Theoretical and experimental studies for strengthening Bohemian brick vaults

I. Bucur-Horváth, M. Miklós & I. Popa
Technical University of Cluj-Napoca, Romania

ABSTRACT: Former researches concerning historical masonry vaults, i.e. a complex process of theoretical and experimental approaches, are continued with mechanical modeling, stress analysis and strengthening proposal for the Bohemian type of the masonry vaults. The study is focused on an old Baroque school building. The Bohemian vaults covering the ground floor were seriously damaged in time. A quasi-general consolidation was imposed. In order to find the compatible repairing materials laboratory tests were performed. The masonry vault structure was modeled like a solid continuum. For stress analysis the bending theory of the shell structures was used. The computing was performed using a SAP2000 program based on finite-elements method. A special technology for strengthening the vaults, using embedded steel profiles, was proposed.

1 INTRODUCTION

1.1 Types of historical masonry vaults
Brick vault structures bridging spans having usually dimensions equal to those of the covered space were frequently used in the Baroque era in the 17th and 18th centuries and also in the Eclectic era of 19th century. The classification of these masonry vaults on the criterion of geometrical form and weaving technique is described (Bucur-Horváth et al. 2001b).

The usual types we meet in the previously mentioned buildings are: cylindrical (barrel) vaults (Fig. 1), cross or groined vaults (Fig. 2), elliptical or Bohemian vaults (Fig. 3) weaved in cooper’s mode, in circular layer and in swallow-tail technique.

1.2 Specific deficiencies and damages of historical masonry vaults
According to the previous researches (Bucur-Horváth et al. 2001b) the characteristic deficiencies and damages are those related to the specific structural behaviour of the masonry vaults like static behaviour under symmetrical and unsymmetrical loading as well as mechanical-physical-chemical characteristics of the masonry, put in certain environmental conditions.

Certainly, under vertical loading the vaults mainly work by compression which corresponds to the mechanical properties of the masonry. Any phenomenon disturbing this compressive state of stress could be dangerous for the structural resistance and...
stability of the brick vaults. In this order earthquake loading represents a natural hazard. In order to decrease the sensibility of the structure to horizontal loading it is advantageous to increase the dead load – in the limits of compressive strength, of course – which can balance the undesirable effects of unsymmetrical loads. Many other natural or man-made deficiencies could lead to major structural damages. From the point of view of their origin they can be classified as: (a) errors of structural design or/and inadequate transformations; (b) differentiated settlements of foundations; (c) lateral displacement of the supports (wall, column) caused by their insufficient stiffness, respectively the lack of horizontal binding.

1.3 Determination of the technical state of the masonry vaults

A methodology of determining the technical state of the brick vault structures has been earlier presented (Bucur-Horváth et al. 2001a). It is based on a certain codification of the defects. By the proposed algorithm one can determine a global quality index which indicates the class of the technical state (good, satisfactory, unsatisfactory, unsafe) respectively the required rehabilitation measures (local repair and preservation, capital repair and consolidation of some structural elements, partial or general consolidation of the structure, partial or total demolition).

2 CASE STUDY PRESENTATION

We are focusing on an old Baroque school building at Orastie. It was built at the end of the 18th century on an L shaped ground plan (Fig. 4). Its present form was achieved in 1847 and one of the wings was expanded in 1865.

The external dimensions of the basic plan are 15 and 29 m. The school was erected on continuous foundations made of alluvial stone and clay mortar. The structure is built of Bohemian brick vaults over the rooms of the ground floor, brick groins in the corridor to the courtyard, and timber slab structure on the second level. The supporting walls are either of brick or brick and stone bastard masonry. The thickness of the walls varies between 450 and 900 mm. The roof has a specific Baroque-type timber framework. The roof carpentry is covered with ceramic tiles.

This school complex was extended once again at the end of the 19th century and at the beginning of the 20th century. Another block in neoclassic style was attached to the first one. In order to fit the exterior look of the older building with the façade of the latter one a series of new windows were cut in the front-side wall. In this way the corner zones of the Bohemian (elliptical) brick vaults and supporting zones of the boundary arches were simply cut out (Fig. 5) gravelly disturbing the mechanical behaviour of the structure.

So, the whole row of the façade adjacent vaults was seriously damaged. In other cases the insufficient rigidity of the marginal walls against the horizontal reactive forces of the vaults, respectively arches, led to lateral displacement of the supporting points causing visible cracks on the interior face of arches and vaults (Fig. 6).

A lot of other causes damaging the building were found. Unequal foundation settlements of the two parts of the construction built at different times have caused the cracking of the structural elements. This
phenomenon was aggravated by a deteriorated sewerage system near by. Generally, besides the above mentioned structural deficiencies, the lack of maintenance and repairing works led to an unsatisfactory technical state of the building. A quasi-general consolidation was imposed.

Besides the consolidation of the foundations the main problem was to find the proper strengthening solution for the brick vaults. As a result of the studies on the possibilities of intervention the first solution was to use tie-bars to overtake the horizontal thrusts and apply a complementary reinforced mortar layer to the existing vault. The well-known disadvantages concerning architectural and functional reasons because of the ties as well as the “breathing” problems of the masonry led us to further studies in order to find a better solution. These researches are resumed as follows.

3 LABORATORY TESTS ON THE MATERIALS

Before any structural repair the compatibility between the old and new materials has to be considered. On the other hand, we have to know the mechanical, physical and chemical characteristics of the materials in order to decide their compatibility to the repairing materials. During this project we have analyzed the characteristics of the old brick and mortar (Fig. 7).

3.1 Tests on the brick

In this study we have compared the characteristics of a few types of bricks. We have compared the brick from the building of the school Orastie with currently produced bricks. The studied bricks are the following: brick from the building of the school Orastie, monumental brick produced in Székesfehérvár, monumental brick produced in Tapolcafő, and solid brick.

The following physical and mechanical characteristics were studied: water absorption, bulk density, density, porosity and resistance to compression. Table 1 presents the results of the measurements.

The compressive strength was measured on cylindrical specimens with reduced dimensions (diameter and height of approximately 30 mm).

It is to be mentioned that the first column (brick of Orastie) in Table 1 refers to the original old bricks. Comparing the results of the tests it can be concluded that the recommended repairing material is the monumental brick of Székesfehérvár. Its characteristics are slightly appropriate to those of the original brick. The completions or replacing the degraded parts of the masonry has to be done using this type of brick.

3.2 Tests on the mortar

The mechanical, physical and chemical characteristics of the mortar have been studied, i.e. the compressive strength, water absorption, bulk density, density and chemical composition.

The derivatograph measurements have showed that the SiO₂ content in the mortar is low, thus we can consider that the binding material of this mortar is lime.

The mechanical resistance of the original mortar is relatively low. The measurements carried out on a set of nine samples of mortar show a great spread of the results. The average value of the compressive strength was of approximately 4 daN/cm².

Concerning the material investigations, the mortar samples were also subjected to the following analyses:

- Binder/aggregate ratio using the dissolution procedure of the binder with hydrochloric solution was determined. The obtained values are between 0.20 and 0.29. The average value can be taken as 0.25.
- The grain size distribution of the aggregate by sieving the undissolved material was also determined. The examined ranges of grain size were: <1, 1–3,
3–5 mm. Some variations of the grain size distribution were put into evidence from one to another sample.

Therefore, we had to choose for restoring the masonry a mortar whose characteristics are appropriate to the original one. Besides, it has to be compatible from both chemical and physical points of view with the original materials of the masonry. It has also to avoid the altering of the degree of humidity within the brick and mortar structure. At the same time, the repairing mortar has to assure the proper mechanical properties, first of all a higher compressive strength as that of the initial mortar.

All the examined mortars were made respecting the initial binder/aggregate ratio by mixing three parts of aggregate and one part of binder. The recommended binding material contains 2 parts of Hydrated lime and 1 part of Pozzolanic cement IV/A having a standard compressive resistance of 32.5 N/mm² (Romanian standard SR 1500). The grain size distribution will be determined according to the technology of putting in work as well as to the size of the cracks that are to be injected, respectively to the thickness of the joints in the case of the rebuilt zones.

4 STRESS ANALYSIS

4.1 Assumptions

The middle surface of the studied vault (Bohemian vault) is an elliptical paraboloid. The masonry vault structure is modeled like a solid continuum. The assumptions of the bending theory of the shell structures are valid.

The Bohemian vault was modeled with the finite elements method. The surface of the vault was divided into plane shells. Between these shells we have considered rigid connections.

The edge conditions are: articulations in the corners; articulations which restrain the translations in two directions (along the edges and normal to the surfaces) at the other supporting points. These supports (boundary arches) are not able to take over lateral pressures.

A vault with dimensions of 5.54 x 3.72 m was modeled (Fig. 8).

4.2 Stress resultants

The stress resultants are represented in Figure 9.

The stress analysis was performed using a SAP2000 program. The Bohemian vault was calculated with the finite elements method.

The loads are:
- permanent loads: \( g_p = 13337 \text{ N/mp} \),
- quasi-permanent loads: \( g_{q-p} = 600 \text{ N/mp} \),
- variable loads: \( p = 2800 \text{ N/mp} \).

The stress resultants were computed in the knot points of the chosen network (Fig. 8).

Figures 10, 11, 12 and 13 give images of the distribution and intensity of the stress resultants (normal forces \( N_{11}, N_{22} \) and bending moments \( M_{11}, M_{22} \)) of the model.

The values obtained in the four sections marked in the Figure 8 are presented in Table 2. It is to be mentioned that the normal stresses are mainly compressions, but important tensile stresses also appear, especially in the corner zones. It is also important to emphasize that the bending moments, even of relatively low values, are of both signs. That means they variously tension the upper or the lower fiber of the vault. Therefore, a double reinforcement seems to be necessary.
Using the membrane stress resultants ($N_{11}$, $N_{22}$ and $N_{12}$) the main stress resultants and their trajectories were determined firstly. Afterwards, the main tensile stress resultants were projected on 1 and 2 directions of the original reference axes for all the key points of the surface. The dimensioning of the necessary reinforcement was performed using the previously mentioned tensile stress resultants combined with the afferent bending moments.

5 CONSOLIDATION OF THE VAULTS

As it is seen, under vertical loading besides compressive stresses tensile stresses also appear on both models. Therefore a proper reinforcement has to be provided. At the same time, it is necessary to repair the existing cracks. The usual method of using tie-bars binding the supports associated with reinforced concrete haunching of the vault surface cannot be used for two reasons. First, the low position of the supporting points of the boundary arches makes impossible to use tie-bars without disturbing the functionality of the building. At the same time, the concrete haunching impedes the brick masonry to breathe freely. So it could alter the degree of humidity within the brick and mortar structure.

Therefore, in this very case another method of strengthening is recommended, namely the Brutt Saver system (Fiala, unpubl.). It was developed in England and it consists in embedding incorrodible steel profiles in narrow grooves having certain trajectories in according to the state of stresses. The special steel spirals are anchored here and there along the profile (Fig. 14) and at their ends as well (Fig. 15). The fixing mortar is a special one compatible with the masonry.

In our very case the restoration and strengthening of the damaged Bohemian vaults consists in the following operations:

- Repairs of the masonry by replacing the damaged zones and rebuilding the missing zones with the

<table>
<thead>
<tr>
<th>Table 2. Stress resultants.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td>-----------------------------</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>2</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>4</td>
</tr>
</tbody>
</table>

Figure 11. Stress resultants $N_{22}$.

Figure 12. Stress resultants $M_{11}$.

Figure 13. Stress resultants $M_{22}$.

Figure 14. Steel profile anchoring along its trajectory.
former recommended repairing materials (brick and mortar);
- Filling the cracks with the prescribed mortar by the injection technique;
- Preparing the place for the strengthening reinforcement by excavating the narrow grooves along the trajectories of the calculated reinforcement;
- Placing and anchoring the special steel spirals (Fig. 14, 15) using a special fixing mortar.

For the Bohemian vault in discussion the strengthening reinforcement is presented in the Figures 16 and 17.

6 CONCLUSIONS

Concerning the presented case study and the previous researches as well, one can conclude:

Any restoration and strengthening operation on historical buildings needs previous complex researches concerning:

(a) the technical state of the building — investigations on structural damages, their type and gravity;
(b) the architectural — including both functional and esthetic — criteria;
(c) the compatibility between the original materials and those proposed for strengthening and between the old composite structure and technology of consolidation as well.

Macro-modeling of the masonry vaults like a solid continuum can be done in a good approach using the bending theory of shell structures for the stress analysis.

The presented study has shown how the mechanical behaviour of the Bohemian brick vaults can be improved and how the gravely damaged vaults can be saved by a special strengthening technique with embedded steel profiles. This method assures an intimate connection between the old and new material. At the same time it is a relatively discreet intervention in comparison with the classical method of tying the supporting points of the vault and applying an upper or/and lower complementary reinforced mortar layer.

REFERENCES


Fiala, J. unpubl. Brutt Saver system of strengthening masonry structures.