BEHAVIOR OF MASONRY ARCHES STRENGTHENED WITH TRM

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Abstract: *This paper presents results of experimental tests on strengthened and unstrengthened masonry arches. They were made of clay bricks and lime mortar. As a strengthening a glass grid embedded in a cement-based matrix was used (TRM - textile reinforced mortar). Thickness, internal span and rise of the arches were 120 mm, 2000 mm and 730 mm respectively. At first specimens without strengthening were tested, then strengthening was applied and the same arches were tested again. Two strengthening arrangements were considered – strengthening at arch extrados or intrados. In all tests the load was applied at a quarter span. The main aims of presented research were to determine load-carrying capacity and examine failure modes of tested specimens. The results of the tests on the arches with and without strengthening are compared and discussed.*

1 INTRODUCTION

Masonry arches are structural elements which were commonly used in buildings and arch bridges in the past. Nowadays some of these historical structures are in bad condition and additionally must fulfill some modern requirements. Masonry arch bridges and vaults in buildings need to carry traffic or live loads for which they were not designed.

In consequence they should be repaired and strengthened or replaced when they are in poor technical condition. Among available strengthening methods externally bonded composites became more common. Research performed in recent years indicated that fiber reinforced polymer (FRP) systems [3], [4], [5], [11], [12], [13] and textile reinforced mortar (TRM) systems [1], [2], [6], [7] are effective strengthening solutions for masonry vaults and arches. Systems which base on inorganic matrices have some advantages in comparison to FRP systems. TRM systems are applicable over irregular deteriorated and damp surfaces without the need of specialized labor. They can be applied in low temperature and are vapor permeable.

Strengthening may be applied at arch intrados or extrados. Application at arch intrados is favorable when repaired bridge is operated and disruption of transport services are unacceptable. When bridge could be closed for renovation works for example during repair of road or railway track, application of strengthening at arch extrados can be considered. During this works backfill can be removed and precise inspection of arch extrados can be made.

In this article results of laboratory tests performed on strengthened and unstrengthened masonry arches are presented. In the case of strengthened arches commercially available externally bonded strengthening system based on inorganic matrix reinforced with glass grid was used. Two strengthening locations were considered. Strengthening was applied at arch extrados or at arch intrados. The main aims of performed tests were to observe collapse mechanisms and experimentally determine load-carrying capacities of considered structures. Tests results were compared in order to check which strengthening location is more effective option.

2 DESCRIPTION OF TESTED SPECIMENS

This paper reports and discusses the results of experiments performed on three masonry arches: one reference arch without strengthening (AU) and two strengthened arches (ASE, ASI). Two strengthening arrangements were considered – continuous strengthening at the arch extrados (ASE) and continuous strengthening at the arch intrados (ASI). The arches were built of solid clay bricks and lime mortar. The experimental mean compressive strength of bricks was 24.4 N/mm^2 and mean compressive strength of lime mortar was 1.0 N/mm^2. The geometry adopted for arches is illustrated in Figure 1. They were segmental arches characterized by 125-mm thickness, 2000-mm internal span and 730-mm rise.

Two of tested arches – ASE and ASI – were externally strengthened with a composite material known as glass textile reinforced mortar (GTRM). The used TRM solution is commercial alkali-resistant coated glass fiber grid embedded in a polymer cement mortar. The total average thickness of composite strengthening was about 7 mm. Mesh size of the grid was about 25 mm x 25 mm (Figure 2a) and its tensile strength provided by manufacturer was 45 kN/m. Experimental 14-day mean compressive strength of polymer cement mortar was 25.0 N/mm^2. Other properties were presented in [8], [9].

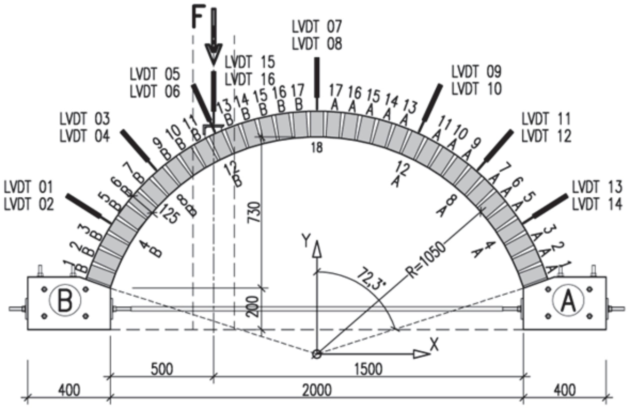

Figure 1: Load and instrumentation arrangements, brick courses numbering (LVDT - displacement transducers)

a) b)

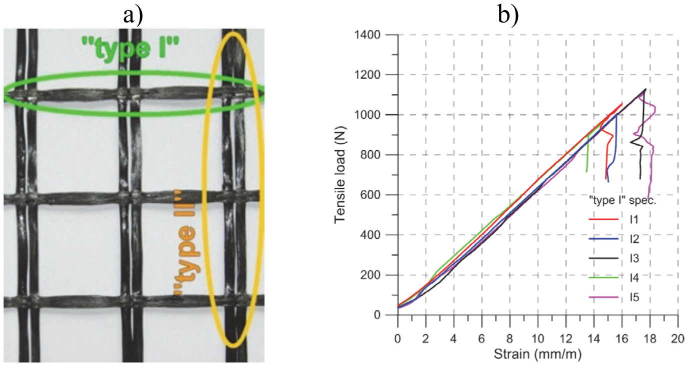

Figure 2: a) Glass grid used in the study – detail; b) Load strain diagrams for "type I" fiber glass strands

The arches were loaded at a quarter span and tested up to failure of the structures. Tests were carried out two weeks after application of the TRM strengthening. During the tests load and radial displacements of arches were measured and recorded. The arrangement of the load cell and displacement transducers is given in Figure 1.

3 TESTS RESULTS

3.1 Unstrengthened arch – AU

Arch AU was tested without strengthening. During the loading process no cracks were observed until the ultimate load was reached. At a load of 4.1 kN tested arch failed by the formation of four-hinged collapse mechanism. The failure occurred suddenly just after reaching the maximum load. The observed collapse mechanism is presented in Figure 3,7a and the load-displacement curve is given in Figure 8a.

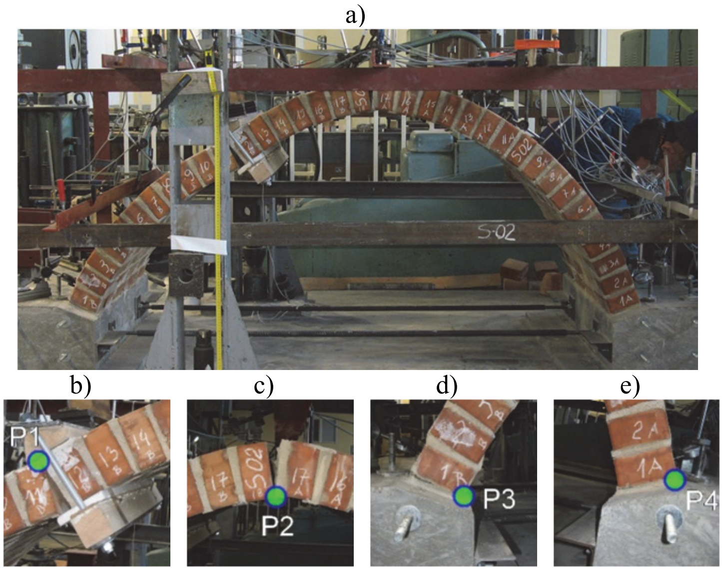

Figure 3: Unstrengthened arch (AU): a) failure mode, b) hinge P1, c) hinge P2, d) hinge P3, e) hinge P4

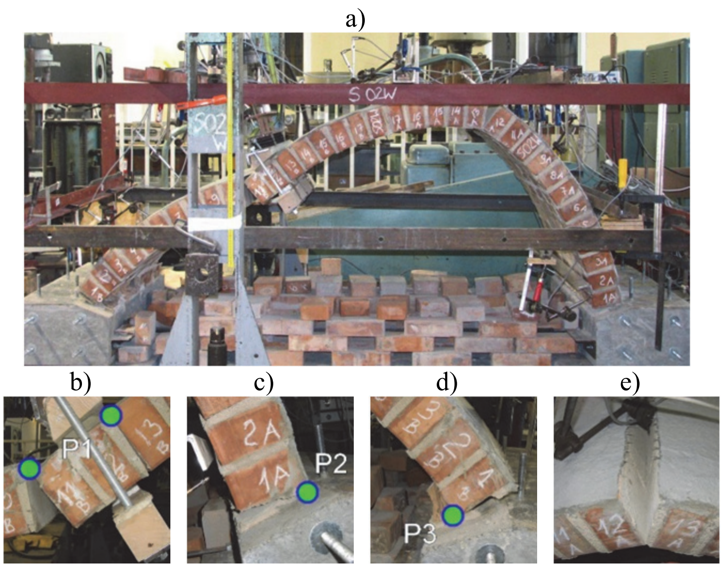

Figure 4: Arch strengthened at the extrados (ASE): a) failure mechanism, b) hinge P1, c) hinge P2, d) hinge P3, e) fourth hinge of failure mode developed

3.2 Arch strengthened at the extrados - ASE

The arch without strengthening (AU) was prevented from collapsing and the initial geometry of arch was restored. Then the strengthening – GTRM material – was applied at the arch extrados. The TRM strengthening was cured for 14 days and then the strengthened arch (ASE) was tested. During the test cracks in joints (mainly at the brick-mortar interface) and in strengthening layer (mainly above joints) were observed. The formation of new cracks in the matrix of composite strengthening caused significant reduction of the stiffness of the arch (see Figure 8a).
Load was progressively applied until it reached the maximum value of 31.0 kN, glass fibers above joint 12A/13A ruptured (Figure 4e) and the arch collapsed. The fourth hinge occurred between 12A and 13A brick courses and the structure turned into mechanism (Figure 4,7b).

3.3 Arch strengthened at the intrados - ASI

The third discussed arch (ASI) was strengthened at its intrados. Prior to strengthening this specimen was tested with backfill until formation of four-hinged mechanism. Before strengthening the initial geometry of arch was restored.
The specimen was tested 14 days after strengthening. In this experiment cracks development between brick courses 10A/11A, 12B/13B, 13B/14B and at the supports were observed. At a load of 22.8 kN glass fibers ruptured and tested specimen collapsed (Figure 5,6,7c).

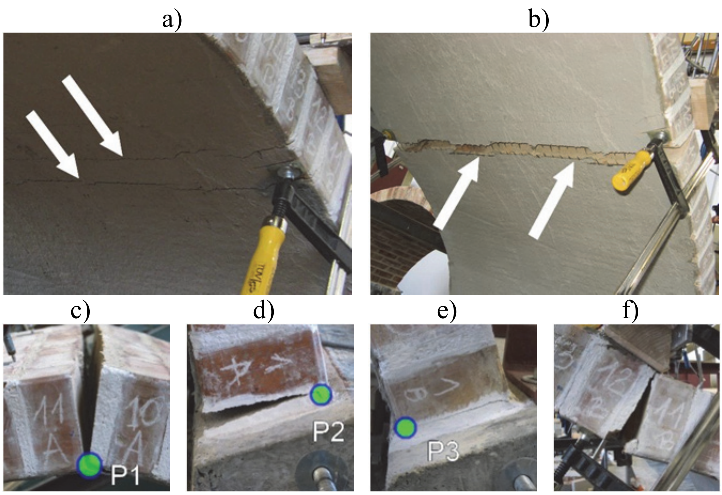

Figure 5: Arch strengthened at the intrados (ASI): a) view of cracks in strengthening, b) view of fourth hinge of collapse mode developed, c) hinge P1, d) hinge P2, e) hinge P3, f) fourth hinge of collapse mode developed

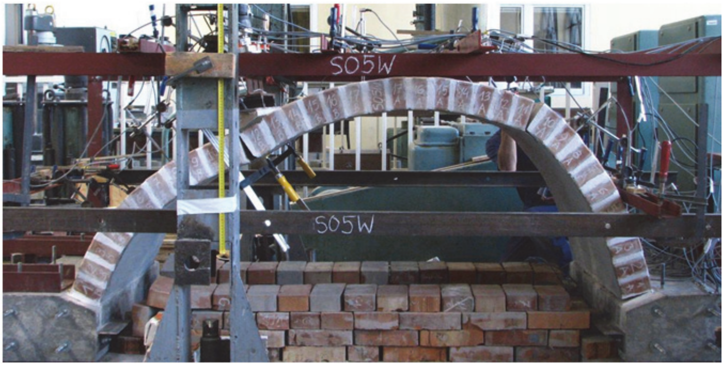

Figure 6: Failure mechanism of arch strengthened at the intrados (ASI)

4 DISCUSSION AND CONCLUSIONS

According to tests results presented above the load-carrying capacity of arches with strengthening were over five times greater than for unstrengthened one (Figure 8). It was precisely 4.1 kN, 31.0 kN and 22.8 kN for specimens AU, ASE and ASI respectively.

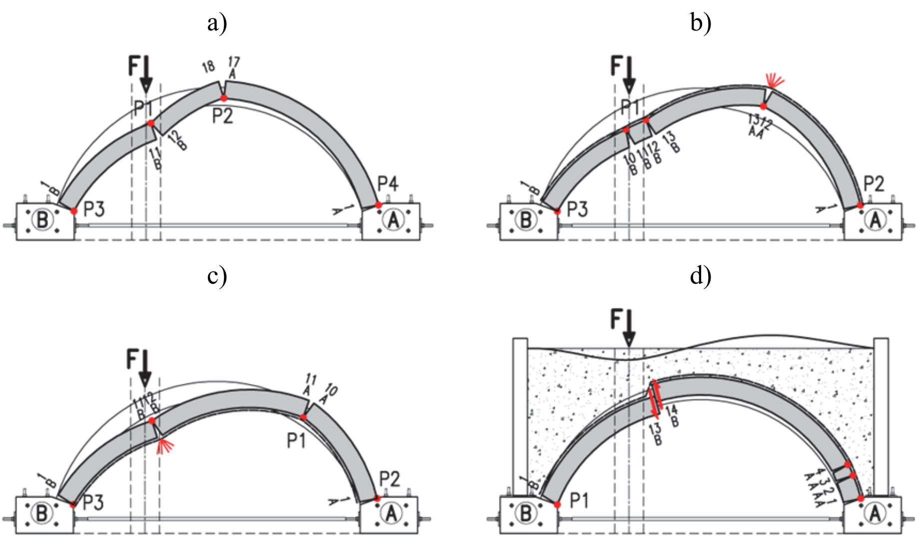

Figure 7: Failure mechanisms: a) specimen AU, b) specimen ASE, c) specimen ASI, d) specimen with backfill, strengthened at the extrados [9]

During the loading of unstrengthened arch no cracks were observed. Specimen AU failed due to formation of four-hinged mechanism. Its collapse took place suddenly, in a brittle manner (see Figure 8a). For the strengthened arches (ASE and ASI) cracks developing in masonry joints and in strengthening layer were observed. In comparison with specimen AU strengthened specimens collapsed in a more ductile manner (see Figure 8a) despite of

sudden rupture of strengthening reinforcement – glass fiber grid. Failure modes observed for tested specimens are illustrated in Figure 7a-c. It is worth mentioning that the most common failure modes that have been identified for FRP-strengthening arches in previous works were masonry sliding and detachment of the strengthening material – for arches strengthened at their extrados or at their intrados respectively [5], [11], [13]. Failure modes observed in presented research for TRM-strengthened arches (tensile rupture of the strengthening) occurred because of relatively small amount of composite reinforcement.
In the case of masonry arch bridges application of strengthening at arch intrados could be preferred because during strengthening application no additional works connected with backfill removal are required. On the other hand in presented research strengthening located at arch extrados turned out to be more effective option in terms of collapse load than strengthening at arch intrados (Figure 8). Similar observations were made for FRP strengthening in [13]. However other researches [5], [11] reported that FRP strengthening located at arch intrados was more effective. In general the load carrying capacity of strengthened arch depends among other things on arch geometry, bond strength of strengthening layer and type and amount of composite. Thus each arch must be analyzed individually taking into consideration these features.

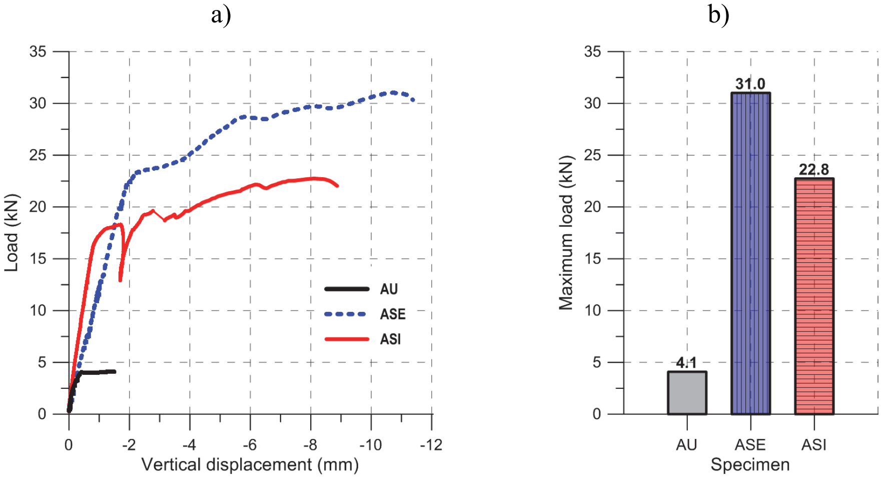

Figure 8: a) Load-displacement curves for tested arches (mean values from LVDT's 15 and 16); b) Collapse loads of tested vaults – summary

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 [9], [10]. The strengthening prevents joint opening at strengthened surface of the arch. Backfill additionally reduces horizontal displacements of buried arch and provides load dispersal. The presence of backfill may change completely observed failure mode – instead of tensile rupture of the strengthening 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 [9] (Figure 7d).

Based on research results presented in this paper, glass grid embedded in polymer cement matrix could be used as an efficient strengthening solution for masonry arches. Decision about strengthening location (intrados, extrados or both) must be taken individually for each case taking into consideration not only mechanical properties of masonry arch and arch geometry but also especially in the case of arch bridges, accessibility of arch surfaces.

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