The influence of longitudinal CFRP strips on the load-bearing capacity of RC columns

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ABSTRACT: In this paper results of experimental investigations of compressed RC columns strengthened with CFRP materials (strips and sheets) are presented. The influence of longitudinal CFRP strengthening with transverse CFRP sheets on failure mechanism and the load-bearing capacity of specimens was analyzed. The model specimens with dimensions 80x150x600 mm and the half natural-scale columns with dimensions 200x200x1500 mm were investigated. The elements were subjected to immediate axial compression. Besides various intensity of strengthening, the specimens have different transversal strengthening. They were locally wrapped with CFRP bands or continually wrapped with CFRP sheet (one layer).

1 INTRODUCTION

The method of strengthening consists of confining the column with an external composite jacket causes an increase of concrete core strength. The concrete core works in a three-axial state of stress. That causes an increase of load-bearing capacity. The main variables are: number of layers of FRP strengthening, shape of cross-section, type of composite sheet. The most advantageous results of strengthening were observed for cylindrical specimens confined with CFRP sheets (Demers & Neale 1994; Mirmiran & Shahawy 1997; Rochette & Labossière 2000). Smaller effects were obtained for specimens with quadrangular cross-section (square and rectangular). However, for the square elements the increase of load-bearing capacity was proved to depend on curve radius of cross-section corners.

The aim of the investigations, conducted in Institute of Building Engineering of Wroclaw University of Technology (Trapko 2003, 2004; Kamiński & Trapko 2006), was to estimate the influence of longitudinal CFRP strips strengthening intensity (with simultaneous transverse CFRP sheet strengthening) on mechanism of failure and load-bearing capacity.

Intensity of strengthening of columns is described with the relation ρ_L, defined as the area of strips A_L to area of concrete A_c in an element.

For this stated purpose, three-stage experimental studies were conducted. The half natural-scale and model-scale RC elements with square cross-section were subjected to immediate axial compression.

2 DESCRIPTION OF STUDIES

2.1 *Stage IIa*

The objects of investigations were models of columns in scale about 1:5 (dimensions of cross-section were 80x150 mm and height was 600 mm). The longitudinal steel reinforcement was four bars ∅8, steel A-II, yield strength f_{yd}=310 MPa (Polish Standard 2002), the transverse reinforcement was stirrups ∅3, steel A-I, yield strength f_{yd}=210 MPa (Polish Standard 2002). Elements were made of concrete with mean cubic compression strength $f_{cm,cube}$=40,84 MPa.

The first series of investigations (marked with letter “a”) consisted of five elements with different intensity of CFRP strips strengthening (S1a; S2a; S3a; S4a; S5a). The second series (marked with letter “b”) consisted of five elements with different intensity of CFRP strips strengthening and confined with external bands made of CFRP sheet (S1b; S2b; S3b; S4b; S5b). Additionally two control elements without strengthening were investigated (S1a; S1b).

In this stage the conclusion was that strengthening only with longitudinal CFRP strips was ineffective because of debonding of the composite and attached concrete.

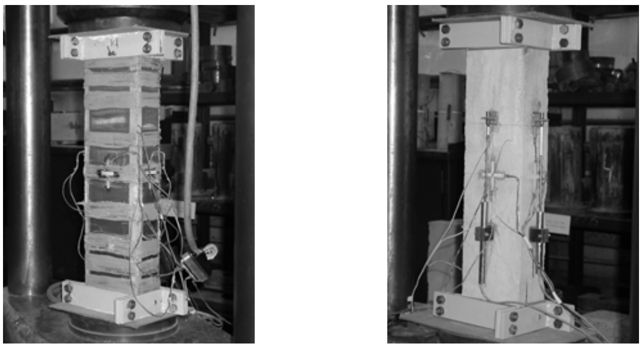
a) S4b - ρ_L=2,80% b) S5b - ρ_L=3,50% c) S1a (control element)

Figure 1. Specimens of stage IIa in investigative emplacement

2.2 *Stage IIb*

Stage IIb was a continuation of studies started in previous stage IIa. Steel reinforcement was constructed the same as in stage IIa. Elements were made of concrete with mean cubic compression strength $f_{cm,cube}$=51,25 MPa.

Three elements with longitudinal CFRP strips strengthening (intensity ρ_L=4,20%) and CFRP sheet bands (St+m1; St+m2; St+m3) were investigated. Additionally two elements without strengthening were investigated (Sb-1; Sb-2).

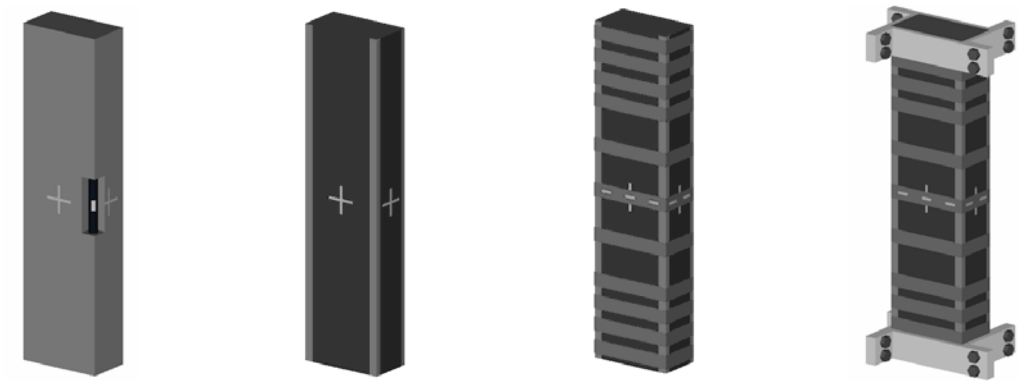


a) St+m2 - ρ_L=4,20% b) Sb-1 (control element)

Figure 2. Specimens of stage IIb in investigative emplacement

Before performing tests strain gauges were attached to longitudinal steel reinforcement. One strain gauge was glued to every of four bars at mid-length to measure longitudinal strains of steel (Fig 3a). Strain gauge rosettes were glued to concrete and CFRP strips. They were attached at mid-length on every side of the element (Figs 3a, 3b). Strain gauges were also attached to the one of CFRP bands to measure transverse strains (Fig. 3c).

This method of strain gauge arrangement, in the middle part of the element, allowed measurements of longitudinal and transverse strains in composite strengthening materials. It enabled the comparison of strains of: concrete ($\varepsilon_{cvm,lim}$), longitudinal steel bars, CFRP strip ($\varepsilon_{Lvm,lim}$) and CFRP sheet in the middle cross-section of element. The results of this analysis are listed in Table 2.

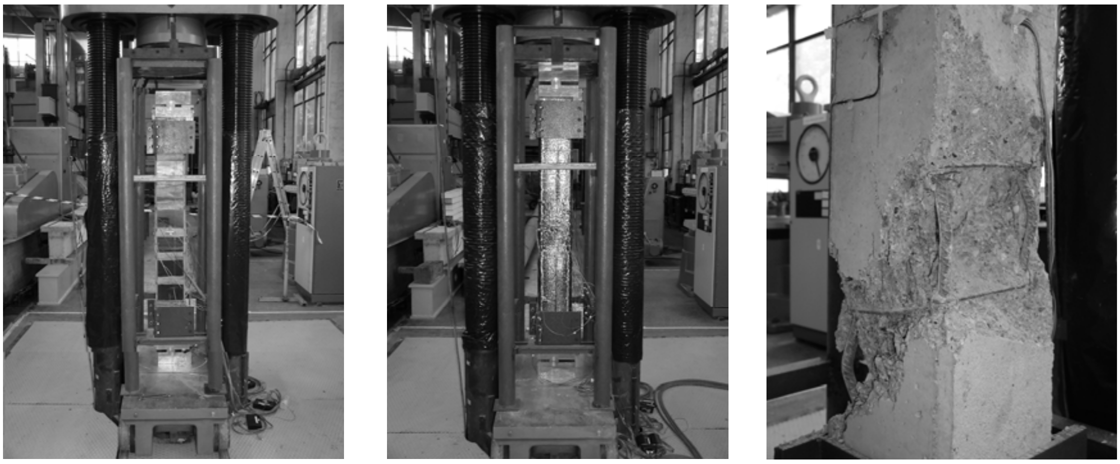


a) b) c) d)

Figure 3. The way of preparation of investigative elements (strain gauges are marked with light lines)

2.3 *Stage III*

Within the framework of stage III the verification with half natural-scale elements was conducted. The purpose of conducting verification was to estimate the influence of the intensity of longitudinal strengthening ρ_L=2,53% and the arrangement of transverse strengthening – bands or continuous jacket, on load-bearing capacity of investigative elements. The maximum possible intensity of longitudinal strengthening was used. However, strengthening was arranged in one layer.



a) SwzA_0 - ρ_L=2,53% b) SwzB_0 - ρ_L=2,53% c) failure of element Sbw_0

Figure 4. Specimens of stage III in investigative emplacement

The investigations were conducted on column models with cross-section 200x200 mm and height 1500 mm. The longitudinal steel reinforcement was four bars ∅12, steel A-IIIN, yield strength f_{yd}=420 MPa (Polish Standard 2002), the transverse reinforcement was stirrups ∅5,5, steel A-I, yield strength f_{yd}=210 MPa (Polish Standard 2002). Elements were made of concrete with mean cubic compression strength $f_{cm,cube}$=61,23 MPa.

Two types of strengthened elements were designed and investigated:

1) type A: ρ_L=2,53%, Sika CarboDur M strips, transverse bands made of SikaWrap Hex 230C sheet (Fig. 4a),

2) type B: ρ_L=2,53%, S&P CFK-Lamellen 200/2000 strips, single continuous confinement with S&P C Sheet 240 (Fig. 4b).

To apply axial load a cylindrical bearing was used. The support zones, where load application causes significant stress concentration, external reinforcement – screwed steel bands, 200 mm high (Figs 1, 2, 3d, 4) was added. They eliminated the risk of failure caused with local pressure.

3 RESULTS OF EXPERIMENTAL STUDIES

3.1 *Load-bearing capacity*

The purpose of destructive investigations was to estimate:
- load-bearing capacity of investigated columns N_u (it answers to measured destructive compressive force),
- maximum, measured longitudinal strains of elements $\varepsilon_{vm,lim}$,
- mechanism (view) of columns failure.

Table 1. Results of load-bearing capacity investigations in stage IIa

No	Column symbol	N_u [kN]	$\varepsilon_{vm,lim}$* [‰]	Mechanism (view) of failure
1	S1a	457	2,44	Shearing of concrete (ω=75°) from top to the middle part of the element
2	S1b	500	2,35	Shearing of concrete (ω=75°) in the middle part of the element
3	S4b	595	2,79	Rupture of bands in upper part on the edges of the element in area of crush of concrete; debonding of bands with concrete cover; crush and cracks of strips along fibers
4	S5b	657	2,77	Rupture of bands in upper part on the edges of the element in area of crush of concrete; debonding of bands with concrete cover; crush and cracks of strips along fibers
5	S6b	712	2,66	Rupture of bands in upper part on the edges of the element in area of crush of concrete; debonding of bands with concrete cover; cracks of strips along fibers

*) $\varepsilon_{vm,lim}$ - maximum, measured longitudinal strains of elements.

Table 2. Results of load-bearing capacity investigations in stage IIb

No	Column symbol	N_u [kN]	$\varepsilon_{cvm,lim}$* [‰]	$\varepsilon_{Lvm,lim}$** [‰]	Mechanism (view) of failure
1	Sb-1	581	2,413	——	Shearing of concrete (ω=65°) from top to the middle part of the element
2	Sb-2	600	2,367	——	Crush of concrete in lower part of the element
3	St+m-1	833	2,342	2,298	Rupture of bands on the edges and crush of concrete in lower part of the element; debonding of strip with concrete cover in area of failure
4	St+m-2	942	2,247	2,374	Rupture of bands in lower part on the edges of the element in area of crush of concrete; debonding of the one of strips with 20mm layer of concrete; crushes and cracks of strips along fibers
5	St+m-3	863	2,283	2,244	Rupture of bands in lower part on the edges of the element in area of crush of concrete; debonding of bands with concrete cover; crushes and cracks of strips along fibers

*) $\varepsilon_{cvm,lim}$ - maximum, measured longitudinal strains of concrete,
**) $\varepsilon_{Lvm,lim}$ - maximum, measured longitudinal strains of CFRP strips.

Table 3. Results of load-bearing capacity investigations in stage III

No	Column symbol	N_u [kN]	$\varepsilon_{cv2,lim}$* [‰]	$\varepsilon_{Lv2,lim}$** [‰]	Mechanism (view) of failure
1	Sbw_0	2241	2,15	——	Shearing of concrete (ω=65°) in lower half of the column
2	SwzA_0	2852	2,19	2,15	Rupture of bands on the edges and crush of concrete in lower part of the element; crushes, debonding and cracks of strips along fibers
3	SwzB_0	2801	2,40	2,40	Rupture of composite jacket on the edges of the column and crush of concrete in lower part of the element; crushes and debonding of strip with concrete cover in area of failure

*) $\varepsilon_{cv2,lim}$ - maximum measured longitudinal strains of concrete on more compressed side,
**) $\varepsilon_{Lv2,lim}$ - maximum measured longitudinal strains of CFRP strips on more compressed side.

In case of elements which underwent failure with shearing concrete the angle ω was measured. It is angle between surface of column base and surface of shearing.

It was proved by Rochette & Labossiére (2000) that the most advantageous results of strengthening were observed for the cylindrical specimens and rectangular specimens with curved corners. The most efficient strengthening was to wrap the cylindrical specimens in a few layers of CFRP sheet. The justification is that an external confinement causes a three-axial state of stress. In case of rectangular specimens the increase of strains and load-bearing capacity was not observed, regardless of the number of layers of CFRP sheet and the radius of corners curvature.

In the investigations the increase of mean compressive strains is small in comparison to the control elements. Their borderline value does not depend on the intensity of longitudinal strengthening. In this case a three-axial state of stress does not occur. The increase of load-bearing capacity of columns is caused almost exclusively with longitudinal CFRP reinforcement. The result of use of longitudinal strengthening with CFRP strips is the increase of stiffness and load-bearing capacity of columns (Kamiński & Trapko 2006).

3.2 *Intensity of strengthening*

The relative increases of load-bearing capacity ($\Delta N_u/N_{u,Sbw\_j}$), is the increases of load-bearing capacity of columns strengthened with CFRP strips and sheets ($\Delta N_u = N_{u,Swz\_j} - N_{u,Sbw\_j}$) in relations to load-bearing capacity of appropriate control columns (N_{u,Sbw_j}), depending on intensity of longitudinal strengthening ρ_L (index "j" answers to number of investigation stage) are listed in Table 4. The results are also presented in graphic form at Figure 4.

Table. 4. Intensity of strengthening

No	Investigation stage	Control elements Symbol	Control elements N_u [kN]	Strengthened elements Symbol	ρ_L [%]	N_u [kN]	$\Delta N_u/N_{u,Sbw\_j}$ [%]
1	IIa	S1	478,5	S4b	2,80	595	24,35
2				S5b	3,50	657	37,30
3				S6b	4,20	712	48,80
4	IIb	Sb	590,5	St+m-1	4,20	833	41,07
5				St+m-2	4,20	942	59,53
6				St+m-3	4,20	863	46,15
7	III	Sbw_0	2241	SwzA_0	2,53	2852	27,26
8				SwzB_0	2,53	2801	24,99

To reach higher intensity of longitudinal strengthening ρ_L multi-layer strengthening or thicker strips (made to order) should be applied. However, this type of study was not an object of analysis presented in the paper.

It should be noted that longitudinal external composite strengthening is not effective if it is not supported with transverse strengthening.

In every experiment are usually a few crucial parameters. They decide the results of experiments. The elements have specific geometry and material structure. In case of the presented investigations crucial parameters are: type and structure of concrete, the way of executing and strengthening of elements, the implementation of load, structural changes in element and dimensions of elements. The parameter which influences on the effectiveness of strengthening is mainly intensity of longitudinal strengthening ρ_L. In case of models it is easy to reach intensity of strengthening ρ_L=4,20%. The value of ρ_L is limited in case of natural-scale elements strengthened with one layer of CFRP strip. Authors realize that all listed above coefficients can cause scale effect and influence on the results of experiment.

Additionally, as a result of the studies authors proposed to modify load capacity (N_u) formula, for axial compressed RC columns strengthened with CFRP materials, proposed by Campione & Miraglia (2003). Numerical analyses based on the own calculation model (Trapko 2004) were verified with experimental studies of Rochette & Labossiére (2000), Campione & Miraglia (2003). The experimental verification was conducted with two kinds of elements – to a scale of 1:5 (80x160x600 mm) and a half natural-scale (200x200x1500 mm). The differences between experimental and theoretical values are within the scope of 1-10%.

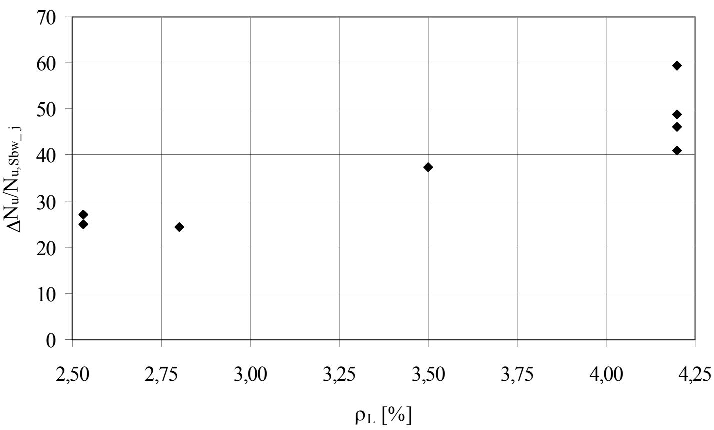


Figure 4. Relative increase of load-bearing capacity of columns strengthened with CFRP materials in relation to load-bearing capacity of control columns depending on intensity of longitudinal strengthening

4 CONCLUSIONS AND FINAL REMARKS

On the basis of the experimental studies the following conclusions are stated:

- Use of CFRP strips as longitudinal strengthening in rectangular columns causes an increase of stiffness and load-bearing capacity,
- An increase of load-bearing capacity of rectangular columns strengthened with CFRP strips is caused almost exclusively with longitudinal strengthening,
- Longitudinal strengthening must be wrapped with transverse strengthening which prevent debonding of the CFRP strip and attached concrete,
- An increase of mean compressive strains in case of strengthened columns is small in comparison to control columns,
- In consequence of tensile stress concentration in corners of transverse composite strengthening in columns with rectangular cross-section occurs rupture of sheet fibres. It is equivalent with failure of element accompanied with immediate crush of concrete and longitudinal composite strip in area of failure.

5 REFERENCES

Campione G., Miraglia N. 2003. Strength and strain capacities of concrete compression members reinforced with FRP. *Cement and Concrete Composites*, No. 25, 31-41.

Demers M., Neale K.W. 1994. Strengthening of existing concrete columns with unidirectional composite sheets. *Proceedings 4th International Conference on Short and Medium Span Bridges*, Edited by: Mufti A.A., Bakht B. and. Jaeger L.G. Canadian Society for Civil Engineering, Montreal, Canada, 895–905.

Kamiński M., Trapko T. 2006. Experimental behaviour of reinforced concrete column models strengthened by CFRP materials. *Journal of Civil Engineering and Management*, Vol. XII, June, 109-115.

Kamiński M., Trapko T. 2006. On effective use of CFRP as strengthening reinforcement of eccentric compressed RC columns. *Inżynieria i Budownictwa,* No. 1, 39-43 (in Polish).

Mirmiran A., Shahawy M. 1997. Behaviour of concrete columns confined by fibre composites. *Journal of Structural Engineering*, Vol. 123, No. 5, 583-590.

Polish Standard PN-B-03264:2002. Plain, reinforced and prestressed concrete structures. Analysis and structural design (in Polish).

Rochette P., Labossière P. 2000. Axial testing of rectangular column models confined with composites. *Journal of Composites for Construction*, Vol. 4, No. 3, 129-136.

Trapko T. 2004. Load capacity of RC columns strengthening with CFRP strips and wraps. PhD. dissertation, Rapport series PRE 22/04, Institute of Building Engineering, Wroclaw University of Technology, 177 p (in Polish).

Trapko T. 2003. Research on load carrying capacity of reinforced concrete columns strengthened with CFRP strips and wraps. *Proceedings 4th PhD. Symposium in Civil Engineering*. The Silesian University of Technology, Gliwice – Wisła, Poland, No. 101, 425-432 (in Polish).