RESEARCH RESULTS ON STRUCTURAL STRENGTHENING WITH FRP COMPOSITES – STATE OF THE ART FROM TIMIŞOARA

Dedicated to Prof. György L. Balázs
for his 65th birthday

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Twenty-five years ago, no one could have expected that the use of Fiber Reinforced Polymer (FRP) composites in construction would be so widespread and so successful. It needed dedicated people like Prof. György L. Balázs, who saw the potential in this material, clearly understood the limits of these solutions, and devoted a lot of time to popularizing, improving, and implementing standards for secure applications. When we are discussing research related to the use of FRP in construction performed in Timișoara, two important personalities must be mentioned. The first is Prof. Balázs, who, starting from 1998, supported the development of FRP research in Timișoara with his advice and active participation by guiding the first BSc and MSc thesis and then taking part as an opponent in the first PhD defended in this field. The second person is Prof. Stoian Valeriu, a dedicated professor and excellent structural engineer who recognized the opportunities of the FRPs and trusted in this research direction. In the last 25 years, he has brought up a generation, conducting nine successfully defended PhD theses and several MSc theses in this domain. Congratulations to both! This paper briefly tries to summarize the main research results obtained in the field of structural application of FRP materials realized in the past two decades at the Politehnica University of Timișoara, Faculty of Civil Engineering.

Keywords: strengthening, FRP composites, EBR, NSM, masonry, RC walls, slabs, dapped-end beam

1. INTRODUCTION

The efficiency of FRP composites for structural applications has been proven and validated over the last two decades through several applications and research performed. This paper tries to review the research performed in this period at the Faculty of Civil Engineering, Politehnica University Timișoara, Romania.

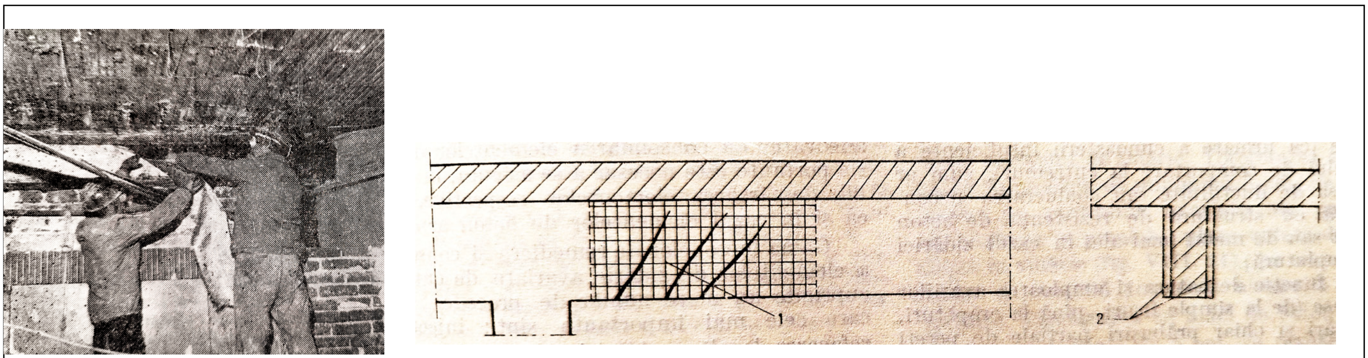
The first documented application of FRP composites for structural strengthening in Romania was in 1978, after the major earthquake of 1977, for retrofitting reinforced concrete (RC) beams and walls with glass FRP (GFRP) fabrics (*Fig. 1*) (Balan et al., 1982).

In Timișoara, research in the field of structural use of different FRP systems was documented in 1983 as a part of the PhD thesis defended by Liana Bob in 1999, consisting of the use of GFRP materials in the form of externally bonded reinforcement (EBR) fabrics as well as near surface mounted (NSM) rebars for glulam beams (*Fig. 2*) (Bob, 1999).

After these studies, there was a longer break in this field until two theoretical studies were published in the frame of a Scientific Student Conferences (Nagy-György, 1999; Nagy-György, 2000), followed by a BSc thesis (Nagy-György, 1999) and then an MSc thesis (Nagy-György, 2001). All four of these last works were supervised and coordinated by Prof. Balázs and Prof. Stoian.

Beginning with 2002, a new era started regarding research in structural strengthening and retrofitting using FRP

Fig. 1: Post-earthquake retrofitting of RC beams and walls with GFRP fabrics - field application in 1978 (Balan et al., 1982)



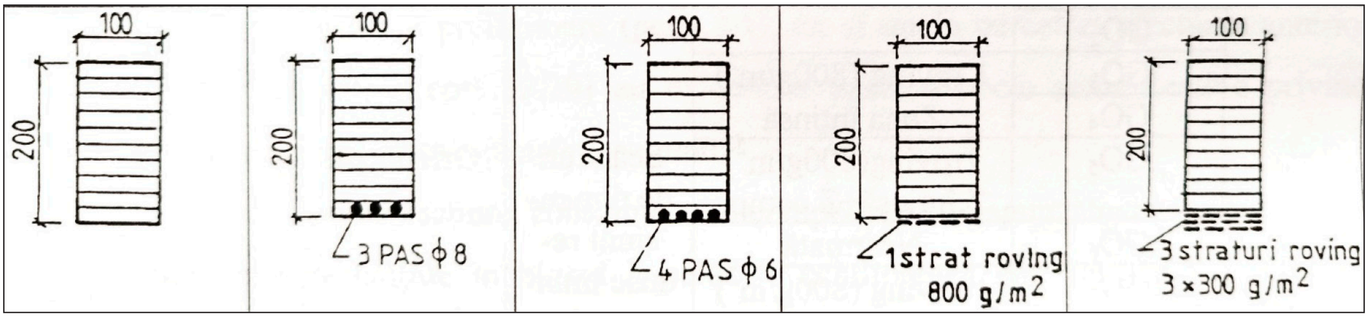


Fig. 2: Strengthening of glulam timber beams with GFRP bars using NSM and EBR techniques (Bob, 1999)

composites. In the following, the most important results will be presented.

2. SHEAR STRENGTHENING OF MASONRY WALLS

The objective of these studies (2000–2007) was to investigate the behaviour of the unreinforced clay brick masonry walls subjected to in-plane shear loads strengthened with different techniques (Nagy-György et al., 2010).

The considered retrofitting systems were different fibre reinforced polymer (FRP) composites, classical reinforced mortar jacketing (RMJ), and bidirectional steel wire meshes (SWM) applied with resins using the EBR technique. Based on the nonlinear numerical analysis results, an experimental program was conceived by realizing more than 20 specimens with 150 x 150 x 25 cm dimensions, tested in the setup presented in *Fig. 3*. The specimens were tested in as-built condition up to failure and then retrofitted and retested. The walls were subjected to a constant vertical force (V) and a monotonic increasing horizontal force (H), applied by an increment of 5 kN up to failure. The recorded data were the horizontal load, the horizontal and vertical displacement, the strain in the retrofitting systems, and the specimens' failure modes.

The correction and the injection mortars played an important role in restoring the load bearing capacity. The width of the initial crack is decisive in the evolution of the final capacity of the strengthened wall: when tight, the capacity increased significantly over the reference value; when wide, the ultimate load capacity was approximately equal or lower compared to the baseline values.

A considerable capacity increase was observed for the pre-cracked shear walls retrofitted with all systems (practically, the load bearing capacity of the cracked walls was negligible). The failure of the retrofitted walls was different in function of the system used.

In the case of FRP strengthened walls, the failure was caused by the extensive opening of the principal crack followed by FRP debonding and not due to tensile or shear failure of the FRP. It is necessary to mention that the vertically applied composites debonded just in the vicinity of the major crack, while those applied horizontally debonded in large areas, in the middle part, and even on the entire wall width. In this case, the use of anchorages could substantially increase the final capacity of the retrofitted wall.

In the case of RMJ strengthened walls, the failure was caused by cracking of the jacketing in tension, followed by debonding of the mortar jacket in the compressed corners, and finally through tensional failure of some horizontal steel bars of the mesh.

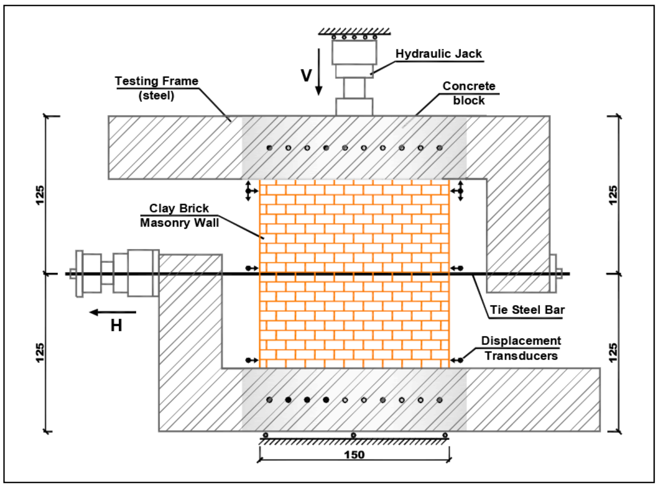


Fig. 3: Setup for in-plane testing of masonry specimens (Nagy-György, 2004).

In the case of SWM strengthened elements, the failure was produced by yielding and then by rupture of the horizontal and vertical wires along the diagonal principal crack, with small debonding near the crack.

The maximum horizontal displacements increased at least twice compared with the displacements of the reference specimens, which demonstrated an increase in the ductility and energy absorbing capacity of the retrofitted walls (*Fig. 4*).

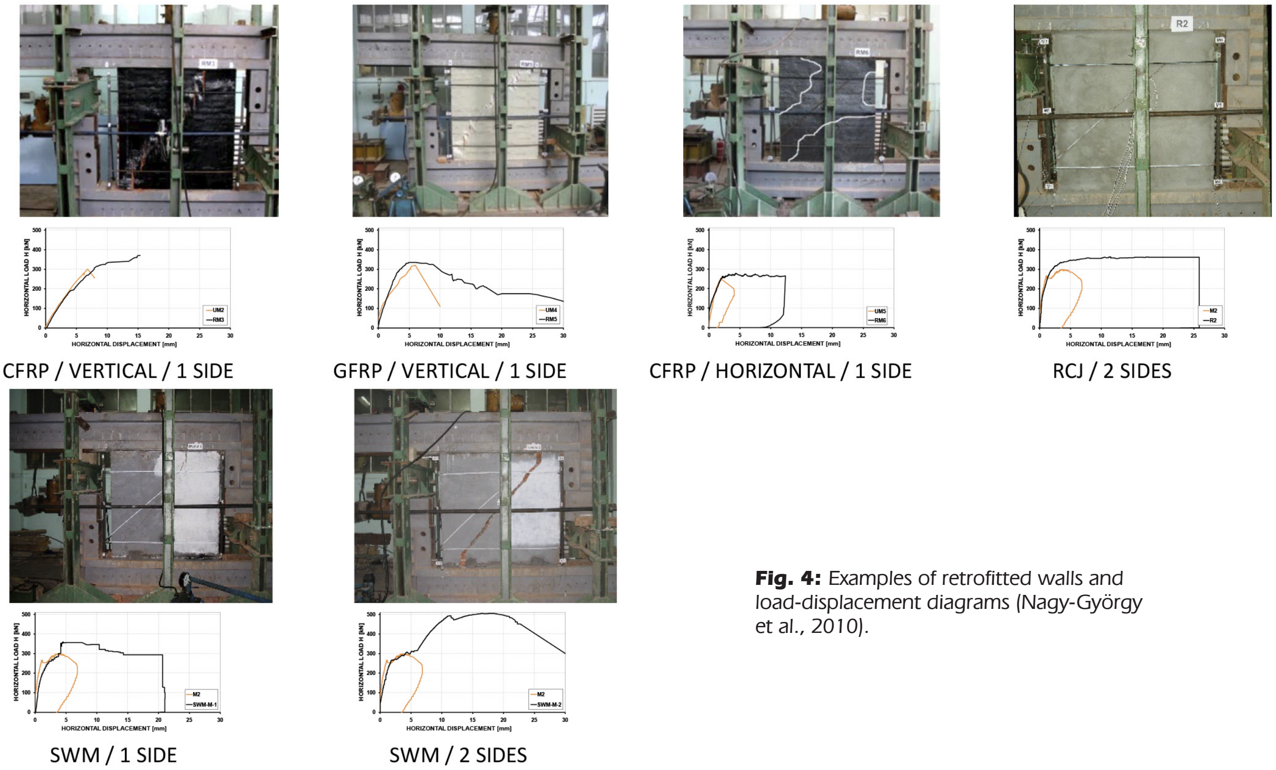
The most advantageous strengthening system with respect to increasing load bearing capacity proved to be the SWM system, while the FRP system with the dry fiber application process proved to be the fastest application method. The cheapest system, considering the material and application costs, and at the same time the most efficient system, calculated from the ratio of the execution costs and the reached maximum loads, proved to be the RMJ system.

2. SHEAR STRENGTHENING OF RC WALLS WITH OPENINGS

2.1 RC walss with staggered openings

The objectives of this study were the experimental investigation of RC shear walls with staggered openings (Moşoarcă, 2004) as well as to assess the CFRP composites efficiency for seismic retrofit of these walls. There have been studied the behaviour of the strengthened elements, a specific anchorage detail, the strengthening system layout, the stiffness and ductility modifications, and the failure mechanism (Nagy-György et al., 2007).

There were tested five 1:4 scale cantilever type shear walls with staggered door openings, which were subjected to a constant vertical load V = 50 kN, while the horizontal load


CFRP / VERTICAL / 1 SIDE

GFRP / VERTICAL / 1 SIDE

CFRP / HORIZONTAL / 1 SIDE

RCJ / 2 SIDES

SWM / 1 SIDE

SWM / 2 SIDES

Fig. 4: Examples of retrofitted walls and load-displacement diagrams (Nagy-György et al., 2010).

(H) was applied monotonically for the wall without openings and cyclically for the rest of the elements in a displacement-controlled mode (*Fig. 5*). The top displacements were increased with an average drift.

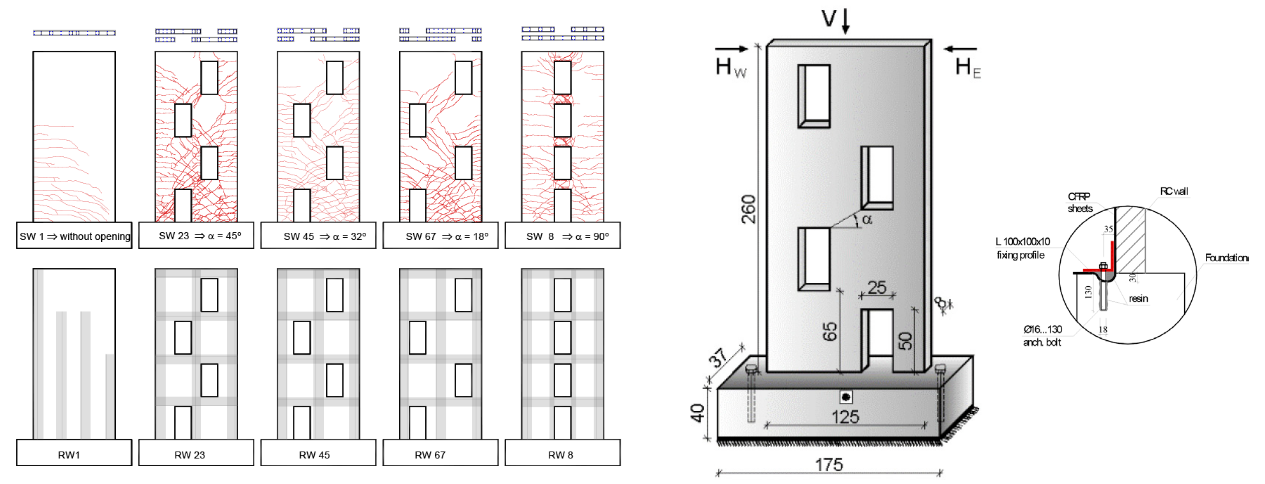
In the next phase, the walls were retrofitted. The damaged or crushed parts of the elements were replaced with an epoxy-based repairing mortar, and the existing cracks were filled with an epoxy resin. All the walls have been strengthened with unidirectional CFRP composite fabric on one side using the EBR technique. There was developed an anchorage zone, which was proven to be very efficient, as later mentioned in fib Bulletin 90.

As conclusions, it was observed that the elastic limit of the walls increased on average by 47%, the failure load increased on average by 45%, the stiffness of the elements decreased on average by 53%, and the ductility of the elements decreased on average by 60%. The failure mode of all the specimens was similar: FRP debonding in compression (fiber buckling), followed by excessive crack openings and tensile or compression failure of FRPs.

2.2 RC walls with cut-out openinigs

The conceptual outline of the research was to investigate the seismic performance of the precast RC walls, considering the outrigger effect of adjacent structural members, assess the weakening effects caused by doorway cut-outs, and reveal the effects of the seismic retrofit by CFRP-EBR. It is important that the foregoing analysis can be achieved at three structural levels of complexity, namely for a structural element, a building system, or the entire building structure. The test program was structured at three levels. The first level is represented by a bare solid wall, which was the reference specimen. The second level included two bare walls with cut-out openings, which were identical in all aspects to the solid reference except for the presence of the cut-outs. The difference between the elements of this level was the width of the door opening. The third level is composed of two pairs of strengthened specimens, which corresponded in all regards to the second level walls and were additionally retrofitted. Besides the opening size, the difference between

Fig. 5: Test setup, crack pattern and retrofitting schemes of the specimens. Anchorage detail (Nagy-György et al., 2007).



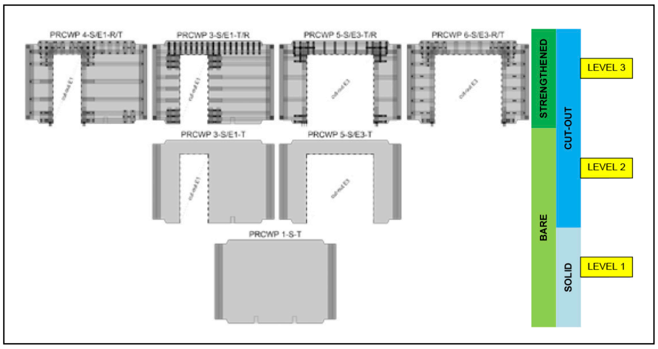


Fig. 6.a: Variables of the experimental program (Demeter, 2011)

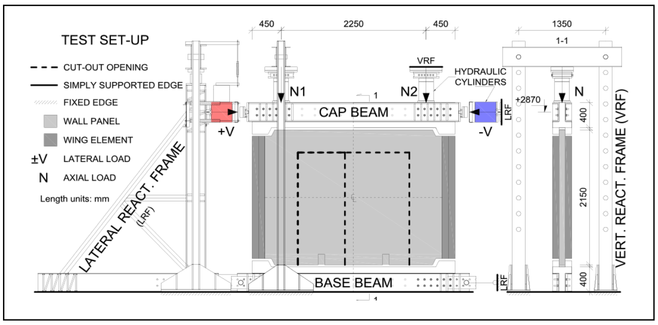


Fig. 6.b: Test setup of the experimental program (Demeter, 2011)

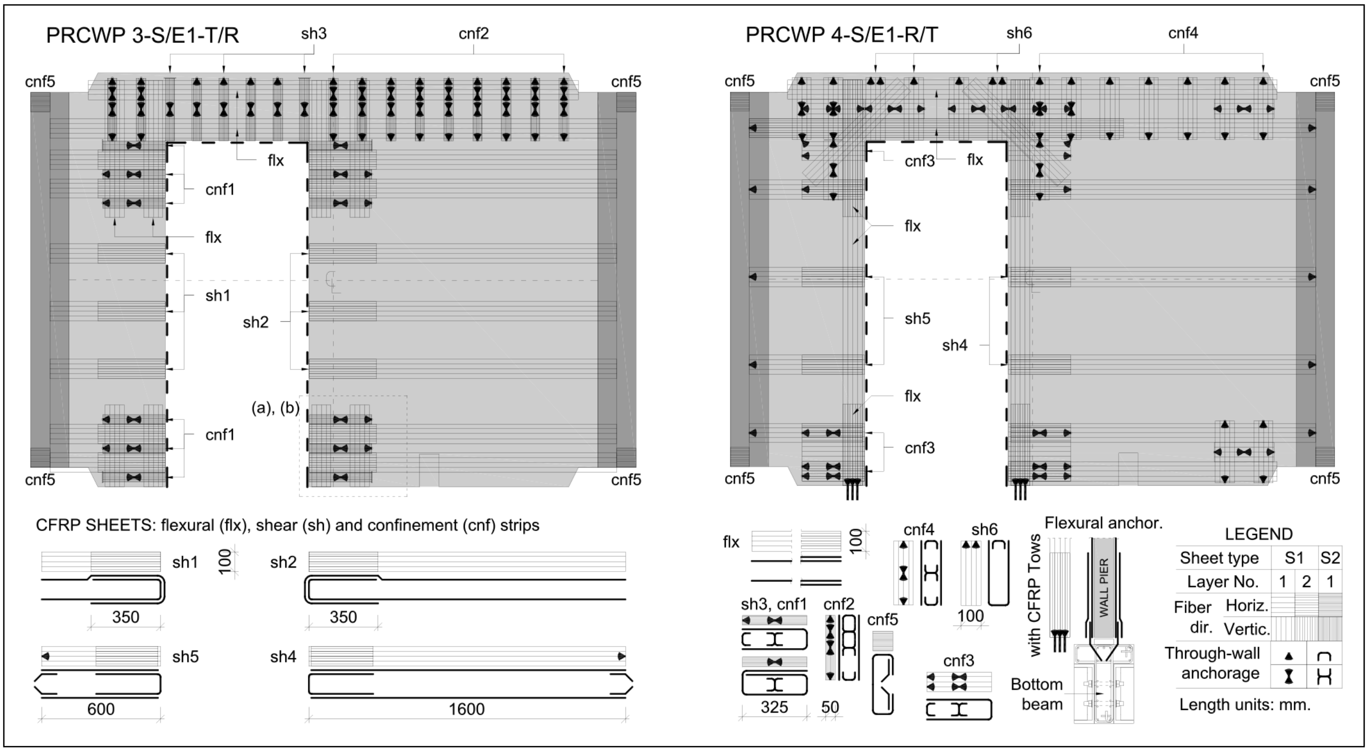
the specimens of the third level consisted of the state of the walls at the time of retrofitting: after sustaining a number of damaging load reversals, the specimens of the second level were upgraded to the third one by repair and post-damage strengthening, whereas their counterparts were prior-to-damage strengthened (Demeter, 2011).

In conclusion of the study, it was shown that in the given circumstances, the response of the RC wall panels is characterized by very high shear resistance and about a 10% energy dissipation ratio. The weakening effect of the cut-out opening was found to be in agreement with the predictions provided in the literature. Regarding the CFRP-EBR strengthening, the experimental results indicated that the energy dissipation capacity of the walls retrofitted by this technique increased significantly, whereas the other response characteristics were influenced to a smaller degree. This improvement in seismic performance should be attributed primarily to the confinement and shear components of the strengthening system (*Fig. 6*). The flexural FRPs were found to be susceptible to premature failure; however, it is not clear whether this type of failure is triggered by concrete substrate deterioration, i.e. local spalling and crushing, or directly by the adverse loading conditions (tension-compression reversals).

3. PRECAST RC SLABS WITH CUT-OUT OPENINGS

The goal of the theoretical and experimental program was to assess the behaviour of RC slabs weakened by cut-out openings retrofitted with CFRP composites (*Fig. 7*). The experimental program consisted of tests on full scale two-way RC slabs. Two full slabs served as control specimens, while within the other four, various configurations of cut-outs were sawn in at a corner or along an edge. All specimens were tested in two stages, as follows: initially in as-built condition up to a level that would imply the need for retrofitting, and then a full failure test conducted after applying the strengthening solution. The applied strengthening technique was a mixed one, associating the use of both NSMR-FRP and EBR-FRP. By performing twelve tests, the effectiveness of the proposed technique was assessed. The results clearly prove that the proposed technique is viable, as the specimens' capacity can be very easily regained or increased by applying the specific strengthening or retrofitting system. The crack patterns of all tested elements show a greater concentration of cracks for the retrofitted elements in comparison with the reference bare elements, suggesting a more favorable behavior in terms of cracking and crack width opening. The proposed simplified analytical calculation approach was verified and was recommended to be applied as a fast design solution for this type of element (Floruț, 2011).

Fig. 6: Example for a strengthening layout (Demeter, 2011)



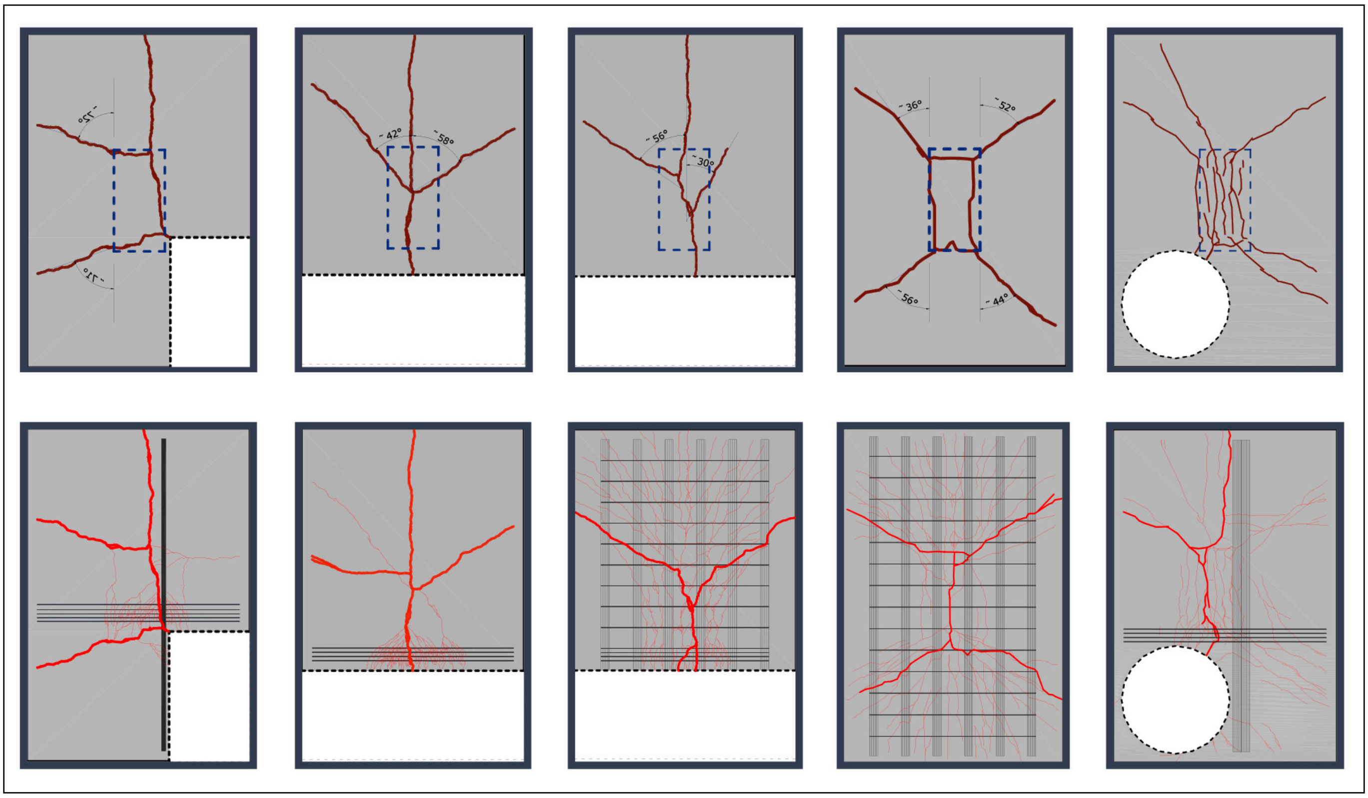


Fig. 7: Crack patterns for un-strengthened and strengthened slabs (Florut, 2011)

4. DAPPED-END BEAMS

In the first phase of this study, an experimental and numerical assessment of the effectiveness of strengthening dapped-end RC beams using EBR CFRPs was performed (*Figs. 8 and 9*). The research was based on a real application in which the dapped-ends of several precast prestressed beams developed diagonal cracks due to errors during assembly. Hence, the dapped-ends were strengthened on-site using CFRP plates to limit further crack opening. In the empirical phase of the study, four similar specimens were tested: one unstrengthened reference specimen, two strengthened with high-strength CFRP plates, and one with high-modulus CFRP sheets. The specimens strengthened with plates had slightly higher load carrying capacity than the reference element but failed by debonding, while the specimens strengthened with sheets showed no increase of capacity and failed by the fibers rupturing. Nonlinear finite element analysis of the specimens under the test conditions indicated that: (a) debonding is more likely to occur at the inner end of dapped-ends and (b) the capacity could have been increased by up to 20% if the plates had been mechanically anchored (Nagy-György et al., 2012).

In the second phase, a parametric investigation based on non-linear finite element modeling was performed to identify the most effective configuration of CFRP strengthening for dapped-end beams. There were 24 EBR and NSM configurations compared, assessing the yield strain in steel and the capacity and failure mode of dapped-end beams. The investigated parameters were the mechanical properties of the CFRP, the strengthening procedure, and the inclination of the fibers with respect to the longitudinal axis. Two failure scenarios were considered: rupture and debonding of the FRP. The results indicate that high-strength NSM FRPs can considerably increase the capacity of dapped-end beams, and the yielding strains in reinforcement can be substantially reduced by using high modulus fibers (Sas et al., 2014).

5. CONCLUSIONS

The research results listed above clearly indicate how much potential there is in the use of FRP composite materials for structural strengthening and retrofitting of RC and masonry elements. All the presented solutions demonstrated their effectiveness, and they were applied in real case studies. Due to space limitations, it is not possible to discuss other research program results, such as the superstition effect of NSM steel rebars with EBR-FRP confinement, several anchorage systems developed for EBR-FRPs, and the efficiency of EBR-FRP systems for strengthening precast and hollow core slabs. But it must be noted that all these studies are the results of the support of Prof. Balázs in the initial stages of the research, as well as of Prof. Stoian's continued and selfless dedication (*Figs.10 and 11*).

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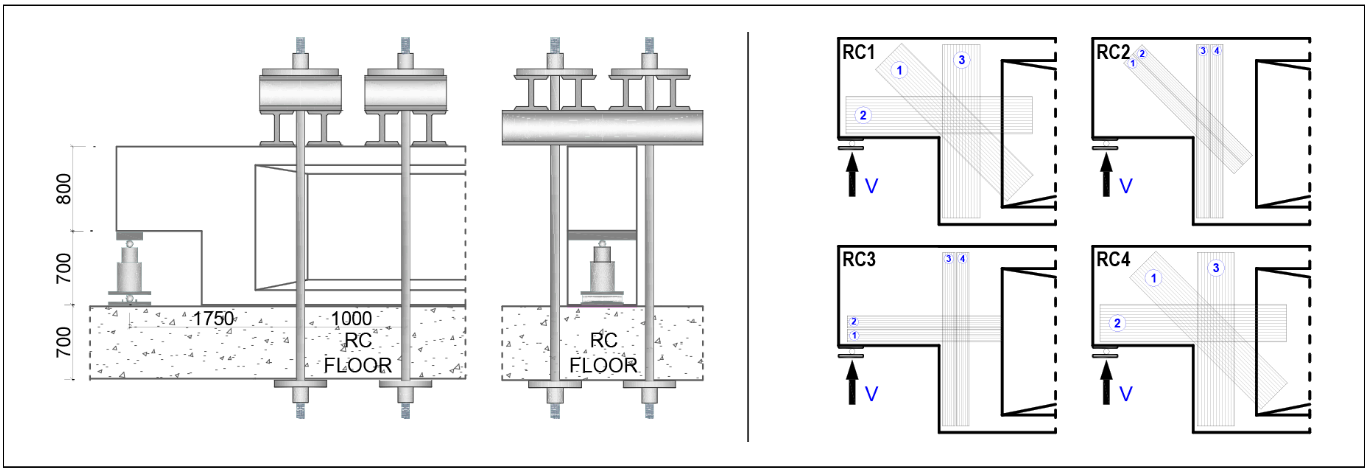

Fig. 8: Test setup and the experimentally tested strengthening systems (Nagy-György et al., 2012).

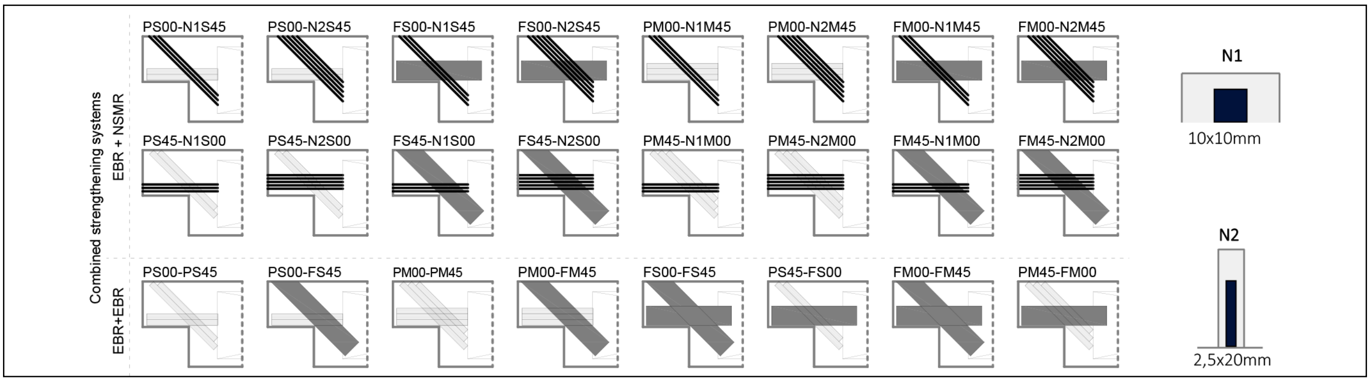

Fig. 9: Schematic presentation of the combined strengthening solutions from the numerical optimization (S – high strength, M – high modulus, 00 – 45 angles, N1, N2 – NSMR types) (Sas et al., 2014)

Fig. 10: Snapshot after the author's PhD defense in 2004 (from left to right: Assoc. Prof. János Gergely - UNC Charlotte, the author, Prof. Valeriu Stoian– Politehnica University Timisoara, Prof. Radu Pascu – Technical University of Civil Engineering Bucharest, Prof. Corneliu Bob - Politehnica University Timisoara, Prof. György L. Balázs - Budapest University of Technology and Economics)

Fig. 11: Prof. Balázs in Timisoara in 2016, after the habilitation thesis defense of the author (in front of the largest span bridge in the world in 1909 with RC beams, designed by Prof. Mihailich Győző)

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