Glass fibre reinforced textile composites strengthening solutions for masonry arches

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Abstract: Masonry arches are frequent components of the monumental buildings, many of them belonging to the historical heritage. Masonry as a structural material has high compressive strength and versatility, in achieving different architectural shapes. Since the tensile strength of masonry is very low, under certain loading conditions, the masonry arches are vulnerable to cracking and to various failure mechanisms. Previous theoretical and experimental studies have proven that the use of textile glass fibre reinforced polymer (GFRP) composite materials has favorable effects upon the structural behaviour and the load bearing capacity of the structural elements. In this paper the results of an extensive experimental program on the structural behaviour and failure mechanisms of unstrengthened and strengthened masonry arches are presented. The experimental results describe the mechanical behaviour of circular masonry arches under vertical and horizontal loadings. The strengthening scheme has been conceived in two phases, on one side only and on both sides of the arch, with the connecting strips made of textile GFRP composites. The overall behaviour and the failure mechanisms have been favorably modified improving the load bearing capacity of the masonry arch type elements.

Key-Words: masonry arches, textile composites, GFRP strengthening solutions, numerical modeling, hybrid structures

1 Introduction

Masonry represents one of the oldest building materials used by mankind. Many of the old masonry structures are now belonging to the historical heritage. Masonry arches were often preferred to beams for covering large spans as the lack of tensile stresses allowed masonry to reveal its good behavior in compression.

Since the tensile strength of masonry is very low, under certain loading conditions, the masonry arches are vulnerable to cracking and to various failure mechanisms.

Previous theoretical and experimental studies have proven that the use of fibre reinforced polymer (FRP) composite materials (based on glass, carbon and aramid fibres) has favorable effects upon the structural behaviour improving the load bearing capacity of the framing systems [1, 2, 3, 4].

An extensive experimental program was initiated and carried out to study the structural behaviour and failure mechanisms of unstrengthened and strengthened masonry arches subjected to typical loading conditions.

Two main FRP strengthening systems, based on glass fibre textile reinforced polymers, with strengthening strips at the upper face only and upper and bottom sides linked with transverse strips have been considered, evaluated and tested.

It has been realised that GFRP strengthening solutions based on textile composites are efficient systems improving structural behaviour, load capacity and failure mechanisms.

2 Materials for the experimental model

The experimental model has been made of masonry with normal bricks and mortars. Prior to construction of the model, preliminary tests on the material properties have been carried out. Tests have been performed on brick sample Fig. 1, mortars cubic test specimens Fig.2, block of bricks Fig.3 and bonding between GFRP strips and masonry block Fig.4.

The compression test has been performed on an universal testing machine, ZWICK/ROELL with displacement and force control. In all tests the stress-strain curves have been determined including the ascending branch up to the peak force and a descending segment up to a 60 % decrease of the loading force.

A comparative illustration of the experimental curves is presented in Fig. 5, for brick specimen, mortar sample and masonry block.

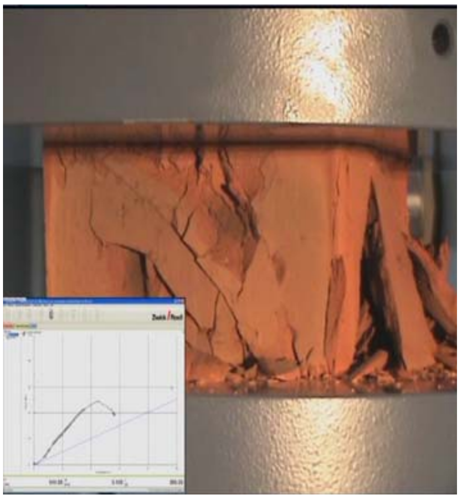

Fig. 1 Compression test on brick sample

Fig. 2 Compression test on mortar specimen

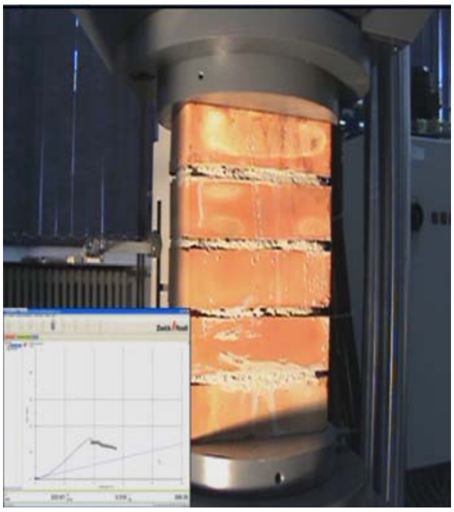

Fig. 3 Compression test on masonry block

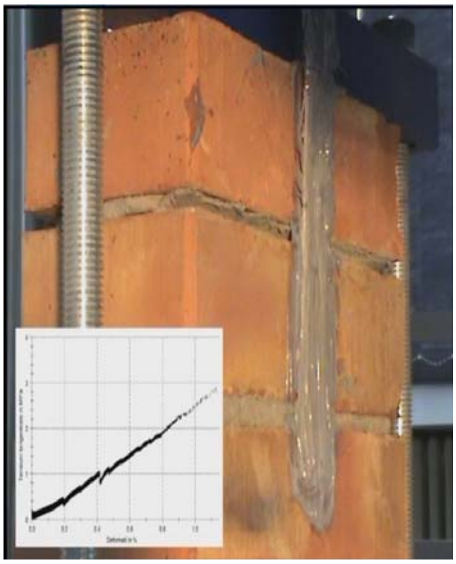

Fig. 4 Bonding test GFRP strip-masonry block

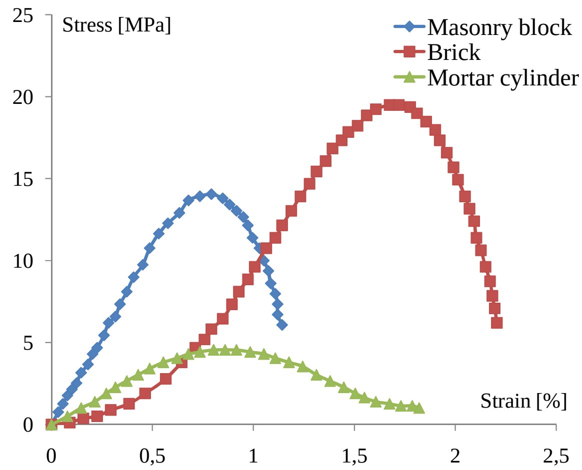

Fig. 5 The stress-strain curves for the materials utilised at the experimental arch

The values of the properties determined on the experimental tests have been utilised in the numerical modelling of describing the structural response of the unstrengthened masonry arch subjected to vertical and horizontal loading.

3 Structural behavior of the unstrengthened masonry arch

The unstrengthened masonry arch has been firstly tested to identify the possible failure loads and failure mechanisms under vertical and horizontal loads, Fig.6 and Fig.7. Common 240x115x63mm bricks and a common mortar, normally utilized in masonry works have been used to make the sample arch.

The arch has been conceived as a two hinged one; on the right hand side a horizontal load has been applied by means of a hydraulic jack [5]. A load cell has been utilized to record the horizontal load magnitude. Gravitational loads have also been applied using five loading positions with water filled recipients hanged as shown in Fig.6 to simulate the effect of service loads.

Fig. 6 The vertical loading of the unstrengthened arch

Fig. 7 Horizontal loading system

Vertical transducers have been positioned so as to monitor the vertical displacements at the loading points (1…5) and a horizontal transducer has been assigned to record the horizontal displacement, point 6, Fig.8. The overall dimensions, the support and loading conditions are illustrated in Fig. 8.

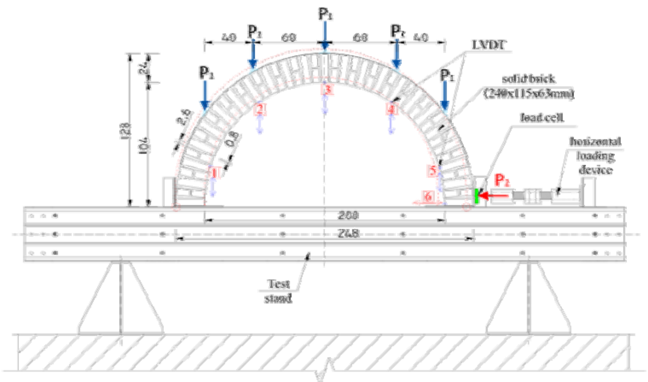

Fig. 8 Loading schemes of the unstrengthened arch

The experimental test started with vertical loading up to 0.75 KN in each of the five loading points mentioned before. After that, the horizontal progressively increasing load has been applied. When the horizontal load reached 3.8 kN a first sign of arch failure has been observed. At the horizontal force 5.00 KN a first hinge was identified at the bottom side of the arch, Fig 9.

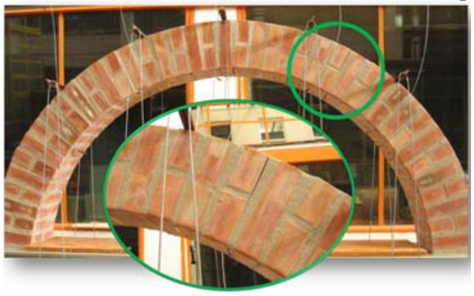

Fig. 9 Unstrengthened arch and the formation the first hinge

A force displacement curve recorded at the level of LVDT no. 6 is illustrated in Fig. 10.

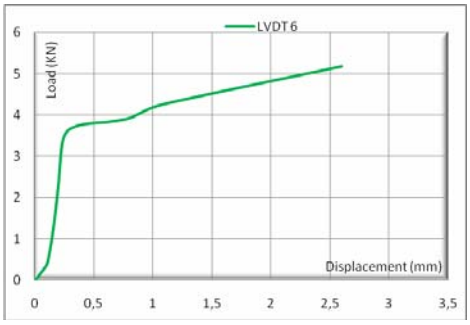

Fig. 10 Structural response of the unstrengthened arch

The failure mechanism of the arch under the horizontal force leads to the formation of an extended crack (Fig. 9) which in combination with the simple support on the right side (Fig. 8) jeopardizes the load bearing capacity of the whole arch. Consequently, the test was stopped due to excessive horizontal displacement of the right end.

4 Strengthening solution with textile glass fibre composite materials

Recent advances in FRP composite technologies have lead to strengthening solutions that can be developed as externally bonded reinforcement. A class of such materials comprises glass fibre textile reinforced polymeric materials commercially available in the form of fabrics that can be bonded to the outer surface of masonry members. These solutions can be successfully applied to restoring or retrofitting structures made of masonry. Textile structural composites reinforced with glass fibres offer the potential of providing adequate structural integrity and good shapeability. Textile composites offer good dimensional stability over a large range of temperatures and impact resistance. These composites provide the unique capability that can be designed to meet the needs of the performance of composite products utilized in structural strengthening.

In particular glass fibres woven fabrics provide resistance to damage, toughness, dimensional stability and easy of manufacturing. Bi-axial woven fabric composites can be successfully applied in strengthening solutions and the fabric geometry can be chosen so that it gives the best possible properties for the application under consideration.

GFRP textile composites should be installed by skilled workers in accordance with the procedures recommended by the material manufacturers.

After failure, the unstrengthened arch was unloaded and prepared for the application of the FRP strengthening system. The surface of the element to be strengthened has been prepared so that the masonry surface was made free of loose deposits on the masonry surface that could affect negatively the bonding of the GFRP external reinforcement [6].

The plastic hinge developed in the unstrengthened arch was repaired by injecting an epoxy mortar. Surface preparation started with cleaning the bonding areas between the textile composite product and the masonry block using an abrasive technique. After removing all foreign deposits the surface voids have been filled with putty leading to a smooth surface. A primer made of epoxy resin has been applied to areas of the masonry surface to be covered with GFRP composites. The primer cured before applying GFRP strips. A wet lay-up system involving the hand-laying of fabric strips and saturation of the formed membrane with epoxy resin has been utilized. To remove any entrapped air pockets, the wet fabric strips have been rolled out while the resin was still wet. This technology has been applied to all composite strips utilized in strengthening systems, Fig 11. A proper fibre alignment has been provided since deviation of fibre orientation from the required directions can substantially decrease the mechanical strength. After application the composite system has been kept in laboratory condition up to a complete cure before testing. After the completion of the curing time, the arch has been tested under the same conditions as the unstrengthened arch, and the structural response recorded for this case is illustrated in Fig.12.

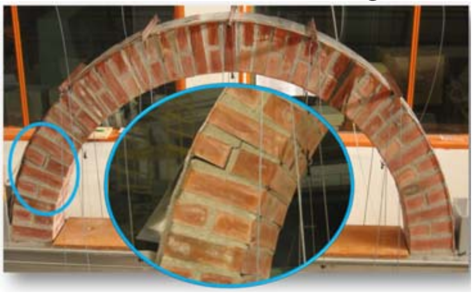

Fig. 11 Plastic hinge in case of the FRP upper side strengthened masonry arch

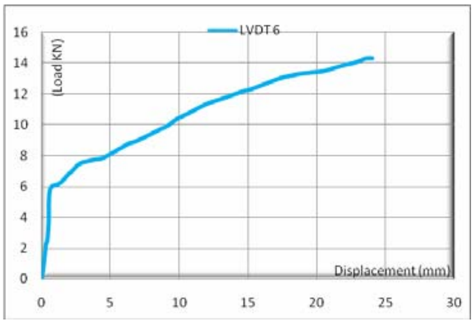

Fig. 12 Load versus lateral displacement of the FRP upper side strengthened masonry arch

The horizontal force has been applied until the load carrying capacity of the arch has been reached corresponding to a horizontal force 14.2 KN and a horizontal displacement equal to 24 mm. At this load the upper side strengthened arch failed and a new plastic hinge appeared Fig.11. Some specific particularities of the one sided strengthened arch have been noticed:

- the strengthened arch behaved in a similar manner to the unstrengthened arch up to a horizontal displacement level of 1mm;
- the strengthened arch had a more convenient deformability;
- the active contribution to the structural response of the FRP composite strip has become obvious after the tensile stresses surpassed the tensile strength of the masonry;
- the load bearing capacity of the strengthened arch was about 3 times higher than that of the un-strengthened one;
- a visible failure occurred by debonding the composite strip from the masonry.

5 Experimental tests on the FRP strengthened masonry arch – FRP composite applied on both upper and bottom sides

In the third stage of the experimental program, after the removal of the FRP composite layer previously applied, the integrity of the unstrengthened arch has been restored. A second layout of the strengthening system, consisting of woven glass roving placed on both (upper and bottom) faces was completed with transversely applied strips. These strips were placed to provide a better anchorage of the longitudinally applied FRP composite layers. The loading procedure was conducted in a similar manner to the previous two cases. Initially, a vertical loading equal to 0.75 KN has been applied in each of the five loading points. After that, the horizontal force has been progressively applied. Up to a magnitude of 6.00 KN the masonry of the arch was

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capable of resisting all external loading. After surpassing the strength of the masonry, the composite strip enabled the arch to have a more appropriate deformability up to an important horizontal load level equal to 26 KN and a corresponding horizontal deformation of 58 mm. The failure mechanisms corresponding to this loading case consist of four different plastic hinges, Fig. 13. A structural response is given in Fig.14 in terms of force and lateral displacements.

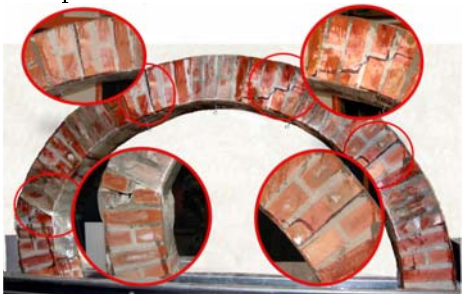

Fig. 13 Failure mechanism of the double sided FRP strengthened masonry arch

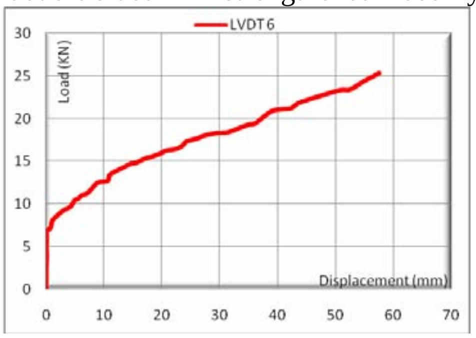

Fig. 14 Structural response of the double sided FRP strengthened masonry arch

A synthetic comparison regarding the three testing cases, for the un-strengthened, the one sided strengthened and the double sided strengthened arch is presented in Fig. 15. The curves give a comparative study for the structural responses of the cases mentioned before. The contribution of the composite strengthened system is obvious and the efficiency of using FRP composites in masonry arches strengthened solutions is undeniable.

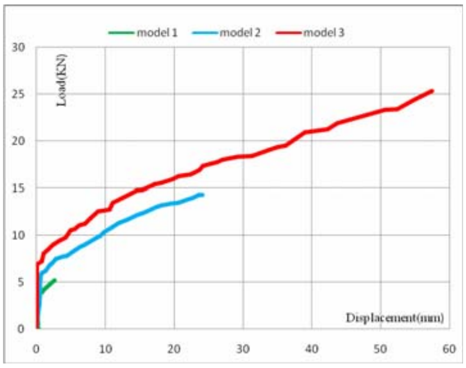

Fig. 15 The load-displacement curves for the main studied cases: model 1 – un-strengthened arch; model 2 - one-sided strengthened arch; model 3 – double sided strengthened arch

The loss of the load bearing capacity has occurred by the debonding of the upper side placed glass woven roving composite reinforcement.

7 Numerical modeling of masonry arch

The numerical modeling has been performed using LUSAS, a specialized software package based on finite element method. The volume type finite elements have been utilized for mesh generation of the constituent materials, Fig. 16.

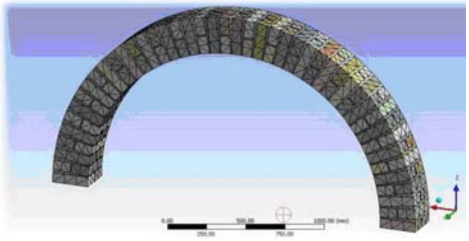

Fig. 16 3D meshing of the unstrengthened masonry arch

Two main loading systems have been considered, one with vertical forces, and another with a horizontal force applied in the right support, Fig.17. The loading schemes correspond to the experimental program carried out on both unstrengthened and strengthened models.

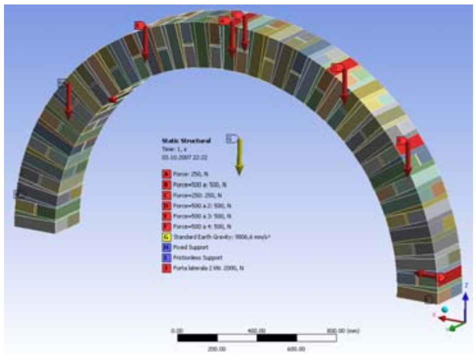

Fig. 17 The loading schemes considered in numerical simulation

From numerical simulation as well as from the experiment it has been realised that the most severe loading condition corresponds to application of the horizontal force acting in the right end support. The map of stresses as well as the deformed shape of the arch is given in Fig. 18.

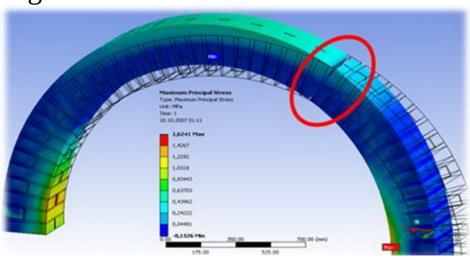

Fig. 18 Maximum stresses and the deflected shape of the unstrengthened arch under vertical and horizontal loads

8 Conclusion

The masonry arches are efficient structural systems for monumental buildings with a favorable behaviour under in plane vertical loads leading to compressive stresses.

Horizontal forces applied at the end of arch, simulating a malfunctioning of a support system may generate severe cracks and failure mechanisms.

Glass fibre textile reinforced composite systems may be successfully applied to strengthened masonry arches.

The most effective strengthening solution proved to be the double sided system with transverse strips connecting the membranes applied on the top and bottom side of the arch.

The following observations can be formulated after performing the loading test on the double sided strengthened arch:

• an obvious improvement of the structural response has been achieved after application of the double sided glass fibre woven strips connected by transverse composite strips;

• the load carrying capacity of the double sided strengthened arch increased up to 26 KN (compared to 14.2 KN in case of single side strengthened arch);

• the deformation capacity of the framing system has also increased from 24 mm horizontal displacement (for the single sided strengthened arch) to 58 mm (in case of the double sided strengthened arch);

• an improvement of the overall structural response of the double sided strengthened arch has also been identified by formation of four plastic hinges;

• an increase of the masonry contribution to the load carrying capacity of the system has also been observed and this aspect has been proven by the appearance and the development of cracks in the brick;

• these cracks have not been noticed in the previous two loading cases (unstrengthened and one sided strengthened arch);

• the mechanical tests conducted in this experimental program did not lead to the failure of the composite strips, therefore it can be stated that their load bearing capacity has not been fully utilized;

• the double sided FRP strengthening system is more efficient than the one-sided system since the former ensures a delay in the formation of the failure mechanism.

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References:

[1] Briccoli Bati, S., Rovero, L., Tonietti, U., Strengthening Masonry Arches with Composite Materials, *Journal of Composites for Construction*, Vol. 11, No. 1, 2007, pp. 33-41.

[2] Foraboschi, P., Strengthening of Masonry Arches with Fiber-Reinforced Polymer Strips, *Journal of Composites for Construction*, Vol. 8, No. 3, 2004, pp. 191-202.

[3] Baratta, A., Corbi, O., Stress analysis of masonry vaults and static efficacy of FRP repairs, *International Journal of Solids and Structures*, Vol. 44, No. 24, 2007, pp. 8028-8056.

[4] Taranu G., Budescu M., Taranu N. Strengthening masonry arches with composites, an efficient solution for historical monuments, *AICPS Review*, No.4, 2008, pp.68-73.

[5] Budescu M., Taranu N., *Building Rehabilitation*, Ed. Societatii Academice "Matei-Teiu Botez", Iasi, Romania, 2003.

[6] Gangarao H., Taly N., Vijay P.V., *Reinforced concrete design with FRP composites*, CRC Press, 2007.