



EXPERIMENTAL BEHAVIOUR OF REINFORCED CONCRETE COLUMN MODELS STRENGTHENED BY CFRP MATERIALS

Mieczysław Kamiński¹, Tomasz Trapko²

^{1,2}*Institute of Building Engineering, Wrocław University of Technology,
Pl. Grunwaldzki 11, 50-370 Wrocław, Poland*

E-mail: ¹mieczyslaw.kaminski@pwr.wroc.pl;

²tomasz.trapko@pwr.wroc.pl

Received 16 May 2005; accepted 17 Oct 2005

Abstract. Strengthening of the reinforced concrete structures is one of the most difficult and important tasks of civil engineering. The paper presents the problem of strengthening of reinforced concrete structures. Experimental tests of load-carrying capacity of reinforced concrete columns strengthened with CFRP strips and wraps have been carried out. The first objective of this research was to determine the influence of the type of reinforcement on load-carrying capacity and strain. The second objective was to determine interdependence of the intensity of external reinforcement and load-carrying capacity of element. Tests results have shown that the subject was worth investigating. Relations between external reinforcement ratio and load-carrying capacity of small models of RC columns with various reinforcement ratio (from 1,4 % to 4,2 %) have been examined.

Keywords: column, compression, load-carrying capacity, strengthening, CFRP.

1. Introduction

Rehabilitation and strengthening of reinforced concrete structures is a dynamically growing division of structural engineering. In recent years an increased application of new repair and strengthening systems of reinforced concrete load-carrying structures has been noted.

The problem of strengthening the reinforced concrete structures appeared for the first time when their proper function was modified or they were used in a different manner than previously planned. Assumptions made in the design are closely connected with a specific function of the structure. The designers of the existing reinforced load-carrying structures constructed many years ago could not predict their use in practice and determine all deterioration effects produced by external factors during their service. It was not rare to find that in this way some structural members could be deteriorated or even damaged. In most cases the increased dead and live loading that should be safely carried by the structures, as well as their poor technical condition necessitate strengthening procedures.

Main reasons of structural strengthening are:

- increase of dead and live loading,
- material aging and corrosion,
- mechanical damage,
- reduction of strain limits,
- decrease of stress in steel reinforcement
- decrease of crack width,

- modification of structure static scheme,
- construction failures.

Strengthening of the reinforced concrete structures is one of the most difficult and important tasks of civil engineering. Individual approach to the problem is a necessity since any ready-made solution can be applied. One of the prime objectives is to provide detailed technical and cost-effective analyses. Structures must be carefully examined in order to determine their technical condition, to find reasons for deterioration and strengthening as well as to establish service requirements of the reinforced structures. It is also essential to analyse their technical design, dig out open pits and carry out suitable measurements. Cost-effectiveness of each of the proposed strengthening techniques should be considered and compared to the cost of a new structure. The strengthening methods applied should ensure the required safety margin and guarantee a sufficient reliability over time.

The following methods used for strengthening the reinforced concrete compressed columns can be distinguished according to their application way:

- increase of the cross-sectional area of a column,
- modification of the structural static scheme.

Conventional techniques using the increase of cross-sectional area of a column comprise the following:

- additional longitudinal and transverse reinforcement and increased cross-sections embedded in reinforced concrete,

- additional steel sections,
- adhesively bonded or bolted steel flat sections or sheet elements.

Modification of the structural static scheme is accomplished by means of additional steel columns or knee braces carrying the load directly to the foundation.

One of the state-of-the-art methods used for strengthening the structural members are those utilising carbon-reinforced composite materials such as strips, wraps, sheet elements or shapes. Over the last decade new alternative solutions are being developed for civil infrastructure applications to meet the growing demand since a conventional technology is known for its many shortcomings and limitations.

The increased applications of these materials to strengthening the reinforced concrete structures are due to their advantageous properties such as high strength, durability and high-fatigue resistance. A lightweight combined with an easy maintenance as well as short time of application make it a worthwhile alternative. The only significant disadvantage is a relatively high cost of materials. The strengthening elements themselves do not influence the size of a structure or adversely affect its aesthetics.

Taking into account a marked increase in the application of CFRP composites utilised to reinforced elements in bending and shear and their advantageous properties, such as an easy maintenance and competitiveness, it was proposed to use CFRP strips and wraps for strengthening the structural elements in compression. For several years the research on the compression reinforced concrete columns strengthening with FRP composites have been carried out. The above-mentioned technology is novel, thus many scientific centres worldwide have been trying to find satisfactory answers to the arising problems. With precursors of this studies were aggregates directed by Priestley [1], Saadatmanesh [2], Demers and Neale [3] and Picher [4]. The satisfactory results obtained in these studies have inspired other scientific centres in the world [5–9] as well as in Poland [10, 11] to embark on further research of this subject.

The research objective was to evaluate the influence of the following parameters on the strength of the column models:

- the stiffness of the confinement (different numbers of FRP sheets) [3, 8, 10],
- the kind of the FRP materials (AFRP, GFRP, CFRP) [3, 8],
- the shape of the section (different corner radius) [3, 8, 10],
- the compressive strength of concrete [3, 6],
- strengthening after “damaged loading” [6],
- eccentric loading [7, 10].

In order to prove the effectiveness of strengthening the reinforced concrete columns in compression with longitudinal CFRP strips and transverse CFRP wraps some studies were conducted at the Institute of Building Engineering, Wrocław University of Technology [12–15]. One of the objectives of this study was to acquire

essential knowledge concerning the influence of slenderness and eccentricity on strain and strength abilities as well as to describe the damage mechanisms of structural elements.

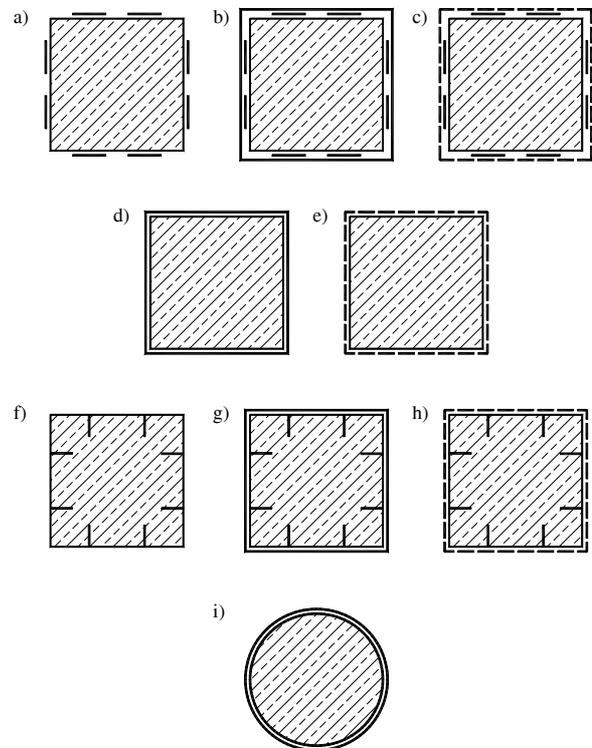


Fig 1. Proposed strengthening solutions for structural elements in compression using CFRP materials

The assumptions for strengthening structural elements in compression utilising carbon-reinforced composites are mainly based on the techniques that involve an increase of element cross-sectional area by means of adhesively bonded or bolted steel flat sections, sheet elements or brackets. The authors propose the following strengthening solutions: external adhesive bonding of longitudinal CFRP strips (Fig 1 a), external adhesive bonding of longitudinal CFRP strips and transverse CFRP band wraps (Fig 1 b), external adhesive bonding of longitudinal CFRP strips and transverse CFRP wraps (Fig 1 c), external adhesive bonding of transverse CFRP wraps (Fig 1 d, i), transverse wrapping (Fig 1 e, j), internal adhesive bonding of longitudinal strips (Fig 1 f), internal adhesive bonding of longitudinal CFRP strips and transverse CFRP band wraps (Fig 1 g), internal adhesive bonding of longitudinal CFRP strips and transverse wrapping (Fig 1 h).

2. Experimental study

The study objective was to determine the interdependence of the intensity of external reinforcement and load-carrying capacity of the element. Reinforced concrete column models (scale 1:5) with a cross-section of 80x150 mm and 600 mm high have been tested (Fig 2).

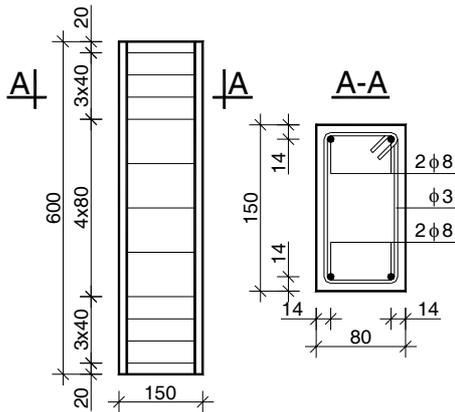


Fig 2. RC columns tested. Elements S1a and S1b

Longitudinal reinforcement consisted of four A-II (18G2) [16] steel bars with $\varnothing 8$ diameters, while transverse reinforcement was made up of A-I (St3SX) [16] steel stirrups with $\varnothing 3$ diameters. The spacing between the stirrups at the element ends was about 40 mm along 150 mm section equal to the length of the longer side of the bar cross-section. The elements were made of medium compression strength concrete $f_{cm} = 40,8$ MPa.

For achieving the designed objectives two series of elements were examined. The first series marked with “a” consisted of 5 elements with different reinforcement ratio using longitudinal CFRP strips (Fig 3). The second series with “b” consisted of 5 elements with different reinforcement intensity using longitudinal CFRP strips and external CFRP band wraps (Fig 3). External band wraps were mounted on the same level as steel stirrups.

Reinforcement ratio (ρ_w) can be expressed by the relationship between CFRP strip area (A_L) and concrete cross-sectional area in the element (A_c).

In addition, two control column models without reinforcement (S1a and S1b) were examined to determine their actual load-carrying capacity and to describe the damage mechanism (Fig 2).

The following materials were used for reinforcement of elements: Sika® CarboDur® M1214 strengthening strips with a thickness of $h = 1,4$ mm and the width adjusted to the desired reinforcement ratio, Sikadur®-30, SikaWrap®-230C, Sikadur®-330 [17]. The reinforcements were applied according to the stringent technological requirements.

	S6a	S5a	S4a	S3a	S2a
Amount of elements	1	1	1	1	1
Strip cross-sectional area [mm]	120x1,4 - 2 pcs 60x1,4 - 2 pcs	90x1,4 - 2 pcs 60x1,4 - 2 pcs	60x1,4 - 4 pcs	60x1,4 - 2 pcs 30x1,4 - 2 pcs	30x1,4 - 4 pcs
Area of strips [cm ²]	5,04	4,20	3,36	2,52	1,68
Reinforcement intensity [%]	4,20	3,50	2,80	2,10	1,40
	S6b	S5b	S4b	S3b	S2b
Amount of elements	1	1	1	1	1
Section of band wraps [mm]	25x0,13	25x0,13	25x0,13	25x0,13	25x0,13

Fig 3. Main characteristics of tested specimens of series “a” and “b”



a) element S6a



b) element S5b

Fig 4. Elements during testing

Values of the material characteristics of concrete, steel reinforcement and CFRP composites are shown in Table 1.

Table 1. Mechanical properties of materials

Concrete		
Compressive strength $f_{cm,cube}$	[MPa]	40,8
Tensile strength f_{ctm}	[MPa]	3,19
Modulus of elasticity E_{cm}	[MPa]	33 490
Steel reinforcement		
Yield stress f_{ym}	[MPa]	393,3
Tensile strength f_t	[MPa]	590,1
Modulus of elasticity E_{sm}	[MPa]	201 875
CFRP strip		
Tensile strength f_{Lm}	[MPa]	3467,7
Tensile modulus $E_{Lm,t}$	[MPa]	228 227
CFRP wrap		
Tensile strength f_{wm}	[MPa]	2936,6
Tensile modulus E_{wm}	[MPa]	237 600

Test specimens were subjected to axial compression. The same testing programme was applied to both series,

as well as to control elements. It consisted of 6 initial loading cycles (up to approx 1/3÷1/2 of the boundary load-carrying capacity). The 7th loading cycle was introduced to observe the damage mechanism. The loadings were applied step-wise according to the Polish Standard [18] requirements. Longitudinal strains were measured using sensors with accuracy of reading of 0,001 mm.

The support area of the elements was additionally protected with steel clamping brackets to eliminate possible damage of the element caused by the piston pressure of the band press (Fig 4).

3. Results of research

It was found on the basis of the obtained results that the load-carrying capacity marked with S2a and S3a with the reinforcement ratio 1,40 % and 2,10 % respectively was not satisfactory, so they were not taken into consideration in analysis.

Figs 5 and 6 show the diagrams comparing mean longitudinal strain values ϵ_{vm} in function of the relationship of the applied loading N to the boundary load-carrying capacity of the elements without reinforcement $N_{u,S1}$ (control columns).

Fig 5 depicts the diagrams of a group of S5 type elements, while Fig 6 shows the diagrams of a group of S6 type elements. In both cases they were compared with the diagram of mean longitudinal strain values ϵ_{vm} obtained for control columns. It could be noticed in Figs 5 and 6 that the application of reinforcement using longitudinal CFRP strips improves strain abilities and load-carrying capacity by 24 % for the elements S5a and S6a respectively, in comparison with control columns. The use of additional transverse reinforcement by means of CFRP band wraps prevents rapid debonding of a strip and increases load-carrying capacity by 37 % and 49 % for the elements S5b and S6b respectively, in comparison with control columns (Table 2).

Mean strains of the elements reinforced on the level of mean boundary load-carrying capacity of control elements are 50 % less than mean longitudinal strains of the columns without reinforcement.

Distortions of the diagram S6a shown in Fig 6 are caused by the damage of the connection between the strip and the column. As a result, this produced the debonding of a strip part.

Table 2. Results of research

	S1a	S4a	S5a	S6a
Amount of elements	1	1	1	1
Load-carrying capacity	[kN] 465	475	595	596
Vertical maximal strain	[‰] 2,44	2,08	1,85	2,05
Growth load capacity	[%]	—	24	24
	S1b	S4b	S5b	S6b
Amount of elements	1	1	1	1
Load-carrying capacity	[kN] 500	595	657	712
Vertical boundary strain	[‰] 2,35	2,79	2,77	2,66
Growth load capacity	[%]	—	24	37

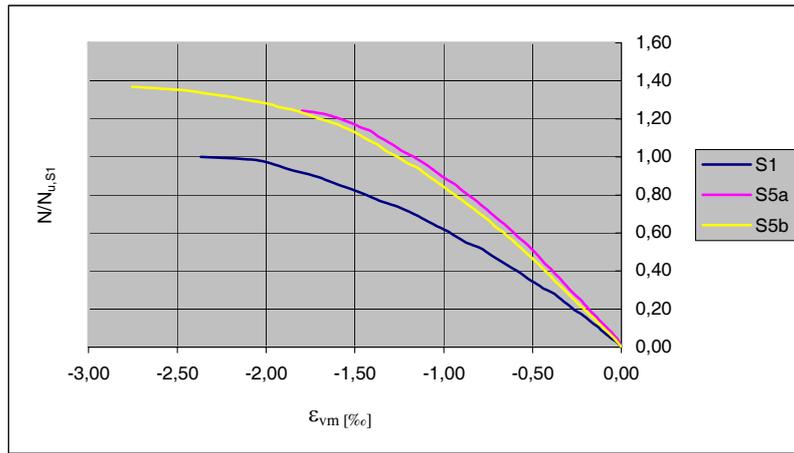


Fig 5. $N/N_{u,S1}$ versus ϵ_{vm} for columns: S1, S5a, S5b

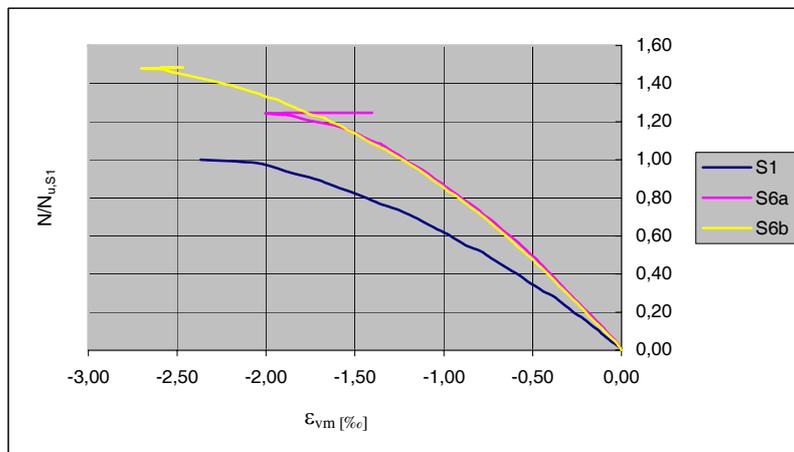


Fig 6. $N/N_{u,S1}$ versus ϵ_{vm} for columns: S1, S6a, S6b



a) S4a



a) S4b



b) S5a



b) S6b

Fig 7. Damaged elements from series “a”

Fig 8. Damaged elements from series “b”

Observation of the damage mechanism and evaluation of the test specimens enabled the authors to draw the following conclusion. The failure of elements from series “a” was caused by debonding a certain part of a strip, instantaneous concrete damage and steel ductility (Fig 7). Three types of debonding could be observed:

- debonding of strip with adhesive and concrete (Fig 7 a),
- debonding of strip with adhesive,
- debonding of strip only (Fig 7 b).

The failure of elements from series “b” was caused by breakage of some bands and instantaneous debonding of strip, concrete damage and steel ductility (Fig 8). Breakage of bands was always preceded by cracking carbon fibres. Similar acoustic effects were observed during strength and strain test of CFRP wraps.

4. Concluding remarks

Results of studies confirmed that the subject was worth investigating. The application of CFRP strips to strengthen compressed elements increases their boundary load-carrying capacity. This is caused by a decrease of longitudinal strains in relation to control elements at an equal increase of longitudinal force. The use of additional external CFRP band wraps prevents debonding of a strip till the moment of the wrap breaking and the element damage.

Results of initial experimental studies aimed at describing the damage mechanism of the reinforced concrete elements in compression strengthened with CFRP show that in case of elements being strengthened only with longitudinal sections of CFRP strip, the failure was caused by the damage of the connection between the composite and the adhesive. The other reason was separation of a strip with concrete wrap from the test element. Debonded sections of the strip with concrete wrap were observed during visual inspection. They were 5–10 mm thick. Reinforced concrete columns strengthened with externally bonded CFRP strips without transverse CFRP band wraps that is subjected to compression, fail prematurely due to buckling (which causes debonding). Due to this fact the use for practical application should be made with caution. Elements reinforced with longitudinal sections of CFRP strip and additional CFRP band wraps were damaged because some bands broke, followed by instantaneous debonding of strip with concrete wrap. In this case the determining value of element load-carrying capacity is rectangular boundary strains of CFRP band wraps.

The authors plan to analyse the influence of particular components of the reinforcement, such as longitudinal strips, external band wraps and wrapping on load-capacity of elements. In order to achieve this, the following elements will be tested: elements without reinforcement, elements strengthened with longitudinal strips only, elements strengthened with longitudinal strips and external bands, elements

strengthened with external bands only, elements strengthened with longitudinal strips and total wrapping and finally elements strengthened with total wrapping only. The intensity of reinforcement shall be 4,20 %.

The authors are fully aware of the influence for scale effects in this study. In the initial research column models were examined in the 1:5 scale. Research results need verification on elements in natural scale. The most important parameter to be taken into consideration is reinforcement ratio (ρ_w). Together with the growth of cross-sectional concrete in the element (A_c), the required CFRP strips will increase. Perhaps it will be necessary to use an external adhesive bonding of longitudinal and multiply CFRP strips or to limitation reinforcement intensity.

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ANGLIES PLUOŠTU ARMUOTO POLIMERO LAKŠTAIS SUSTIPRINTŲ GELŽBETONINIŲ KOLONŲ EKSPERIMENTINIS TYRIMAS

M. Kamiński, T. Trapko

Santrauka

Gelžbetoninių konstrukcijų stiprinimas – vienas iš sudėtingiausių ir svarbiausių statybinių konstrukcijų srities uždavinių. Straipsnyje nagrinėjama gelžbetoninių konstrukcijų stiprinimo problema. Čia pateikti anglies pluoštu armuoto polimero lakštais (CFRP) sustiprintų gelžbetoninių kolonų laikomosios galios eksperimentinių tyrimų rezultatai. Pirmasis tyrimų tikslas – nustatyti armatūros rūšies įtaką laikomajai galiai ir deformacijoms. Antrasis tikslas – nustatyti priklausomybę tarp išorinės armatūros intensyvumo ir elemento laikomosios galios. Bandymų rezultatai parodė tyrimų svarbą. Taip pat išnagrinėta priklausomybė tarp išorinės armatūros procento ir nedidelių gelžbetoninių kolonų su skirtingais armavimo procentais (nuo 1,4 % iki 4,2 %) laikomosios galios.

Reikšminiai žodžiai: kolona, gniuždymas, laikomoji galia, sustiprinimas, CFRP.

Prof PhD Eng **Mieczysław KAMIŃSKI**. Chief of Division of Concrete Structures part of Institute of Building Engineering at Wrocław University of Technology, Poland. Member of fib (International Federation for Structural Concrete), IABSE (International Association for Bridge and Structural Engineering). His main research areas include silo structures (both reinforced and pre-stressed), cooling towers and use of CFRP materials for strengthening constructions.

PhD Eng **Tomasz TRAPKO**. Assistant of Division of Concrete Structures part of Institute of Building Engineering at Wrocław University of Technology, Poland. His research includes repairs of concrete structures and use of CFRP materials for strengthening constructions.