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K. OLIVOVÁ, J. BILČÍK

STRENGTHENING OF CONCRETE COLUMNS WITH CFRP

Katarína Olivová, PhD.
Research field: Strengthening of Concrete Structures
Former PhD. Student at the Department of Concrete Structures and Bridges.
Námestie slobody 23, 811 06 Bratislava, Slovakia, e-mail: katarina.olivova@gmail.com

Juraj Bilčík, PhD., Professor
Research field: Reliability, Diagnose and Repair of Concrete Structures
Department of Concrete Structures and Bridges, Slovak University of Technology, Faculty of Civil Engineering, Radlinského 11, 813 68 Bratislava, Slovakia, e-mail: juraj.bilcik@stuba.sk

ABSTRACT

The use of fiber reinforced polymer (FRP) materials for structural repair and strengthening has continuously increased in recent years, due to several advantages associated with these composites when compared to conventional materials like steel.
This paper presents the results of an experiment at study on the structural behavior of reinforced concrete columns strengthened with carbon fiber sheets and strips in pre-cut grooves. The reinforced columns were strengthened before testing. The main tasks of these experiments were conducted to investigate the effects of additional strengthening of reinforced columns.

KEY WORDS

- *polymer,*
- *concrete columns,*
- *strengthening,*
- *confined concrete columns,*
- *CFRP strips,*
- *strength,*
- *stress,*
- *strain*

1. INTRODUCTION

Cracking and spalling of concrete columns often accompany the corrosion of internal steel reinforcements. The loss of cementitious material, as well as the corrosion-induced reduction in cross-section areas of a steel reinforcement, leads to drastic reductions in the structural integrity and load-carrying capacity of columnar supporting elements.
Until recently, the most common method of strengthening was to install reinforced steel jackets around circular sections. The use of a steel encasement to provide the lateral confinement to concrete in compression has been extensively studied and has been shown to be able to significantly increase the compression load-carrying capacity and deformation of the columns. However, the major disadvantages of using steel jackets are low resistance to corrosion, high cost and high dead-weight (Karbhari, M., Douglas, A.E., 1995).
Fiber reinforced composites, due to their high strength-to-weight and stiffness-to-weight ratios, large deformation capacity, corrosion resistance to environmental degradation, and tailorability, present an attractive option as an alternative and extremely efficient retrofitting technique in such cases through the use of composite jackets or wraps around a deteriorated column (Mirmiran, A., et al., 2002). Carbon sheets have been applied to increase the concrete confinement and loading resistance of reinforced concrete columns. The confinement effectiveness of externally bonded FRP jackets depends on different parameters, namely, the type of concrete, steel reinforcement, thickness of the FRP jackets (number of layers) and stiffness (type of FRP) and loading conditions (Bogdanovic,

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

A., 2002). Also, the shape of the cross sections and sharp edges in the cross sections of columns can directly affect the confinement effectiveness of externally bonded concrete. The efficiency of FRP confinement is higher for circular than square sections. The mitigation of the effect of this shape is achieved by rounding the corners of rectangular sections with the effectiveness increasing with the rounding radius, until a certain threshold is reached. The ultimate strength of the confined concrete is closely related to the failure strength of the FRP wraps. The CFRP strain at the rupture of the confined columns is usually lower than the ultimate strain obtained by tensile testing of the CFRP coupons (de Paula, R.F., de Silva, 2002).

External jackets provide lateral confinement to the column and cause the development of a triaxial stress field within the confined concrete. The axial strength and ductility of the confined concrete increases with the increased lateral pressure, which results in an increase in the concrete's compressive strength and an increase in the strain at which the concrete crushes (Fig.1).

The axial stress-strain relationship is almost similar until the FRP sheet ruptures when the strengthening stiffness is the same regardless of the type of FRP used. The curve of the CFRP confined concrete is bilinear (Fig.1). The first slope of the curve will be referred to as the initial elastic zone with the initial rigidity equal to E_1 and the second slope as the final plastic zone with a rigidity E_f. The elastic slope is not substantially altered with confinement, as it is identical to that of the unconfined concrete. The transition zone occurs shortly after the peak strength of the unconfined concrete has been reached. The slope in the plastic zone increases in accordance with the strengthening stiffness, and the slope is closely connected with the strengthening stiffness E_f, and is not influenced by the kind of FRP sheet (de Lorenzis, L., Tepfers, R., 2000, Miyauchi, K., et al 1999).

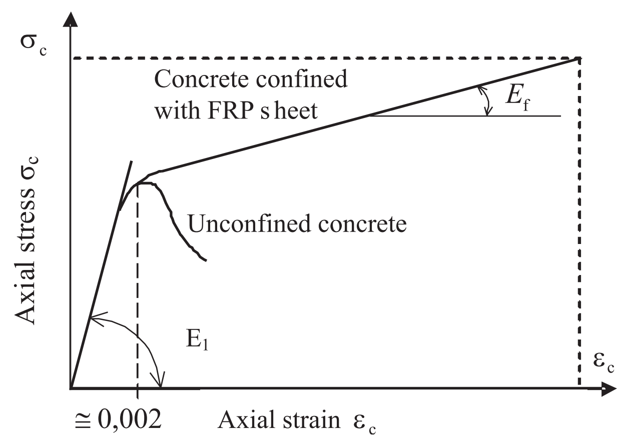

Fig. 1 *Ideal axial stress-strain diagram $\sigma_c - \varepsilon_c$ for concrete confined with a FRP sheet [6]*

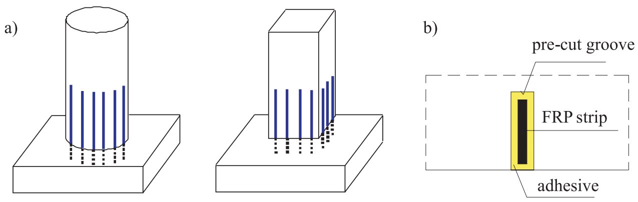

Fig. 2a) *Technique of strengthening columns NSM FRP reinforcement [8], b) detail of FRP strip in pre-cut groove*

A recent strengthening technique based on near-surface mounted (NSM) laminate strips of carbon fiber reinforced polymer (CFRP) has been used to increase the load-carrying capacity of concrete structures by introducing laminate strips into pre-cut grooves on the concrete cover of the elements to be strengthened (Fig.2).

This method has many advantages versus the method of externally bonded reinforcement on the surface of concrete, such as no surface preparation work after cutting the groove, and it requires minimal installation time compared to the externally bonded reinforcing technique. A further advantage associated with NSM CFRP is its ability to significantly reduce the probability of harm resulting from fire, acts of vandalism, mechanical damage, and aging effects (Huang, P.C., et al., 2000; de Sena Cruz, J.M., et al., 2004; Barros, J., et al., 2004).

After completing the installation of the NSM reinforcement, an FRP jacket prevents premature failure of the concrete cover and buckling of the steel bars, leading to a substantially improved performance. The use of NSM FRP laminate strips increases the flexural strength of deficient columns and can be more convenient than using externally bonded FRP laminates in the negative moment regions of a deck. In this case, the externally bonded reinforcement would be subjected to mechanical and environmental damage and would require a protective cover, which could interfere with the presence of floor finishes (de Sena Cruz, J.M. 2005).

2. EXPERIMENTAL PROGRAM AND STRENGTHENING TECHNIQUE

An experimental investigation was performed in the laboratory of the Department of Concrete Structures and Bridges at the Slovak University of Technology in Bratislava.

In order to asses the effectiveness of the NSM method and wrapping with CFRP sheets for strengthening concrete columns submitted to a static axial compression load and cyclic horizontal load, four series of reinforced concrete columns with dimensions of 250x250x1500 mm were tested. The first series consisted of non-strengthened reinforced concrete (RC) columns; the second

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

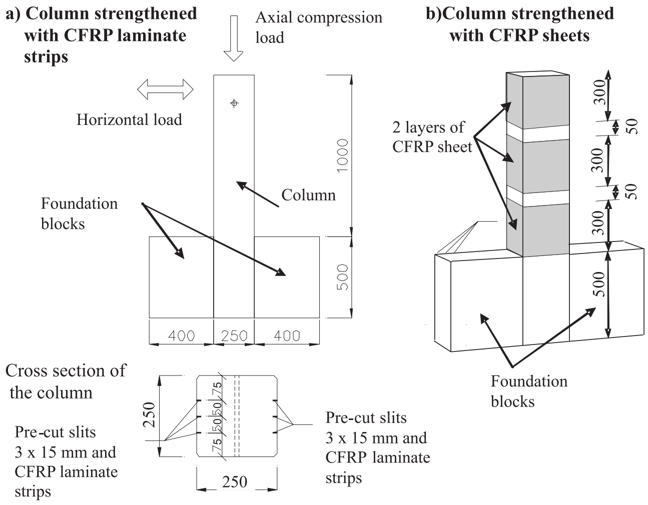

Fig. 3 *Strengthening technique adopted for reinforced concrete (RC) columns*

series was composed of concrete columns strengthened with CFRP laminate strips before testing; the third series was columns strengthened with CFRP sheets (Fig.3); and the last series was composed of columns strengthened with CFRP laminate strips and sheets.

Table 1 *Average cube strength of concrete at ages of 28 days and 82 days*

Strength according to	EN 1992-1-1	Measured values	
Design concrete class C20/25	$f_{cm,cube}$ (MPa)	$f_{cm,cube}(28)$* (MPa)	$f_{cm,cube}(82)$ (MPa)
	33,00	25,16	32,37

* The average ambient temperature during the hardening of the concrete was 11 °C, which resulted in the slow increase of the strength.

3. MATERIALS

One concrete mixture was used for the experiment. In order to evaluate the material models for an analysis of the experimental columns, the following material properties were tested: the compressive strength of the concrete and the modulus of elasticity.

The concrete's compressive strength was obtained from uniaxial compression tests with cubic specimens of 150 mm at concrete ages of 28 and 82 days. The test results are presented in Tab. 1.

The curve in Fig.4 represents the theoretical time development of the concrete's strength with normal hardening cement according to EN 1992-1-1 for concrete with a cubic strength of 33 MPa at an age of 28 days. The curve matches the results of the strength test performed at the age of the concrete of 28 and 82 days.

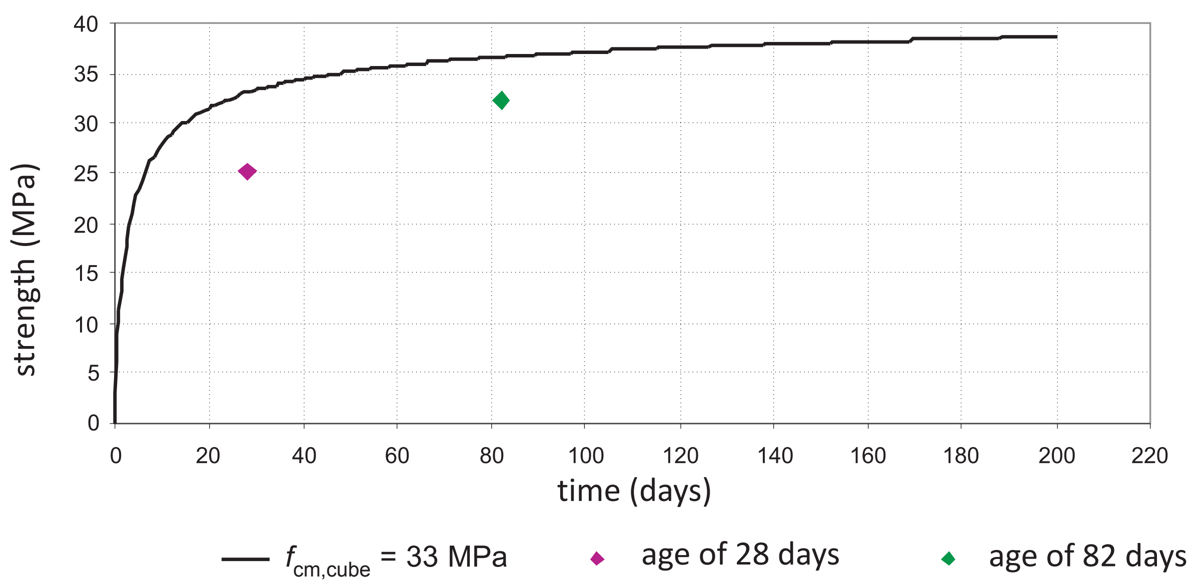

Fig. 4 *Development of the concrete's strength*

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 – 9

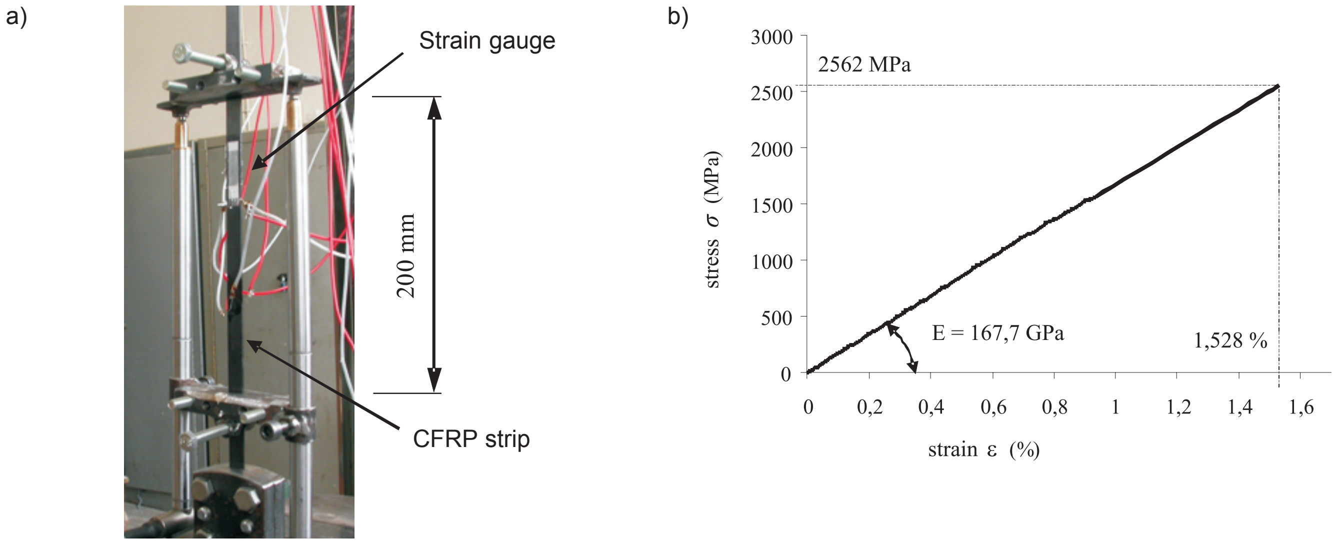

Fig. 5 *Tension test and stress – strain diagram of CFRP strip*
a) tension *test of CFRP strip, b – stress-strain diagram of CFRP strip CFK 150/000*

The secant modulus of the elasticity of the concrete was tested on three 100x100x400 mm prisms before the load test. The measured value of the concrete at the age of 82 days was 33.08 GPa. The longitudinal steel reinforcement for all the column specimens was composed of bars of a 10 mm diameter (an actual yield strength of 514 MPa), while the stirrups had a diameter of 6 mm. The concrete cover over the longitudinal bars was maintained at 25 mm in all the specimens. The CFRP laminate strips used in the NSM technique, with a designation of CFK 150/2000 were delivered in rolls, the dimensions of which were 10x1.4 mm. The tension test revealed the strength of the CFRP strips (2562 MPa), the modulus of elasticity (167 GPa) and the ultimate tensile strain (1.528 %). The CFRP sheet, which was applied for wrapping the specimen columns had a fiber thickness of 0.176 mm, a modulus of elasticity of 204 GPa, an ultimate strength in tension of 3800 MPa and an ultimate strain of 1.55 %.

4. TEST OF THE ANCHORAGE LENGTH

Since the bond behavior analysis is a requirement for understanding the stress transfer process between concrete and CFRP, the study conducted also included a pull-out test for assessing the bond characteristics of a CFRP strip. Using the same slit size and epoxy adhesive, the bond behavior was analyzed in order to determine the effect of the anchorage's length.

The pull-out test of the laminate strip inserted in a groove in a concrete fragment specimen was done in order to determine the anchorage's length (Fig.6). The specimens were composed of concrete cubes with dimensions of 150 mm with a continuous slit of 3x15 mm, where the CFRP strips were placed. The embedded lengths were 50, 100 and 150 mm.

A concrete cube was situated in a tension testing machine where the tension force was continuously increased up to failure. Two alternative failure modes were observed in these experiments, namely, either the pullout at the interface between the CFRP laminate strip and epoxy paste or the rupture of the CFRP strip. A displacement transducer was used to control the test and measure the slip at the free end.

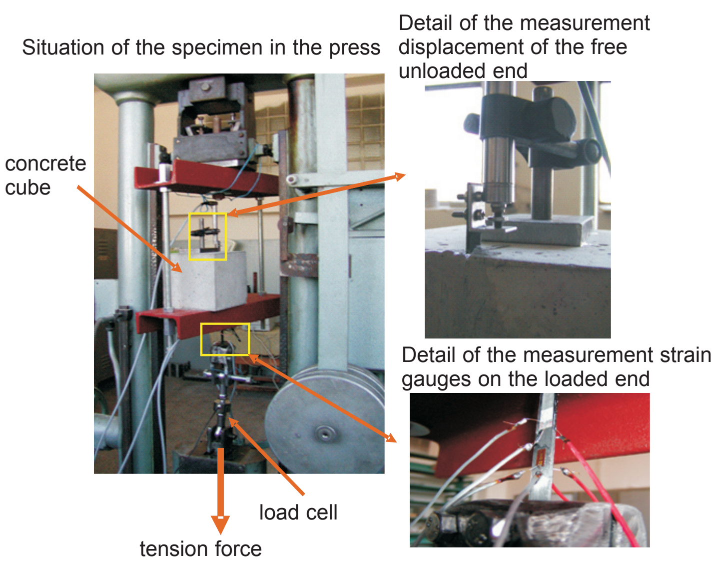

Fig. 6 *Pull-out test of the anchorage length of the CFRP strip*

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

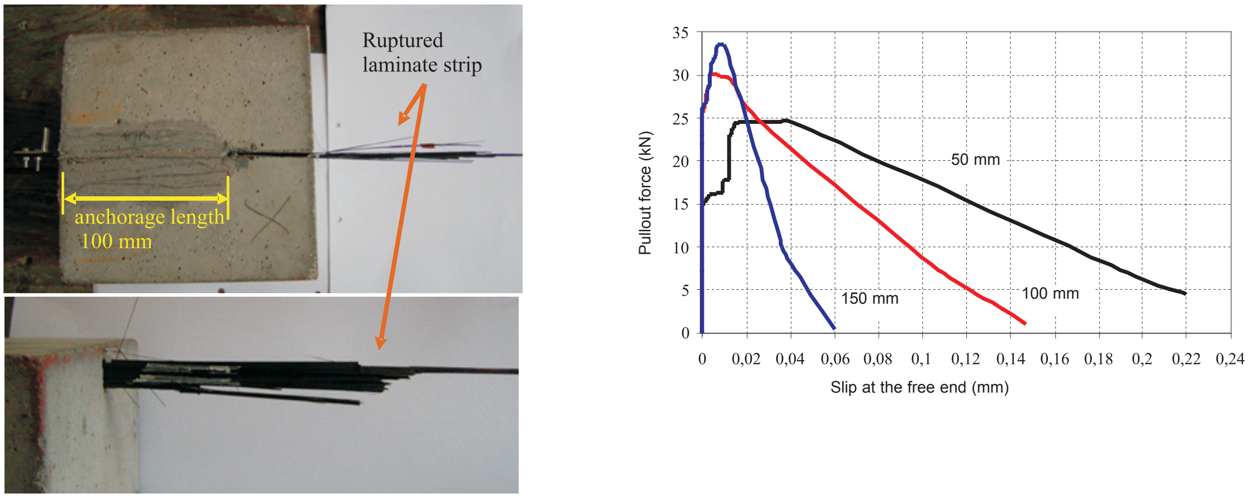

Fig. 7 *Pull-out test of the laminate strip inserted in a groove in the concrete fragment*

Strain gauges glued to the CFRP were used to control the ultimate strain of the strip. The force applied was measured using a load cell placed at the loaded end of the strip (Fig.6).
The results from this test were taken into consideration during the application of laminate strips on the strengthened columns and indicated that the sufficient anchorage length of the CFRP laminate strip in the footing is 100 mm (Fig.7).

5. ANALYTICAL MODELING

The typical moment-thrust interaction of a short column represents the cross-sectional strength. In order to study the behavior of RC and FRP-RC columns, fiber element models were developed by discretizing the section into a number of integration layers. The concrete was modeled by a stress-strain curve. Steel reinforcing bars were modeled as elastic material. The FRP reinforcing bars were assumed to be linear-elastic with the same modulus of elasticity and strength in tension and compression. A perfect bond was assumed between the concrete and reinforcement, FRP, or steel. It was also assumed that the proper spacing and adequate size of FRP ties can provide the same level of confinement as steel ties. The tensile strength of the concrete was ignored, making the analysis slightly conservative. The reinforcement was placed in one layer on the tension and compression sides of the section. The effect of the creep and shrinkage of the concrete and the creep and relaxation of the reinforcement were ignored.
The interaction curves were constructed for each strengthened column (Fig.8). For each curvature, the maximum compressive strain of the section was assumed, and an iteration was carried out until the equilibrium of forces in the section was satisfied. The process was repeated for increments of curvature until the failure of the section was triggered by one of the following conditions:

- crushing of concrete at its ultimate strain 0.0035
- rupture of the reinforcement in compression or tension.

The level of the axial load was then increased until the column failed and in pure compression. The moment-thrust interaction diagram of the short column was constructed from the maximum moments at each axial load level.

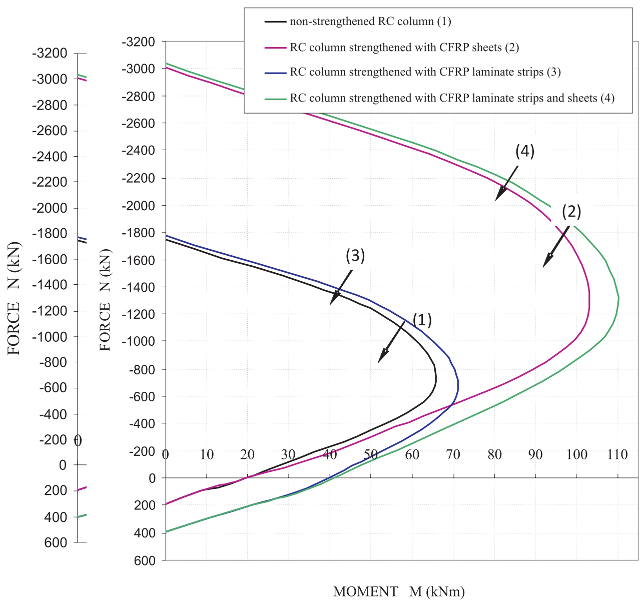

Fig. 8 *The interaction curves for all the columns tested*

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

The combination of force and moment which were used in the test of the columns were obtained from interaction diagrams.
For the numerical analysis using the Finite Element Method (FEM), the ATENA program was used. This FEM system is suitable for solving non-linear problems in RC structures. Three-dimensional (3D) numerical models of non-strengthened and strengthened RC columns were created in the program. A stress-strain curve of composite laminate strips based on the previous theoretical analysis was implemented into the computer calculations. The stress-strain curves for the concrete and reinforcement bars derived from the laboratory tests of these materials were also considered.

6. TEST SET-UP AND PROCEDURE

The test set-up is illustrated in the left side of Fig.9. Each specimen is composed of a column connected to foundation blocks. A constant vertical load of 250, 450, 650, 750 and 850 kN were respectively applied to the columns. The history of the horizontal force placed at a distance of 0.95 m from the footing was included in the load cycles in increments of 10 and 5 kN up to failure.
Linear variable displacement transducers (LVDTs) were used to record the horizontal displacement of the column as well as any vertical movement of the footing. The LVDT1 was located at the same height as the horizontal force.

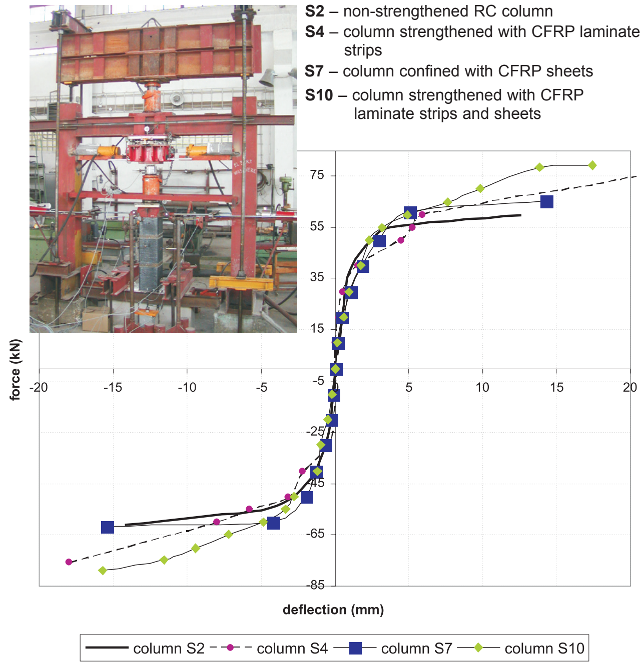

Fig. 9 *Force – deflection (LVDT1) relationship for columns, vertical load 250 kN and increasing horizontal load*

Table 2 *Comparison of the results of the load-carrying capacity for all the tested columns*

	Axial load F (kN)	Interaction curve		Experiment		ATENA
		Horizontal load H (kN)	Moment M (kNm)	Horizontal load H (kN)	Moment M (kNm)	Horizontal load H (kN)
Non-strengthened concrete columns						
S2	-250	44,11	41,9	60,1	57,09	54
S3	-650	68,84	65,4	84,2	79,99	81
Concrete columns strengthened with CFRP laminate strips						
S4	-250	59,90	56,9	75,6	71,82	70
S5	-650	74,95	71,2	91,7	87,12	85
S6	-850	72,95	69,3	89,2	84,74	86
Concrete columns strengthened wit CFRP sheets						
S7	-250	48,00	45,6	65,3	62,04	57
S8	-450	65,90	62,6	78,5	74,58	76
S9	-750	90,63	86,1	96,1	91,30	100
Concrete columns strengthened with CFRP laminate strips and sheets						
S10	-250	62,95	59,8	79,2	75,24	74
S11	-450	78,42	74,5	86,3	81,99	90
S12	-650	92,42	87,8	99,2	94,24	104

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

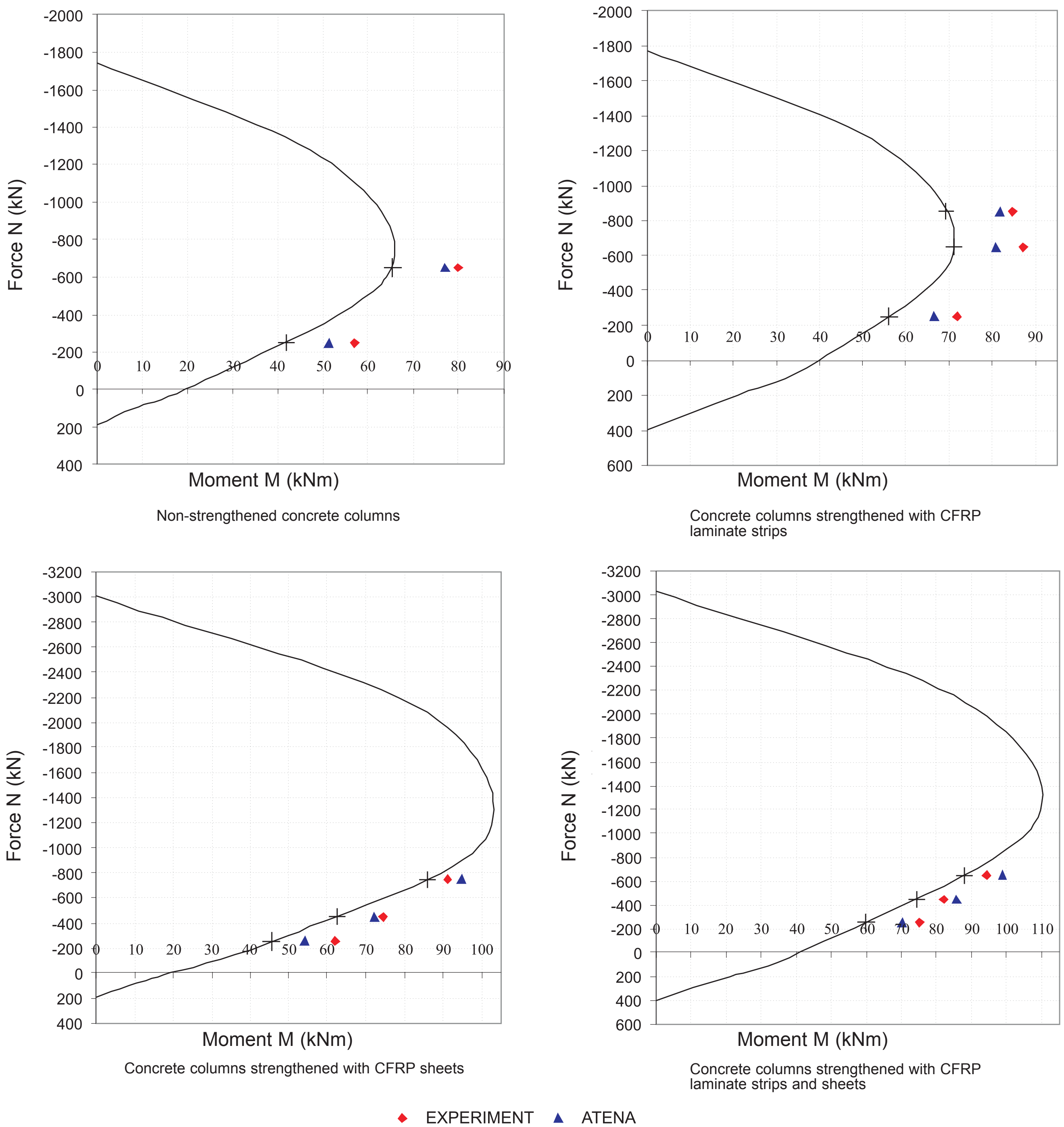

Fig. 10 *Graphic comparison of the results of the tested columns*

SLOVAK JOURNAL OF CIVIL ENGINEERING

2009/1 PAGES 1 — 9

7. RESULTS

The failure of the columns occurred by the crushing of the concrete on the compression face. Considerable deflection was observed near the failure (15 to 20 mm). In Fig.9, the right side depicts a typical relationship between the horizontal force and its corresponding deflection in LVDT1 (at the top of the columns). The strengthening technique does not provide a significant concrete confinement for the second series of columns. The increase on the dissipated energy was marginal.

The strengthening techniques for the columns loaded by a vertical load of 250 kN provided an average increase in the load carrying capacity:

- 10% of the columns confined with a CFRP sheet
- 26% of the columns strengthened with CFRP laminate strips
- 32% of the columns strengthened with CFRP laminate strips and a sheet .

For columns loaded by a vertical load of 650 kN an average increase on the load carrying capacity was provided:

- 9% of the columns strengthened with CFRP laminate strips
- 18% of the columns strengthened with CFRP laminate strips and a sheet .

The ultimate load of all the columns obtained from the experiment was compared with the result from the analytical modeling and is presented in Table 2.

In a comparison of the load carrying capacity:

- the results obtained from the numerical analysis (FEM – ATENA program) were approximately 20% higher than the theoretical analysis results (interaction curves) for all the tested column specimens
- the results obtained from the experiment were approximately 25 – 35% higher than the theoretical analysis results and about 6 – 14% higher than the numerical non – linear analysis.

By testing the ultimate strain of the CFRP strips during failure, the actual strain in the strip was verified. The value decreased with the increased axial load.

The values of the ultimate strain in the failure for columns strengthened by the CFRP strips in the slits and confined by the sheets were relatively higher than for other strengthened columns under an equal axial compression load.

8. CONCLUSIONS

The premature debonding, which generally occurs in the externally bonded reinforcement (EBR) technique, was avoided. In the majority of the strengthened columns some laminate strips of the CFRP reached tensile strain values close to the ultimate rupture strain of the CFRP. Some CFRP laminate strips have even failed at the failure crack of the concrete column. The results indicate that the strengthening technique proposed by the near surface mounted (NSM) technique is promising for increasing the load-carrying capacity of concrete columns failing in bending.

For eccentrically loaded columns, the failure of the unconfined columns was marked by the crushing of the concrete on the compression side of the specimen. For the vertical force, 650 kN was an indication of the reinforcement's buckling until the concrete was completely crushed. The observed behavior of the confined columns was similar to the unconfined columns up to the peak load of the unconfined columns. Increases in the lateral deflection of the confined columns resulted in the concrete failing in compression and rupturing the FRP confining jacket at approximately mid-height. The deflected shape of the columns at peak load was symmetrical, and there was no local buckling in the columns.

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