Retrofitting of two-way RC slabs with and without cut-out openings by using FRP composite materials

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Abstract: - The paper presents some aspects regarding a research program that studies the behavior of reinforced concrete slabs retrofitted by using Fiber Reinforced Polymer composites. Theoretical and experimental investigations are being performed in order to determine the effectiveness of these strengthening solutions. The particular case of cut-outs created in the corners and on the edges of the slabs is of interest.

A preliminary section of the experimental program involves tests on four reinforced concrete slabs. The elements are large scale ones, having dimensions of 2650x3950x120 mm. The first element is a full slab, while in each of the other three elements a different shape of cut-out is created. The slabs are tested in horizontal position, being simply supported along all of the edges and loaded gravitationally. Before being retrofitted, all of the elements are tested up to a certain stage. Afterwards, a combined retrofitting solution that involves the use of both externally bonded and near surface mounted reinforcement techniques is applied. After allowing materials to cure, the slabs are retested up to failure. In this paper, the results obtained on the full slab (without any cut-out openings), are presented.

Key-Words: - Two-Way Slabs, Retrofitting, FRP Composite Materials, Near Surface Mounted, Externally Bonded.

1 Introduction
Nowadays, civil engineering considers 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 from local strengthening to highly complex works. Preferring composites in some applications instead of traditional steel or reinforced concrete (RC) based strengthening solutions is grounded on many reasons. The composites’ very high corrosion resistance along with the short amount of needed construction time and low weight are probably the most important of all.

One of the experimental programs that are in progress at the “Politehnica” University of Timisoara concerns the study of retrofitting solutions that involve the use of FRP for two-way RC slabs with cut-outs. In many situations, openings are needed in slabs, in places that were not considered during the design of a building. This need emerges mostly due to a series of changes in functionality. There is also the case in which some openings were considered in the design process but due to changes in functionality or in destination, the loads to which the slabs are subjected become much higher. In either one of these situations, the slab’s overall behavior becomes deficient, both as stiffness and load bearing capacity. The area in which these effects are of most importance is the area around the cut-out, where stresses are highly concentrated. Any situation from the two previously mentioned, leads also to an important change in the overall failure mode, leading to new and unexpected ones.

2 Characteristics of similar studies previously performed worldwide
Most of the researches on the strengthening of RC slabs were made on one-way ones. In some of those studies, the slabs’ behavior was very similar to that of beams. The usual strengthening method presumes the placing 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.
Generally speaking, the two-way RC slabs are elements subjected to flexure with irrelevant shear effect. That is why they are susceptible rather to flexural than shear failure. This particularity makes the use of composite materials in two-way RC slabs strengthening to be considered as an optimal solution. In addition to the important increase in serviceability and flexural capacity, using of FRP strengthening methods is justified by its unlaborious appliance. The reserve in using of FRP materials in strengthening of flexural structural members is the brittleness of such materials that can cause a decrease in the element’s stiffness. The retrofitting method, same as one-way RC slabs, presumes the laying up of the lamellas or sheets bonded on the tensioned side by using resins, the FRPs being, off course, mounted parallel to both length and width of the slabs. This method increases the capacity in both directions of the element.

For slabs with cut-out openings strengthened using FRP, the available research is not as extended, only several research programs being reported in literature, the work conducted by Tan & Zhao [12] and Vasquez & Karbhari [13], Enochsson [3] or Smith [10] 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 using epoxy based resins on the tensioned side. 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.

In all of the previous research programs, the cut-outs were created in the center of the tested slabs and none of the programs dealt with circular cut-outs. Considering these two main aspects, the research program conducted at the “Politehnica” University of Timisoara can be considered innovative, covering a research area that has not yet been approached.

3 Experimental elements
The experimental program consists in testing four RC two-way slabs up to failure. The elements are large scale ones, having dimensions of 2650x3950x120 mm. The first specimen (denoted RCS-FS-01) was a full slab and served as reference, while in each of the other three elements a different shape of cut-out will be created. The purpose of the program is to verify the design of strengthening solutions that will restore the strength for the elements with cut-out up to the level of the full slab.

The geometrical characteristics of the experimental elements are presented in Fig. 1.

All of the slabs were cast using C30/37 concrete and 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 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.

4 Loading and testing strategy
In order to match the loads considered for the design, the slabs should be subjected to uniformly distributed loads. Since this type of loading 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 central of the full slab, quite close to the cut-outs, it creates an unconservative type of loading. Using this system, the inferior side becomes the tensioned one, the steel welded wire mesh reinforcement becoming
the tensioned reinforcement. The edges of the experimental elements rest 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 on to the loading surface. The load is applied in one single cycle at constant rate.

Before being retrofitted, all of the elements are to be tested up to a certain stage. Afterwards, a mixed retrofitting solution that involves the use of both NSMR-FRP and EB-FRP techniques is applied.

A general view of the entire test setup can be observed in Fig. 2. A top view of the slabs with highlight of the position of the cut-outs and of the load patch is presented in Fig. 3.

![Fig. 2. Test setup](image)

![Fig. 3. Top view of slabs with the position of patch load](image)

5 Design of strengthening system

A simplified analytical approach was applied in order to determine the total amount of carbon fiber reinforced polymer (CFRP) that is to be placed on each element. For all elements subjected to flexure, the strengthening procedure consists in applying of the CFRP components on the tensioned side, in the required direction and quantity. In the case of the present research program, the CFRP elements will be placed at the inferior side, on two directions, parallel with the edges.

Two different approaches were applied for the full slab on one hand and for the slabs with cut-outs on the other, based on two different assumptions.

The full slab is tested unstrengthened up to the level at which almost all of the reinforcement on the short direction reaches its yield strength. Thus, considering that this reinforcement has reached its capacity, the slab would have to be retrofitted. The required amount of CFRP is determined analytically by equalizing the tensile force that would have been undertook by the steel reinforcement (that is now yielded) with the tensile force that will be undertook by the retrofitting CFRP system. In Fig. 4, the lay-up of CFRP composites for the full slab is depicted.

For the elements with cut-outs, the CFRP strengthening material will be placed around the cut-out on the tensioned side, also along the two directions parallel to the edges of the element. The amount of CFRP is to be determined analytically by equalizing the tensile force that would have been undertook by the steel reinforcement eliminated by creating the cut-out, with the tensile force that will be undertook by the FRP.

\[ F_s = F_f \quad \Rightarrow \quad A_f = \frac{f_{yd}}{E_f \cdot \varepsilon_f} A_s \quad (1) \]

In these formulas, 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 [15]. 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.
6.2 Retrofitting procedure

The slab was then retrofitted and renamed RCS-FS-DS-01. On the direction parallel to the short edge of the slab, fourteen NSMR-FRPs were mounted while on the direction parallel to the long edge of the slab six EB-FRPs were applied (as shown in Fig. 4). The NSMR-FRPs consist of CFRP lamellas and the EB-FRPs consist of CFRP sheets of fabric. The properties for the strengthening materials are given at section 5.

The grooves into which the NSMR-FRPs were mounted had a rectangular cross section of 5x14 mm and a length of 2000 mm and were distributed evenly along a central length of 3250 mm, the spacing being of 250 mm. The width of the cross section of the NSMR was of 1.2 mm while the height was of 10 mm.

The length of the EB-FRP was of 3700 mm, the spacing between two adjacent sheets being 380 mm. The width of the cross section of the EB-FRP was of 100 mm while the height (thickness) was of 0.12 mm.

The technological steps that were followed are:
- cutting of the grooves
- grinding of the areas in which the EB-FRPs are to be mounted
- vacuuming and air-cleaning of the entire surface of the slab
- filling of the grooves with epoxy resin (2, 3 grooves at a time)
- mounting of the NSMR-FRPs in the grooves. It was decided to use the solution of three side bonded NSMR strips as classified by De Lorenzis and Teng [2].
- lay-up of the EB-FRP.

A significant section of the strengthening process is related to the mounting of the NSRM-FRPs. Since the width of the grooves is quite small and the strips that are mounted are rather long, the mounting process becomes a very cumbersome operation. In the same time, perfect centering of the NSMR-FRP inside the middle of the groove is critical for the effectiveness of the system. As far as the best of authors’ knowledge, in scientific literature, there is no mention what so ever, of any practical solutions for overcoming this decisive aspect of the NSMR-FRP system. The solution that proved to be effective in the case of the present study, involved the use of a series of plastic cotters. The NSMR-FRP is to be mounted and pushed inside the groove in the same time with the cotters. In each section, two identical cotters are used, one on each side of the NSMR-FRP. For the present NSMR-FRP that had length of 2000 mm, six cotters (placed in three sections alongside the length of the element) were considered.

6 Retrofitting procedure and experimental results for the full slab

6.1 Behavior of element prior to retrofit

It was decided to test the full slab element prior to any retrofitting interventions up to a certain level, the test being named RCS-FS-UU-01. The measured parameters were: deflection in 10 points, the strain in six rebar and on concrete, crack width and load level. The test was stopped after yielding of a sufficient number of reinforcement bars. As it can be observed on the load-displacement curve (Fig. 8), 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 past the maximum allowable deflection (L/250=2400/250=9.60 mm).

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. The cracks originated at the corners of the load patch, being inclined at angles of 37°, 45°, 52°, and 55°.
to be sufficient. The previously described solution is depicted in Fig. 5. The inferior side of the completely retrofitted element is presented in Fig. 6.

Fig. 5. Solution of using cotters to perfectly center the NSMR-FRP inside the grooves

Fig. 6. Inferior side of the retrofitted slab

6.3 Behavior of retrofitted element
The 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 (the ones highlighted in Fig. 7 with thicker lines), have failed due to CFRP rupture, no type of premature failure (e.g. slipping, debonding, delamination, etc) being observed.

In Fig. 7 the final crack patterns for both the unstrengthened and strengthened element are presented. For the retrofitted element the high number of cracks, that appeared at various directions and are distributed on large areas of the slab, is in contrast with the unretrofitted one, for which only the four cracks on the direction of the yield lines have opened. It is also important to mention the fact that the principal cracks in the case of the strengthened element are not necessarily on the same direction as the cracks that remained opened after the test on the unretrofitted element. In Fig. 9 the load displacement diagrams for the element prior and after retrofitting are presented.

Fig. 7. Crack pattern of the element prior and after strengthening

Fig. 8. Load-displacement diagram

7 Conclusions
The behaviour of the slab 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 levels being 102 kN and 140 kN, prior and subsequent to retrofitting, respectively.

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References: