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LABORATORY TESTS ON MASONRY VAULTS STRENGTHENED AT THE EXTRADOS

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Abstract. *Research done in recent years showed that fiber-reinforced polymers and textile-reinforced mortars are effective strengthening solutions for masonry structures. The use of externally bonded composites has become a more popular technique for strengthening historic masonry vaults and arches. Strengthening may be applied at lower, upper or both vault surfaces. The reasonable location of composite strengthening depends on the geometry of the vault and on possible loads, but also on the condition of the vault and the way of finishing its intrados. When a historic vault with frescoes or plasterwork is analyzed and needs to be strengthened, the only option for strengthening with composite materials is strengthening applied at the vault extrados.*

This paper deals with the experimental behavior of masonry vaults strengthened externally with a composite material. The thickness, internal span and rise of the vaults were 120 mm, 2000 mm and 730 mm, respectively. Masonry was made of solid clay bricks and lime mortar. The vaults were tested under a monotonic vertical load applied at a quarter span. An alkali-resistant coated glass fiber grid embedded in a cement-based matrix was used as the strengthening. The tensile strength of the glass grid specified by the manufacturer was about 45kN/m. All of the tested vaults were strengthened continuously at their extrados. Both ends of the strengthening above the abutments were either bonded to the masonry or anchored mechanically using steel plates to the concrete abutments.

The main aim of the presented research was to determine the load-carrying capacity and to examine the failure modes of the tested specimens. All of the tested specimens failed due to fibers rupture. The strengthening system used in the presented research turned out to be an effective strengthening solution for masonry barrel vaults with frescoes or plasterwork.

1 INTRODUCTION

The use of externally bonded composites for strengthening masonry structures has been widely investigated in recent years. Carbon, glass, basalt or steel fiber reinforced composites improve the masonry flexural capacity and can successfully be used to strengthen masonry structures. The effectiveness of such a strengthening method was confirmed in many laboratory tests that were carried out on masonry arches and vaults strengthened with both fiber-reinforced polymers (FRP) [1, 2, 3, 4] or cement-based composites (Textile Reinforced Mortar – TRM, Fiber Reinforced Cementitious Matrix – FRCM) [3, 6, 7, 8]. Strengthening applied at upper [1, 2, 4, 5, 7, 9], lower [1, 2, 4, 5, 10] or both surfaces [5, 6] of the arch/vault significantly increases the load-bearing capacity and changes observed collapse mechanism of the structure.

Deciding on the location of the strengthening on historical vaulted structures depends not only on the geometry of the vault, the estimated loads and the technical condition of the structure, but also on the way of finishing its intrados. When a historic vault with frescoes or plasterwork is analyzed, locating the strengthening at the lower surface of the vault is usually not permitted from the point of view of architects and historians, and the only option is strengthening at the vault extrados. In this paper such vaults were taken under consideration.

Research studies on vaults strengthened with glass or carbon grids were carried out in the last few years at the Cracow University of Technology in order to make recommendations for strengthening masonry vaults with composites. Barrel vaults of a geometry similar to the geometry of typical vaults that can be found in historic buildings in Cracow's Old Town were considered. This paper deals with the results of tests conducted on vaults strengthened continuously at their extrados with glass fibers. The main goal of the present study was to check the effectiveness of the strengthening method and to examine if fixing the ends of the strengthening grid to the vault's supports affects the behavior and load-bearing capacity of the vault.

2 TESTING PROCEDURE

The tested barrel vaults were characterized by 125 mm thickness, a 2000 mm internal span, a 730 mm rise and a 1040 mm width (Fig. 1a). The masonry was made of solid clay bricks (250x125x65 mm^3) and pre-mixed lime mortar. The vaults were strengthened with a glass fiber grid, Fig. 2a (with a width of about 91 cm), embedded in a polymer-cement mortar – this strengthening system is also known as the textile reinforced mortar system (TRM) [10, 11, 12]. Selected mechanical properties of the materials used in the tests are presented in Table 1.

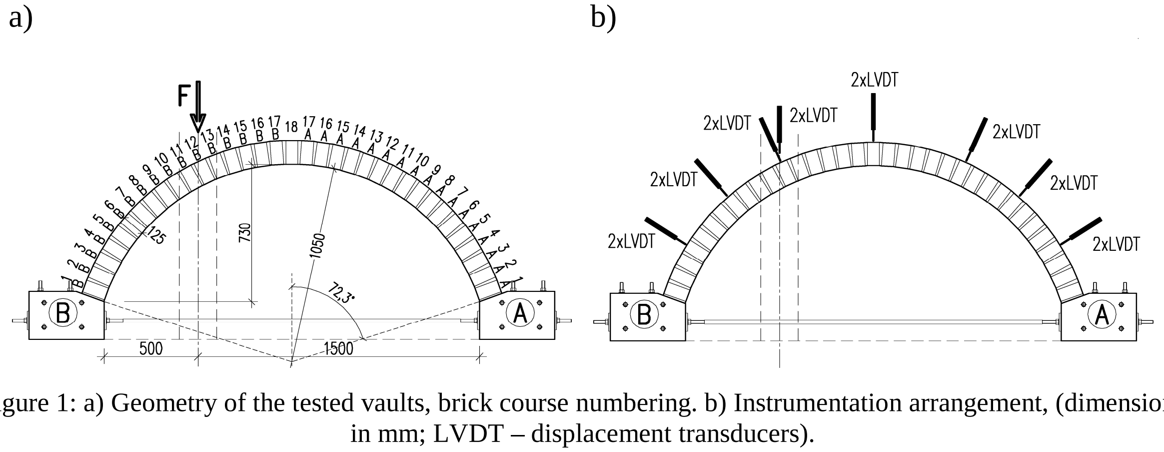

Figure 1: a) Geometry of the tested vaults, brick course numbering. b) Instrumentation arrangement, (dimensions in mm; LVDT – displacement transducers).

All of the tested specimens were strengthened at their extrados. The strengthening was applied continuously between the first brick courses above the supports (from 1A to 1B – see Fig. 1a). The ends of the glass fiber grid were not connected to the concrete supports – only bonded to the masonry of brick courses 1A and 1B (specimens VG1, VG2 – Fig. 3, VG3) or anchored mechanically to the supports using steel plates, Fig. 2b-c (specimen VG-An – Fig. 4). Before strengthening, vaults VG1, VG2 and VG-An were tested as non-strengthened vaults up to the formation of a four-hinge mechanism [10, 13]. Then the initial geometry of the vaults was restored and they were strengthened with TRM.

a) b) c)

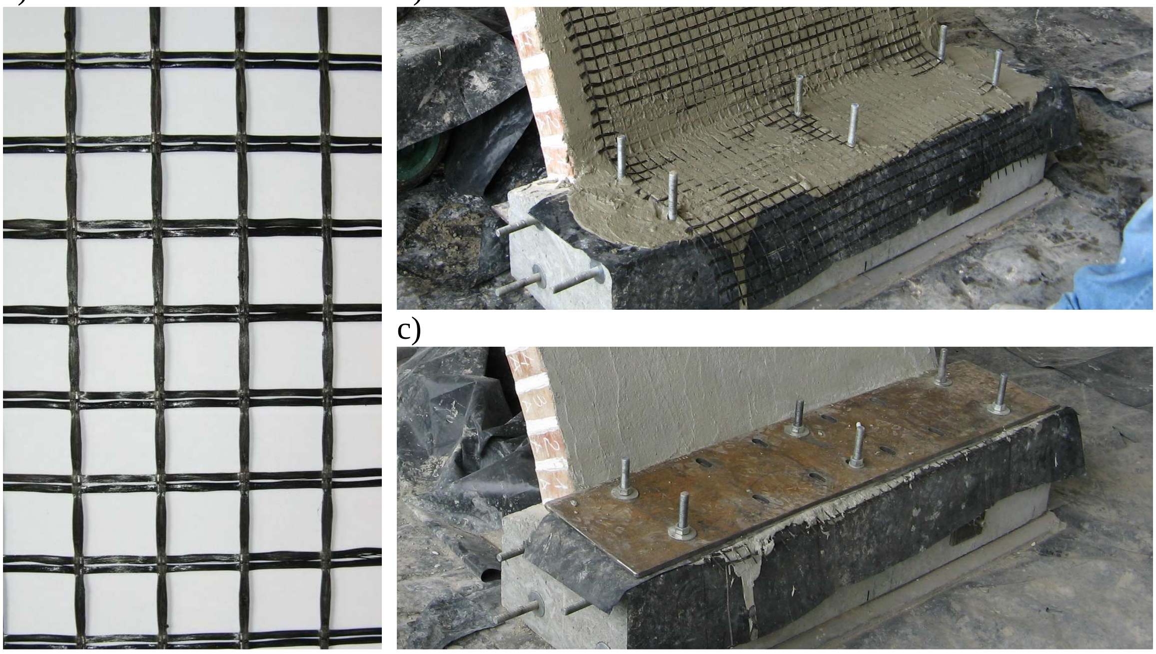

Figure 2: a) Glass fiber grid used in the study – detail. b) Glass fiber grid arrangement above the abutment – during application of the strengthening – vault VG-An. c) View of the strengthening's anchorage on the abutment of vault VG-An.

Tests were carried out 14 days after strengthening under a monotonic vertical load applied at a quarter span to the top of the vaults' extrados. The load increased until failure of the vaults took place. During the tests load, both radial and vertical displacement of the vault were measured. The test setup and instrumentation arrangement are presented in Fig. 1 [7, 10].

Table 1: Selected mechanical properties of materials used in the tests.

Clay brick	
- compressive strength (N/mm^2)	24.4
Lime mortar at 28 days	
- compressive strength (N/mm^2)	1.1
Cement-polymer mortar	
- compressive strength at 14 days (N/mm^2)	25.0
- compressive strength at 28 days (N/mm^2)	31.8
- bond strength by pull-off (to concrete) (N/mm^2)	>2.4
Glass fiber grid	
- tensile strength /specified by manufacturer/ (N/mm)	45

3 TEST RESULTS

3.1 Specimens VG1, VG2, VG3

Observations conducted during tests of vaults strengthened with glass grids not connected to the abutments were similar. In the initial stage of the experiments (at a load of 7-9 kN), cracks appeared under the point of loading on the intrados. At a load of 22-23 kN the first cracks in the strengthening layer were observed, which resulted in a considerable reduction of the stiffness of the vaults (Fig. 5a). As the load was increasing, further cracks on the extrados (in the strengthening above the mortar joints between brick courses 8A and 18) appeared. In the final stage of the tests, cracks in the mortar joints under brick courses 1A and 1B occurred.

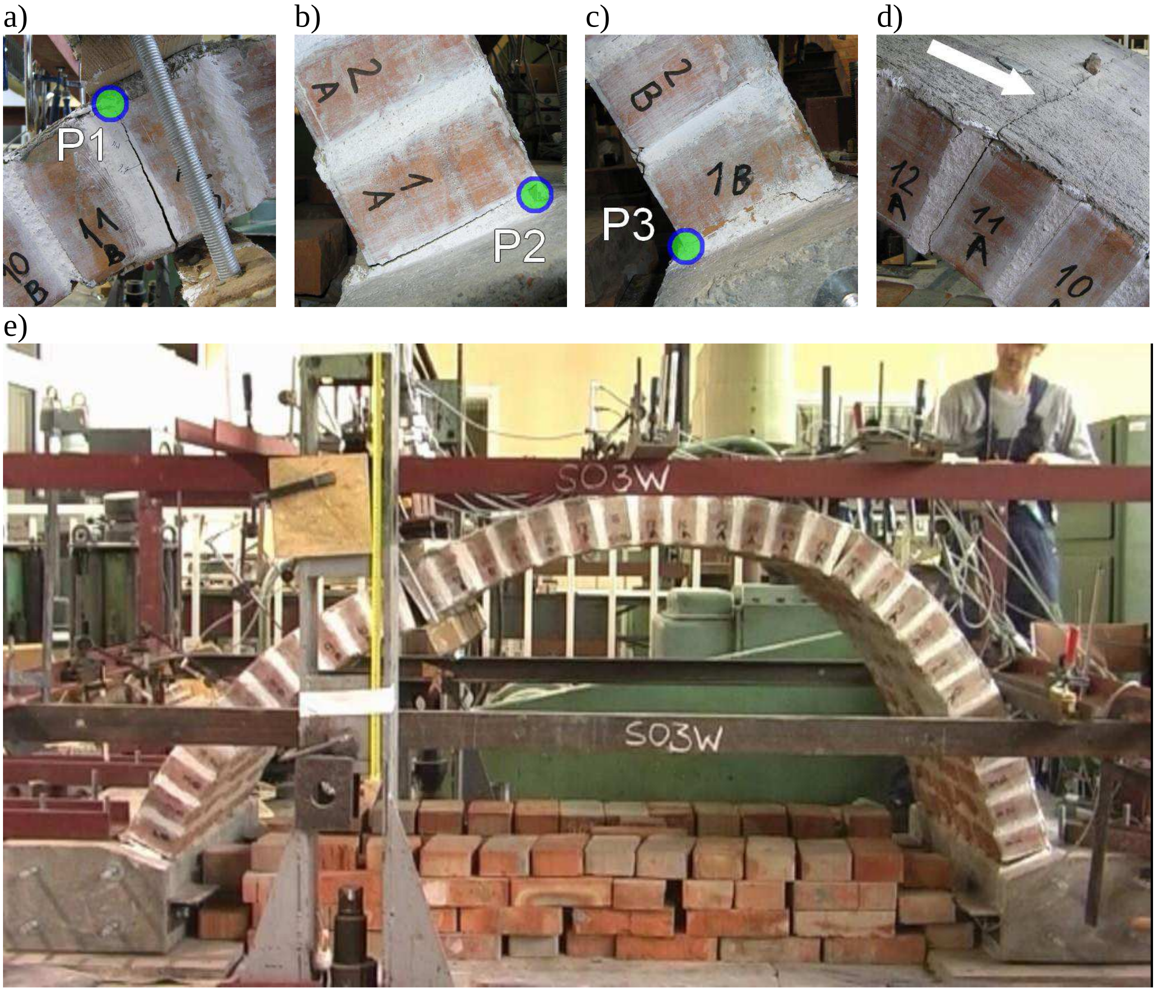

Figure 3: Vault VG2 (originally named S03W): a)-c) cracks and hinges developed, d) crack at the extrados – ruptured glass fibers, e) failure mechanism.

Finally, the composite (strengthening layer) near brick course 12A exceeded its tensile strength and the vaults collapsed. The maximum loads noted during the tests were 31.0 kN, 28.2 kN and 34.0 kN for vaults VG1, VG2 and VG3, respectively. The typical failure mechanism observed during these tests is shown in Fig. 3 and Fig. 6a.

3.2 Specimen VG-An

Similarly as in tests on vaults VG1-VG3, the first crack appeared on the intrados under the point of loading. Afterwards, at a load of 23-30 kN, cracks developed at the vault's extrados in the strengthening layer and at the intrados between the first brick course and abutment A. In the final stage of the test (when the load exceeded 30 kN), cracks were observed in the strengthening layer above abutment B and several other cracks were observed at the extrados between brick courses 9A and 15A.

a) b) c) d)

Figure 4: Vault VG-An (originally named S04W): a)-d) cracks and hinges of the collapse mode, e) failure mechanism.

Finally, at a load of 31.4 kN, glass fibers between brick courses 12A and 13A ruptured, then the fibers connected to abutment B ruptured (near brick course 1B) and the vault collapsed. Initially, the structure of the vault consisted of two masonry curved bars connected together by means of a "hinge" (at the extrados under the point of loading) with hinged support above abutment A and fixed support above abutment B. The structure was a stable one. After the formation of the third "hinge" at the intrados of the vault – after rupture of the strengthening between brick courses 12A and 13A – the vault changed to a three-hinged vault/frame (still stable). Immediately after the third hinge formation the fibers above support B ruptured and the structure changed to a mechanism. This happened suddenly because the actuator was load-controlled (load-controlled test) and the load-bearing capacity of the three-hinged structure (with "hinges" between brick courses 12B/13B, 12A/13A and above support A) was lower than before.

4 DISCUSSION AND CONCLUSIONS

When comparing the results of the tests presented above with the test performed on non-strengthened vaults, discussed among others in [7, 10, 13], it must be noted that the adopted strengthening system is an effective solution for masonry vaults and arches (Fig. 5b). Vaults without strengthening loaded at a quarter span typically failed due to the formation of the four-hinge mechanism [10, 13] at a load of about 4.5 kN. Continuous strengthening at the extrados of the vault prevented the formation of hinges at the vault's intrados and prevented (until the glass fibers ruptured) failure due to the four-hinge mechanism formation [4]. Therefore, the load-carrying capacity of the strengthened vaults increased to more than 28 kN (Fig. 5b).

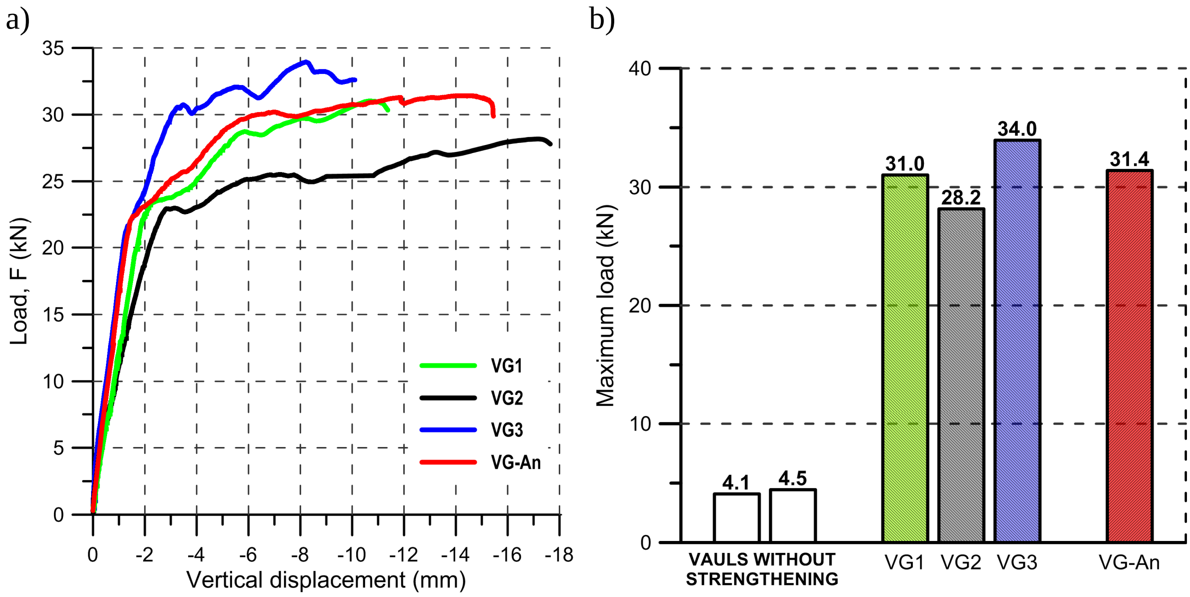

Figure 5: a) Load – vertical displacement (at the point of loading) curves for the tested vaults. b) Maximum loads for the tested vaults – summary.

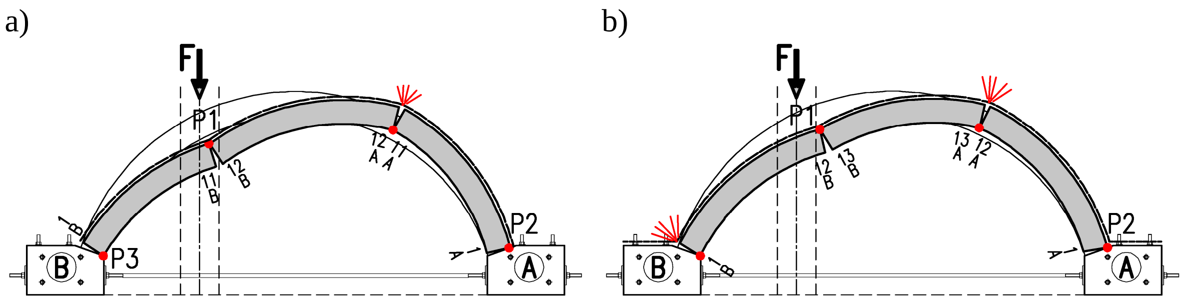

Figure 6: Failure mechanisms observed during the tests: a) vault VG2, b) vault VG-An.

The strengthening of vaults as discussed here was treated above the abutments in two different ways. The strengthening of vaults VG1-VG3 was applied continuously between the first brick courses and was not connected to the abutments. Thus hinges could freely develop between brick courses 1A or 1B and the abutments. The vaults collapsed due to fibers rupture. In the case of vault VG-An, the strengthening was anchored to the supports. Consequently, during the test the anchorage (Fig. 2b-c) resisted the possible negative bending moment at support B, prevented rotation of the vault (around abutment B) and prevented sliding (along abutment A). It can be concluded that vault VG-An collapsed due to glass fibers rupture between brick courses 12A and 13A and an almost simultaneous rupture of the fibers connected to support B. It was not possible to determine the load-bearing capacity of vault VG-An after rupture of fibers 12A/13A and just before rupture of the fibers above support B because the test was load-controlled. There was no significant increase in the load-bearing capacity of vault VG-An as compared to vaults VG1 and VG2 (Fig. 5b) – these three vaults were tested before strengthening. The anchorage of the strengthening at the abutments had a negligible effect on the obtained failure loads and the observed collapse mechanisms (Fig. 6).

During the tests, higher stiffness of vault VG-An as compared to vaults VG1 and VG2 was observed in the first stage of the tests (before the first crack in the strengthening layer occurred). As cracks at the extrados appeared, a clear reduction of all of the tested vaults' stiffness was observed (Fig. 5a). It should be noted that the first cracks in the strengthening layer appeared at a load of about 23 kN for all of the tested vaults (Fig. 5a).

Although the tests presented here were carried out on a limited number of vaults, the results show that continuous strengthening with TRM materials at the extrados should be considered during restoration works performed on masonry vaults, especially in the case of vaults with frescoes or plasterwork.

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REFERENCES

[1] M.R. Valluzzi, M. Valdemarca, C. Modena, Behavior of brick masonry vaults strengthened by FRP laminates, *Journal of Composites for Construction*, **5(3)**, 163-169, 2001.

[2] P. Foraboschi, Strengthening of masonry arches with Fiber-Reinforced Polymer strips, *Journal of Composites for Construction*, **8(3)**, 191-202, 2004.

[3] S. Briccoli Bati, S. Rovero, U. Tonietti, Strengthening masonry arches with composite materials, *Journal of Composites for Construction*, **11(1)**, 33-41, 2007.

[4] D. Oliveira, I. Basilio, P. Lourenco, Experimental Behavior of FRP Strengthened Masonry Arches, *Journal of Composites for Construction*, **14(3)**, 312-322, 2010.

[5] A. Borri, P. Casadei, G. Castori, J. Hammond: Strengthening of brick masonry arches with externally bonded steel reinforced composites, *Journal of Composites for Construction*, **13(6)**, 468-475, 2009.

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

[7] Ł. Hojdys, Z. Janowski: Strengthening of masonry vaults with glass grids (in polish), *Technical Transactions*, **3-B**, 71-91, 2011.

[8] L. Garmendia, P. Larrinaga, D. García and I. Marcos: Textile-reinforced mortar as strengthening material for masonry arches, *International Journal of Architectural Heritage*, **8(5)**, 627-648, 2014.

[9] L. Garmendia, J.T. San-José, D. García, P. Larrinaga, Rehabilitation of masonry arches with compatible advanced composite material, *Construction and Building Materials,* **25**, 4374-4385, 2011.

[10] Ł. Hojdys, P. Krajewski, Behavior of masonry arches strengthened with TRM, *7th International Conference on Arch Bridges (ARCH'13)*, 739-746, 2013.

[11] Ł. Hojdys, P. Krajewski, Experimental tests on strengthened and unstrengthened masonry vault with backfill, *8th International Conference on Structural Analysis of Historical Constructions (SAHC 2012)*, 668-674, 2012.

[12] Ł. Hojdys, P. Krajewski, Experimental tests on strengthened masonry vaults, *Applied Mechanics and Materials*, **578-579**, 1396-1399, 2014.

[13] P. Krajewski, Ł. Hojdys, Experimental studies on buried barrel vaults, International Journal of Architectural Heritage, DOI:10.1080/15583058.2013.860499 (in press).