ADDITIONAL STRENGTHENING OF MASONRY VAULTED STRUCTURES BY NONPRESTRESSED REINFORCEMENT

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Abstract

Performed experiments on additionally strengthened vaults with metallic helical reinforcement and non-metallic composite glass reinforcement (GFRP) proved expressive influence on carrying – capacity of masonry vaults. These experiments were nevertheless carried out on vaults without backfill. The question then is, what kind of interaction takes place between non-strengthened or strengthened vault with backfill. Realization of experiments in real conditions would be technically and financially very difficult, and therefore cooperation of vaults in combination with backfill has been simulated in computational programme Atena based on earlier performed experiments.

Streszczenie

Badania wykonane na sklepieniach wzmocnionych śrubowym zbrojeniem stalowym i szklanym zbrojeniem kompozytowym (GFRP) potwierdziły wyraźny wpływ na nośność sklepień ceglanych. Badania te zostały wykonane na sklepieniach bez nadbudowy. Zachodzi zatem pytanie, jaka jest współpraca sklepienia wzmocnionego oraz sklepienia bez wzmocnienia z nadbudową? Realizacja takich badań byłaby technicznie i finansowo bardzo trudna, stąd też współpraca sklepień z nadbudową była symulowana w programie obliczeniowym Atena na podstawie wcześniej wykonanych eksperymentów.

Keywords: **Bridges; GFRP; Masonry; Mathematical model; Backfill; Strengthening; Vault.**

1. INTRODUCTION

Masonry continues to be popular because of its relative simplicity of application in the technical practice. Indeed, for a new use of structural masonry reasonable constructional rules are required, because conventional approach based on the experience is unacceptable nowadays. In addition, most methods of carrying capacity assessment and of strengthening for the existing masonry construction are increasingly based on analyses of mathematical simulation and appropriate (linear and nonlinear) computational models. One method of load-bearing elements strengthening is application of additional external reinforcement into chases in masonry on bottom side of vaults, which will provide stiffening and increasing of load carrying capacity of the individual load-bearing elements. This paper is based on the experiments in the field of masonry structures strengthening that were performed on Faculty of Civil Engineering Brno University of Technology.

This paper presents the results of the load tests of masonry vaults strengthened with the metallic helical reinforcement system Helifix and with non-metallic glass reinforcement (GFRP) (Fig. 1). The aim of this work is to document possibilities of the use of the additional reinforcement for strengthening of masonry structures loaded with the interaction of a normal force and a bending moment and to verify experimentally the behaviour of specially shaped profiles of the HeliBar reinforcement and the HeliBond grout in masonry, respective glass reinforcement (GFRP) and the Sikadur grout.

Similar test on additionally strengthened vaulted structures were performed at a Transport Research Laboratory in London. These tests were performed on three layers masonry bridge with span 5 m strengthened by additional reinforcement HeliBar [1].

The method of additionally inserted non-prestressed reinforcement allows additional strengthening of masonry structures without a necessity of large intervention into vaults especially in case of external application. This system is capable redistributing newly originated stresses from load that act on a strengthened construction. The aim of reinforcement is to restrict development of existing cracks and eliminate possibly an origin of the new ones, and to improve load-bearing capacity of vaulted masonry constructions.

Figure 1.
Shape of HeliBar and wrapped surface GFRP

2. DESCRIPTION OF EXPERIMENTS

Within experimental parts of the project three sets of masonry vaults with for various loading types were manufactured. To distinct individual vaults are used notation jKi, where "j" corresponds to series number (1-3) and "i" to the strengthening method (1-3). The vaults were symmetrically loaded in ½ of the span – 1.series (j=1), asymmetrically in ¼ of the span – 2.series and symmetrically in both quarters of the span – 3.series (j=3) (Figure 2). Each series consists of three vaults: non-strengthened one – comparative (i=1), a vault reinforced in two chases (i=2) and a vault reinforced in three chases (i=3). The vaults were bricked up from full burnt bricks on lime-cement mortar with width equal 890 mm, span 2600 mm, deflection 750 mm and radius 1500 mm. Into every reinforcing chases were embedded 2 bars. Previous experiments were performed with reinforcement HeliBar of special helical shape of 8 mm diameter. For verification of behaviour on another's type of reinforcement was selected glass armature of 6 mm diameter and used only unsymmetrical loading in ¼ of the span (2.series) [2,3,4].

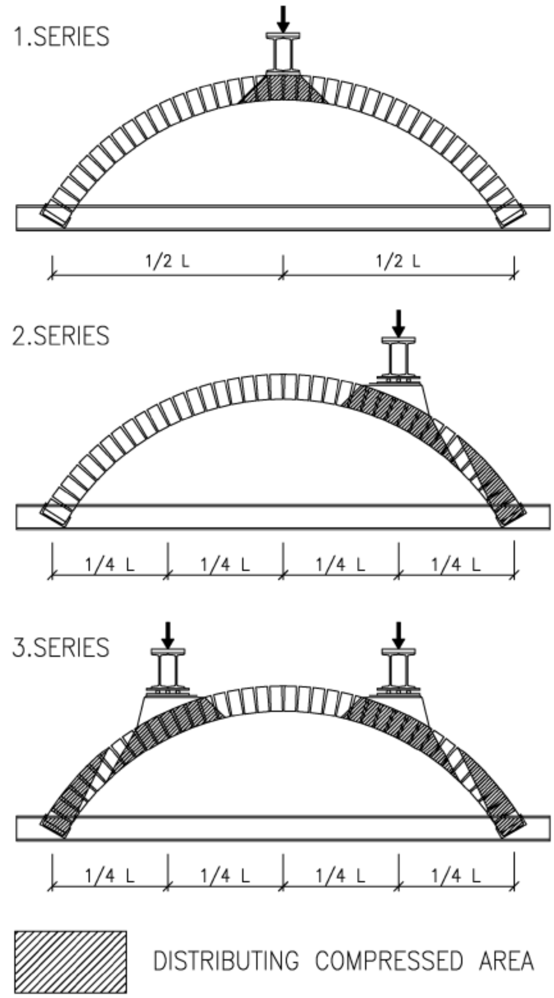

Figure 2.
Loading schemes of vaults and distribution of load in vaults

For the last part of experiments was selected dynamical testing of the vaults. These tests were performed on vaults loaded only in ¼ of the span (2.series – Fig. 2), because of maximum influence of additionally reinforcement on final load bearing capacity of the vaults. This last series of vaults were strengthened only with glass reinforcement GFRP. Dynamical loading was initialized by dynamical hydraulic press and deformation of the structure was read by inductive displacement transducers (Figure 3).

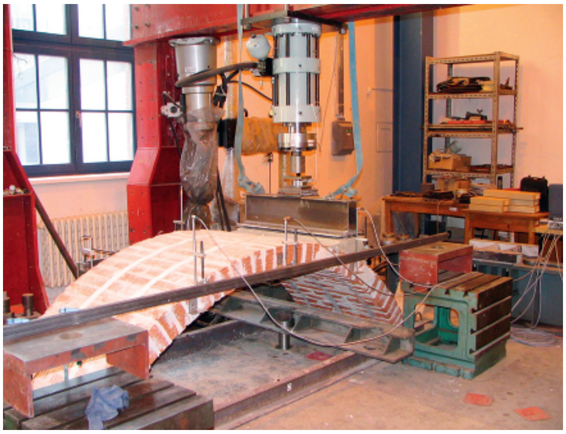

Figure 3.
Set-up of the experiment for the dynamical tested vaults loaded in ¼ of the span

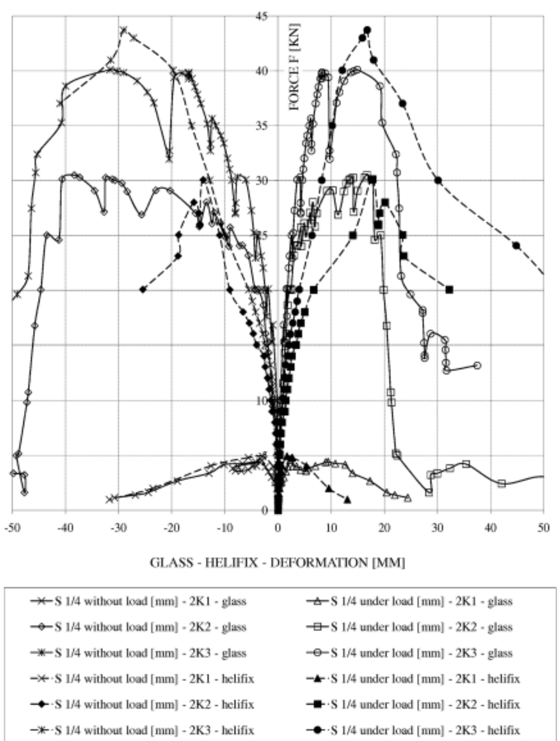

Figure 4.
Comparison of deformations on vaults loaded in ¼ of the span strengthened with GFRP and metallic helical reinforcement – statical test

3. INTERPRETATION OF TEST RESULTS – STATICAL TEST

Based on comparison of load-bearing capacity of individual vaults in the series results that essential growth of the load-bearing capacity was achieved especially in case of 1st series and 2nd series of the

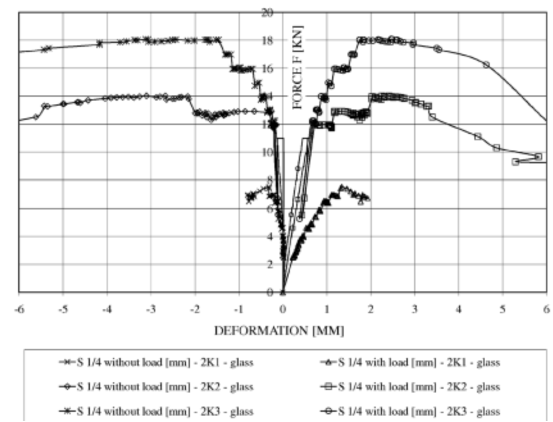

Figure 5.
Comparison of deformations on vaults loaded in ¼ of the span strengthened with GFRP reinforcement – dynamical test

vaults, namely more than eight multiple growth. This growing of carrying-capacity can be watch for both cases of reinforcement – helical metallic and glass nonmetallic. It was related to the vaults stressed by either concentrated or one-sided load, at which the vaults were loaded by means of the interaction of normal forces and bending moments. That's why was on basis of previous experiments [2,3] select unsymmetrical loading in ¼ of the span for vaults strengthened with glass reinforcement (Fig. 4). In case of 3rd series the experiments did not prove the effects of strengthening by additionally inserted reinforcement on the vaults load-bearing capacity; no effects of reinforcement demonstrated because the vaults were mainly compressed. The result values of loading and corresponding deformations for all series of vaults strengthened with metallic reinforcement are presented in [2,3,4].

4. INTERPRETATION OF TEST RESULTS – DYNAMICAL TEST

Dynamical tests were performed on vaults loaded asymmetrically in 1/4 of the span and reinforced only with glass reinforcement (GFRP). Based on results of first dynamical tests is again visible increasing of load-bearing capacity of reinforced vaults (2K2, 2K3) compared to vault unreinforced (2K1) (Figure 5). But low set of tested specimen prohibited comparison with test data from statical experiments and it also in connection with big nonhomogeneity of masonry constructions. As well a fracture mode, failure of vault by opening of tension cracks in bed joint, is not uniform and position of crack can influence

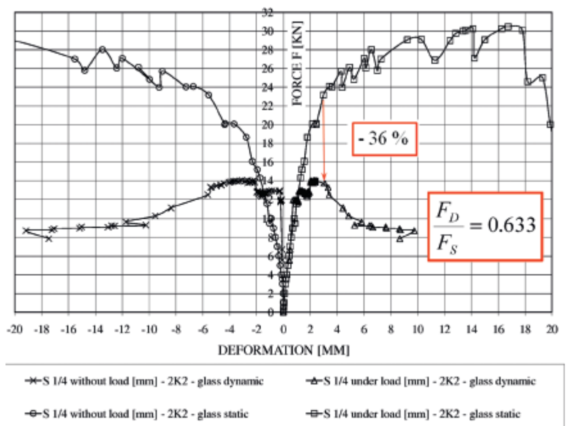

Figure 6.
Comparison of statical and dynamical tests on vaults strengthened by means of glass reinforcement with two chases

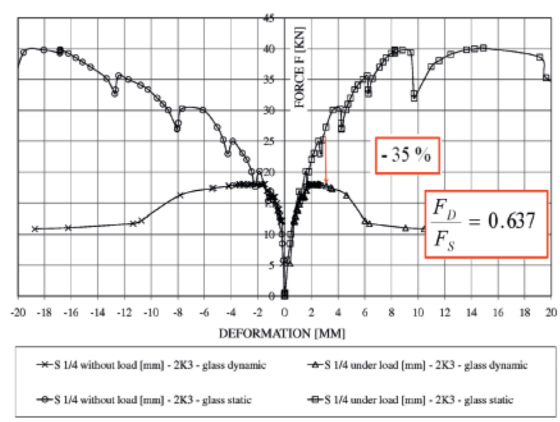

Figure 7.
Comparison of statical and dynamical tests on vaults strengthened by means of glass reinforcement with three chases

final load bearing capacity. Especially load-bearing capacity of unreinforced vault loaded by dynamical loading is higher in comparison with statical examination which can be incurred especially by nonhomogeneity in masonry. Strengthened vaults can be partially compared by relation of their load-bearing capacity. Ratio of load-bearing capacity of dynamically loaded vaults and statically loaded vaults (F_D/F_S – dynamical coefficient) with two reinforcing chases is 0.633 (Figure 6) and with three reinforcing chases is 0.637 (Figure 7). Comparison is performed for deformation 3 mm.

5. MATHEMATICAL MODEL IN PROGRAM ATENA

Several attempts have been made to categorise computational modelling frameworks for structural masonry, where it's inherent discontinuous nature (unit, joint, interface) needs to be recognised. Perhaps the most appropriate categorisation comes from the "Delft School" (Rots [5] or Lourenço [6]).

Based on these theoretical studies result conclusion that the most convenient model for describing orthotropic non-continuous character of masonry is a micro-model and was used for modelling in programme Atena which is determined for non-linear analysis on the base of FEM method and has specially designed tools for computation simulation of the composite materials behaviour. The micro-modelling can describe not only the materials characteristic of individual materials (bricks, mortar), but also their co-acting that is in the mathematical model of masonry considered by 2D contact among the materials. This contact task describes in the best way the behaviour of masonry on the boundary of the masonry units and mortar. A disadvantage of the micro-modelling is its high time-consuming of computation and extensive number of the physically-mechanical properties to be determined for the material behaviour description and for the contact behaviour description among individual materials.

For the mathematical model of masonry units was selected, optionally, 3D Concrete [7], i.e. brittle-plastic material with linear compressive area, for the mortar was used optioned 3D non-linear concrete [7], i.e. brittle-plastic material with linear compressive area, and for description of contact behaviour was used 2D contact [7]. This model of a contact in Atena is based on a model of the dry friction (Mohr-Coulomb) defined by the shear cohesion c and by the friction factor φ. Maximum shearing stress is restricted by a linear relation

$$\tau = c + \varphi\sigma,$$

where σ is a magnitude of the contacting pressure stress (positive value). The contact task is extended in addition by limited damage of the contact by a tension f_t.

For reinforcement model is in the calculating Atena program used 1D Reinforcement model [7] which is unfortunately unable in 2D model precisely simulate the reinforcement global behaviour in the chases, i.e. pull-out of the reinforcement bars with bond from the chases. For reinforcement is only implemented a

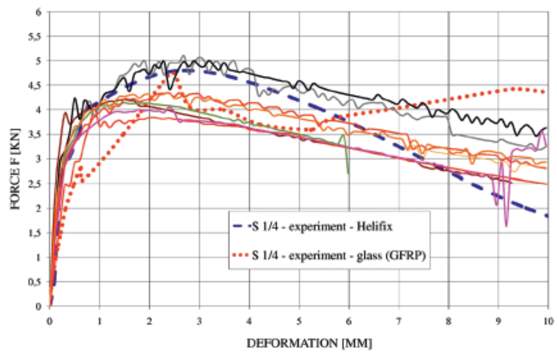

Figure 8.
Comparison of mathematical models with experiments – nonstrengthened vault loaded in ¼ of the span – 2K1 (the 1st experimental result was obtained from series, where was for strengthening used reinforcement Helifix and the 2nd from series, where was for strengthening used reinforcement GFRP)

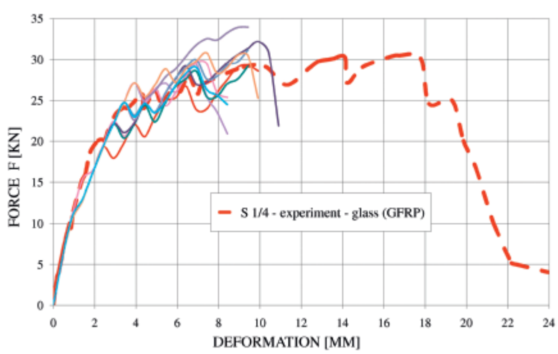

Figure 9.
Comparison of mathematical models with experiments – strengthened vault with two chases with GFRP reinforcement loaded in ¼ of the span – 2K2

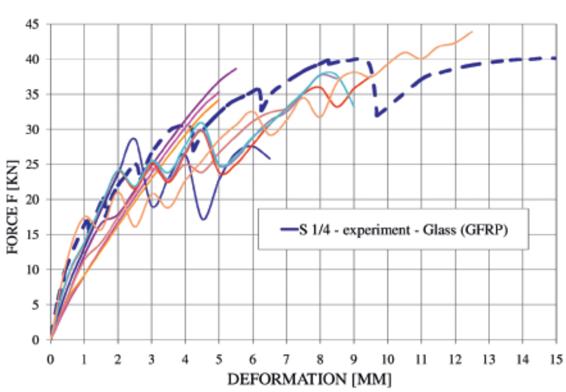

Figure 10.
Comparison of mathematical models with experiments – strengthened vault with three chases with GFRP reinforcement loaded in ¼ of the span – 2K3

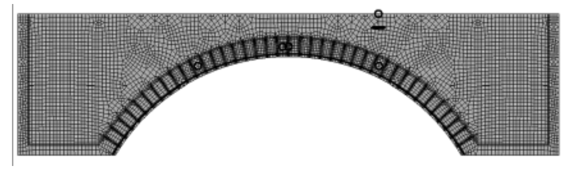

Figure 11.
Mathematical detailed micro-model of masonry vault with backfill – simulation of tested shape of vaults (span 2.6 m, deflection 0.75 m)

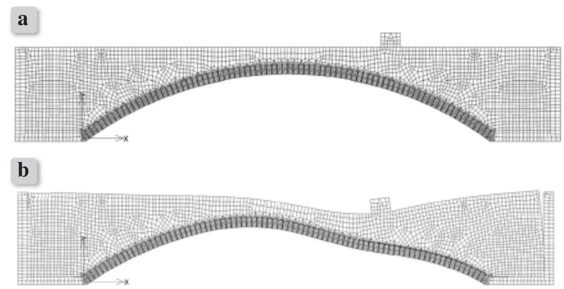

Figure 12.
Mathematical detailed micro-model of masonry vault with backfill – simulation of real construction (span 6 m, deflection 1 m) – a) undistorted shape, b) deformed shape

presumption about its behaviour, namely by the multi-linear working diagram of the reinforcement. Into the calculation is also implemented a presumption about the reinforcement coherence with ambient material (bond-slip relation). The presumption about the reinforcement coherence with ambient environmental, in our case the special reinforcement of a helical shape and GFRP reinforcement, is possible to express on the bases of performed pull out tests at the BUT-FCE in Brno [8,9].

For description of the physically-mechanical characteristic of materials (brick, mortar, reinforcement) are used the data obtained from the tests. But determination of characteristics for contact behaviour is much more complicated and unfortunately the mathematical calculation is very sensitive on these material properties. Therefore was chosen two levelled method for determination of contact behaviour.

In the first step were identified the properties of 2D contact on unreinforced arch for all types of loading, so to be reach good agreement between the experiment and numerical calculation. Comparison of experiments (dashed line) with mathematical models (full lines) on unreinforced vaults loaded asymmetrically in ¼ of the span is show on following diagram (Fig. 8). In the second step then the reinforced arches were modelled with 2D contact parameters which were identified in first step. The comparison of models with experiments performed on vaults strengthened by GFRP and loaded asymmetrically in ¼ of the span is show in Figure 9 and 10.

Appearance to shapes variety of vaulted masonry construction is this way optimal for investigation of these structures. Mathematical simulation is also suitable for investigation of backfill influence on load-bearing capacity of strengthened masonry vaults (Fig. 11, Fig. 12).

6. CONCLUSIONS

The method of repairs and strengthening of the masonry vaulted bridges and structures using additionally inserted reinforcement have a wide usage. Its application is possible in cases when in a structure either originates or may originate the tension stresses in unreinforced masonry, whose magnitude is close (or exceeds) to the strength of unreinforced masonry, i.e. in places where the cracks on a construction have been already developed, alternatively when their origin is expected, whereas it may dealt with the strength of masonry in plain tension, in tension in bending or in main tension.

From the experiments, influence of the reinforcement on load bearing capacity of the structure is evident, namely in case of concentrate loading, asymmetrically loading or in case of the damaged structures, i.e. cracks, degraded materials, overloading or support movement. In case of undamaged, uniformly loaded structures without cracks, influence of this type additional strengthening is insignificant.

In the next phase of investigation we will concentrate on mathematical simulation of reinforced and unreinforced vaults in interaction with backfill, which would had prove influence of reinforcing system on carrying – capacity of whole construction (vault/backfill). For comparison of backfill interaction with masonry vault and influence of strengthening will be except experimentally tested vaults also simulated vaults with other shape and proportions.

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