EXPERIMENTAL TESTS ON MASONRY ARCHES STRENGTHENED WITH A MORTAR-BASED STRENGTHENING SYSTEM

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SUMMARY

This paper deals with the experimental behaviour of masonry arches strengthened externally with a mortar-based strengthening system. A carbon fibre fabric embedded in a cement-based mortar matrix was used as the strengthening. The tested arches were strengthened continuously at their extrados. Both ends of the strengthening above the abutments were either bonded to the masonry or anchored using steel plates to the concrete abutments. The main aim of the presented research was to check the influence of the anchorage of the textile ends to the abutments on the load-carrying capacity and on the failure modes of the tested arches. One of the tested specimens failed due to sliding along a mortar joint just above the abutment, whereas the other one failed due to fibres rupture.

Keywords: *Strengthening, masonry, arches, vaults, composite materials, mortar-based strengthening system, carbon fibres, experimental tests, arch bridges.*

1. INTRODUCTION

The use of textile reinforced strengthening systems for masonry arches and vaults has been investigated in recent years. In these research FRP (Fibre Reinforced Polymer) based systems [1, 2, 3, 4] or cement- and lime-based systems (Textile Reinforced Mortars – TRM, Fibre/Fabric Reinforced Cementitious Matrix – FRCM) [5, 6, 7, 8, 9] were considered. The research were performed on arches and vaults strengthened at their extrados [1, 2, 4, 6, 10, 11] or intrados [1, 2, 4, 6, 12] or both surfaces [6, 7]. The strengthening methods used in the tests increased the load-carrying capacity and influenced observed failure mechanisms of the tested structures. The effectiveness of such strengthening methods was confirmed.

This paper deals with the results of the experimental tests performed on masonry arches strengthened at the extrados with carbon fibre grid embedded in cementitious matrix (FRCM strengthening system). The main goal of the study was to check the effectiveness of the strengthening method and to examine if fixing the ends of the strengthening fabric to the arch's supports affects the behaviour and load-carrying capacity of the arch.

2. TESTING PROCEDURE

The tests were performed on masonry arches made of clay bricks (250x125x65 mm^3) and pre-mixed lime (NHL) mortar. The mechanical properties of adopted materials were similar to materials used in the past [13].The geometry of the specimens adopted in test is presented in Fig. 1. The thickness, internal span, rise and width of the arches were 125 mm, 2000 mm, 730 mm and 1040 mm respectively. The arches were strengthened with a carbon fibre grid (Fig. 2) embedded in an cementitious matrix – strengthening system called FRCM (Fabric Reinforced Cementitious Matrix). Mechanical properties of materials used in the research are presented in Table 1 and in [8].

Table 1. *Selected mechanical properties of materials used in the research.*

Clay brick	
- compressive strength	24.4 N/mm^2
Lime mortar at 28 days	
- compressive strength	1.1 N/mm^2
Cement-polymer mortar	
- compressive strength at 14 days	23.7 N/mm^2
- compressive strength at 28 days	26.5 N/mm^2
Carbon fibre grid	
- tensile strength /specified by manufacturer/	>160 N/mm

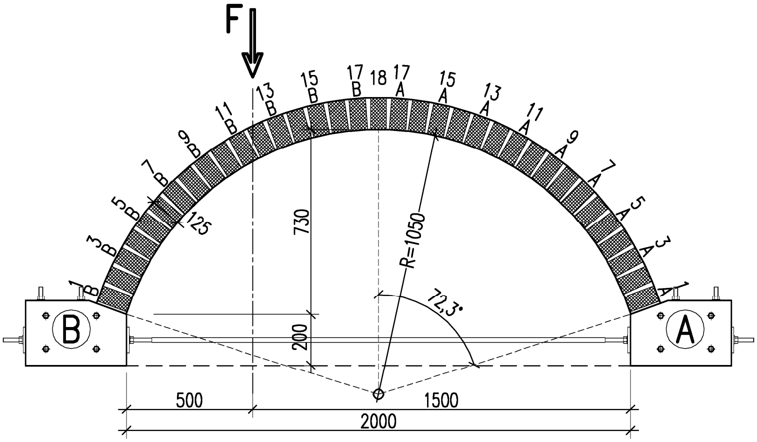

Fig. 1. *Geometry of the tested arches, brick course numbering (dimensions in mm).*

Both tested specimens were strengthened externally at their extrados using one layer of 102-cm-wide textile. The strengthening was applied continuously between the first brick courses above the supports (form 1A to 1B). The ends of the reinforcement were not connected to the supports – only bonded to the masonry of brick courses 1A and 1B (arch VC) or anchored to the supports by means of steel plates bolted to the concrete abutments (arch VC-An – Fig. 3a-b). Before strengthening both arches were tested as non-strengthened ones up to the formation of four-hinge mechanism [14]. Then the initial geometry was restored and the strengthening was applied.

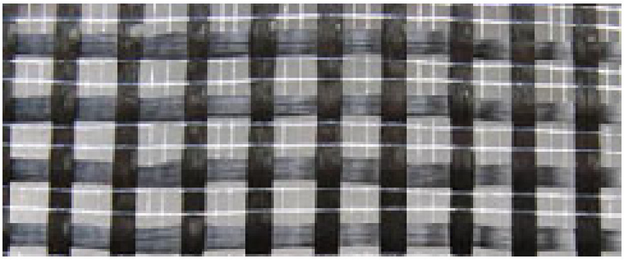

***Fig. 2**. Carbon fibre grid used in the study – detail.*

All arches were tested under a monotonic vertical load applied at a quarter span up to failure. During the tests load, radial and vertical displacements of the arch were recorded. Details of adopted test setup can be found in [15, 16].

***Fig. 3.** a) Carbon fibre grid arrangement above the abutment – during application of the strengthening – arch VC-An. b) View of the strengthening's anchorage on the abutment of arch VC-An.*

3. TEST RESULTS

3.1. Specimen VC

During the test performed on the arch VC cracks in mortar joints and strengthening layer were observed. The first cracks appeared in mortar joint under loading point at a load of 9–14 kN. At a load of 24 kN first cracks in the strengthening were observed. As the load was increasing further cracks on the extrados were noticed – above the all mortar joints between brick courses 8A and 17A and in the mortar joints under brick courses 1A and 1B. Finally at a load of 37.9 kN sliding of the arch at the skewback above support “A” occurred and the specimen collapsed. The collapse mechanism of the arch VC is presented in Fig. 4 and Fig. 6a.

Fig. 4. *Arch VC (originally named S06W): a)-b) cracks and hinges of the collapse mode, c) sliding of the arch at the skewback, d) cracks at the extrados, e) failure mechanism.*

3.2. Specimen VC-An

Similarly as in the previous test (arch VC) the first cracks in the arch VC-An appeared under the point of loading. Afterwards, at a load of 22-30 kN cracks developed at the arch’s extrados in the strengthening layer near brick course 14A, 4B and at the intrados between the first brick course and abutment “A”. In the final stage of the test (when the load exceeded 50 kN) cracks in the strengthening layer were observed – between brick courses from 1B to 7B and from 17B to 1A in the plane of every masonry bed joint. At a load of 62.5 kN the carbon fibres between brick courses 14A/15A and 1B/2B ruptured almost simultaneously. The failure mechanism is presented in Fig. 5 and Fig. 6b.

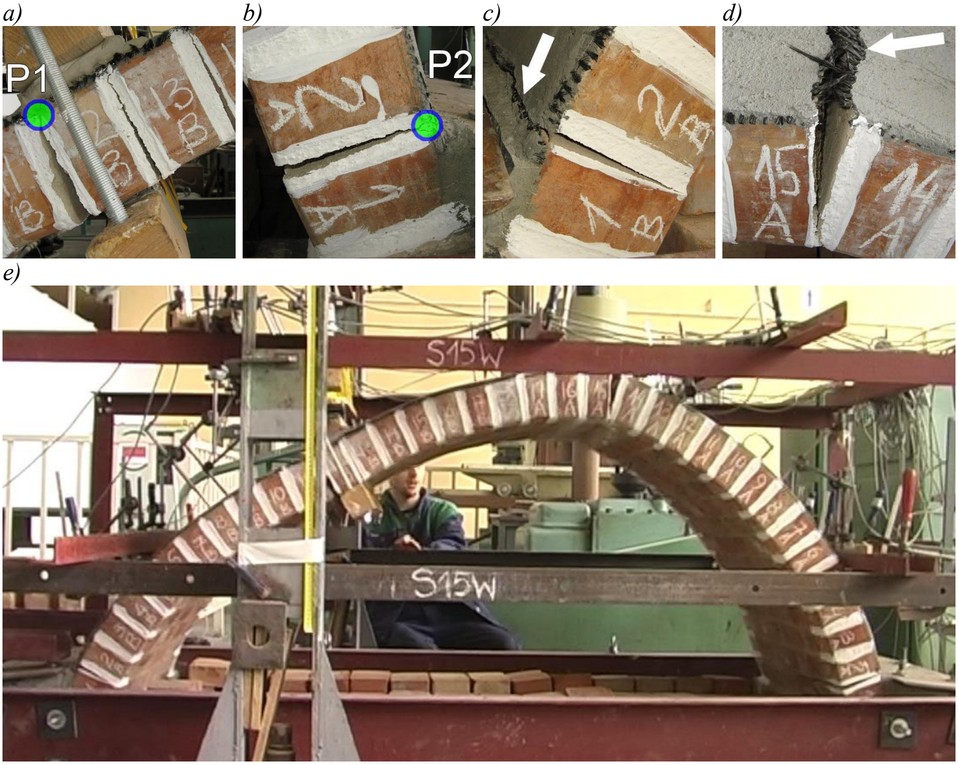

Fig. 5. *Arch VC-An (originally named S15W): a)-d) cracks and hinges of the collapse mode, e) failure mechanism.*

4. DISCUSSION AND CONCLUSIONS

Comparing the results of the tests presented here with the test preformed on non-strengthened arches of the same geometry, discussed among others in [12, 14], it can be concluded that the adopted strengthening system is an effective solution for the masonry arches and vaults. Arches without strengthening [14] loaded at a quarter span failed due to the formation of the four-hinge mechanism at a load of about 4.5 kN. The strengthening prevented the formation of hinges and the load-carrying capacity of the strengthened arches increased to 37.9 kN and 62.5 kN for arches VC and VC-An respectively.

The strengthening of specimens VC and VC-An was treated near the abutments in two ways. The strengthening of arch VC was not connected to the abutments and hinges could develop between brick courses 1A or 1B and the abutments. The arch collapsed due to masonry sliding above support "A". The strengthening of arch VC-An was anchored to the supports. During the test the anchorage resisted the possible negative bending moment at supports, prevented rotation of the arch around abutment B and prevented sliding along abutment A. The arch VC-An collapsed due to carbon fibres rupture between brick courses 14A and 15A and an almost simultaneous rupture of the fibres connected to support B. The significant increase in load-carrying capacity of specimen VC-An as compared to arch VC (Fig. 7) was observed. The anchorage of the strengthening at the abutments had a significant effect on the obtained failure loads and the observed collapse mechanisms (Fig. 6 and Fig. 7).

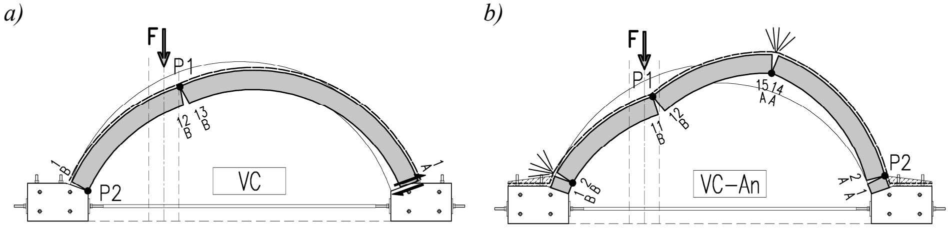

Fig. 6. Failure mechanisms observed during the tests: a) arch VC, b) arch VC-An.

During the tests, higher stiffness of arch VC-An as compared to arch VC was observed. As cracks at the extrados appeared, a clear reduction of the tested arches' stiffness was observed (Fig. 7).

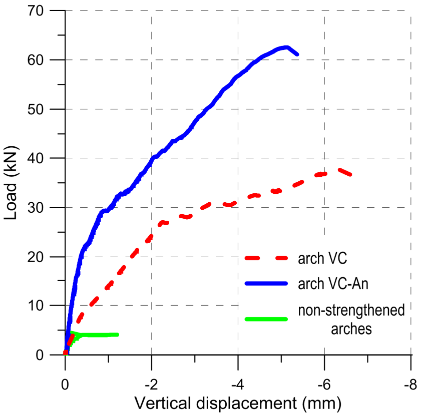

Fig. 7. Load – vertical displacement (at the point of loading) curves for the tested arches.

In this article tests on arches without backfill were discussed but it should be noted that in masonry arch bridges backfill is present. The presence of fill material above the arch could modify failure mechanisms obtained in studies performed on arches without backfill. Instead of tensile rupture of the strengthening or shear sliding of the masonry along the skewback shear sliding under the load point may occur. Such failure was observed in tests carried out on buried arch strengthened at its extrados and presented in [15, 16].

Although the tests presented here were carried out on a limited number of arches, the results show that continuous strengthening with FRCM systems could be considered during restoration works performed on masonry arches and vaults. It should be noted that based on results presented here and in [10] the anchorage method of reinforcement at the supports could influence the failure load and collapse mechanism of vaulted structures.

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