CONCRETE AND MASONRY ELEMENTS REINFORCED WITH NEWLY DEVELOPED FRP REINFORCEMENT

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ABSTRACT

A new reinforcement based on glass or carbon fibre reinforced polymers in frame a Czech ministry of industry and trade research task was developed. A set of experiments was made for reinforcing concrete structures with this FRP internal reinforcement. The developed reinforcement was used for reinforcing several concrete elements. These elements were exposed to different types of loading. Their behaviour 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 type of reinforcing (longitudinal or shear reinforcement). This reinforcement was also used for additional strengthening of masonry vaults stressed with static and dynamic loads. Obtained results are compared with theoretical results of nonlinear numerical analysis of constructions.

KEYWORDS

FRP, RC beams, strengthening, interfacial stresses, analytical solution.

INTRODUCTION

At present non-metallic reinforcement is used very frequently (because of their resistibility) in constructions that are exposed to aggressive environmental influence. It makes possible to reduce costs needed for special protection finishing of the common reinforcement and eventually consecutive repairs. However the price of the non-metallic reinforcements is quite high. And because this reinforcement form the significant part of the total cost 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. The economic aspect mentioned above is not so strong in the Czech Republic since there is not any national producer of this kind of reinforcement. Provided the reinforcement is used, it is necessary to import it from abroad, which makes construction often more expensive.

In terms of a research in the frame of The Czech Ministry of Industry and Trade, development of “home” reinforcement based on glass and carbon fibres has started. Indeed, it is necessary to check out the functionality of this system – i.e. the functionality of the interaction of reinforcing bars and surrounding concrete.

However, not only new concrete structures are in the centre of interest. Masonry structures continue to be popular because of their 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 existing masonry construction are increasingly based on analyses of mathematical simulation and appropriate (linear and nonlinear) calculation models. One method of load-bearing members strengthening is application of additional external non-prestressed reinforcement into chases in masonry on intrados of vaults, which will provide both stiffening and increasing load carrying capacity of the individual load-bearing members. Nowadays, the existing and especially historical masonry structures are considerably monitored. Many of them are in need of some retrofitting or strengthening. In such cases the non-metallic reinforcement with minimal requirements for covering could be the best solution even in aggressive environment. Therefore some tests were performed to analyse the behaviour of masonry vaults additionally strengthen with GFRP bars. These tests logically followed the 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 data obtained from the tests are used to set up and verify a numerical model of FRP reinforcing materials used in calculations. This model should allow predict the
behaviour of concrete and masonry structures reinforced with FRP bars as accurate as possible. Mathematical model is set up using 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, stress-strain diagram, modulus of elasticity). The cohesion between reinforcement and concrete (grouting) is modelled 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 Stepanek et al. (2006)).

**Concrete Reinforcement**

Tests are performed in several partial fields:

1. obtaining physical-mechanical characteristics of reinforcement,
2. obtaining cohesion between reinforcement and concrete,
3. monitoring behaviour of specimens reinforced with non-metallic reinforcement (i.e. real function of reinforcement in loaded construction).

The first two research items were completed and all the results were analysed (Stepanek et al. (2006)). The choice of the most suitable type of reinforcement was achieved on the base of 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 both as longitudinal and shear type of reinforcement.

**Strengthening 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 redistribute newly originated stresses from load acting on a strengthened construction. The aim of reinforcement is to restrict an extension of existing cracks and eliminate possible origin of the new ones, and to improve load-bearing capacity of vaulted masonry constructions.

From the static viewpoint, non-reinforced masonry structure is unable to transfer tensile forces that can originate on existing structure from following actions:

1. action of the higher imposed load against the designed one,
2. 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 masonry structures were used two types of reinforcing materials (shape of these reinforcing bars can be seen in Figure 1):

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

Figure 1. 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 that the reinforcing bars compose with grouting substance and with origin masonry the reliable and durable system.
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 with different pitch height). This test was classical four-point bending test (Figure 2). The span of the beam was 2.2 m and the loading forces were applied at 1/3 of the beam length. The 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 built into the reinforcement (Horak et al. (2006)).

Five specimens with two different types of longitudinal reinforcement (with different surfacing) were exposed to load forces. Three specimens without the reinforcement were also loaded to provide reference data and to make possible the comparison of effects of the reinforcement. Results of specimens without reinforcement also allowed validate the input data (i.e. material model of the concrete) used in FEM calculation model.

All reinforced beams collapsed because of exceeding the tensile strength of the GFRP bars. Two of them collapsed in the middle, the rest of the beams collapsed under the load force. 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 3. The comparison of the behaviour between reinforced beams (specimen 1-3), non-reinforced beams (reference specimens 1-3) and calculation model of the reinforced beam (Athena 3D results) can be also found there.

There is also significant influence of the surfacing of the reinforcement bars. Just a small difference of the surfacing i.e. surface characteristics of the reinforcement can cause big growing of the deformation. In this case the deformation growth of 30 mm (almost 40% of maximal deflection) was caused by minor change of the pith of the one-direction-wrapped surface (Stepanek et al. (2006)).

Because of the high influence of this point it is advisable to pay attention to this problem during development of new kinds of reinforcement. Optimisation and verification of the surfacing can cause huge differences in the behaviour of reinforced constructions. Not only concerning load capacity of the construction but also the ductility and maximal deformations that can be the limit factors for state estimation and calculations.
CONCRETE MEMBERS WITH LONGITUDINAL AND SHEAR GFRP REINFORCEMENT

The non-metallic reinforcement was tested also as shear reinforcement. The longitudinal reinforcement in these beams was formed by the GFRP bars (diameter 14 mm, one-side-wrapped bars – the same as mentioned before). The shear reinforcement was formed by one GFRP bar (diameter 8 mm, one-side-wrapped bars) shaped into spiral looped around all longitudinal reinforcement bars – see Figure 4.

This reinforcement had to be shaped before hardening. Therefore 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.

All beams (dimensions 115 x 240 x 2100 mm) were loaded in 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 mode of failure was exceeding the shear capacity in the area near to supports.

Again, the test set involved 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).
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).

![Loading scheme of the vaults and distribution zones of the load in the vaults](image)

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. 2 bars were embedded into every reinforcing chase. 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 – see Stepanek and Zlamal (2006)).

**Behaviour under Static Load**

From the comparison of the load-bearing capacity of the individual vaults in the series results (Figure 8a) 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.

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 rupture of the metallic reinforcement from the chases. All glass reinforcing bars were in the ultimate limit state ruptured.

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.

**Behaviour 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 the first dynamical tests it is visible the increasing of load-bearing capacity of the reinforced vaults (2K2, 2K3) in comparison to the non-reinforced vaults (2K1) (Figure 8b).

Unfortunately the low set of tested specimen prohibited comparison with the test data from static 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 static loading is 1.33 and at dynamical loading it is 1.29.
**CONCLUSIONS**

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 materials).

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. Also the resistibility of the reinforced structures in the aggressive environment has to be verified.

During dynamical loading of the FRP reinforced masonry vaults in some cases the reinforcement was ruptured even though the stress level did not reach the load capacity of the material and at the same time there was only tension in the bar (assumption based on mathematical solution of the problem type). Therefore it is probable the material characteristics of the FRP bars change during dynamical loading and there is significant drop in their performance. Further studies on this problem are planed and should be completed in the early future.

**ACKNOWLEDGEMENTS**

This research has been proceeded under the support of The Czech Ministry of Industry and Trade (MPO) within a research task 1H-PK2/57 – “Durable concrete structures” and with the financial support of The Ministry of Education, Youth and Sports, project No. MSM0021630519 - “Progressive reliable and durable load bearing structures”.

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