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Behavior of newly developed FRP reinforcement in structures under various load schemes

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Summary

An own reinforcement based on glass or carbon fiber reinforced polymers in frame a Czech ministry of industry and trade research task was developed. A set of experiments was made for reinforcing of concrete structures with this FRP internal reinforcement.

The developed reinforcement was used for reinforcing of several concrete elements. These elements were exposed to different types of loading. Their behavior was monitored to verify the functionality of new reinforcement. Based on this results it is possible to determine required properties of reinforcement used for every sort of reinforcing (longitudinal or shear reinforcement).

This reinforcement was also used to additionally strengthen the masonry vaults loaded with static and dynamic loads. Obtained results are compared with theoretic results of nonlinear numerical analysis of constructions.

KEYWORDS: Longitudinal and shear GFRP reinforcement, reinforced concrete structures, strengthened masonry vaults.

1. INTRODUCTION

At present non-metallic reinforcement is used very frequently (because of their resistibility) in constructions that are exposed to aggressive environment's influence. It makes possible to reduce costs needed for special arrangements for protection the common reinforcement and eventually consecutive repairs.

However the price of the non-metallic reinforcements is quite high (see Fig. 1). And because this reinforcement form the significant part of the final costs of the cross-section price, it is very advisable to (next to economical optimizing of the cross-section [1]) use local non-imported (i.e. probably cheaper) materials.

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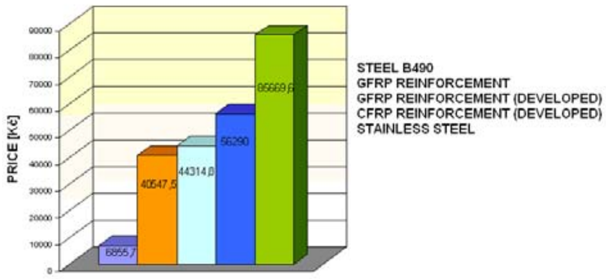

Figure 1. Comparison of the average prices in the Czech Republic
(common materials and developed reinforcement)

The economic aspect mentioned above isn’t in the Czech Republic so strong, because there isn’t any native producer of this kind of reinforcement. While using it is necessary to import the reinforcement from abroad, which makes construction sometimes more expensive.

In terms of research in frame of the Czech Ministry of Industry and Trade, development of “home” reinforcement based on glass and carbon fibers has begun. It is of course necessary to check out functionality of this system – i.e. functionality of interaction of reinforcing bar and surrounding concrete.

But not only new concrete structures are in the centre of interest. 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 non-prestressed reinforcement into chases in masonry on intrados of vaults, which will provide stiffening and increasing of load carrying capacity of the individual load-bearing elements.

The existing and especially historical masonry structures are nowadays considerably monitored. Many of them are in need of some retrofitting or strengthening. In such cases the non-metallic with minimal requirements for reinforcement cover even in aggressive environment could be the best solution. Therefore some tests were undertaken to learn about behavior of masonry vaults additionally strengthened with GFRP bars. These test logically followed previous research of the additionally strengthened masonry structures.

To achieve good usable results it is necessary to provide also statistical evaluation and theoretical backgrounds for further designs of such structures. Therefore all

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data obtained from the tests are used to create and verify the numerical model of FRP reinforcement material used in calculations. This model should allow to predict as accurate as possible the behavior of concrete and masonry structures reinforced with FRP bars.

Mathematical model is created in physically non-linear FE software based on fracture mechanics of quasi-brittle materials. Results obtained from real tests are used as input data for all materials. It means all material characteristics for both concrete (strengths, modulus of elasticity, fracture energy, etc.) and non-metallic bars (tensile strength, load-deflection diagram, modulus of elasticity). The cohesion between reinforcement and concrete (grouting) is modeled via cohesion parameters for each type of the surfacing.

Comparison of the real and numerical results shows very good correspondence (some results are shown in the text below and in [2] and [3]).

1.1. Concrete reinforcement

Tests are performed in several partial fields:
- obtaining physical-mechanical characteristics of reinforcement,
- obtaining cohesion between reinforcement and concrete,
- monitoring behavior of specimens reinforced with non-metallic reinforcement (i.e. real function of reinforcement in loaded construction).

The first two research points were completed and all the results were analysed [2]. Choice of the most suitable type of reinforcement was achieved based on obtained results. The best cohesion with the concrete, material properties and demand factor of the production of the reinforcement and the surface preparation were confronted. All these parameters influence the price and the efficiency of the developed reinforcement.

After the decision about the surfacing of the reinforcement it was necessary to confirm the functionality of the reinforcement. Therefore several tests were performed on the concrete specimens. GFRP bars were used as both longitudinal and shear type of reinforcement.

1.2. Strengthening of the masonry structures

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 the development

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of existing cracks and eliminate possibly an origin of the new ones, and to improve load-bearing capacity of vaulted masonry constructions.

From the static viewpoint, unreinforced masonry structure is unable to transfer tensile forces that can originate on existing structure from following action:

- action of the higher imposed load against the designed one,
- action of either identical or the lower load against the designed one.

Another consequence of the retrofit reinforcement application into masonry structures is the rigidity improvement. The effect is evident especially at the structures cracked by the previous traffic utilisation. Nevertheless, from the practical viewpoint this consequence could be smaller for railway bridges.

For reinforcing the masonry structures it were used two types of reinforcing materials (shape of this reinforcement bars can be seen in Figure 2):

- commonly used steel reinforcement (Helifix),
- non-metallic reinforcement (GFRP bars).

Figure 2. Shape of Helibar and wrapped surface GFRP

As a binding (transferring) medium between reinforcement and origin masonry was used special mortar (grouting substance). It is important to mention that it is essential the reinforcing bars compose with grouting substance and with origin masonry the reliable and durable system.

2. CONCRETE MEMBERS WITH LONGITUDINAL GFRP REINFORCEMENT

These tests are related to concrete beams (dimensions 350 x 100 x 2200 mm) reinforced only with longitudinal GFRP reinforcement (diameter 14 mm, one-side-wrapped bars).

This test was classical four-point bending test (Figure 3). The span of the beam was 2.2 m and the loading forces were applied at 1/3 of the length of the beam. Beams were designed to obtain failure caused by a bending moment. During the experiment following input data were monitored – force load, deflection on several points and strain of the reinforcing bars (monitoring units build into the reinforcement [2]).

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Three specimens with the longitudinal reinforcement were exposed to load forces. Also three specimens without the reinforcement were loaded to provide reference data and to make possible the comparison of effects of the reinforcement. Results of specimens without reinforcement allowed also validating the input data (i.e. material model of the concrete) used in FEM numerical model.

Figure 3. Deflection of the loaded beam before the collapse

All three reinforced beams collapsed because of exceeding the tensile strength of the GFRP bars. Two of them collapsed under the load force, one beam collapsed in the middle. Maximal average load carrying capacity of this beam improved from total 6.11 kN (calculation presumption 6.09 kN) to 17.19 kN (calculation presumption 16.38 kN - according to ACI 440.1R-03 without any safety factors). The tests results demonstrated the functionality of the developed non-metallic reinforcement.

The development of the load-deflection curve is in Figure 4. Also comparison of the behavior between reinforced beams (specimen 1-3), non-reinforced beams (reference specimens 1-3) and numerical model of the reinforced beam (Atena 3D results) can be found there.

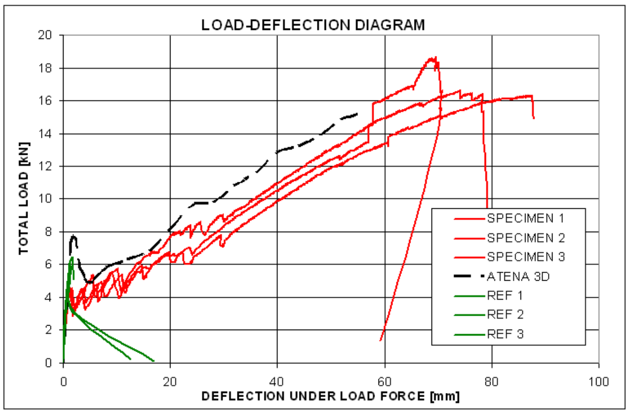

Figure 4. Deflection of the beam with longitudinal GFRP reinforcement

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2. CONCRETE MEMBERS WITH LONGITUDINAL AND SHEAR GFRP REINFORCEMENT

The non-metallic reinforcement was tested also as shear reinforcement. The longitudinal reinforcement in these beams were the GFRP bars (diameter 14 mm, one-side-wrapped bars – same as mentioned before). The shear reinforcement was created from one GFRP bar (diameter 8 mm, one-side-wrapped bars) shaped into spiral looped around all longitudinal reinforcement bars – see Figure 5.

This reinforcement had to be shaped before hardening. Thus the curing method was changed and the curing of the already shaped and fixed reinforcement proceeded at the room temperature. The hardening of the bar took more time, but the material characteristics were not reduced.

Figure 5. Shear reinforcement shaped into spiral

All beams (dimensions 115 x 240 x 2100 mm) were loaded by the same way as the beams with longitudinal reinforcement only. It means the load scheme was classical four-point bending test with load points at 1/3 of the span. Supposed failure mode was exceeding the shear capacity in the area near supports.

Again the test set was made from three test specimens with shear reinforcement and from three “reference” specimens without shear reinforcement. The reinforcement influenced positively the shear capacity of the tested beam and confirmed its functionality. The shear capacity improved from 54.7 kN (reference specimens without shear reinforcement) to 82.2 kN (reinforced specimens).

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Figure 6. Cracked beam with GFRP shear reinforcement

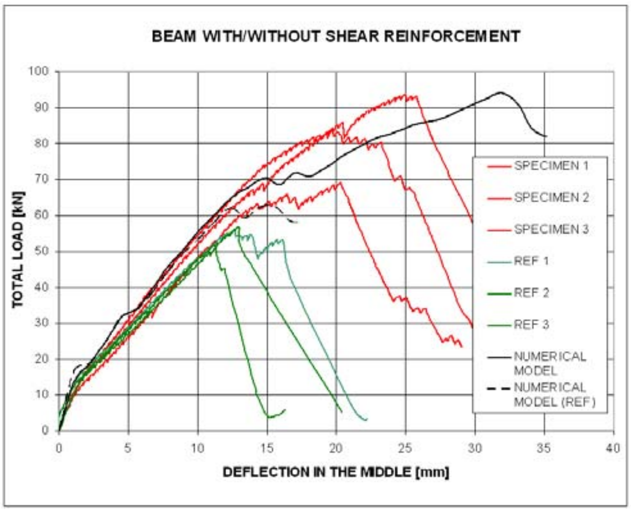

Figure 7. Deflection of the Beam with GFRP Shear Reinforcement
(REF Specimens are Reference Specimens Without Shear Reinforcement)

The tests results demonstrated the functionality of the developed non-metallic reinforcement.

3. MASONRY STRUCTURES STRENGTHENED WITH GFRP BARS

Within experimental parts of the project three sets of masonry vaults with for various loading types were manufactured. For the distinction of 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).

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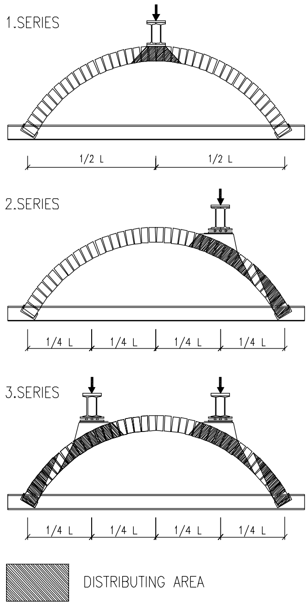

Figure 8. Loading scheme of the vaults and distribution zones of the load in the vaults

Each series consists of three vaults: non-strengthened – 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 of the width 890 mm, span 2600 mm, deflection 750 mm and radius 1500 mm.

Into every reinforcing chases were embedded 2 bars. First experiments were performed with reinforcement HeliBar of special helical shape of diameter 8 mm and the second set of test specimens were reinforced with GFRP bars of diameter 6 mm (one-side wrapped). Only unsymmetrical loading in ¼ of the span was used for testing vaults with non-metallic reinforcement (it is the case of the biggest influence of the additional strengthening [4]).

3.1. Behavior under static load

From the comparison of the load-bearing capacity of the individual vaults in the series results that essential growth of the load-bearing capacity was achieved especially in the case of 1st series and 2nd series of the vaults, namely more than eight multiple growth. This growing of carrying-capacity can be watch for both cases of reinforcement – helical metallic and non-metallic. It was related to the vaults stressed by either concentrated or one-sided load, at which the vaults were loaded by the interaction of normal forces and bending moments.

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In the 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 themselves because the vaults were mainly compressed.

In the case of non-strengthened vaults of 1st and 2nd series the failure was acute, main crack was opened and the vault ruptured. In the case of the strengthened vaults of 1st and 2nd series came to the gradual opening of separate cracks until the failure, which was accompanied by the rapture of the metallic reinforcement from the chases. All glass reinforcing bars were in the ultimate limit state ruptured.

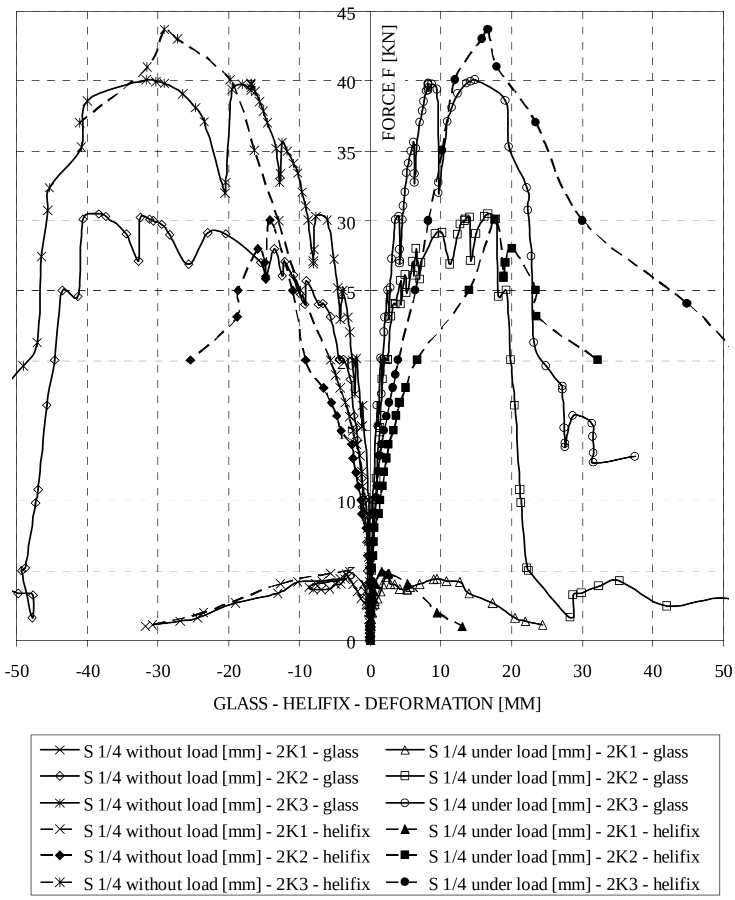

Figure 9. Comparison of deformations on vaults loaded in ¼ of the span strengthened with GFRP and metallic helical reinforcement

On the basis of thus obtained results from numerical studies and on the base of the designed algorithm, it will be possible to obtain (substantiate) simple constitutive relations for the evaluation and design of strengthening by simplified designed methods used in the practice and to set up simple algorithms for design and checking calculation of the masonry vaulted construction with additional reinforcement for the practice.

3.2. Behavior under dynamic load

Dynamical tests were performed on vaults loaded asymmetrically in 1/4 of the span and reinforced with glass reinforcement (GFRP) only. From results of first dynamical tests it is visible increasing of load-bearing capacity of the reinforced vaults (2K2, 2K3) compared to the non-reinforced vault (2K1) (Figure 10).

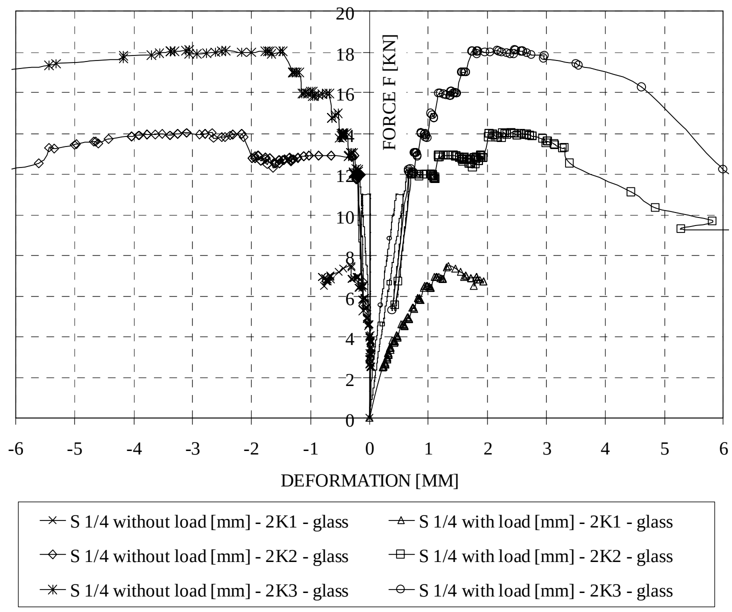

Figure 10. Comparison of deformations on vaults loaded in ¼ of the span strengthened with GFRP reinforcement – dynamical test

Unfortunately the low set of tested specimen prohibited comparison with the test data from statical experiments. The results are also influenced by the big non-homogeneity of masonry structure. Also the fracture mode (i.e. failure of the vault by opening of tension cracks in the bed joint) is not uniform and the position of cracks can influence the final load bearing capacity.

Strengthened vaults can be partially compared by relation of their load-bearing capacity. Ratio of the load-bearing capacity of the vaults with three reinforcing chases and with two chases (2K3/2K2) at statical loading is 1,33 and at dynamical loading is 1,29.

3. CONCLUSION

The tests showed that the developed system is functional. The reinforcement bars can work as concrete reinforcement and they are capable to transfer the load forces generated in the construction during the loading.

There is also very positive benefit for the strengthening of the masonry vaults. This system can be used to repair the historical structures with minimal impact to the structure itself (thanks to low requirements for cover – there is no need to provide additional layers of cover materilas).

So far only short term tests were performed. To fully confirm the functionality and safety of the newly developed reinforcing system it will be necessary to verify the long term characteristics of the reinforcement. The main subjects of research will be the behavior of the reinforced structures under the long term loads. Also the resistibility of the reinforced structures in the aggressive environment has to be verified.

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