Łukasz Hojdys[1], Piotr Krajewski[2]

Experimental tests on strengthened and unstrengthened masonry vault with backfill

Badania doświadczalne wzmocnionego i niewzmocnionego sklepienia z zasypką

Keywords: Strengthening, Vault, Arch, Masonry, Backfill, Composite Materials, FRG

Słowa kluczowe: wzmacnianie, sklepienia, łuki, konstrukcje murowe, zasypka, materiały kompozytowe, tynki zbrojone

1. INTRODUCTION

The one of the effects of the progress of civilization and society lifestyle changes is need for adaptation of existing buildings to a new function. Period houses in the market squares are converted into shopping centers, hotels, restaurants, pubs etc. Due to this conversion new loads for buildings must be considered and usually there is a need for strengthening of structural elements e.g. vaults [1, 2].

Nowadays externally-bonded composites are often used for vaults strengthening. Research performed in recent years indicated that fiber reinforced polymer systems [3-6] and systems that use cement-based matrices [7-9] are effective strengthening solutions for vaults. Most of these tests were performed on arches or vaults without backfill. In historic buildings buried vaults are common and it is obvious that vaults are not isolate structural elements but they interact with fill. Previous tests carried out on unstrengthened arches with fill material indicated that the presence of fill material and its properties strongly influence the behavior and load-carrying capacity of vault-soil system [10-13]. Most of these tests were performed on masonry arch bridge models but according to tests presented in [14] similar conclusions can be drawn in case of vaults in historic buildings.

Taking into consideration the facts mentioned above, the question arises whether strengthening systems based on composite materials are an appropriate solution for the vaults with backfill or not. The research presented in this paper was performed in order to observe collapse mechanism and determine load-carrying capacity of buried vault with and without strengthening. The masonry vault with light expanded clay aggregate backfill was tested twice. The element without strengthening was tested first and after application of the strengthening system it was tested again. Tests results were compared in order to check the effectiveness of applied strengthening system in the case of buried vaults.

2. CHARACTERIZATION OF TESTED ELEMENTS

The tested elements consisted of: unstrengthened or strengthened masonry vault supported by reinforced concrete abutments, fill material above the vault, end and side walls surrounding backfill material (Fig. 1, Fig. 2). The vault was built of clay bricks and lime mortar. Thickness, internal span and rise of the vault were 125 mm, 2000 mm and 730 mm respectively (Fig. 1). The width of the specimen was 1040 mm.

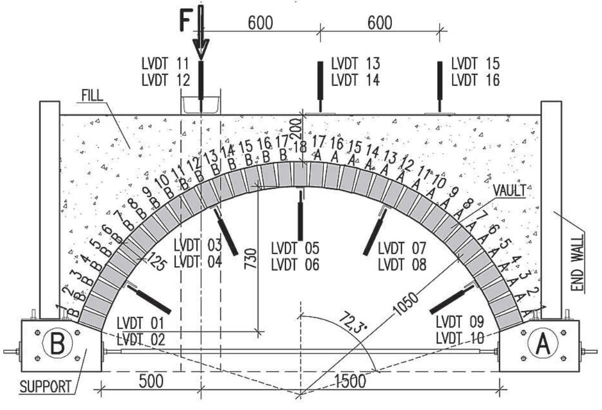


Fig. 1. Geometry of the vault, dimensions in mm. Arrangement of displacement transducers, brick courses numbering

The end walls were made of reinforced concrete whereas side walls were made of OSB or Plexiglas board stiffened with

---

[1] *Ph.D., Cracow University of Technology, Cracow, Poland, lhojdys@pk.edu.pl*
[2] *Ph.D., Cracow University of Technology, Cracow, Poland, pkrajews@pk.edu.pl*

Praca dopuszczona do druku po recenzjach *Article accepted for publishing after reviews*

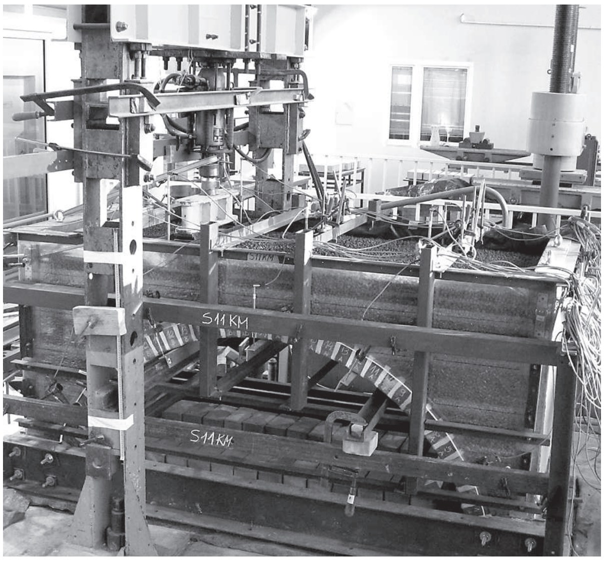


Fig. 2. General arrangement of tested vault – specimen S11KM during the test procedure

steel elements. The side walls were not structural elements so between walls and vault about 15 mm wide gaps were left.

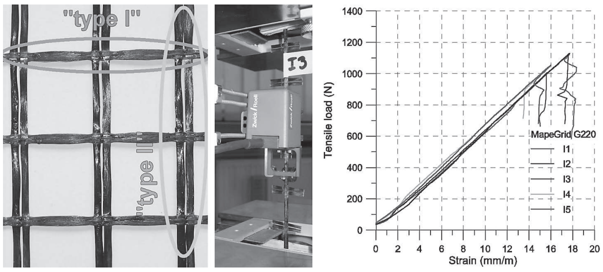
In both tests light expanded clay aggregate was used as the fill material. The particle size ranged from 10 to 20 mm and bulk density was about 300 kg/m3. The fill material was placed and compacted in 200 mm thick layers. The total depth of the fill at the crown was equal to 200 mm. The vault in the second test was externally strengthened with alkali-resistant glass grid (Mepegrid G220) embedded in cement-based matrix (Planitop HDM). Strengthening system was supplied by MAPEI Polska Sp. z o.o. The grid is consisted of longitudinal (type I) and transversal (type II) fiber glass strands connected perpendicularly at about 25 mm spacing (Fig. 3a). In the research both components of strengthening system were tested – type I and type II strands of glass grid (according to PN-EN ISO 527-1) and grout specimens (according to PN-EN 12190). Selected mechanical properties of the matrix and glass fibers are presented in Table 1.

Table 1. Selected mechanical properties of strengthening system components

Material	Flexural strength		Compressive strength		Maximum tensile load*	
	MV (N/mm^2)	CV	MV (N/mm^2)	CV	MV (N)	CV
Planitop HDM after 14 ±1 days	10.5	19%	25.0	11%	–	–
Planitop HDM after 28 ±1 days	12.5	14%	31.8	12%	–	–
Mapegrid G220 “type I” fiber glass strand	–	–	–	–	1102	8%

* from “type I” specimens tests (see Fig. 3b-c)
MV – mean value
CV – coefficient of variation

Tested elements were loaded at a quarter span. The load was applied to the top of the fill material and was increasing continuously until failure. During the tests load, radial displacements of vault and vertical displacements of upper surface of the fill were measured and recorded. The arrangement of the load cell and displacement transducers is given in Fig. 1.



a) b) c)

Fig. 3. Glass grid tensile tests: a) Mapegrid G220 glass grid – detail; b) “type I” glass grid specimen test, c) load-strain diagrams for “type I” fiber glass strands

3. TEST RESULTS

3.1. Unstrengthened vault – S11KM

The unstrengthened vault was the first tested element. During the test apart from measuring loads and displacements development of cracks were observed. The first crack appeared at a load of 7.7 kN between brick courses 13B and 14B. These brick courses were situated beneath loading point. The numbering of brick courses is given in Fig. 1. Next crack appeared between brick courses 12A and 13A at a load of 10.0 kN. At a load equal to 14.5 kN another crack became visible. It was situated between brick courses 13A and 14A. Next two cracks appeared at the extrados of the arch at a load of 16.7 kN. The first one was situated between brick courses 15A and 16A and the second one between brick courses 16A and 17A. At a load of 19.3 kN a new crack appeared at the intrados of the vault between brick courses 3A and 4A. Another two cracks became visible at a load of 21.5 kN. The first one appeared between brick courses 3B and 4B and the second one between brick courses 4B and 5B. At a load of 24.1 kN new cracks at the intrados of the vault were observed. They were situated between brick courses 4A and 5A and 5A and 6A. Finally at a load of 24.7 kN the tested element turned into four hinge collapse mechanism. The hinges P1, P2, P3 and P4 developed between brick courses number 13B and 14B, 15A and 16A, 6A and 7A, 4B and 5B respectively. The collapse mechanism is presented in Fig. 7a and photos of each hinge are given in

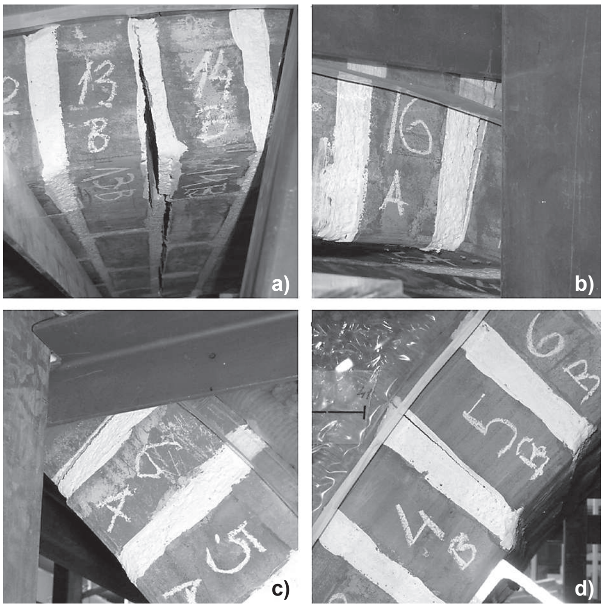


Fig. 4. Hinges of collapse mechanism for element S11KM (see Fig. 7a): a) hinge P1, b) hinge P2, c) hinge P3, d) hinge P4

Fig. 4. Mean displacements which were recorded at a failure load were given in Table 2. These displacement were calculated as an arithmetic mean of two recorded displacements from the transducers situated in the same cross-section of the vault.

Table 2. Displacements of element S11KM at failure load

Measuring point	01-02	03-04	05-06	07-08	09-10	11-12	13-14	15-16
Mean displacement (mm)	-0.74	-6.75	7.33	10.16	0.54	-9.22	11.87	11.68

3.2. Strengthened vault – S11W

After first test the vault without strengthening (S11KM) was prevented from collapse. The backfill was removed and the initial geometry of arch was restored. Then the strengthening was applied at the vault extrados. Alkali-resistant glass grid Mapegrid G220 was embedded in grout Planitop HDM (Fig. 5). The total average thickness of composite strengthening was about 7 mm. Strengthened element was cured for 14 days and then end and side walls were mounted and fill material was placed on the arch. Next displacement transducers and load cell were set in the analogical arrangement as during the first test.

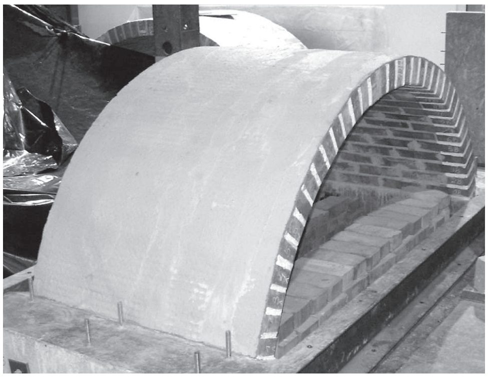


Fig. 5. Specimen S11W (strengthened vault)

During the second test cracks in joints (mainly at the brick-mortar interface) and in strengthening layer (mainly above joints) were observed. The first cracks appeared on intrados between brick courses 13B and 14B (Fig. 6a) and above support "A" at a load of 11 kN and 27 kN respectively. At a load of 41 kN cracks on the vault's extrados were observed. They were situated near the brick courses number 13A and 18 (Fig. 6b). At a load of 55 kN a sliding between brick courses 13B and 14B occurred. In a final stage of the test additional cracks were observed. They appeared above reinforced concrete supports "A" and "B". At a load of 79.95 kN significant increase of displacements at the loading point were observed and then the load started to decrease. The failure of the element S11W was due to sliding between brick courses 13B and 14B at the brick-joint interface (Fig. 6c).

a) b) c)

Fig. 6. Failure mechanisms of specimen S11W: a) first crack observed between 13B and 14B brick courses; b) cracks at extrados in strengthening layer observed after backfill removal; c) sliding along a mortar joint beneath the load application point.

4. DISCUSSION OF RESULTS AND CONCLUSIONS

According to test results presented above the load-carrying capacity of vault with strengthening was almost three times greater than for unstrengthened one. Precisely it was equal 24.69 kN and 70.95 kN for specimens S11KM and S11W respectively. The unstrengthened vault failed due to formation of classical four-hinge mechanism [15]. For the specimen S11W the failure was characterized by a shear sliding which occurred underneath the loading point along bed joint (Fig. 6c). The strengthening prevented joint opening at the extrados (except joints at abutments) and prevented failure due to four-hinge mechanism formation.

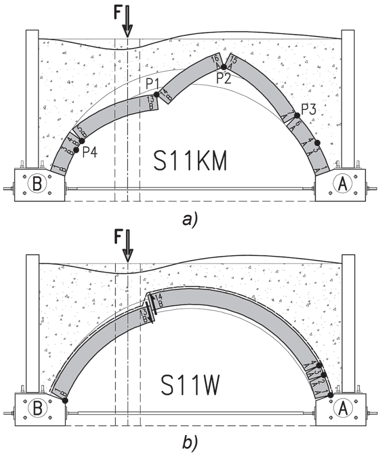


Fig. 7. a) Specimen S11KM – failure mechanism developed; b) Specimen S11W – failure mode observed

The comparison of the load displacement curves for considered vaults is shown in Fig. 8. The presence of the strengthening changed behavior of the buried vault not only in terms of a failure mechanism and load capacity but also in terms of ductility. Despite the fact that test of specimen S11W was interrupted just after reaching the maximum load, large deformation capacity of the strengthened vault prior to the failure is noticeable.

According to reports presented in the literature (i.e. [3] [6]) strengthening at the extrados of isolated masonry vaulted structures using composite systems is effective. Based on research results presented in this paper, glass grid embedded in cement-base matrix could be used as an efficient strengthening solution for buried vault.

It is worth mentioning that applying strengthening at the extrados of buried vault is favorable in the fire situation especially in case of FRP and TRM systems. Fill material placed above

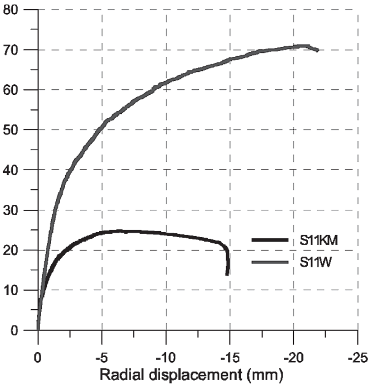


Fig. 8. Radial load-displacement diagrams for tested vault (S11KM – before strengthening; S11W strengthened specimen)

strengthening make additional thermal insulation. This is crucial when mechanical resistance (R) in the case of fire is required.

In many cases strengthening solutions based on composite materials could be more effective than traditional strengthening methods. Application of glass grids embedded in a cement-base grout allows to provide adequate load-carrying capacity of vault, reducing application costs and ensuring esthetic appearance.

ACKNOWLEDGEMENTS

Materials of strengthening system were supplied free of charge by Mapei Polska Sp. z o.o. The work was developed at Cracow University of Technology, Poland. The authors gratefully acknowledge Prof. Z. Janowski for his support and guidance throughout this work.

REFERENCES

[1] Janowski Z. (2001) Diagnostyka, naprawy i rekonstrukcje obiektów murowych. In: *XX Konferencja Naukowo-Techniczna Awarie Budowlane*, 205-234.

[2] Janowski Z., Janowski M. (2009) Problemy projektowe związane z adaptacją budynków zabytkowych na cele użyteczności publicznej. *Czasopismo Techniczne*, vol. 2-B, 139-150.

[3] Valluzzi M.R., Valdemarca M., Modena C. (2001) Behavior of brick masonry vaults strengthened by FRP laminates. *Journal of Composites for Construction*, vol. 5, no. 3, 163-169.

[4] Foraboschi P. (2004) Strengthening of masonry arches with Fiber-Reinforced Polymer strips. *Journal of Composites for Construction*, vol. 8, no. 3, 191-202.

[5] Briccoli Bati S., Rovero S., Tonietti U. (2007) Strengthening masonry arches with composite materials. *Journal of Composites for Construction*, vol. 11, no. 1, 33-41.

[6] Oliveira D., Basilio I., Lourenco P. (2010) Experimental Behavior of FRP Strengthened Masonry Arches. *Journal of Composites for Construction*, vol. 14, no. 3, 312-322.

[7] Borri A., Casadei P., Castori G., Ebaugh S. (2007) Experimental analysis of masonry arches strengthened by innovative composite laminates. In: *10th North American Masonry Conference*

[8] Bednarz Ł., Górski A., Jasieńko J., Rusiński E. (2011) Simulations and analyses of arched brick structures. *Automation in Construction*, vol. 20, 741-754.

[9] Hojdys Ł. (2010) Wpływ wzmocnienia materiałami kompozytowymi sklepień murowych na ich nośność [in Polish] (The influence of strengthening with fibre reinforced composites on load bearing capacity of masonry vaults). Ph.D. thesis, Cracow University of Technology.

[10] Royles R., Hendry A.W. (1991) Model tests on masonry arches. *Proceedings of the Institution of Civil Engineers. Part 2. Research and Theory*., vol. 91, 299-321.

[11] Fairfield C.A., Ponniah D. (1994) Model tests to determine the effect of fill on buried arches, Proceedings of the Institution of Civil Engineers. *Structures and Buildings*, vol. 104, 471-482.

[12] Hughes T.G., Davies M.C.R., Taunton P.R. (1998) The influence of soil and masonry type on the strength of masonry arch bridges. In: *Arch Bridges. History, analysis, assessment, maintenance and repair*, 321–330, A.A. Balkema Rotterdam Brookfield.

[13] Gilbert M., Smith F.W., Wang J., Callaway P.A., Melbourne C. (2007) Small and large-scale experimental studies of soil-arch interaction in masonry bridges. In: *5th International Conference on Arch Bridges ARCH'07*, 381-388.

[14] Krajewski P. (2010) Analiza wpływu materiału zasypowego na nośność sklepień murowych [in Polish] (Analysis of the backfill material influence on load carrying capacity of masonry vaults). Ph.D. thesis, Cracow University of Technology.

[15] Page J. (1993) Masonry arch bridges. HMSO.

Abstract

This paper presents the results of two experimental tests on masonry barrel vault with fill material. The vault was built of clay bricks and lime mortar. Thickness, internal span and rise of the vaults were 125 mm, 2000 mm and 730 mm respectively. Light expanded clay aggregate was used as a fill material. The fill depth at the crown was 200 mm. The first test was performed on unstrengthened vault. In this case the main aims were to determine load-carrying capacity and examine the collapse mechanism of vault with backfill. In order to perform the second test the arch used in the first test was strengthened externally and tested again. The aims of this test was to determine load-carrying capacity and examine the general behavior of strengthened barrel vaults with fill material. Results of both tests were compared. The presence of strengthening influenced on load-carrying capacity and ductility of the vault. The strengthened element had higher failure load and was more ductile then vault without strengthening.

Streszczenie

W artykule przedstawiono wyniki badań eksperymentalnych sklepień z pachami wypełnionymi materiałem zasypowym. Elementy murowano z ceramicznej cegły pełnej na zaprawie wapiennej a zasypkę wykonano z keramzytu. Badania przeprowadzono na pasmach sklepień walcowych rozpiętości w świetle podpór wynoszącej 2000 mm, grubości 125 mm i strzałce 730 mm. Sklepienia obciążano w 1/4 rozpiętości aż zniszczenia rejestrując deformacje i poziom siły niszczącej. W pierwszym badaniu testowano sklepienie bez wzmocnienia wyznaczając jego nośność oraz identyfikując mechanizm zniszczenia. Po badaniu sklepienie wzmocniono powierzchniowo siatką z włókien szklanych i ponownie poddano testom. Celem badania było wyznaczenie obciążenia niszczącego oraz poznanie pracy sklepienia wzmocnionego z zasypką. Sklepienie wzmocnione charakteryzowało się większą nośnością i większą zdolnością do deformacji pod obciążeniem niż przed wzmocnieniem.