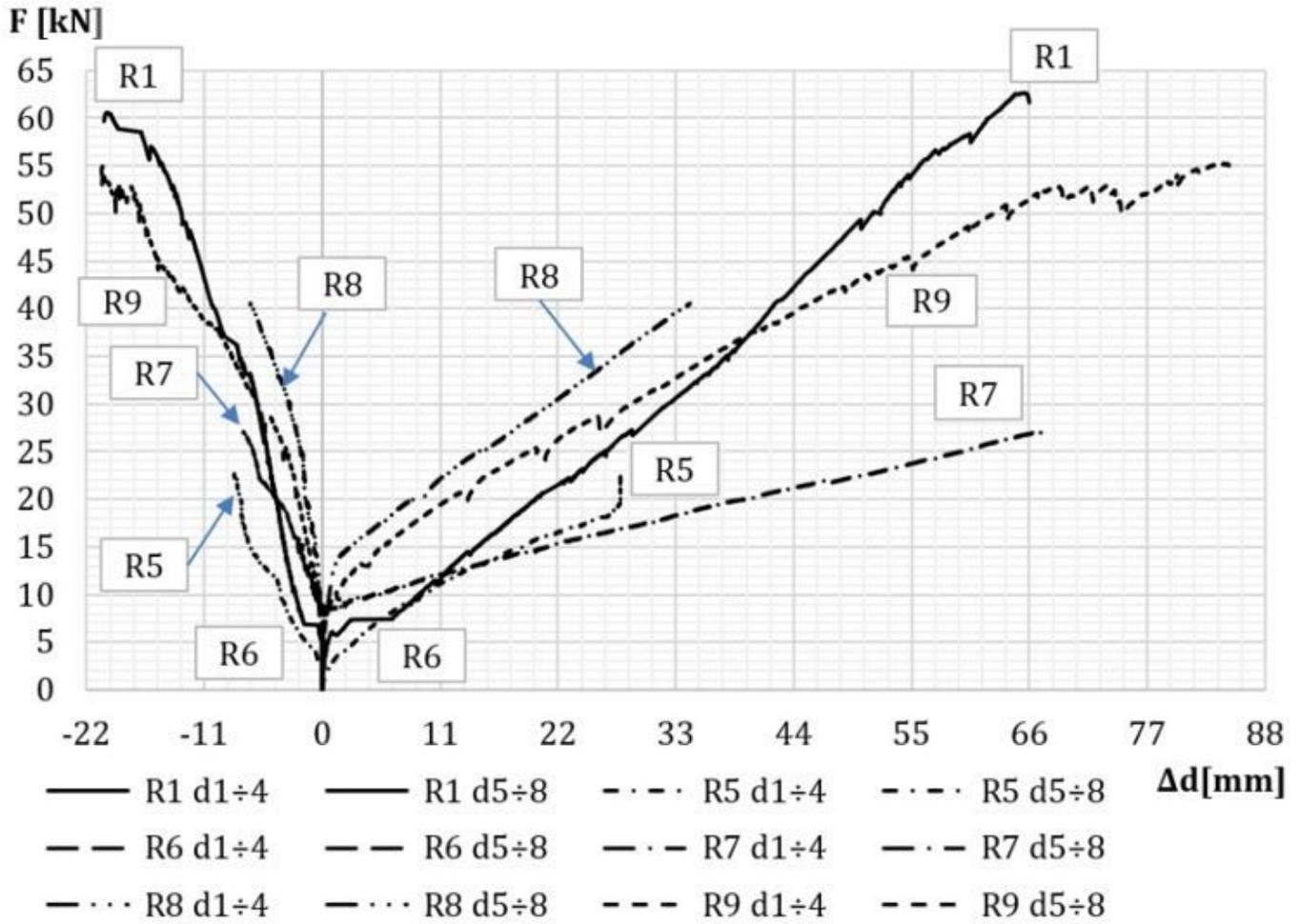


Figure 6

Comparison of ring test results: force displacement relation

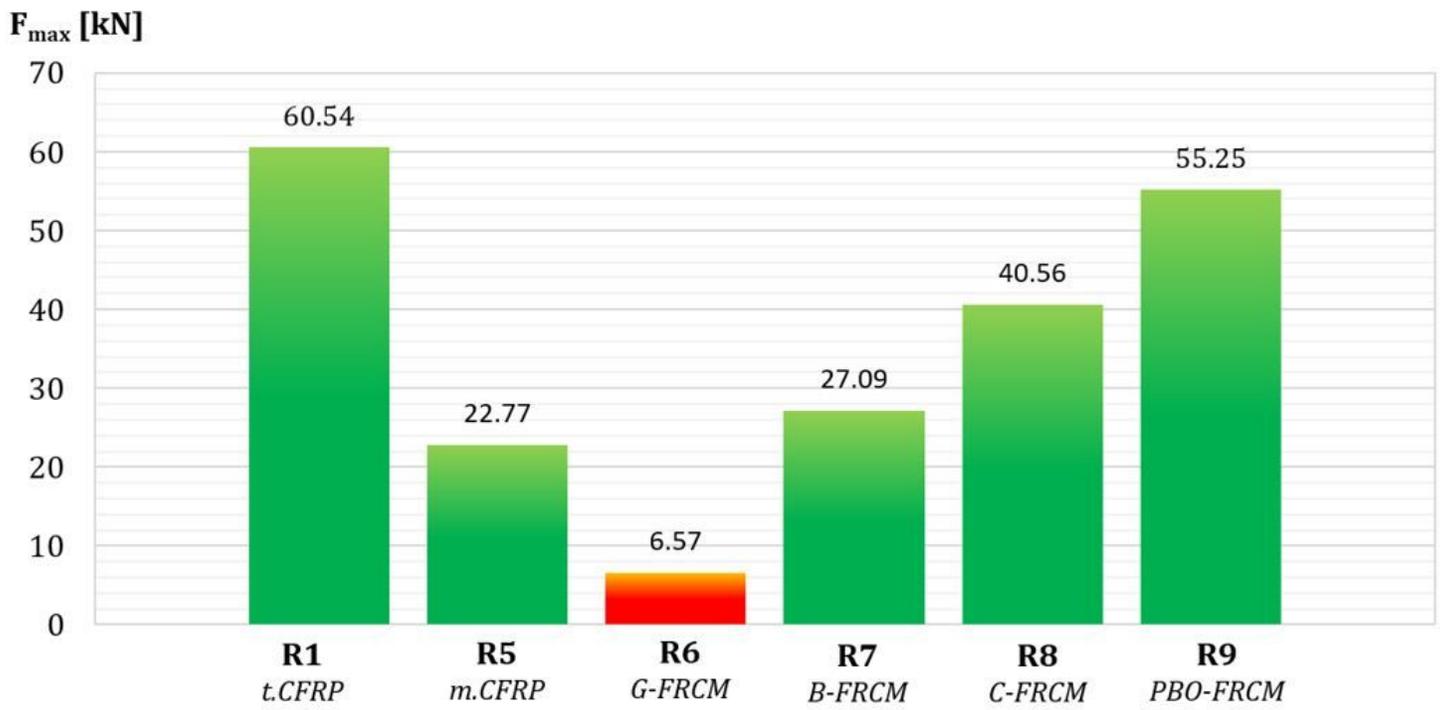


Figure 7

Comparison of load bearing capacity of strengthened ring models