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THE INFLUENCE OF CFRP SHEETS ON THE STRENGTH OF SHORT COLUMNS PRODUCED FROM NORMAL STRENGTH CONCRETE AND FIBRE REINFORCED CONCRETE

WPŁYW MAT Z WŁÓKIEN WĘGLOWYCH NA WYTRZYMAŁOŚĆ KRÓTKICH KOLUMN ŚCISKANYCH Z BETONU ZWYKŁEGO I FIBROBETONU

Abstract

This article presents the influence of carbon fibre reinforced polymer sheets (CFRP) on the strength of normal and fibre concrete columns determined in uniaxial compression. Fibre reinforced concrete (FRC) belongs to a special concrete group which is characterised by special properties without strength [12]. By using CFRP, we can modify the process of work of these composites, which are adhered to a prepared surface using a high performance resin, especially as is shown in this article. This composite material works in an elastic-plastic range with strengthening.

Keywords: composite column, fibre reinforced concrete, carbon reinforced polymer material, stress-strain, strengthening

Streszczenie

W artykule przedstawiono wpływ stosowania mat z włókien węglowych na wytrzymałość kolumn z betonu zwykłego i fibrobetonu określoną w próbie jednoosiowego ściskania. Fibrobeton należy do grupy betonów specjalnych, które cechują się specjalnymi właściwościami oprócz wytrzymałości [12]. Modyfikację sposobu pracy kolumn z tego betonu możemy uzyskać, stosując maty z włókien węglowych, które są przyklejane do odpowiednio przygotowanej wcześniej powierzchni elementów słupowych przy użyciu wysokowytrzymałych żywic, co zostało wykazane w pracy. Powstały w ten sposób element zespolony pracuje w zakresie sprężysto-plastycznym ze wzmocnieniem.

Słowa kluczowe: słup zespolony, fibrobeton zwykły, włókna węglowe, naprężenie–odkształcenie, wzmocnienie

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1. Introduction

In recent years, we have observed a significant increase in the use of carbon fibres for reinforcing concrete structures. This is due to the many advantages of this material which include its high strength and Young's modulus, resistance to aggressive environments, a high strength-to-weight ratio and good fatigue properties [9, 16].

Cracking and spalling of concrete columns often accompany the corrosion of inner steel reinforcements. The loss of cementitious material causes the corrosion of steel reinforcement and leads to reductions in the structural integrity and load-carrying capacity of columnar supporting elements [11].

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 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 drawbacks of using steel jackets are their low resistance to corrosion, high cost and high dead-weight [6].

As the result, CFRP presents a very attractive option as an alternative and extremely efficient retrofitting technique in such cases through the use of composite jackets or wraps around a degraded column [10]. Carbon sheets have been applied to increase the concrete confinement and loading resistance of concrete columns. The confinement effectiveness of externally bonded fibre reinforced polymer (FRP) sheets depends on different parameters, such as the type of concrete, steel reinforcement, thickness of the FRP jackets (number of layers), stiffness (type of FRP) and loading conditions [1].

The use of CFRP sheets can be of significant importance for the strengthening of historical buildings and monuments where change of use is considered as this often causes an increase of loads. The experience of the authors indicate that many historical buildings were built using low performance concrete which corresponds to the current C15/20 class. Strengthening it with CFRP confinement can increase bearing capacity and maximum strains.

Due to the increasing usage of concrete with steel microfibres in load-carrying concrete elements [5, 7, 8], the authors present a study of FRC columns for comparative purposes.

2. Experimental programme

2.1. The specimens and materials

A total of twelve circular columns were manufactured in a local laboratory and tested under uniaxial compression. All specimens were produced using normal concrete – half of them contained fibre reinforcement at an amount of 1.5% by volume. Table 1 presents details of the mixture used in the research. In this study, the constituent materials making up the normal concrete were Portland-fly ash cement type II – CEM II/B-V 32.5R with a 0.5 water cementitious ratio. Diabase (ϕ2–8) and fine sand (ϕ0–2) were used as aggregate. Hooked end steel fibre (50 mm long and 1mm in diameter, tensile strength greater than 1050 MPa) was used throughout the experimental programme.

All specimens were divided into four groups: normal concrete columns (NCC); fibre reinforced concrete columns (FRCC); reinforced normal concrete columns by CFRP (NCC-CFRP); fibre reinforced concrete columns confined by CFRP (FRCC-CFRP). As a result, three specimens from normal concrete and three specimens from fibre reinforced concrete were tested for comparison purposes – the remaining 6 CFCT wrapped columns were tested to evaluate the effect of CFRP sheets. All of the specimens were 400mm in height and 150mm in outer diameter.

Table 1

Proportions of concrete mixture

Mix type	Cement [kg/m^3]	Sand [kg/m^3]	Gravel [kg/m^3]	Water [kg/m^3]	w/c ratio [–]	Steel fibres [% by vol.]
Normal Concrete	366	942	942	183	0.5	–
Fibre Reinforced Concrete	366	942	942	183	0.5	1.5

2.2. Specimen preparation

The concrete specimens were ripened in a water bath for twenty-eight days and then dried out for seven days. A proportion of them were then wrapped with CFRP-Sikawrap301c by using epoxy resin – Sikadur330. The process of resin hardening took the next seven days at 20°C, which provided a full cure of the epoxy resin. To ensure adequate bond strength between the fibre sheets and the concrete surface, the concrete surface was sanded, cleaned and thoroughly dried. The moisture level of the concrete surface was 5%. Each of the six specimens was wrapped with one layer in a continuous manner. To achieve a reliable bond, a 150mm overlap was provided in the direction of the fibres in all the reinforced specimens. The fibre sheets with fibres orientated in the hoop direction were wrapped onto the concrete tube using a manual dry layup process. The age of the concrete specimens at the moment of testing was six weeks. The strength parameters of the CFRP and epoxy resin according to the manufacturer are shown in Tables 2 and 3, respectively.

Table 2

Characteristic parameters of Sikawrap301c [18]

Areal Weight	300 g/m^2 $\pm$ 5 %	
Fibre Density	1.80 g/cm^3	
Fabric Design Thickness	0.17 mm (based on carbon content)	
Mechanical / Physical Properties		
Dry Fibre Properties	Tensile strength Tensile E-modulus Elongation at break	4'900 N/mm^2 (nominal) 230'000 N/mm^2 (nominal) 2.1% (nominal)

Table 3

Characteristic parameters of epoxy resin Sikadur330 [18]

Density	Mixed Resin: 1.31 kg/lt (at +23°C)	
Tensile Strength	30 N/mm² (7 days at +23°C)	(DIN 53455)
Bond Strength	Concrete fracture on sandblasted substrate: > 1 day	(EN 24624)
E-Modulus	Flexural: 3800 N/mm² (7 days at +23°C) Tensile: 4500 N/mm² (7 days at +23°C)	 (DIN 53452) (DIN 53455)
Elongation at Break	0.9% (7 days at +23°C)	(DIN 53455)

2.3. Instrumentation and testing

The uniaxial compression tests of the concrete columns were performed using a servo-controlled MTS Rock and Concrete Mechanics Testing System. The testing system, equipped with a high-capacity and high-stiffness load frame coupled with servo-hydraulics and digital control technology, provided a versatile tool for the investigation of the deformation behaviour of the concrete samples over a wide range of conditions.

The research was carried out at room temperature and humidity, with the constant axial strain rate of the columns in all of the experiments being approximately 5×10^{-5} [s^{-1}]. The measurement of the axial force was carried out by means of a force transducer, while the displacements were measured by LVDT sensors. Radial and axial displacements were determined through the measurement of the whole columns' dimension changes, where the LVDT sensors were mounted directly between compression plates (Fig. 1).

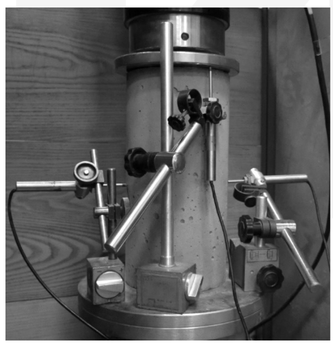


Fig. 1. MTS testing system for uniaxial compression tests and measurements of axial and radial column displacements

3. Results and discussion

3.1. Observations and failure modes

The experimental results from the tests are summarised in Table 4. Moreover, Figures 2 to 4 show the typical failure modes of the unconfined and the confined specimens.

Table 4

Summary of the experimental results

Specimen	Ultimate load [kN]	Nominal compress-ive strength [MPa]	axial strain during fracture of columns [‰]	axial strain during fracture of concrete [‰]	transverse strain during fracture of concrete [‰]	modulus of elasticity E_1 [GPa]	modulus of elasticity E_2 [GPa]
Normal Concrete Columns							
NCC1	520	30.25	3.95	3.95	1.04	8.52	–
NCC2	622	35.69	3.73	3.73	1.98	12.20	–
NCC3	517	29.28	3.78	3.78	3.77	10.12	–
Fibre Reinforced Concrete Columns							
FRCC1	690	40.13	4.79	4.79	1.31	12.46	–
FRCC2	648	38.6	6.15	6.15	2.26	8.22	–
FRCC3	727	42.24	5.22	5.22	4.27	13.68	–
Reinforced Concrete Columns by CFRP							
NCC-CFRP1	1290	72.99	25.69	5.44	2.75	12.72	1.36
NCC-CFRP2	1255	71.97	25.21	6.34	4.11	10.30	1.36
NCC-CFRP3	1236	71.87	22.86	5.01	3.57	14.40	1.40
Fibre Reinforced Concrete Columns confined by CFRP							
FRCC-CFRP1	1386	78.45	23.78	6.67	3.30	12.47	1.60
FRCC-CFRP2	1416	81.20	24.28	6.39	2.76	11.00	1.64
FRCC-CFRP3	1404	80.53	25.30	6.43	1.99	13.16	1.56
Summary							
Group of specimens	average compressive strength [MPa]	standard deviation of the mean [MPa]	average axial strain during fracture of columns [‰]	average axial strain during fracture of concrete [‰]	average transverse strain during fracture of concrete [‰]	average modulus of elasticity E_1 [GPa]	average modulus of elasticity E_2 [GPa]
NCC	31.74	2.63	3.82	3.82	2.26	10.28	–
FRCC	40.32	1.28	5.39	5.39	2.61	11.45	–
NCC-CFRP	72.28	0.48	24.59	5.60	3.48	12.47	1.37
FRCC-CFRP	80.06	1.07	24.45	6.50	2.68	12.21	1.60

a) b)

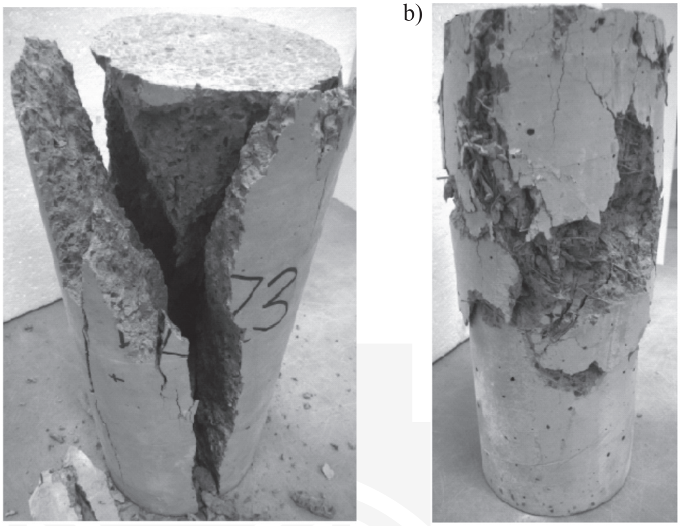


Fig. 2. Typical failure modes of NCC (a) and FRCC (b)

a) b)

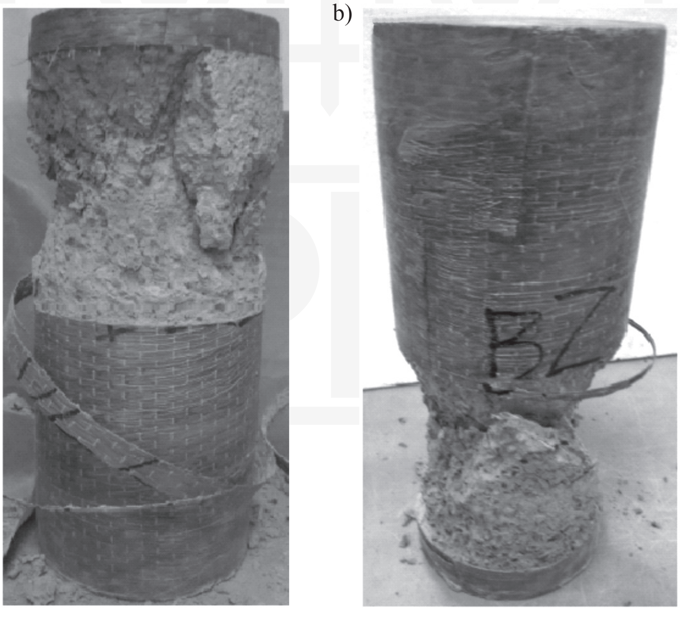


Fig. 3. Typical failure modes of NCC-CFRP

As we see, the fracture of NCC and FRCC can be considered as normal and typical. In the cases of NCC-CFRP and FRCC-CFRP, we cannot predict the location of the fracture. The rapid destruction of the columns with CFRP occurs in the weakest location of the specimens with the release of huge amounts of energy.

a) b)

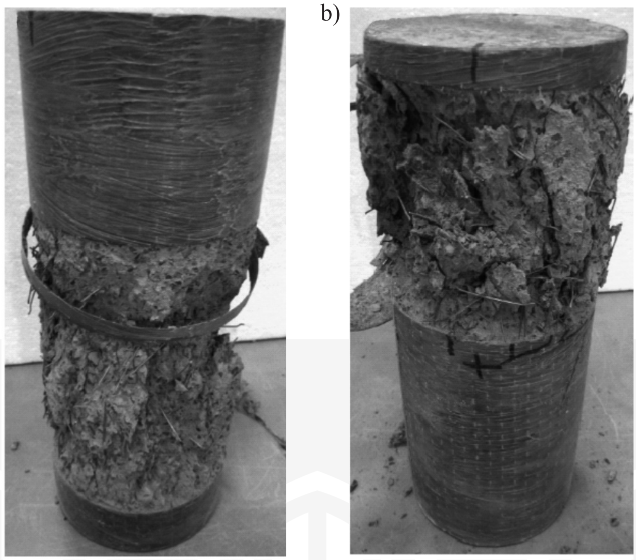


Fig. 4. Typical failure modes of FRCC-CFRP

3.2. Axial and transverse stress–strain response

Figures 5 (a) to (d) show axial stress versus axial and transverse strains for specimens with unconfined concrete columns (a), (b), and confined concrete columns (c), (d). The nominal axial stresses were calculated by dividing the axial loads by the total cross-sectional areas of the columns, and the small thickness of the CFRP was negligible in this calculation. The modulus of elasticity E_1 and E_2 were designated without preloading cycles; therefore, the results are qualitative. The modulus of elasticity E_1 and E_2 were determined in a range of stress ranging from 15% to 33% [3] and from 75% to 95% value of maximum stress, respectively. Axial and transverse strains during the fracture of concrete in the case of CFRP columns were determined at the point of inflection on the stress-strain curve.

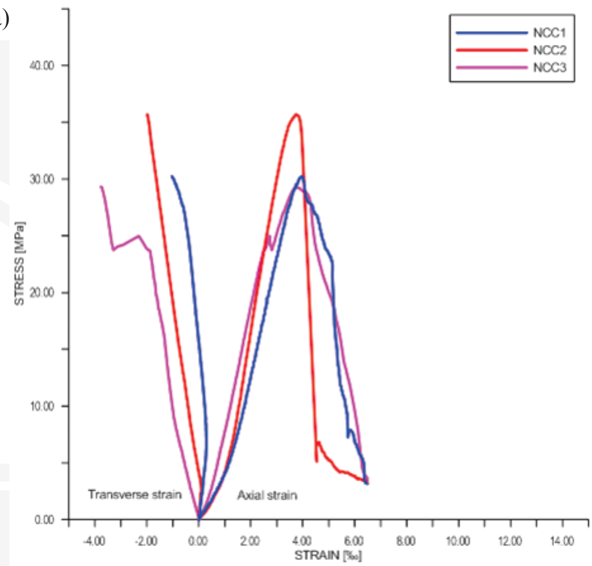
The average compressive strength of NCC is 31.74 MPa. The average longitudinal and transverse strains of NCC at the time of destruction are 3.82‰ and 2.26‰, respectively.

The average compressive strength of FRCC is 40.32 MPa. The average longitudinal and transverse deformations at the time of FRCC destruction are 5.39‰ and 2.61‰, respectively. The destruction is less fragile in comparison to NCC.

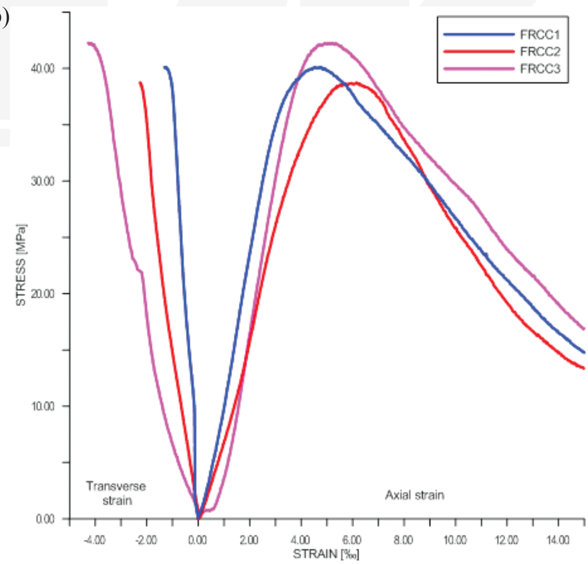
The average compressive strength of NCC-CFRP is 72.27 MPa and is 128% higher than the NCC. The average value of the longitudinal strains at failure is more than six times greater in comparison to NCC. CFRP leads to the occurrence of a tri-axial state of stress in concrete which receives a higher strength. After crossing the border of concrete strength, the CFRP sheets begin to work actively until the time of destruction which is explosive in nature, though the manner of conducting this test (axial strain control) enabled a post-failure analysis of the columns. The NCC-CFRP columns are treated as composite material working as elastic-plastic with strengthening. The average modulus of elasticity E_1 is 21% higher than for NCC and more than nine times greater than the modulus of elasticity E_2.

The behaviour of FRCC-CFRP, until its destruction, is similar to NCC-CFRP. The average compressive strength of FRCC-CFRP is 11% higher than NCC-CFRP and nearly 100% higher than unconfined FRCC. The average values of the longitudinal strains at failure are the same and increment of the transverse strains is similar in both cases. The failure process is also explosive in nature, but in the case of CFRP-FRCC, we do not observe residual strength values immediately in each case due to the presence of the steel fibres. The average modulus of elasticity E_1 is 6.6% higher than FRCC and nearly eight times greater than the modulus of elasticity $E_{2.}$

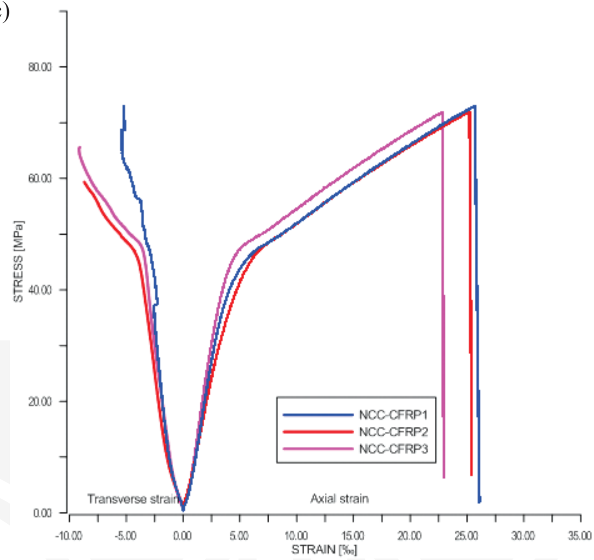
a)



b)



c)



d)

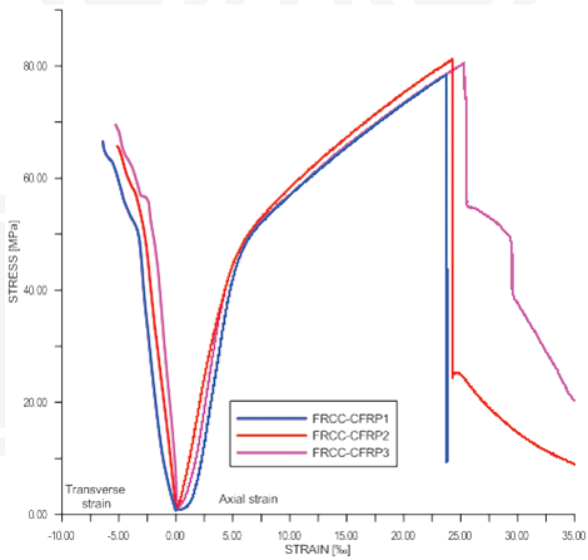


Fig. 5. Axial stress–strain relationships for specimens: NCC (a), FRCC (b), NCC-CFRP c), FRCC-CFRP (d)

3.3. Adhesion of CFRP to the concrete surface

The most crucial aspect determining the full performance of the CFRP sheets is the good adhesion of CFRP to the concrete surface [13]. On the basis of the macroscopic analysis, we can claim that the debonding, which generally occurs in the externally bonded reinforcement technique, was avoided. Figure 6 shows the laminate which was breaking away from the concrete. We can observe that the epoxy resin which was used adhered perfectly to the concrete surface. The grain aggregates and cement paste were torn from the concrete in the case of NCC-CFRP. In the case of FRCC-CFRP steel microfibers were torn from the concrete additionally, what proves a good connection of CFRP with the concrete surface. It is worth noting that the rupture of the jacket can be accompanied by a slight delamination of the layers [17].

a) b)

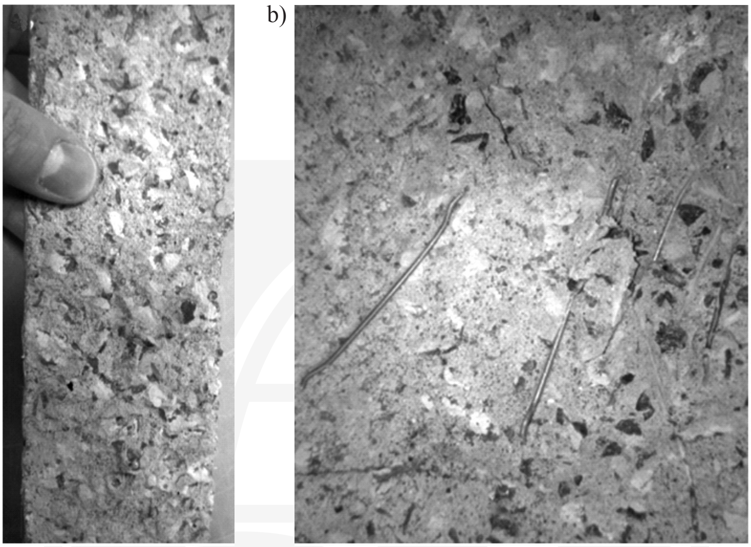


Fig. 6. CFRP sheets which were torn from NCC-CFRP (a) and FRCC-CFRP (b)

4. Conclusions

This paper presents an experimental investigation of the performance of short, circular concrete columns confined with CFRP under uniaxial compression. The following conclusions may be drawn from the work presented in this paper:

1. The confined specimens made from normal concrete fail via rupture of the CFRP in the region of weakness. In contrast with the unconfined specimens, external CFRP confinement effectively increases the compressive strength and axial strains.
2. The stress–strain curves of the confined specimens can be divided into two distinct regions, which is in line with the literature [2, 4, 11, 15]. These regions include, firstly, the elastic stage involved with the transfer of stresses by the concrete and secondly, the hardening stage, where stresses are carried by CFRP confinement, which provides the columns with post-yield stiffness for load carrying. In the case of NCC-CFRP and FRCC-CFRP, we received similar values of compressive strength and maximum strains during fracture – this may indicate that usage of fibre concrete reinforced by CFRP in new constructions is not justified.

3. The efficiency of the CFRP sheets depends largely on the proper preparation of the concrete surface before the lamination process.
4. The use of steel microfibre can cause a lack of total immediate destruction of the columns after reaching the critical stresses in comparison with unreinforced concrete with CFRP. To clearly confirm this proposal, further testing needs to be conducted on a larger number of samples.
5. The different character of the stress–strain curves for unconfined concrete and concrete confined by CFRP causes that during design of concrete structures reinforced by CFRP, use of standard model of stresses distribution under compression as a function of the strains which EC2 shows [14], is not appropriate in this case.

One of the drawbacks of the presented solution is the low fire resistance of the composite. The properties of the carbon fibres do not change even at 2000°C [9], and are more heat resistant than steel and concrete. Unfortunately, in the case of fire, the epoxy resin burns relatively quickly, causing relaxation of the CFRP confinement. Therefore, when using this solution, we need to protect the composite surface from heat and fire, for example, by the use of an additional insulation layer.

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[1] Bogdanovic A., *Strengthening Circular Concrete Columns Using FRP Sheets-Applications*, Composite Materials in Civil Engineering, 2002.
[2] de Lorenzis L., Tepfers R., *Applicability of FRP Confinement to Strengthen Concrete Columns*, Nordic Concrete Research, Publication No. 31. The Nordic Concrete Federation, 2000.
[3] EN 12390-13:2013, Testing hardened concrete, Part 13: Determination of secant modulus of elasticity in compression.
[4] Faella C., Realfonzo R., Salerno N., *FRP confined concrete constitutive relationships*, FRP Composites in Civil Engineering, Adelaide 2004.
[5] Hulimka J., *Strefa podporowa żelbetowego stropu płaskiego o podwyższonej nośności na przebicie*, Wydawnictwo Politechniki Śląskiej, Gliwice 2009.
[6] Karbhari V.M., Eckel D.A., *Effects of Short-Term Environmental Exposure on Axial Strengthening Capacity of Composite Jacketed Concrete*, American Society for Testing and Materials, 1995.
[7] Karwowska J., Łapko A., *Przydatność stosowania nowoczesnych kompozytów fibrobetonowych w konstrukcjach budowlanych*, Budownictwo i inżynieria środowiska, 2011.
[8] Kinash R., Bilozir V., *Deformational calculation method of bearing capability of fiber-concrete steel bending elements*, Technical Transactions, Architecture, Politechnika Krakowska, 2014.
[9] Mayer P., Kaczmar J., *Właściwości i zastosowania włókien węglowych i szklanych*, Tworzywa Sztuczne i Chemia, nr 6, 2008.

[10] Mirmiran A., Yuan W., Chen X., *Design for Slenderness in Concrete Columns Internally Reinforced with Fiber-Reinforced Polymer Bars*, ACI Structural Journal, January–February 2002.

[11] Olivová K., Bilčík J., *Strengthening of concrete columns with CFRP*, Slovak Journal of Civil Engineering, Vol. 1, 2009.

[12] Ostrowski K., *Wpływ zbrojenia rozproszonego na wytrzymałość betonu zwykłego*, II Ogólnopolska Studencka Konferencja Budowlana, Poznań 2015.

[13] Piekarczyk J., *Macherzyńska B., Błażewicz S., Badania nad wykorzystaniem laminatów węglowych do wzmacniania kształtek betonowych, Kompozyty, 2005.*

[14] PN-EN 1992-1-1:2004, Projektowanie konstrukcji z betonu. Część 1–1: Reguły ogólne i reguły dla budynków.

[15] Rousakis T., *Experimental Investigation of Concrete Cylinders Confined by Carbon FRP Sheets, under Monotonic and cyclic Axial Compressive Load*, Chalmers University of Technology, Göteborg 2001.

[16] Shehata I.A.E.M., Carneiro L.A.V., Shehata L.C.D, *Strength of short concrete columns confined with CFRP sheets*, Materials and Structures, Vol. 35, 2002.

[17] Xiao Y., Wu H., *Compressive behavior of concrete confined by various type of FRP composite jackets*, Journal of Reinforced Plastic and Composites, Vol. 22, 2003.

[18] www.sika.com (access: 15.05.2016).