BURIED VAULTS WITH DIFFERENT TYPES OF EXTRADOS FINISHES – EXPERIMENTAL TESTS

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Keywords: Arch, Vault, Masonry, Backfill, Vault-fill interaction.

Abstract. Buried vaults are common in basements and on the ground floors of masonry historic buildings where infill is used to obtain a flat floor. During renovation works the fill material should be removed. The removal of backfill allows for proper assessment of the vault’s technical condition. After repairing or required strengthening, the backfill should be returned to the vault extrados because, as previous experimental studies have shown, the presence of backfill affects the behavior and load-carrying capacity of masonry vaults.

This paper presents the results of experimental tests on models of masonry barrel vaults with a lightweight fill material. Particular emphasis was placed on the influence of the finishing method of the vault extrados on the behavior of masonry vaults. Experimental tests were performed on three vaults built of clay brick and lime mortar. The thickness, internal span and rise of the vaults were 125 mm, 2000 mm and 730 mm, respectively. During the experiments, three types of extrados finishes were investigated: brickwork with flush joints, one layer of PVC film or steel angles bolted to the masonry vault parallel to the bed joints. In all of the tests, expanded clay aggregate was used as a fill material. The fill depth at the crown was 200 mm. The vaults were tested under monotonic vertical load applied at a quarter span.

The main aim of the study was to determine the load-carrying capacity and to examine the general behavior of buried barrel vaults with different extrados finishes. The results of the experiments showed that the type of vault extrados finish affected the behavior and load-carrying capacity of the tested specimens.
1 INTRODUCTION

Buried vaults are common in basements and on the ground floors of masonry historic buildings where infill is used to obtain a flat floor. During renovation works the fill material should be removed. The removal of backfill allows for proper assessment of the vault’s technical condition. After repairing or required strengthening, the backfill should be returned to the vault extrados.

Research carried out in recent years showed that the behavior and load-carrying capacity of buried vaults and arches depends on the properties of the infill material that is present on the vault extrados [1,2,3,4,5,6,7]. Most of these tests were carried out on laboratory models of masonry arch bridges, yet, despite the existing structural differences, some conclusions may also be correct for buried vaults in residential buildings [7]. Previous studies mainly dealt with the influence of infill material properties (e.g. bulk density, angle of internal friction, cohesion etc.) on the behavior of vaults/arches, thus they did not focus on the influence of the infill-vault interface’s properties. The properties of the interface may be modified, e.g. during structural strengthening or other renovation works, by application of new layers on the vault extrados [8,9,10,11].

This paper presents the results of experimental tests on three models of masonry barrel vaults with a lightweight fill material. Particular emphasis was placed on the influence of the finishing method of the vault extrados on the behavior of the masonry vault. During this study, three types of vault extrados finishes were considered. The main goal of the study was to determine the load-carrying capacity and to examine the general behavior of buried barrel vaults with different extrados finishes.

2 MATERIALS, GEOMETRY AND TESTING PROCEDURE

The tests presented in this paper were performed on three vaults built of clay brick and lime mortar. The thickness, internal span and rise of the vaults were 125 mm, 2000 mm and 730 mm, respectively (Fig. 1). The width of the specimen was 1040 mm. The masonry vaults were supported by reinforced concrete abutments connected with steel rods and channel beams C260. During the experiments, three types of extrados finishes were investigated: brickwork with flush joints, one layer of PVC film or steel angles bolted to the masonry vault parallel to the bed joints (Fig. 2).

![Figure 1: Geometry of the tested specimens (dimensions in mm), brick course numbering](image-url)
Figure 2: Tested vaults – finishes of the extrados – details: a) brickwork with flush joints – specimen SKM, b) one layer of PVC film – specimen SKF, c) steel angles bolted to the vault – specimen SKK.

Figure 3: a) Load and instrumentation arrangements (dimensions in mm), b) General view of the tested specimen - SKM.

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

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay brick</td>
<td>Compressive strength [N/mm²]</td>
<td>21.4</td>
</tr>
<tr>
<td>Lime mortar at 28 days</td>
<td>Compressive strength [N/mm²]</td>
<td>1.1</td>
</tr>
<tr>
<td>Expanded Clay Aggregate</td>
<td>Bulk density [kg/m³]</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td>Aggregate size [mm]</td>
<td>10/20</td>
</tr>
<tr>
<td></td>
<td>Angle of internal friction [°]</td>
<td>37</td>
</tr>
</tbody>
</table>

In all of the tests, expanded clay aggregate (ECA) was used as a backfill. The fill material was placed and compacted in 200 mm layers up to 200 mm above the crown. In order to prevent the backfill from escaping, reinforced concrete end walls and plexiglass/OSB side walls
stiffened by steel beams were used. The reinforced concrete end walls additionally substituted the building walls. Selected properties of the materials used in the study are presented in Table 1.

All vaults were tested up to failure under a monotonic vertical load. The load was applied at a quarter span, through a 20 cm wide steel loading beam, to the top of the fill material. Load, radial and vertical displacements of the vaults were measured during the tests. Additionally, development of cracks in the masonry was observed. Details of the test setup are presented in Fig. 3 and were also discussed in [7,9,12].

3 TEST RESULTS

3.1 Specimen SKM

During the first test, cracks mainly at the brick and mortar joint interface were observed. The first crack appeared at a load of 7.7 kN on the intrados, under the point of loading, between brick courses 13B and 14B.

Figure 4: Vault SKM (originally named S11KM): a)-d) hinges of the failure mechanism, e) view of the specimen after the test.
The 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 developed. It was situated between brick courses 13A and 14A. The next two cracks appeared on the extrados of the vault at a load of 16.7 kN. The first crack was situated between brick courses 15A and 16A and the second crack was between brick courses 16A and 17A. At a load of 19.3 kN a new crack appeared on the intrados of the vault between brick courses 3A and 4A. Another two cracks developed at a load of 21.5 kN. The first crack appeared between brick courses 3B and 4B and the second crack between brick courses 4B and 5B. At a load of 24.1 kN subsequent cracks on 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 failed due to the formation of the four-hinge collapse mechanism. Hinges P1, P2, P3 and P4 developed between brick courses number 13B and 14B, 15A and 16A, 6A and 7A, 4B and 5B, respectively, which divided the vault into five segments (Fig. 4, Fig. 7a). More details are given in [7,9].

3.2 Specimen SKF

The second test was performed on a specimen with a PVC film layer on its extrados. Similarly as in the first test, cracks were observed mainly at the brick and mortar joint interface.

![Figure 5: Vault SKF (originally named S05KF): a)-d) hinges of the failure mechanism, e) view of the specimen after the test.](image-url)
The first crack appeared at a load of 9.6 kN. It developed on the vault intrados under the point of loading between brick courses 12B and 13B. The next crack appeared on the vault extrados between brick courses 14A and 15A at a load of 11.1 kN. Another crack then developed at a load of 15.2 kN on the specimen intrados between brick courses 3A and 4A.

When the load was increased to 19.4 kN, a crack on the vault extrados between brick courses 4B and 5B developed. The tested specimen failed due to the formation of a four-hinge mechanism at a load of 22.7 kN. The observed collapse mechanism is presented in Fig. 5 and Fig. 6b. The hinges developed between brick courses: 12B and 13B – hinge P1, 14A and 15A – hinge P2, 3A and 4A – hinge P3, and 4B and 5B – hinge P4. They divided the tested specimen into five parts – similarly as in the test on specimen SKM.

3.3 Specimen SKK

The third test was carried out on a vault with steel angles bolted to its extrados. During this test some similarities were noticed in specimen behavior with the previously tested specimens. All of the observed cracks developed at the brick-mortar joint interface; the first crack appeared under loading point and the specimen failed due to the formation of the four-hinge mechanism.

![Figure 6: Vault SKK (originally named S06KK): a)-d) hinges of the failure mechanism e) view of the specimen after the test.](image-url)
The first crack appeared at a load of 10.4 kN between brick courses 11B and 12B. The next crack was noticed at a load of 10.7 kN. It was located between brick courses 13A and 14A. At a load of 13.9 kN, near the first crack, another crack was observed between brick courses 12B and 13B. It developed on the vault intrados. Subsequent cracks appeared at a load of 22 kN on specimen extrados and intrados between brick courses 4A/5A and 4B/5B, respectively. At a load of 26.5 kN a crack developed on the vault extrados between brick courses 15A and 16A. Finally, at a load of 36.3 kN the tested vault collapsed. At the collapse load, new cracks developed between brick courses 6A/7A and 3B/4B. The final failure mechanism is presented in Fig. 6 and Fig. 7c. Hinges P1, P2, P3 and P4 developed between brick courses: 11B/12B and 12B/13B – P1, 15A/16A – P2, 6A/7A – P3, 3B/4B, and 4B/5B – P4. In contrast to the previous tests (specimens SKM and SKF), hinges P1 and P4 were divided between two mortar joints (Fig. 6a and Fig. 6c).

4 DISCUSSION AND CONCLUSIONS

On the basis of the presented results it could be assumed that using a PVC film layer as an extrados finish has a negligible influence on the failure load obtained, whereas the application of steel angles on the extrados resulted in a significant increase in failure load (Fig. 8). The increase in load-carrying capacity obtained in the test on a vault with steel angles as compared to vaults with flush joints was about 47%. The presence of steel angles in the SKK specimen limited backfill sliding along the extrados of the arch. The layer of grains locked between the steel angles caused transfer of the soil-arch sliding surface from the vault extrados into the backfill and also increased the effective depth of the vault cross-section, which resulted in an increase in load-carrying capacity.

![Failure mechanisms](image1.jpg)

Figure 7: Failure mechanisms: a) specimen SKM [9], b) specimen SKF, c) specimen SKK, d) vault without backfill - AU [10]

All of the tested specimens collapsed due to the formation of a four-hinge mechanism. Different types of extrados finishes caused modifications in the obtained failure mechanisms. For
specimens SKM and SKF, hinges developed in the single mortar joints, whereas in the case of vault SKK, hinges P1 and P4 divided into two adjacent joints (Fig. 7a-c). The presence of a PVC film or steel angles on the vaults extrados influenced the location of hinge P3 in the collapse mechanisms. For models with the PVC film, hinge P3 was closest to support “A” in comparison with the other finishing methods, whereas for specimen SKK hinge P3 was located closest to the crown of the vault (Fig. 7).

A comparison of the test results as presented above with test results carried out on a specimen without backfill, discussed in [10], shows that the presence of fill material on the haunches of the vault causes an increase in the load-carrying capacity (Fig. 8) and modifies the failure mechanisms of the buried vaults. The beneficial effects of backfill are due to a reduction in the horizontal displacements of the vault and the provision of additional load dispersal. Additionally, the presence of fill material increases the ductility of the tested structures (Fig. 8a) and prevents a brittle collapse of the tested specimen as was observed during a test on a specimen without backfill [10]. The specimen without fill collapsed in a brittle manner without any indication that the failure was approaching (i.e. cracks), whereas in the case of arches with backfill, new cracks appeared when the load increased.

It should be emphasized that the tests were only carried out on a single specimen in each case and that a larger number of buried vaults should be tested in order for more specific conclusions to be drawn. However, the comparison of test results presented here and in [10] show that backfill is not only an additional dead load for the vault but that it also influences the behavior of the buried vault (Fig. 8). Furthermore, modifications made in the extrados configuration (additional nonstructural layers or elements mounted to the extrados) may affect the behavior and load-carrying capacity of the vaults. Thus, any changes in the applied backfill material or the parameters of the vault-infill interface should be taken into account during analysis of renovated buried vaults.

Figure 8: a) Load-radial displacement curves for the tested vaults (mean values from the LVDTs at brick course 12B); b) Collapse loads of the tested vaults – summary.
ACKNOWLEDGMENTS

Laboratory tests were performed at the Cracow University of Technology, Poland. The authors gratefully acknowledge Prof. Z. Janowski for his support throughout this work.

REFERENCES


