# Experimental investigations of the behavior of RC slabs retrofitted by a mixed NSMR-FRP and EB-FRP technique

S. C. Floruț[1], V. Stoian [1], D. Diaconu[1] and D. Dan[1]

[1] "Politehnica" University of Timisoara, Timisoara, Romania

ABSTRACT: The paper presents some aspects regarding a research program that is in progress at the "Politehnica" University of Timisoara. The program deals with FRP composite based solutions for strengthening of reinforced concrete slabs with and without cut-out openings. Theoretical and experimental researches have been performed in order to determine the effectiveness of these strengthening solutions in the particular case of cut-outs created in the corners and on the edges of the slabs.

The first phase of the experimental program involves tests on four large scale elements. Before being retrofitted, all of the elements are to be tested up to a certain stage. Afterwards, a mixed strengthening solution that involves the use of both near surface mounted reinforcement (NSMR-FRP) and externally bonded (EB-FRP) techniques is applied. After allowing the materials to cure, the elements are retested up to failure.

In the present paper, the experimental results obtained on two of the slabs are presented.

## 1 INTRODUCTION

In today's world of civil engineering, specialists consider more and more the composite materials, especially the fiber reinforced polymers (FRPs). The composite materials properties have made their use to prove a real success in a series of applications, starting with local strengthening up to highly complex works. One of the circumstances in which the use of FRP might be suitable refers to strengthening/retrofitting of reinforced concrete slabs. In many situations, the need of creating new openings into existing structures' slabs arises, mostly due to changes in functionality or in destination.

Thus, one of the experimental programs that is in progress at the "Politehnica" University of Timisoara concerns the study of strengthening/retrofitting solutions that involve the use of FRPs for reinforced concrete slabs, with and without cut-out openings. Similar studies were previously performed worldwide, on one-way and two-way slabs, with or without cut-out openings. However the amount of information on this topic is quite limited, the present research program being developed with the purpose of providing supplementary data to interested research communities.

Most of the researches on reinforced concrete slabs strengthening were made on one-way ones. In some of those studies, the reinforced concrete slabs' behavior was very similar to that of beams. The usual strengthening method presumes the disposal of the lamellas or sheets bonded on the tensioned side using resins. The sheets are mounted parallel to the long edge of the slabs, the same way as flexural strengthening of beams. There is also the possibility to prestress the sheets, complementarily to the simple procedure of bonding them.

Two-way reinforced concrete slabs are elements subjected to flexure with irrelevant shear effect. In addition to the important increase in serviceability and flexural capacity, provided to a RC slab by a retrofitting system that uses FRPs, the unlaborious appliance of such a system also consists in an important advantage. The strengthening method, same as one-way reinforced concrete slabs, presumes the disposal of the lamellas or fabrics bonded on the tensioned side by using resins. In two-way reinforced concrete slabs, the composite material is, off course, mounted parallel to both length and width of the slabs.

For slabs with cut-out openings strengthened using FRP, the available research is scarce, only several research programs being reported in literature, as work conducted by Tan & Zhao (2004), Vasquez & Karbhari (2003), Enochsson (2005) or Smith (2009) being of high importance. The solution applied by all of the researches consisted in laying up CFRP or GFRP strips or sheets of fabrics around the cut-out and bonding them to the concrete surface, on the tensioned side, using epoxy based resins. Different configurations for the lay-out of the strengthening materials were used, the most common being the one in which the material is placed parallel to the edges of the cut-out.

## 2 EXPERIMENTAL PROGRAM

The experimental program consists in testing four reinforced concrete two-way slab panels up to failure. The elements are large scale ones, having dimensions of 2650x3950x120 mm. The first specimen (denoted RCS-FS-01 standing for Reinforced Concrete Slab - Full Slab) was a full slab and served as reference. Into the second element (denoted RCS-RSC-01 standing for Reinforced Concrete Slab - Rectangular Small Cut-out) a rectangular cut-out of 960x1540 mm. The experimental results obtained on these two slabs are presented in this paper. The other two elements also have cut-outs designed into them, but they do not represent the scope of the present paper. The purpose of the program is to verify the design of strengthening solutions. The geometrical characteristics of the first two experimental elements are presented in Fig. 1.

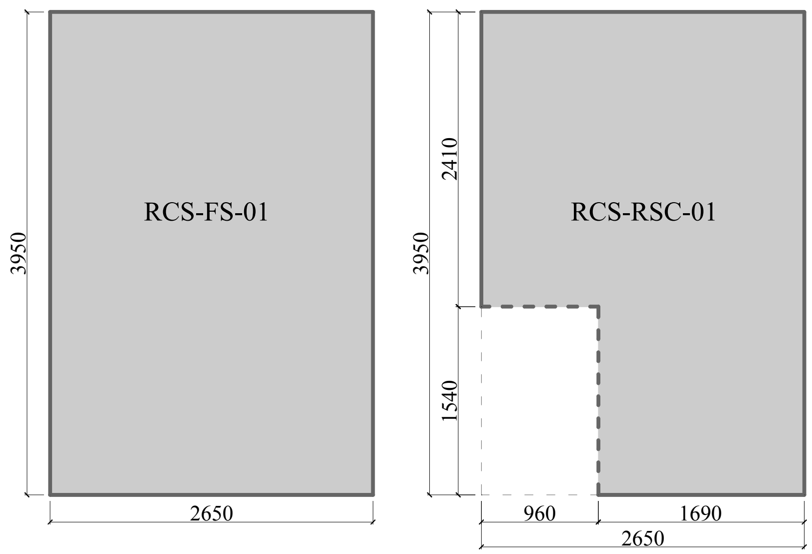


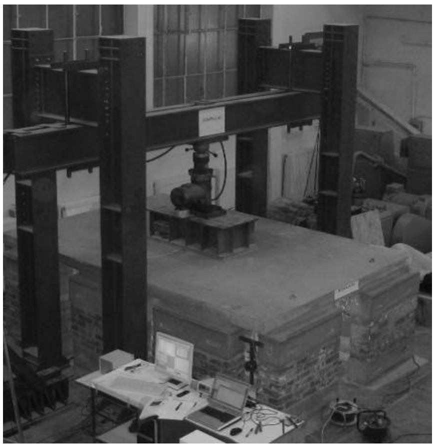

Figure 1. Geometrical characteristics of first two elements of the experimental set.

Based on experimental tests on samples, it was evaluated that elements RCS-FS-01 and RCS-RSC-01 were cast using concrete with cubic compressive strength of 65 MPa (N/mm$^2$). The slabs were reinforced with steel welded wire meshes at the inferior side (4 mm in diameter with spacing of 100 mm) and with steel rebars at the superior one (6 mm and 10 mm bars). The bars in the steel welded wire meshes had average yield strength of 597 MPa and 537 MPa for the RCS-FS-01 and RCS-RSC-01, respectively. The inferior reinforcement was laid on the entire surface of the slab, while the superior one was placed only along the edges. Since the reproduced situations involved simple supported slabs, the superior reinforcement was designed mainly due to constructive reasons.

## 3 TESTING PROCEDURE

Since applying uniformly distributed loads on entire surface of slabs is quite cumbersome, it was decided to use a uniformly distributed load over a central patch of 600x1200 mm. Since the loading patch is positioned in the center of the full slab, quite close to the position of the cut-out for the second slab, it creates an unconservative type of loading. The edges of the experimental elements rest with 10 cm on a series of supporting elements through a layer of mortar. For inducing the load, a hydraulic jack with a maximum load capacity of 500 kN and a maximum stroke of 160 mm was used. Underneath the hydraulic jack, a steel piece was placed, with the purpose of distributing the concentrated load induced by the jack onto the loading surface. The load is applied in one single cycle at constant rate.

The strategy is to test elements before being retrofitted up to a stage that would assume the need of retrofitting interventions. Afterwards, a mixed strengthening solution that involves the use of both NSMR-FRP and EB-FRP techniques is to be applied. Finally the retrofitted element is tested up to its complete failure. A general view of the entire test setup can be observed in Fig. 2, along with a transversal cross section through the setup.



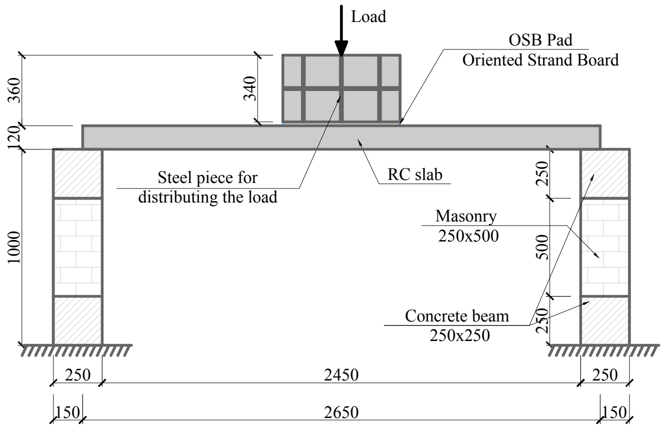



Figure 2. General view and a transversal cross section through the test setup.

## 4 BEHAVIOR OF EXPERIMENTAL ELEMENTS PRIOR TO RETROFITTING

As mentioned previously, each slab is tested prior to retrofitting up to a stage that corresponds to a level of damages that would impose retrofitting. The two slabs were denoted RCS-FS-UU-01 and RCS-RSC-UU-01 (UU - standing for Undamaged-Unretrofitted, characterizing the state of the slab at the beginning of the test through its damage and retrofitting perspectives).

For the full slab (RCS-FS-UU-01) the measured parameters were: deflection in 10 points, strain in 6 rebars and on concrete, crack width and load level. As it can be observed on the load-displacement curve (Fig. 4), the maximum load level reached during this test was 113 kN. Past this value, the strain in numerous reinforcement bars has reached yielding point and the vertical mid-span displacement has passed the maximum allowable deflection (L/250=2400/250=9.60 mm), thus the progress of the test was stopped. During the test, the maximum strain in reinforcement was 7.52‰ while the vertical mid-span displacement had a value of 10.28 mm. The behavior of the slab was as expected, four cracks appearing on the direction of the yield lines, as depicted in Fig.4. The cracks originated at the corners of the load patch, being oriented at angles of 37°, 45°, 52°, and 55°.

For the second slab (RCS-RSC-UU-01) the measured parameters were: deflection in 8 points, strain in 4 rebars and on concrete, crack width and load level. As shown on the load-displacement curve (Fig. 5), the maximum load level reached during this test was 87 kN while the maximum vertical displacement had a value of 11.36 mm, being larger then the maximum allowable deflection. Three cracks appeared, as depicted in Fig. 5.

## 5 CFRP RETROFITTING SYSTEM AND BEHAVIOR OF RETROFITTED ELEMENTS

The required amount of CFRP that needs to be mounted is determined analytically, based on two simple assumptions. For the full slab amount of CFRP is determined by equating the tensile force that would have been taken up by the steel reinforcement (that is now yielded) with the tensile force that will be undertook by the CFRP. For the element with cut-out, the CFRP strengthening material will be placed around the cut-out on the tensioned side, along the two directions parallel to the edges of the element. The amount of CFRP is to be determined analytically by equating the tensile force that would have been taken up by the steel reinforcement eliminated by creating the cut-out, with the tensile force that will be undertook by the FRP.

$$F_s = F_f \quad \Rightarrow \quad A_f = \frac{f_{yd}}{E_f \cdot \varepsilon_f} A_s \tag{1}$$

Inside formula (1), the strain in CFRP composite is limited to 0.8%, this value being an accepted limit for elements subjected to flexure, according to the strain limitation approach as presented in fib bulletin 14 [13]. This value is much lower than the ultimate strain provided by the producers, being considered the value at which composite action is lost due to premature failure. For strengthening, it was decided to use CFRP lamellas that have a modulus of elasticity of 165000 MPa and a thickness of 1.2 mm and also CFRP sheets that have a modulus of elasticity of 230000 MPa and a thickness of 0.12 mm. On the direction parallel to the short edges of the slabs it was decided to use the NSMR-FRP technique and on the direction parallel to the long edges the EB-FRP technique. In Fig. 3, the lay-up of CFRP composites for the two slabs is depicted.

After being retrofitted, the slabs were renamed RCS-FS-DS-01 for the full slab and RCS-RSC-DS-01 for the slab with cut-out.

The RCS-FS-DS-01 slab was tested up to failure, reaching a maximum load of 180 kN corresponding to a vertical mid-span deflection of 50 mm. After this level, the deflection increased while the load diminished. The slab was able to deflect almost 110 mm before failure, thus giving an ample visual warning before collapse. Both the EB-FRP sheets and the NSMR-FRP that were intersected by the principal cracks, have failed due to CFRP rupture, no type of premature failure being observed.

The RCS-RSC-DS-01 tested after retrofitting reached a maximum load of 85.75 kN before failure. Maximum deflection was of 33 mm (40 mm if the residual deflection from the test performed prior to retrofitting is included). All of the five NSMR-FRP have failed by fiber rupture, while the EB-FRP has debonded from the concrete surface at relatively low strain, most probably due to high deflection of the slab.

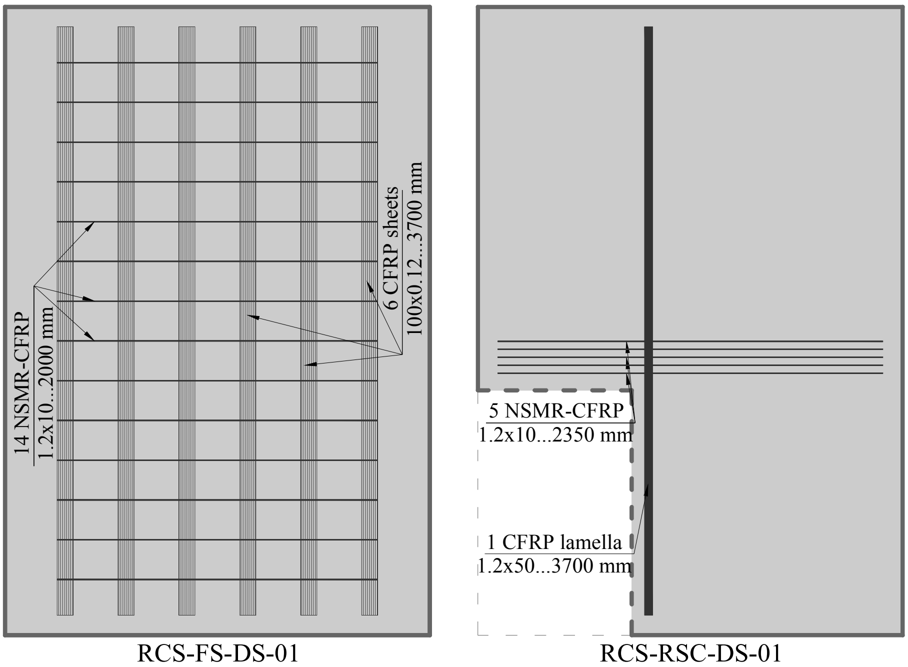



Figure 3. Retrofitting solutions for the two slabs.

In Fig. 4 and Fig. 5 the load-displacement diagrams for the two slabs prior to strengthening and after strengthening are presented.

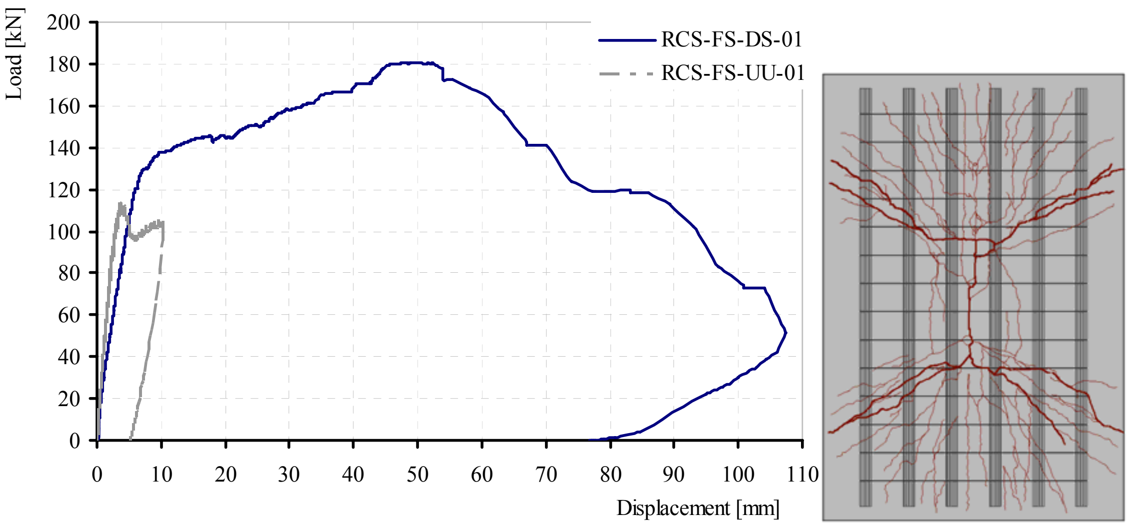



Figure 4. Load-displacement diagrams for RCS-FS-UU-01 and RCS-FS-DS-01 and crack pattern for RCS-FS-DS-01 slab.

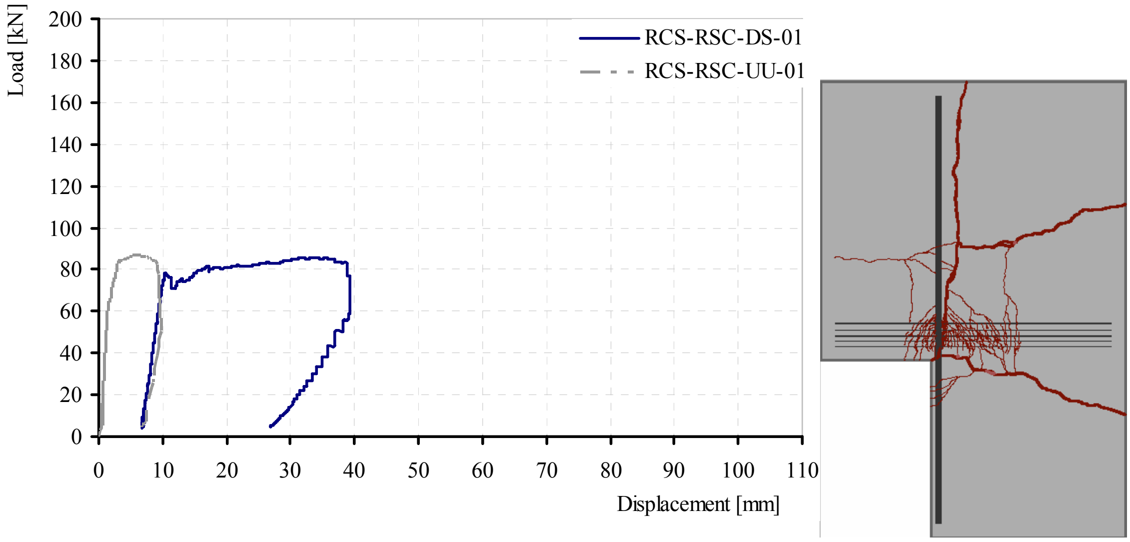



Figure 5. Load-displacement diagrams for RCS-RSC-UU-01 and RCS-RSC-DS-01 and crack pattern for RCS-RSC-DS-01 slab.

The strain gauges mounted on CFRP provided some information regarding the way the NSMR-FRP and EB-FRP work. For the RCS-FS-DS-01 slab, nine strain gauges were mounted on CFRP, five of them on NSMR and four of them on EB-FRP. Three of the gauges mounted on NSMR-FRP were placed on the same strip, at various distances from the center of slab. Gauge G-F-01 was mounted right in the center and starting from the center towards the long edges, G-F-02 and G-F-03 were placed at 450 mm and 900 mm respectively. The values of the maximum strain recorded in all of the three gauges are presented in Fig. 6. For the RCS-RSC-DS-01 slab seven strain gauges were mounted, four on the NSMR-FRP strips and three on the EB-FRP lamella. Three of the gauges mounted on NSMR-FRP were placed on the same strip (on the strip that was nearest to the edge of the cut-out). Gauge G-F-01 was placed near the corner of the cut-out while G-F-02 and G-F-03 were positioned at 300 and 550 mm respectively, to the left. The principal crack, highlighted in Fig. 5 passed at a very small distance of gauge G-F-01, this gauge recording the highest strain from all of the three gauges. The values of the maximum strain recorded in all of the three gauges are presented in Fig. 6. The variation of the strain in gauges mounted on strips, sheets or lamellas also give some indications regarding development and anchorage length.

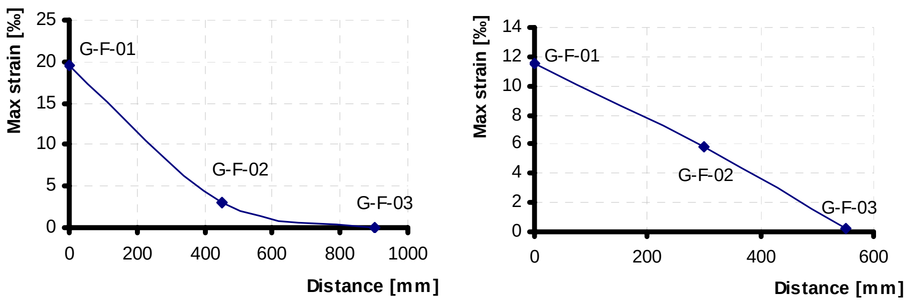



Figure 6. Maximum strain recorded by gauges at various positions.

## 6 CONCLUSIONS

The behavior of the full slab (RCS-FS-UU-01) was improved quite significantly after applying the retrofitting system. Considering that the test of the RCS-FS-UU-01 slab was stopped after reaching its maximum load capacity at 113 kN, it can be stated that the load capacity at U.L.S. is improved by 59.3%. However, if the allowable deflection at S.L.S. is considered, the load capacity is improved only by 37.3%, the corresponding load level being 102 kN and 140 kN, prior and after retrofitting, respectively.

Regarding the slab with cut-out (RCS-RSC-UU-01), by applying the retrofitting solution, the capacity was restored, but no gain was achieved. The amount of CFRP laid-up around the cut-out was insufficient for increasing the bearing capacity of the slab. The failure of NSMR-FRP by fiber rupture along with the crack pattern, proved the effectiveness of the CFRP elements. The determinant area of failure in the slab has shifted away from the edges of the cut-out, into the area that was unretrofitted. The scope of the retrofitting is considered to have been fulfilled, by restoring initial capacity.

## ACKNOWLEDGEMENTS

The research work was granted partially by the Ministry of Education and Research through the CEEX and CNCSIS programs of the National University Research Council of Romania.

## REFERENCES

Arduini M., Nanni A., Romagnolo M., Performance of one-way reinforced concrete slabs with externally bonded fiber-reinforced polymer strengthening, ACI Structural Journal, V. 101, No. 2, 2004, 193-201.

Enochsson O., CFRP strengthening of concrete slabs, with and without openings. Experiment, analysis, design and field application. Licentiate thesis, Luleå University of Technology, 2005.

Floruț S. C., Nagy-György T., Stoian V., RC slabs strengthened with externally bonded FRP composite materials - Literature review, Composite Materials Elements and Structures for Construction, Timisoara, Romania, may 2007, pp 175-180.

Floruț S.C., Stoian V., Nagy-György T., Dan D., Diaconu D., Combined NSMR-FRP and EB-FRP technique applied for retrofitting of RC slabs, Proceedings of 13th International Conference Structural Faults and Repair, 2010, pp. 113.

Limam O., Foret G., Ehrlacher A., RC two-way slabs strengthened with CFRP strips: experimental study and a limit analysis approach, Composite Structures 60 (2003), pp. 467-471.

Mosallam, A. S., Mosalam, K. M., Strengthening of two-way concrete slabs with FRP composite laminates, Construction and Building Materials 17 (2003), pp. 43-54.

Mosallam A., Kreiner J., Lancey T., Haroun M., Elsanadedy H., Experimental and numerical analysis of two-way concrete slabs repaired with polymer composites, Center for Advanced Composites & Smart Systems for Repair and Rehabilitation.

Nagy-György T., FRP composite materials for strengthening masonry and concrete elements (in Romanian), Ed. Politehnica, Timişoara, ISBN 978-973-625-445-1, 2007.

Smith S.T., Kim S.J., Strengthening of one-way spanning RC slabs with cutouts using FRP composites, Construction and Building Materials, Volume 23, Issue 4, 2009, pp 1578-1590.

Stoian V., Nagy-György T., Dan D., Gergely J., Dăescu C., Composite materials for construction (in Romanian), Editura Politehnica Timişoara, ISBN 978-973-625-948-7, 2009.

Tan K. H., Zhao H., Strengthening of openings in one-way reinforced-concrete slabs using carbon fiber-reinforced polymer systems, J. Compos. for Constr., Volume 8, Issue 5, pp. 393-402 (September/October 2004).

Vasquez A., Karbhari V. M., Fiber-reinforced polymer composite strengthening of concrete slabs with cutouts, ACI Structural Journal, V. 100,No. 5, September-October 2003, pp. 665-67.

Guide for the Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures, ACI 440.2R – 02, 2002.

Technical Report on the Design and Use of Externally Bonded FRP Reinforcement for Reinforced Concrete Structures, fib Bulletin 14, TG.