Improving structural response of masonry vaults strengthened with polymeric textile composite strips

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Abstract: - Masonry vaults are important structural components of many monumental buildings belonging to the historical heritage. However, since the tensile strength of masonry is low, under certain loading conditions the masonry vaults are vulnerable to cracking and dangerous failure mechanisms. The strengthening systems based on textile glass fibre reinforced polymer (GFRP) composite materials have favourable effects upon the structural response and load bearing capacity of framing systems made of masonry. In this paper the results of an extensive study including testing and numerical programs on structural behaviour and failure mechanism of unstrengthened and strengthened vaults are presented. A comprehensive study program, including numerical modelling and extensive tests, has been conceived and performed to fully characterize the dynamic/seismic behaviour of the masonry unstrengthened and GFRP composites strengthened vaults. The overall behaviour and the failure mechanism have been favourable modified by GFRP strips network improving the structural characteristics, the global seismic behaviour and the failure mechanisms.

Key-Words: - barrel vaults, GFRP strengthening solutions, hybrid structures, composite strips, seismic test, numerical analysis, failure mechanisms

1 Introduction
The structural analysis of masonry framing systems from historical buildings is more challenging than that of modern structures made of the same materials. Many of the mechanical characteristics of old masonry structures are not adequately known and introduce additional difficulties in the evaluation of structural response under various types of loading.

A large number of monumental buildings in Romania and abroad have been constructed with unreinforced masonry (URM). These structures have been in use for a long time and, in the past they were many times constructed with the unsafe features. Important structural deficiencies have been produced in masonry structures due to various causes such as different loading due to environment or structural modifications, leading to overloading the original elements [1]. Masonry structures with historical value have generally large cross sections giving important permanent loads from self weight and low stresses. However, significant changes have often been operated to meet different architectural requirements and such modifications may reduce the structural safety. The earthquake loading are very aggressive to unreinforced masonry structures and the weakness of these structures is aggravated by poor anchorage to different load bearing parts. During seismic actions failure of unreinforced masonry elements may suffer major degradations that become serious threats to the occupants or to the goods stored in the sheltered space. Due to various environmental exposures from moisture, corrosion, air pollution, freeze/thaw cycles or biological attacks the masonry materials can be seriously degraded and localized damages or global deterioration may develop.

Foundation movements as well as high temperature variations may impose different displacements that can affect URM structures. In particular historical buildings including curved masonry elements such as masonry vaults are very sensitive to the above mentioned actions leading to potential instability [1].

Consequently retrofitting techniques are needed to structurally rehabilitate masonry elements. Techniques based on traditional materials have been designed and applied to masonry structures for long time. Nowadays, fiber reinforced polymer (FRP) composites may bring an important load bearing contribution by compensating the lack of tensile capacity of brittle unreinforced masonry elements. The use of FRP composites to retrofit masonry structures of historical buildings offer a number of certain advantages compared to the traditional techniques based on other building materials. Previous research works in strengthening of unreinforced masonry have demonstrated the advantages and disadvantages of conventional strengthening techniques which based on traditional construction materials.

Classic strengthening techniques refer to external jacketing using shotcrete retrofitting, mortar injection, post-tensioning, external steel plates, anchored welded...
steel mesh covered with mortar, confining of URM using reinforced concrete ties columns, centre core technique, steel tie rods for masonry barrel vaults and arches etc. [2]. Compared to traditional strengthening methods of masonry structures the use of FRP composites provide significant advantages: the low size and weight of FRP composite products do not add noticeable permanent loads and do not substantially modify the dynamic/seismic characteristics of the original structure. The methods based on FRP solutions do not involve high labour consumption, do not require long term relocation of occupants or disruptions of use.

The application of FRP composite products has a minimum aesthetic influence on the architectural features of the historical buildings [3]. However the long term properties of FRP composites and their compatibility with the masonry substrate in various moisture and temperature conditions are not yet fully understood. Fiber reinforced polymers (FRP) composites can be utilized to improve in-plane shear, flexural strength or their ultimate displacements. Modern strengthening solutions based on FRP strips bonded with epoxy adhesives [4], near surface mounted (NSM) glass fiber reinforced polymers (GFRP), aramid fiber reinforced polymers (AFRP) and carbon fiber reinforced polymers (CFRP) elements [5] as well as prestressing of CFRP strips [6] have successfully been utilized.

Application of GFRP strips over the inside and outside surfaces of the arches and barrel vaults can prevent/limit the cracks opening and the formation of hinges prior to collapse [7]. An extensive experimental program aiming to prove the suitability of GFRP strengthening solutions for masonry barrel vaults is presented in this paper. The structural behaviour of masonry structures has acquired much knowledge in a recent period but little is known and understood about the structural behaviour of masonry vaulted structured subjected to dynamic and seismic action [8].

The masonry barrel vaults strengthened with GFRP composite strips subjected to static and dynamic loading have shown significant increase in strength and minimization of the displacements. Failure mechanisms have also been identified for different loading cases. Obvious improvements have been obtained using GFRP composite strips, in both static and dynamic/seismic loading, showing obvious improvements.

2 Structural response under static loading

2.1 Experimental structural response

The experimental model has been designed at a 1/3 scale observing the Cauchy similitude criteria. The scale has been selected to provide an adequate characterization of the mechanical behaviour and also to fit the capacity of the shaking table for dynamic/seismic loading [9, 10].

The experimental model has been conceived as an assembly vault-parapets made of old masonry and weak mortar. The model was constructed on a strong reinforced concrete plate utilised to attach the experimental structure to the shaking table. In Figure 1, the geometric dimensions of the model (200x214x116,5 cm) are presented.

![Fig. 1 The geometric characteristics of the experimental model](image)

A preliminary testing phase has been carried out to determine the structural response of the masonry barrel vault under static loading. An adequate instrumentation has been attached to the experimental model to record the magnitudes of the characteristics specific to structural response. The test specimen was equipped with linear variable differential transformer (LVDT) - MICRO-EPSILON, Tip DTA-10D, located as shown in Figure 2 and with a data acquisition system National Instruments, Model SCXI 1540, SCXI 1520.

![Fig. 2 Instrumentation of the experimental model with LVDTs](image)

A uniformly distributed load, Figure 3, has been preliminarily applied to evaluate the properties needed for numerical modelling and for further testing of the model under dynamic/seismic loading.

![Fig. 3 The loading scheme of the model subjected to uniformly distributed gravitational loading: a. uniformly distributed load on the masonry vault extrados; b. disposal of the lead loading sacks](image)
The load has been progressively applied in steps of 0.25 kN/m\(^2\) up to 3.25 kN/m\(^2\), considered appropriate to initially characterize the structural response of the model under static loading. In Figure 4 the load-displacement diagrams are illustrated.

![Load-displacement diagrams](image)

**Fig. 4** Load displacement diagrams for test model under uniformly distributed static loading

### 2.2 Numerical modelling response

#### 2.2.1 Static analysis of the unstrengthened model

Preliminary tests on the materials properties have been carried out prior to construction of the experimental model to determine the mechanical parameters for modelling. Tests have been performed on brick sample, Fig. 5a, mortars cubic test specimens, Fig. 5b and blocks of bricks, Fig. 6.

![Compression test on materials](image)

**Fig. 5** Compression test on materials: a. normal brick; b. mortar

![Compression test on masonry block](image)

**Fig. 6** Compression test on masonry block

The compression test has been performed on a universal testing machine, ZWICK/ROELL with displacement and force control. In all tests the stress-strain curves have been determined including the ascending branch segment up to the ultimate force and a descending segment up to a 60 % decrease of the maximum force. A comparative illustration of the experimental curves is presented in Fig. 7, for brick specimen, mortar sample and masonry block.

![Stress-strain curves](image)

**Fig. 7** The stress-strain curves for the materials utilized at the masonry vault

The software package ANSYS WORKBENCH MULTIPHYSICS version 11 has been utilized to perform the static and dynamic analyses. The mesh of the masonry vault is presented in Figure 8; its configuration has been selected to adequately cover the aspects to be studied including the maximum principal stresses map, an indication of the envisaged strengthening network of composite strips.

![Finite element analysis (FEA)](image)

**Fig. 8** Finite element analysis (FEA) of the unstrengthened barrel vault: a. mesh of the unstrengthened barrel vault b. the maximum principal stresses

In addition, the vertical displacements have been determined, Figure 9, with maximum vertical value 0.252 mm at the mid span of the barrel vault.

![Deformed shape](image)

**Fig. 9** The deformed shape of the unstrengthened vault

#### 2.2.2 Static analysis of the strengthened model

The mechanical characteristics of glass fiber reinforced polymer (GFRP) composites with epoxy resin are given in Table 1. The properties of the GFRP composite membranes resulted from impregnation of glass fibre strips have been determined using the formulas utilized in micromechanics of fibrous composites [11]. Since the
glass fibre fabrics have been distributed quasi-unidirectional with limited transverse (fill) fibres, a good correspondence between the direction of the main stresses and the longitudinal fibres of the composite reinforcing products could be achieved. The bonding between the composite strips and the support masonry has been realised by impregnating the glass fibre strips with epoxy resin using the wet-out procedure [12, 13].

Table 1 GFRP characteristics

<table>
<thead>
<tr>
<th></th>
<th>Glass fabrics</th>
<th>Epoxy adhesive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile strength</td>
<td>2250 MPa</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus</td>
<td>70 GPa</td>
<td>3.800 GPa</td>
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<tr>
<td>Elastic modulus</td>
<td>3.800 GPa</td>
<td></td>
</tr>
<tr>
<td>Shear adherence to masonry</td>
<td>3.5 MPa</td>
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GFRP strips with the width of 20 cm and the distance between them equal to 25 cm have been selected. In Fig. 10 the main results of the FEA analysis of the strengthened barrel vault are illustrated. The stress concentrations are localized as shown in Fig. 10.b., on the abutments top, justifying the extension of the GFRP strips as shown in Fig. 10 a.

![Fig. 10 Finite element analysis (FEA) of the strengthened barrel vault: a. mesh of the strengthened barrel vault with GFRP strips bonded to extrados; b. maximum principal stresses](image)

After strengthening, the maximum vertical displacement determined by numerical modelling was 0.026 mm, about 1/10 that of the unstrengthened model. A significant displacement reduction has also been noticed on top of the abutment, Fig. 11.

![Fig. 11 The deformed shape of the strengthened vault](image)

2.2.3 Dynamic analysis of masonry vault models
The theoretical modal analysis has lead to a fundamental frequency of the unstrengthened model equal to 74.8Hz, Fig.12a, and 76.3Hz in case of the strengthened model, Fig. 12b.

![Fig. 12 Vibration mode shape](image)

2.3 Experimental dynamic structural response of the masonry vault
The masonry vault has been instrumented with LVDTs and accelerometers as it can be seen in Fig.13. The accelerometers A0 and A4 have recorded vertical accelerations while A1, A2, A3, A5, A6 have registered the accelerations in the horizontal direction.

The fundamental frequency of the unstrengthened model equal to 75.2 Hz has been determined experimentally in the first stage, using a vibration generator fig. 14; in the second stage the fundamental frequency of the strengthened model equal to 76 Hz has been recorded. The dynamic characteristics obtained using FEA were compared with experimental results to be further utilised in the test program carried out on shaking table.

![Fig. 13 Locations of LVDTs and accelerometers](image)

![Fig. 14 Data recorded on the accelerometer A0: a. on unstrengthened model; b. on strengthened model](image)
2.4 The structural response under seismic action

2.4.1 The experimental setup for seismic response

The masonry vault model has been installed on the shaking table platform having the following performance characteristics: the gravity load capacity = 160 kN; the dynamic displacement amplitude = ±15 cm; the frequency range = 0.5 ÷ 50.0 Hz; the action type is triaxial (two in horizontal plane, one in vertical direction); the peak acceleration with a payload 100 kN = ± 3g and the maximum velocity = ±0.8 m/s. The acquisition of the test data has been digitally performed, by simultaneously recording signals from 2 types of transducers Fig 15: Dytran 3202A1 LIVM (accelerometer) and PT5AV (displacement transducer).

2.4.2 The applied seismic action

To evaluate the structural response under seismic load, the accelerograms of two representative earthquakes, Fig 16a,b, and an artificial accelerogram, Fig. 16c, have been imposed. The selected earthquakes were El Centro (1940), and Vrancea, Romania (1986). The amplitudes of the accelerations ranged between 0.1g and 0.41g for the El Centro earthquake and between 0.22g and 0.5g for the Vrancea earthquake.

Fig. 16 The imposed accelerograms:

- a. El Centro-California, 1940;
- b. Vrancea-Romania, 1986;
- c. sine-sweep accelerogram

2.4.3 Test results

The application of El Centro and Vrancea earthquakes (which are the typical seismic actions for structural design in Romania) have not produced significant damages to the masonry vault model. After the Vrancea and the El Centro seismic actions have been applied, the following recorded results have been obtained: the maximum recorded horizontal acceleration equal to 0.5g; the absolute displacement equal to 2.5 mm and the maximum relative displacement recorded between LVDT 2 and LVDT 4 equal to 0.17 mm.

To stimulate the development of the failure mechanisms of the strengthened model the sine sweep action has been applied; the acceleration has been kept equal to 0.5g but the frequency of the action has been brought close to the fundamental frequency of the structural model leading to the resonance phenomenon.

Five plastic hinges have been formed, localized as shown in Fig. 17a. The collapse has been initiated due to high relative transverse displacements in the mortar beds near abutment, as it can be seen in Fig. 17b.

Fig. 17. Failure of the masonry vault under the sine-sweep action:

- a. location of the five plastic hinges;
- b. enlarged detail of the plastic hinge number 1

Four successive failure stages as illustrated in Fig. 18 have been identified; the first plastic hinge appeared in the middle of the vault.

Fig. 18 Stages of the masonry vault collapse

3 Conclusions

The masonry barrel vaults are valuable structures for monumental buildings but their behaviour is significantly affected by the low tensile strength of the component materials, brick units and mortar.

FRP composite strengthening systems can be efficiently utilised to overcome this shortcoming. The
stabilization solutions can be applied efficiently when the structural response under static and dynamic loading is well understood.

An extensive theoretical and experimental program has been carried out at the Faculty of Civil Engineering, the Technical University of Iasi, to prove the adequacy of stabilization solutions based on GFRP strips impregnated with epoxy resins. The network of strips was applied on the extrados of the masonry barrel vault.

The initial study, consisting of statically applied uniformly distributed load provided some information on structural response of the framing system.

A numerical analysis completed the preliminary data indicating the location and the layout of the strengthening network of strips.

A significant improvement has been noticed when the model was strengthened with the GFRP composite membranes in terms of dynamic characteristics and of seismic behaviour.

The improvement was materialised through the modification of vibration frequency, formation of plastic hinges and a more ductile character of failure.

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References: