

# RC Beams and Columns retrofitted with FRP composites – Experimental Investigations

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*Abstract:* - Strengthening with fibre reinforced polymer (FRP) composites is a widely used method for retrofitting or increasing load bearing capacity of structural members. In this paper the experimental studies on RC beams and columns, retrofitted using FRP composites are presented. All the experimental work has been performed in the Civil Engineering Laboratory of the Politehnica University of Timișoara. In the first part of the article investigations made on pre-stressed concrete beams' dapped end strengthened with various FRP systems were described. The second part is dedicated to RC beams flexural capacity increase by applying FRPs. In the final part the bending strengthening of RC columns with FRP confinement are presented.

*Key-Words:* - RC beams, RC columns, dapped-end, bending, confinement, strengthening, FRP composites

## 1 Introduction

In the past few years, in many research centres around the world there was investigated a new consolidation technique, which involves fibre reinforced polymer (FRP) composites overlays, in this way increasing the strength and stiffness of the structural elements.

The FRPs used in constructions is a non-ductile material, with high strength-to-weight ratio, low thickness and high durability. Although the initial material cost of this solution is higher than the investigated traditional retrofitting methods, such as reinforced concrete overlays, these materials have been used in numerous applications worldwide to retrofit different reinforced concrete (RC) structural elements, such as beams, columns or walls. Their efficiency and ease of application lead to a substantial economy, in several situations.

In the Department of Civil Engineering of the Politehnica University of Timisoara, this solution of retrofitting is under study in a frame of several research projects. The elements under investigations are: unreinforced clay brick masonry walls subjected to in-plan shear loads; RC shear walls with monotonic, staggered and cut-out openings; beams with dapped end; beams with composites applied with different anchorage systems; columns with fibre wrapping and near surfaces mounted reinforcement.

In this paper the experimental research results obtained in the last two subjects will be presented.

## 2 Dapped Beam Ends Strengthening

The research program was carried out in order to study the pre-stressed concrete beam support zone with dapped-ends, retrofitted with different externally bonded FRP composite systems, based on several specific theoretical and experimental investigations. The theoretical calculus for the un-retrofitted elements was made both in the linear and nonlinear ranges, correlated with the results of the strut-and-tie models. The strengthening was designed so as to increase the service load of the dapped-ends by 20%, in terms of displacement and strain level in steel reinforcement, without a significant modification of the stiffness. For this reason, four full scale dapped beam ends were tested.

In the theoretical model, the characteristic strengths of the concrete and of the steel reinforcement were used. The elastic analysis was performed so as to obtain the level and the distribution of stresses in the concrete. The load level corresponding to the yielding limit in the horizontal reinforcement resulted in 1150kN. The nonlinear analysis gave the crack pattern at different load levels, the failure load and the collapse mechanism of the element. The yielding level in the horizontal reinforcement was achieved at the load level of 900kN. In order to check the obtained results, there was used an alternative strut-and-tie modelling, which also allowed the determination of the necessary steel reinforcement. Since the steel

reinforcement was known, the analysis was performed just to determine the maximum force applied on the element at the moment when the dapped-end's horizontal bars started to yield.

Preliminary dimensioning and detailing of the studied dapped beam end were performed according to the Romanian standards and verified with those from EC2, ACI318 and PCI, in order to reach the bearing capacity of 800kN. The dapped-end was reinforced by using horizontal and vertical stirrups.

Within the experimental phase of the program, two full scale dapped-end beams with the same dimensions and internal reinforcement were manufactured for the experimental tests. The beam height was 150cm, the dapped zone had 80/80cm and the element width was 66cm. The dapped-end was reinforced by using horizontal and vertical stirrups. Since the research focused on the dapped beam ends, the mid-span was over-reinforced. The dapped-ends were tested one by one in an experimental stand, as shown in Fig. 1.

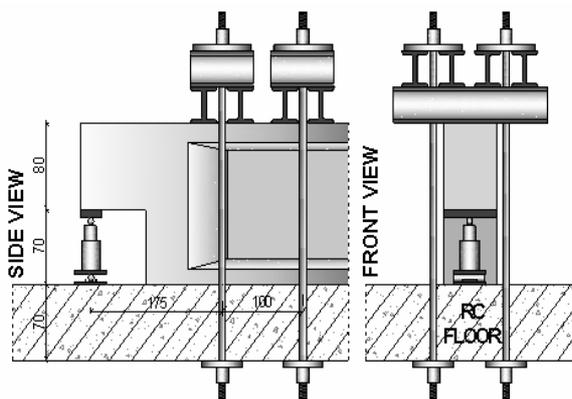


Fig 1. The specimens loading scheme

The first element C1 was tested prior to failure, this being considered the reference element, while the other elements (C2, C3, C4) were tested up to 800kN, this corresponding to the yielding level of the horizontal reinforcements from the cantilever zone. The monotonic increasing load was applied through a hydraulic system, in load control mode.

The strengthening of the elements was done by using three systems of CFRP composites, in four different retrofitting solutions. The data recorded during the tests were: the vertical load and the displacements, the strains in the composite and in the steel reinforcements, as well as the elements' failure modes. An identical test set-up was used for both the un-strengthened specimens (C) and the retrofitted ones (RC).

Element C1 was renamed RC1 after retrofitting. The strengthening of the element was performed by using 30cm wide unidirectional carbon fibre fabric,

applied in 3 layers on both sides in  $45^\circ/0^\circ/90^\circ$  directions. The retrofitting system (1) used was made of SikaWrap Hex 230C fabric and SikaDur 330 impregnation resin applied by the dry fabric application process.

Element C2 was renamed RC2 after retrofitting. The strengthening was made by using pairs of 10cm wide carbon fibre plates, applied in  $45^\circ$  and  $90^\circ$  direction, on both sides. The system (2) used was made of Sika CarboDur S1012 plates and SikaDur 30 adhesive resin. The length of the inclined plates was determined by the geometrical characteristics of the web.

Element C3 was renamed RC3 after strengthening. The strengthening was done by using 30cm wide unidirectional carbon fabric with high modulus, applied in 3 layers on both sides in  $45^\circ/0^\circ/90^\circ$  directions. The system (3) used was made of SikaWrap 400 HiMod NW fabric and SikaDur 300 impregnation resin applied by wet fabric application process.

Element C4 was renamed RC4 after strengthening. For strengthening it was used the system (2) with pairs of 10 cm wide carbon fibre plates, applied in  $0^\circ$  and  $90^\circ$  direction, on both sides. The length of the horizontal plates was limited by the sectional change of the web.

More details about the strengthening systems and their characteristics can be seen in [3] and [4].

During the first phase, the elements showed similar behaviour with respect to the maximum force and deflection. The design value of the serviceability limit state was of 800kN. For this value of the experimental load, we have observed the following:

- the stress level recorded in the reinforcement was comparable for all the experimental elements;
- a good similarity was noted between the crack patterns of all specimens, and the general aspect was identical.

Based on the studies performed, respectively on the behaviour of the tested specimens, the following conclusions were drawn:

1. The theoretical models used in the study approximate with sufficient accuracy the un-strengthened elements' behaviour.
2. The FRP systems used for retrofitting the elements proved to be viable for these kinds of applications, increasing the service load by 25% for RC3, 40% for RC4 and 45% for RC2 (compared with the reference strain in the steel reinforcement at 800kN), consequently demonstrating the effectiveness of the solutions used. The maximum load bearing capacity of the elements increased by 11% for RC1, by 10% for RC2, by 6% for RC4 and

by 0% for RC3. Further increase of the ultimate load could have been reached by supplementing the fabric cross-sectional area in the case of RC1 and RC3 and by using anchorages for plates in the case of RC2 and RC4.

3. Elements strengthened with fabrics failed more ductile compared to those retrofitted with plates. The strengthened elements show a delay in cracking, the failure occurring by peeling-off the horizontal or inclined plates, or by fibre rupture along the main diagonal crack in the case of fabric strengthening.

4. With respect to the baseline specimen (C1), the maximum displacement had a very close value for fabric retrofitted elements, but a decreased value, by more than 30%, in the case of plate retrofitted elements.

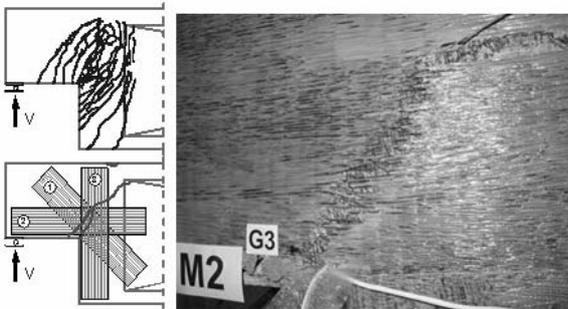


Fig 2. Crack patterns and failure detail of the C1 and RC1 elements

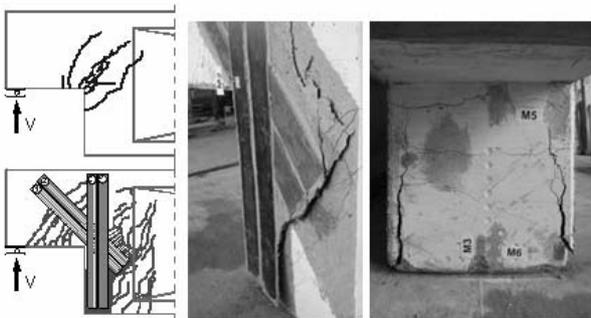


Fig 3. Crack patterns and failure detail of the C2 and RC2 elements

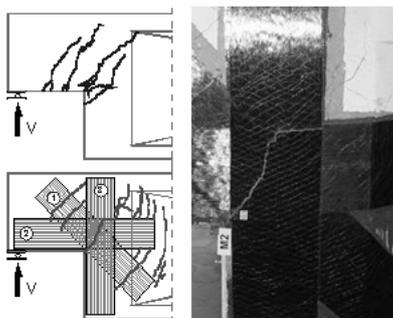


Fig 4. Crack patterns and failure detail of the C3 and RC3 elements

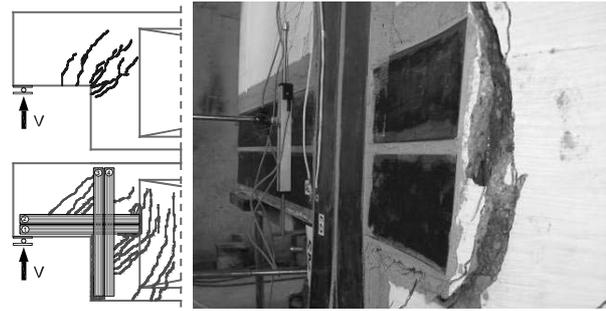


Fig 5. Crack patterns and failure detail of the C4 and RC4 elements

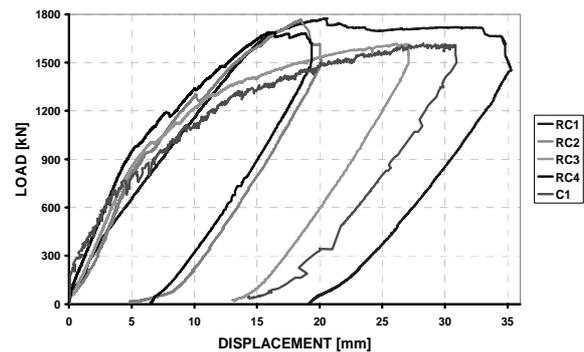


Fig 6. Comparative load – displacement diagram

### 3 RC Beams Flexural Strengthening

Flexural strengthening of RC beams with FRP composites is a well known field, researches being started in the 80's. Since then numerous theoretical and experimental studies have been carried out, recommendations and design guides were published, and also numerous applications were completed.

The objective of this research was to clarify some aspects regarded to the influence of some special anchorage and there influences to the overall behaviour of the RC beams subjected to flexure.

Because this is an ongoing project there will be presented just some of the first results.

Preliminary dimensioning and detailing of the studied elements were performed according to the Romanian and European standards. The first reference beam (RB) was reinforced with  $3\phi 16$ , while the second reference beam with  $2\phi 16$  (RB2). The rest of the beams were reinforced with  $2\phi 16$ , and strengthened with different FRP composites systems, which were designed to reach an appropriate ultimate load bearing capacity as the first reference beam (RB). The cross section of the elements c was  $20 \times 40$  cm with a 400 cm span and was subjected to four point bending test. Since the research focused on the flexural behaviour, the stirrups was oversized to resist for the increased shear forces.

The R-2W element was strengthened with 2 layer of 18cm wide unidirectional carbon FPR fabric in the bottom part. The failure mode of the element was debonding of the FRP.



Fig 7. Failure mode of the R-2W – FRP debonding

The RL-2W-A element was strengthened with 2 layer of 9cm wide unidirectional carbon FPR fabric applied in the lateral part of the both side. This theoretically would have the same capacity with the previous one, despite of the reduced effective depth, because there were used 3 spikes/end/side, serving as anchorage for the fabrics. The failure mode of the element was debonding inside the FRP (interlaminar shear failure).

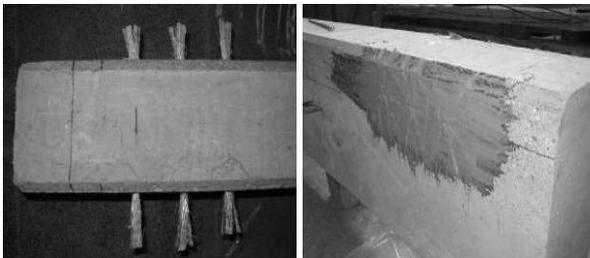


Fig 8. Anchor spikes - top view before and lateral view after the finishing

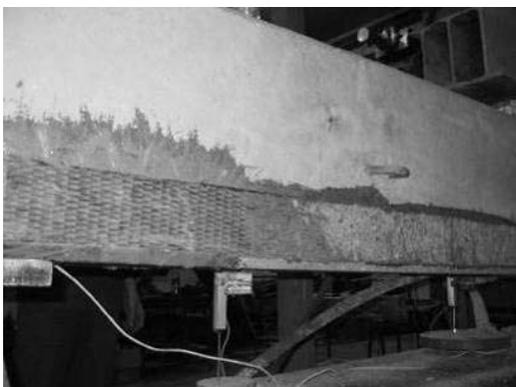


Fig 9. Failure mode of the R-2W-A – debonding inside the FRP

The R-1S element was strengthened with 1 layer of 5cm wide carbon FPR strip, applied in the bottom part and anchored at the ends with steel plates fixed through 6 bolts. Although theoretically the element would have the same capacity with the previous ones, the ultimate load bearing capacity exceeds all anticipations. The failure mode of the element began with the composite debonding between the anchorages, followed by concrete crushing in the compression zone, and finally by the sliding out of the FRP from the anchorage simultaneous with the failure of the strip.

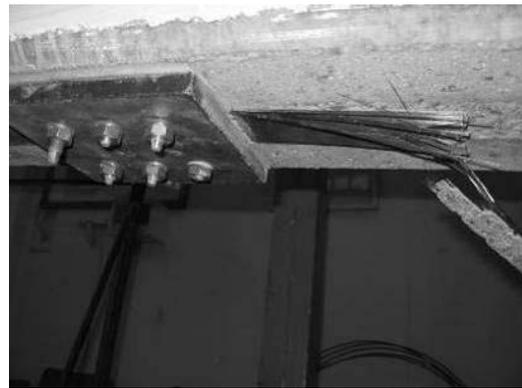


Fig 10. The anchorage and the failure mode of the R-1S element

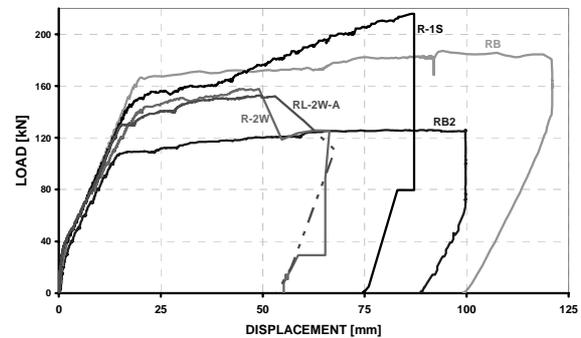


Fig 11. Comparative load – displacement diagrams

Based on the performed experiment, respectively on the behaviour of the tested specimens, the favourable effects of mechanical as well as chemical anchorage were experimentally demonstrated, both for bottom and laterally applied composites.

#### 4 RC Columns Retrofitting

The aim of this research program was the theoretical and experimental study regarding the reinforced concrete columns, strengthened with FRP composite materials. Based on the results the intention was to clarify some of the aspects regarding the interaction between two methods of consolidation, namely in

bending and confinement. The present design codes and guides show only the computational methods for each individual situation, but not for the superposition of the two strengthening methods.

In this program a number of ten experimental tests will be performed, in various configurations. The strengthening systems used were divided into their main components, each one being tested individually on one column. The benefits brought up by the different parts of the strengthening systems were studied. Each part was applied on a different column and tested afterwards. Up to this date, the preliminary tests on subsystem components have been performed and five specimens in different configurations have been tested. The recorded data were the lateral drift, strain in the internal reinforcements and in the strengthening systems.

The first specimen (C1) was tested in the as-built form, without any strengthening, serving as reference element. The column was subjected to a constant vertical load while the horizontal load was applied monotonically. Due to the fact that the maximum axial compression level in the column was not reached, for the next experimental tests (C1M), the axial force was removed. This approach was preferred in order to emphasise the bending effect. The failure mode for these elements was typical, through steel yielding followed by concrete crushing in compression zone.

The specimen C3M-BM-AF was strengthened with two  $\varnothing 12$  near surface mounted (NSM) steel bars, which were well anchored with resins into the foundation. The height of the vertical slits was 80cm. The bottom anchorage depth was about 18cm. The testing was done monotonically. Failure of the specimen was caused by internal steel reinforcement yielding, followed by peeling-of the NSM bar and concrete crushing in the compression zone.



Steel bars in slits      Resin applied in the slits

Fig 12. Strengthening phases of the C3M-BM-AF specimen



Fig 13. Failure mode of the C3M-BM-AF specimen

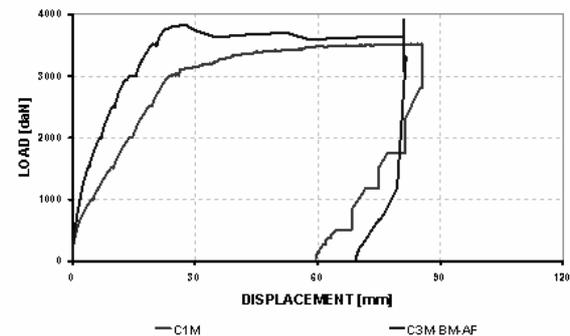


Fig 14. Comparative load – displacement diagrams of the C1M and C3M-BM-AF specimens

The reference specimen for cyclic load test was C1C. The element was tested in accordance to the ICC-ES recommendations [9], in load control mode up to the first yield of the steel reinforcement and then in displacement control up to failure, as shown in Fig. 15.

The specimen C1C-CW-BC was strengthened using unidirectional carbon fiber fabric, by wrapping (confining) the column base in a height of 60cm.

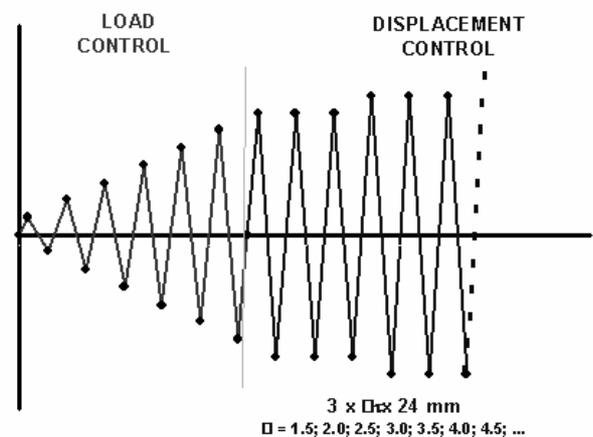


Fig 15. The loading diagram of the columns in the cyclic tests



Fig 16. Strengthening and failure detail of the C1C-CW-BC specimen

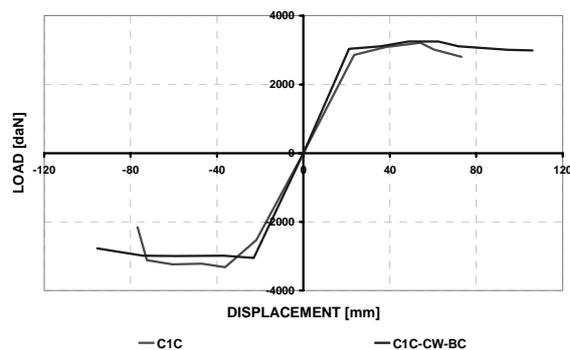


Fig 17. Comparative load – displacement diagrams of the C1C and C1C-CW-BC specimens

Based on the tests performed up to now, the following conclusions were drawn relating to changes in flexural capacity and stiffness:

1. The flexural capacity of C1M was greater with 8% compared to C1C, and was smaller with 9,4% compared to C3M-BM-AF. Differences in the bending moment capacity for C1C-CW-BC and C1C specimens were not registered.
2. The stiffness of C1M was greater with 2,6% compared to C1C and with 40,1% than C3M-BM-AF. The stiffness of C1C-CW-BC was greater with 18,2% compared to C1C.

Further test with NSM bars with carbon and glass FRP confinement, respectively NSM FRP rods with different FRP confinement are programmed and will be done in near future.

## 5 Acknowledgements

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