COMPARISON OF BEHAVIOUR OF CONCRETE BEAMS WITH PASSIVE AND ACTIVE STRENGTHENING BY MEANS OF CFRP STRIPS

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Abstract

Since late 1980s in concrete structures the new repair technique based on externally bonded CFRP materials has been used. These materials are characterised by high efficiency and reliability. Applications of these materials were required because of the appearance of problems of insufficient load-bearing capacity of concrete structures, particularly at bending or shear. Presently, strengthening with CFRP composites can be considered as being passive or active. Pre-tensioning of such composites, mostly the CFRP strips, is relatively new strengthening method, which allows for more effective utilization of mechanical properties of the CFRP, particularly strength and deformability of this composites.

The experimental tests on six large-scale reinforced concrete beams, with cross-sections of 0.25×0.50 m and 8.0 m long, were undertaken. The main aim of the tests was the analysis of the efficiency of three detailed methods used for strengthening of reinforced concrete beams by means of CFRP strips used as passive or active external reinforcement. The elements differed each other in the fixing of free ends of the CFRP strip, and in pre-tensioned strips – with the intensity of prestressing. All other factors in tests could be considered as invariable. The test was focused on the serviceability aspects of the behaviour of elements, i.e. flexural stiffness of elements, resistance against cracking and pattern of cracks, as well as determination o actual strains in CFRP strips, steel reinforcement and on concrete surfaces. Finally, the increase of load-capacity of the strengthened beams and the mode of failure has been recorded. The test results allowed for formulation of some general conclusions concerning the effectiveness of passive and active strengthening of concrete beams by means of CFRP strips.

Streszczenie

Od końca lat 1980-tych stosowano nową technologię naprawczą, bazującą na zewnętrznie dołączanych materiałach CFRP (polimerach wzmocnionych włóknami węglowymi). Materiały te charakteryzują się wysoką skutecznością i niezawodnością. Zastosowania takich materiałów były wymagane wskutek występowania problemów z niewystarczającą nośnością konstrukcji betonowych, zwłaszcza przy zginaniu i ścinaniu. Wzmacnianie za pomocą kompozytów CFRP może być obecnie rozważane jako pasywne lub aktywne. Wstępny naciąg takich kompozytów, głównie taśm CFRP, stanowi stosunkowo nową metodę wzmacniania, która pozwala na bardziej efektywne wykorzystanie właściwości mechanicznych CFRP, szczególnie wytrzymałości i odkształcalności tych kompozytów.

Zostały podjęte badania eksperymentalne sześciu belek żelbetowych w dużej skali, o przekroju 0.25×0.50 m i o długości 8.0 m. Głównym celem tych badań była analiza skuteczności trzech szczegółowych metod stosowanych do belek żelbetowych za pomocą taśm CFRP, stanowiących pasywne lub aktywne zbrojenie zewnętrzne. Elementy różniły się między sobą zamocowaniem końców taśm, a w taśmach wstępnie naciąganych – intensywnością sprężenia. Wszystkie pozostałe czynniki w badaniach mogą być uznane jako niezmienne. Badania były ukierunkowane na zachowanie się elementów w aspekcie użytkowalności, to jest sztywności zginania, rysoodporności i rozkładu rys, jak również na określenie rzeczywistych odkształceń taśm CFRP, zbrojenia stalowego i powierzchni betonu.

Ostatecznie, rejestrowane były przyrosty nośności we wzmocnionych belkach oraz postać zniszczenia. Wyniki badań pozwoliły na sformułowanie pewnych ogólnych wniosków w odniesieniu do efektywności pasywnego lub aktywnego wzmacniania belek żelbetowych za pomocą taśm CFRP.

Keywords: **Applications of CFRP; Concrete structures; Prestressing; External strengthening.**

1. INTRODUCTION

Adaptation to new standards and requirements, elimination of results of incorrect design or execution, as well as changes in the material properties of the structure itself due to ageing (corrosion and fatigue) gave rise to a need for strengthening of existing structural members. The problem of strengthening concerns most often reinforced concrete elements subjected to bending. The typical situation in such cases is sufficient capacity of compression zone in cross-section, and insufficient capacity of reinforcement in the tension zone. Then the increase of load-bearing capacity is possible through the application of additional external reinforcement.

The basic strengthening method applied for years was the introduction of steel external reinforcement if form of anchored, stuck on or stuck in bars or strips and prestressing steel tendons [1], [2]. However, these techniques are unreliable, require laborious preparation works, special protection against corrosion, as well as frequent maintenance.

Following the progress in building materials technology the new repair technique based on the Carbon Fibre Reinforcement Polymers (CFRP) was developed. The externally bonded CFRP strips or sheets have been characterised by high reliability and efficiency [3], [4], [5], [6]. The considerable material properties of carbon fibers, particularly high tensile strength, high modulus of elasticity and almost complete resistance against corrosion, allow CFRP composites to be used to increase the flexural resistance of beams or slabs and to improve their serviceability. Strengthening with CFRP strips can be regarded as being passive or active in behaviour. The passive strengthening method is easy for application but does not allow using full material properties of CFRP [7], [8]. In this method failure of the member may occur at limited strain level in strengthening strip, because an activation of premature debonding mechanisms usually earlier leads to the anchorage failure. To inhibit this process various mechanical anchorages, e.g. two aluminium plates mounted at the ends of strips, has been applied [9]. By comparison, active techniques with application of prestressed CFRP strips allows better use to be made of the upper range of the CFRP strain capacity and full load-bearing capacity of this material [10]. Additionally, the required anchorage system, placed at the ends of the strips, prevent delamination and debonding effects [11]. Unfortunately, introduction of the prestressing process is much more complicated in comparison to the passive method. Active strengthening requires careful use of the special tension device because small deviation in the alignment of the strip results in rapid damage of the composite [12], [13]. In Poland, the first laboratory tests concerning strengthening of the pre-tensioned girder by means of prestressed laminate were conducted in 2005 [14].

The experimental study described in this paper was undertaken to analyze the efficiency comparisons of three strengthening methods used for reinforced concrete beams by means of externally bonded CFRP strips as passive or active reinforcement. The research program consisted of six large-scale elements, 8,0 m long. Three of them were strengthened with active CFRP, while other two were strengthened using the passive method – with anchorages at the end of the laminate and without. One beam without strengthening was used as the reference element. All details about elements with active strengthening have been described in the thesis [15]. Variations in beams with active strengthening were provided by introducing different values of prestressing force, measured by elongation of the strips. The analysis was focused on the assessment of strains in CFRP strips and steel reinforcement, as well as on the concrete surface strains, flexural stiffness of beams and mode of failure of all tested beams.

Unfortunately, direct comparisons between the tests described here and the tests presented by other researchers are not possible. The other tests dealt with different types of elements [16], [17] or of relatively small scale [18], [19], [20]. The method of prestressing, materials used, and equipment were also different [10], [21], [22].

2. GENERAL DESCRIPTION OF TESTED ELEMENTS

The tests were carried out on the six large-scale reinforced concrete elements, with rectangular cross-section of 0.25×0.50 m, 8.0 m long. All beams were prepared with the same dimensions and reinforcement, shown in Fig. 1. Tensile reinforcement was provided by 6Ø20 mm rebars (1885 mm^2) with nominal yield strength of 450 MPa, while compressive reinforcement was provided by 2Ø10 mm rebars (157 mm^2) with nominal yield strength of 345 MPa. The shear reinforcement was provided by 8 mm closed stirrups of rectangular shape at the spacing of 150 mm and 300 mm. The shear reinforcement was conservatively oversized to avoid shear failure, because the main objective of this research work was to analyze the increase of the resistance of elements at bending.

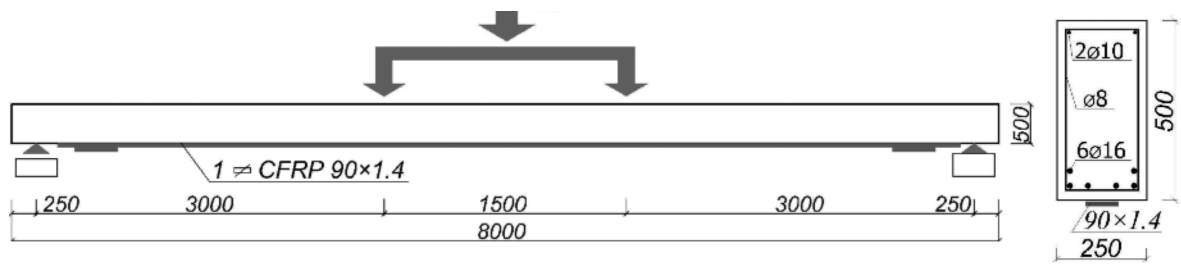

Figure 1.
Dimensions, static schema and reinforcement of the beams in tests

Table 1.
Description of tested beams

Symbol of the beam	Strengthening method	Strengthening material	Initial strain in the laminate / prestressing force
B1 RC	non-strengthened	—	—
B2 CFRP	passive strengthening	CFRP LM*	—
B3 CFRP-ANCH		CFRP LM with anchorages	—
B4 CFRP 3‰	active strengthening		3‰ / 65kN
B5 CFRP 4.5‰			4.5‰ / 97kN
B6 CFRP 6‰			6‰ / 130kN

LM* - low modulus carbon fibres

Fig.1 presents also the location of strengthening strips.

The elements differed each other in the strengthening method – passive or active strengthening, stabilization of the free ends of the CFRP strip, and the intensity of the prestressing. All other factors could be considered as almost invariable. Description of elements is presented in Table 1.

Apart from the main tests of beams the accompanying tests for determination of material properties were made. Concrete and steel properties were tested on the specimens according to the Standards. Basic properties of CFRP strips (separately for each series) were given by the manufacturing company which supported the research program. The results of testing of mechanical properties for all materials used are presented in Table 2.

In order to obtain the complete information about

Table 2.
Basic material properties

Material	Specimens	Strength of material [MPa]		Modulus of elasticity [MPa]
Concrete in elements:	beam B1	compressive strength f_{cm}	38.2	26 700
	beam B2		39.2	26 200
	beam B3		35.1	24 200
	beam B4		38.2	26 700
	beam B5		39.8	26 000
	beam B6		35.1	24 200
Steel	bars Ø16 mm	ultimate tensile strength f_{um}	680	205 000
	bars Ø10 mm		483	205 000
CFRP strip	90mm×1.4 mm		2504	170 800

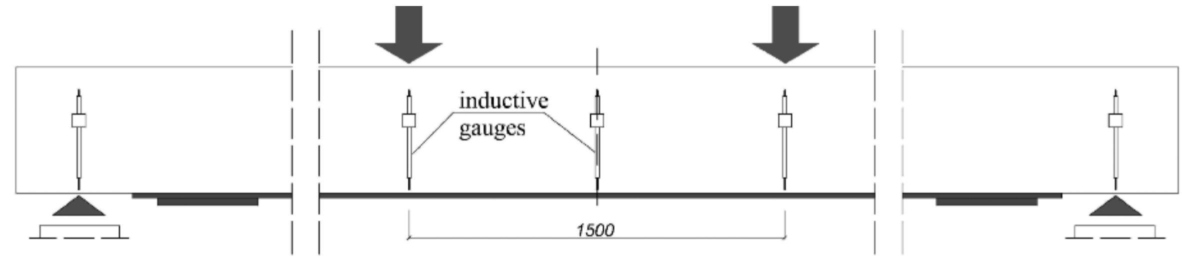

Figure 2.
Location of inductive gauges at displacement measurement

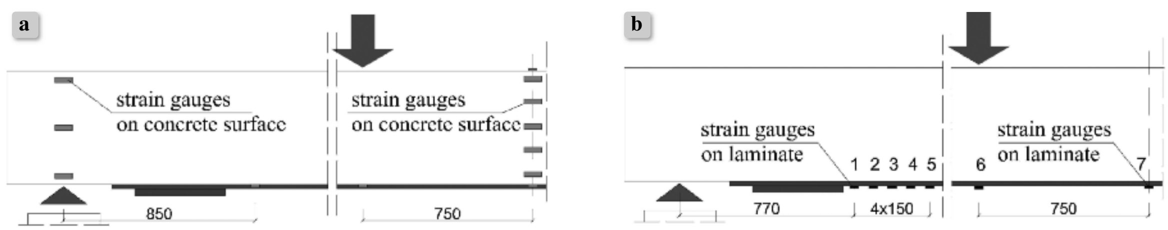

Figure 3.
Location of strain gauges: a) on the concrete surface, b) on the CFRP strip

the behaviour of the strengthened beams all elements were instrumented to measure the applied load, deflection and strains. The following data were recorded:

- total load applied (2F) in steps of 10 kN up to failure – by means of hydraulic jack of 500 kN capacity,
- displacements in selected points of element – by means of inductive gauges (0.001 mm),
- strain on the concrete surface using electro-resistance gauges (with base of 100 mm),
- strain on steel reinforcement surface – using foil strain gauges (with base of 20 mm),
- strain on the CFRP strip surface – using strain gauges (with base of 20 mm).

The arrangement of typical measuring equipment is shown in Fig. 2 and 3.

Additionally, the crack pattern on both surfaces of beams, as well as width of cracks measured in direction perpendicular to crack, was recorded. The course and mode of failure was recorded at the final stage of the test.

The prestressing process was performed using original

Figure 4.
View of the passive anchorage

Figure 5.
Elements of the active anchorage

Figure 6.
View of the hydraulic jack during stressing process

Figure 7.
Bottom view of the prestressed beams

S&P prestressing system. The fixed end anchorage (Fig. 4) was first placed in position, and next the adjustable anchorage (Fig. 5) was located. The tension was achieved by means of the special hydraulic jack. When the required level of the strip elongation was reached (Fig. 6), the jacking system was left for 24 hours, and then removed. The anchorage system held the stressed strip until the epoxy glue was hardened and strips were fully bonded to the beam. In Fig. 4 and 5 the passive and active anchorages are shown.

The prestressing force in strips was designed to use the different parts of ultimate strain in material at tension. The strip pre-strain was measured during the operation, as well as corresponding prestressing force showed on the jack. The strips were tensioned to obtain the strip pre-strain equal to 3‰, 4.5‰ and 6‰. These values corresponded with the following stresses in laminate: 510 MPa, 750 MPa and 1030 MPa. The beams after prestressing process are shown in Fig. 7.

3. TEST RESULTS

3.1. Deflection and stiffness

The serviceability aspect of the introduction of externally CFRP reinforcement is increasing of the flexural stiffness and reduction of the deflection of elements. In Fig. 8 the development of the deflection at mid-span of each strengthened beam compared with the reference element is presented.

At loading, up to the level causing yielding of the steel bars, there was almost linear relationship between increase of load and increase of deflection. In this range of loading the passive strengthening with CFRP laminates did not influence the deflection of the beams (B2, B3) compared with reference non-strengthened beam (B1). The introduction of prestressed strips caused significant reduction in deflection.

The non-strengthened element showed a typical load-deflection relation of the reinforced concrete element subjected to bending. After reaching the level of steel yielding the sudden increase of deflection, without increase of load occurs. In opposite to this state, for all strengthened beams, the point at which the steel reinforcement yielded did not mean the members' load capacity had been reached. This was because neither the stress in the laminate had reached its tensile strength, nor the concrete compressive zone had not reached its capacity. The significant reduction of deflection compared with the reference beam was observed for all beams with prestressed strips. Additionally, the reaching of steel yielding in case of beams with active strengthening appeared at higher bending moments:

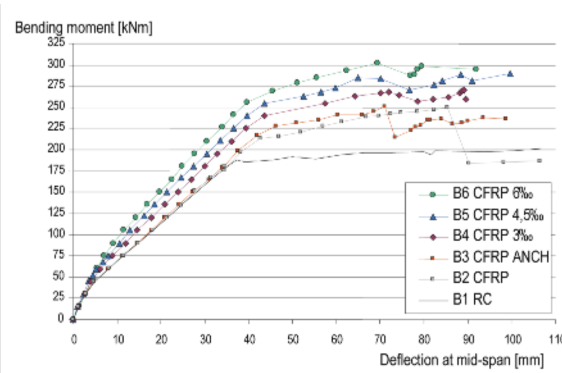

Figure 8.
Load – deflection characteristics in all tested beams

- in both beams with passive strengthening: (B2) – 213 kNm, and (B3) – 217 kNm,
- in beams with prestressed strips: (B4; 3‰) – 240 kNm, (B5; 4.5‰) – 255 kNm, (B6; 6‰) – 263 kNm.

After the steel yielding the beginning of strips delamination was observed, and it was noticed as an interruption of the load-deflection relation. The application of the anchorages in the beam B3 and in the prestressed beams B4, B5, B6 allowed extending of the loading in those beams after the delamination began. For all those members the strip delamination took place at similar value of deflection, assessed on about 70mm. This situation was connected with the reaching of bond strength at the interface of concrete and epoxy glue.

The influence of non-tensioned and pre-tensioned strips on the changes of the elements' stiffness is presented in Fig. 9. The stiffness of all elements, determined for each load level, was calculated as:

$$B_i(M_{Si}) = \frac{M_{Si}}{\chi_i} \tag{1}$$

where:

$$\chi_i = \frac{1}{R_i} \tag{2}$$

The radius of curvature R_i was determined on the basis of measured deflection in the middle of the beam, a_i^{test}, according to the formula:

$$R_i = \frac{(l_n^2 - 4 \cdot a_i^{test\,2})}{8 \cdot a_i^{test}} \tag{3}$$

Flexural stiffness of beams with passive strengthening and non-strengthened beam was almost the same because in such large elements the non-tensioned strips changed the moment of inertia of cross-sections in imperceptible degree. However, additional longitudinal force resulting from prestressing of beams B4÷B6, caused significant enhance of their stiffness. This phenomenon was connected with reduction of deflection (Fig. 8). The increased stiffness can be observed already at the small value of load, and is kept up to the failure of elements. Comparing with the beams with passive strengthening, at the load corresponding with the bending moment of 75 kNm, the increase of stiffness for prestressed members amounted to: 28% for the beam B4; 46% for the beam B5; and 64% for the beam B6.

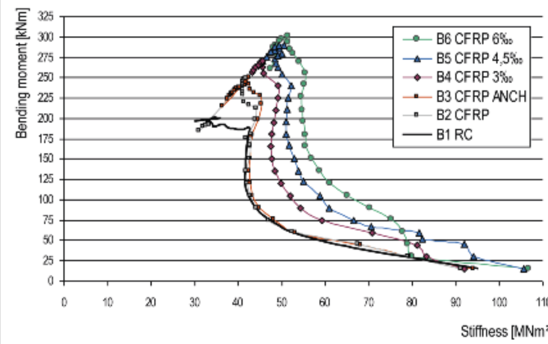

Figure 9.
Load versus stiffness of tested beams

3.2. Pattern of cracks

The influence of passive or active glued laminates on the crack development is presented in Figures 10÷13, in form of the final crack patterns recorded on one half of each beam. Additionally, Table 3 presents the load at which the first crack appeared.

In the members: B1 (non-strengthened), B2 (without anchorages of strip), and B3 (with anchored strip) very similar crack pattern was recorded. The presence of strip marginally delayed the appearance of the first crack. The vertical crack range did not change in visible way due to the introduction of passive strengthening strip (Fig. 10, 11). The development of cracks up to failure was also very similar: several main vertical cracks were opened at the failure phase.

The prestressing force significantly reduced crack development and varied the crack pattern (Fig. 12, 13). The range in the height and number of cracks were smaller, and they formed more multi-direction mesh. The significant lowering of the natural axis caused by the introduction of prestressing force was observed. Additionally, the prestressing

Table 3.
Bending moments at the first cracking of tested beams

Beam	B1 RC	B2 CFRP	B3 CFRP ANCH	B4 CFRP 3‰	B5 CFRP 4.5‰	B6 CFRP 6‰
M_{cr} [kNm]	30.0	37.5	45.0	60.0	67.5	75.0

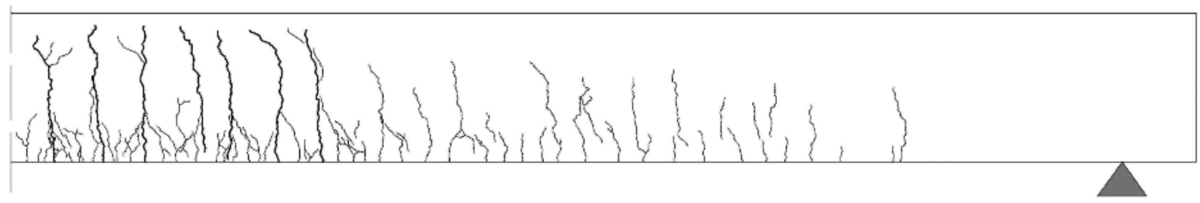

Figure 10.
Pattern of cracks in non-strengthened beam (B1–RC)

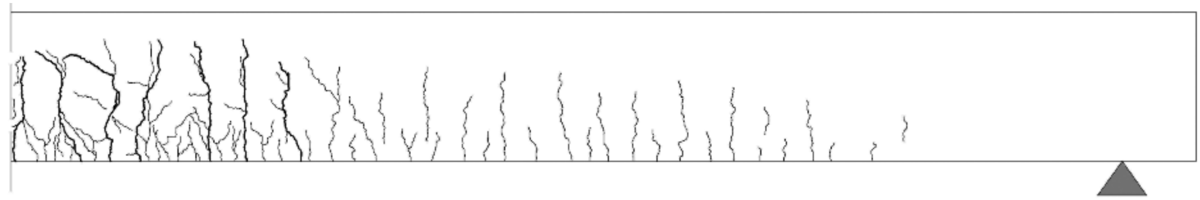

Figure 11.
Pattern of cracks in the beam (B3) with passive strengthening by means of CFRP strip with anchored ends

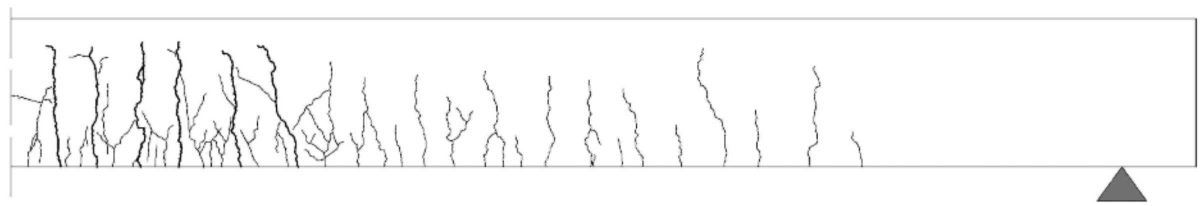

Figure 12.
Pattern of cracks in the beam (B4) with active strengthening by means of CFRP strip pre-tensioned to the level of strain equal to 3‰

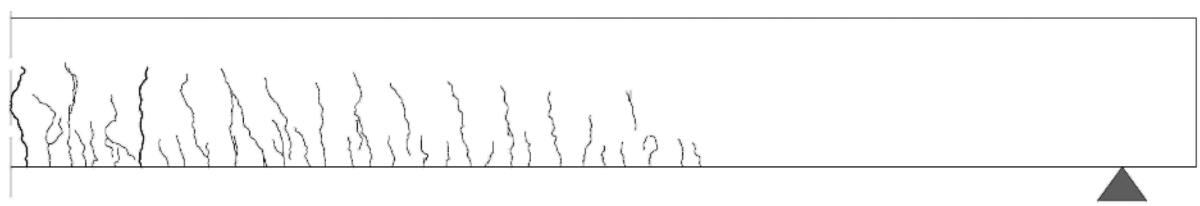

Figure 13.
Pattern of cracks in the beam (B6) with active strengthening by means of CFRP strip pre-tensioned to the level of strain equal to 6‰

allowed the concrete section to remain uncracked to the higher level of load, compared with beams with passive strengthening (Table 3).

At analyzing the recorded maximum width of single crack (Table 4) the influence of anchorages at the end of strips is directly visible. The presence of mechanical anchorages maintains tension in the strip after delamination, which is similar to the case of an unbonded external prestressing tendon. This effect significantly decreased the possibility of excessive deformation and reflected in reduction of crack widths. The reduction of the maximum width of single crack for beams with strips with and without anchorages, recorded close to the failure load, was equal to:

- 35% (B3) to 66% (B6) at load 210 kNm,
- 50% (B3) to 75% (B6) at load 270 kNm.

As a result, the summarized crack widths for beams with anchored strips were also smaller than in beams without anchorages.

3.3. Strains in the CFRP strip, steel reinforcement and on the concrete surface

The usage and behaviour of the CFRP strip is analyzed on the basis of the value of strain measured in the mid-span of the beams during one cycle of load-

Table 4.
Maximum width of single crack recorded at selected load levels

Beams	Maximum crack width recorded in tests [mm]							
Load level [kNm]:	60	90	120	150	180	210	240	270
B1 RC	0.050	0.075	0.10	0.15	0.35	-	-	-
B2 CFRP	0.050	0.075	0.10	0.15	0.20	0.60	1.00	-
B3 CFRP ANCH	0.025	0.050	0.10	0.15	0.20	0.40	0.45	-
B4 CFRP 3‰	0.025	0.075	0.125	0.15	0.20	0.25	0.35	-
B5 CFRP 4.5‰	0.025	0.050	0.10	0.15	0.175	0.25	0.30	-
B6 CFRP 6‰	no crack	0.025	0.10	0.125	0.15	0.20	0.25	0.45

ing. In the Fig. 14 the relationship between load and strain is presented. The measured strains in the CFRP laminate corresponded with the strains of the adjacent concrete and were a function of the beam's deflection. This can be seen when comparing the diagrams of deflection development (Fig. 8) and the development of the strain in the laminate (Fig. 14).

In the CFRP strip the same work-stages as in the whole beam's behaviour were recognized. In the first two stages (before cracking and up to reaching the steel yield point) quasi-linear form of the diagram was noticed (Fig. 14), exactly the same as at deflection of the beams (Fig. 8). The reaching of the yield limit in the steel reinforcement caused a distinct change in the load-strain relationship. Such change corresponded with rapid increase in the deflection and significant increase of strain in the strip.

In the next phase, the strain in the strip in case of beam with passive strengthening without anchorages (B2) increased gradually, until complete delamination along the strip occurred. Such kind of behaviour was not registered when the strip was anchored at the end. The mechanical fixing of the strip caused that after strip's delamination partial transfer of the stress in the strip from the middle of the strip to the anchorage zone followed. The interruption noticed in the diagram (Fig. 14) resulted from a compensation of the strain on the strip's length. This phenomenon was observed not only in prestressed beams but also in the beam with passive strengthening by means of glued strip additionally anchored at the end.

The distribution of strains along the strip length (measured in 7 points) for the beam (B4) is presented in Fig. 15. All beams with anchored strips behaved similarly. Prior to the yielding of steel (lower 3 lines) the increase of strains measured in each point was adequate to the deformation of the beam. Beginning of the delamination caused strong increase of the strain in the middle of the strip (fourth line from the bottom). The dashed two lines show the strain distribution along the strip after delamination. The complete delamination caused full transfer of the prestressing forces into the anchorages (top dashed line).

The comparison of strains measured in prestressed beams on the strip and on the steel bars of internal reinforcement for selected load levels is listed in Table 5. The strains in strips are the summarized values of initial elongation (coming from prestress) and increase of strains measured during the load test.

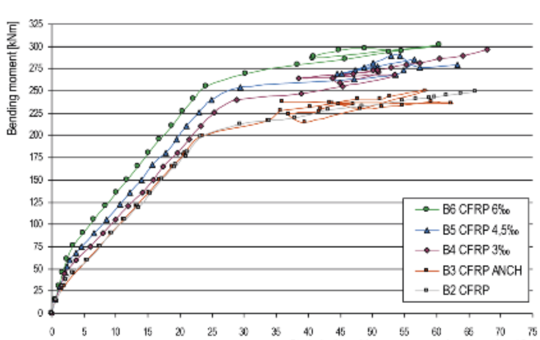

Figure 14.
Strains in the CFRP strip measured at the mid-span of the strengthened beams

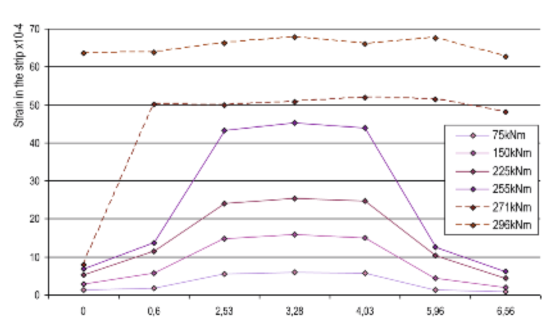

Figure 15.
Distribution of strains along the strip in the beam (B4) at increasing load

Table 5.
Strain measured in the CFRP strip and in internal steel reinforcement

Bending moment [kNm]	Strain $\times 10^{-4}$					
	B4 CFRP 3‰		B5 CFRP 4.5‰		B6 CFRP 6‰	
	steel bars	CFRP strip	steel bars	CFRP strip	steel bars	CFRP strip
75	5.9	36.0	4.8	49.6	4.0	63.4
150	15.7	45.9	14.5	59.1	13.1	71.8
225	25.8	55.4	22.1	67.9	22.2	80.4
failure	yield limit	97.8	yield limit	108.3	yield limit	114.6
Percent usage of ultimate strain in CFRP [%]						
failure	67		74		78	

In all strengthened beams full use of steel reinforcement took place. It has been observed, that the higher the initial strain in the strip was applied, the smaller the strain in internal reinforcement was noticed. The usage of the steel reinforcement decreased along with increase of the summarized strain in the strip. The pre-tensioned strip slightly relieved the internal reinforcement.

The strain level obtained during the loading test was different for the pre-tensioned strips. The higher the initial strain, the smaller was the measured strain additional value at failure. This phenomenon was evoked by the limit ultimate strain in CFRP strip, measured in separate tests as high as 146.6×10^{-4}. The higher the pre-strain was applied to the strip, the less the deformation capacity of the strip remained. The final strain achieved in the strips as a sum of initial pre-tensioning and additional part due to loading was the following (see Table 5):

- in the beam (B4) 30×10^{-4} + ca. 68×10^{-4},
- in the beam (B5) 45×10^{-4} + ca. 63×10^{-4},
- in the beam (B6) 60×10^{-4} + ca. 55×10^{-4}.

The maximum strain measured for the beam without prestressing was recorded in the beam (B3) as equal to 65×10^{-4}. In such a case, not more than 45% of the ultimate strain in the strip was reached.

Fig. 16 presents the strain distribution on the height of the beam section at mid-span measured on the concrete surface. The values in this diagram were taken from measurements for the beam (B6). It should be noted that this strain distribution was registered without taking into account the initial strain evoked by the prestressing of the element. The changes in localization of the neutral axis for all tested elements are presented in Fig. 17.

The introduction of prestressing forces into the concrete cross-section caused a distinct lowering of the neutral axis. This phenomenon is visible already at the small load values – Fig.17. For the bending moment of 30 kNm the increase of the height of compressive zone amounted to: 12% in the beam (B4), 21% in the beam (B5) and 29% in the beam (B6), compared with the unstrengthened beam. This tendency is hold up to the failure of prestressed elements. The higher the initial prestressing level applied, the lower the neutral axis was placed. This

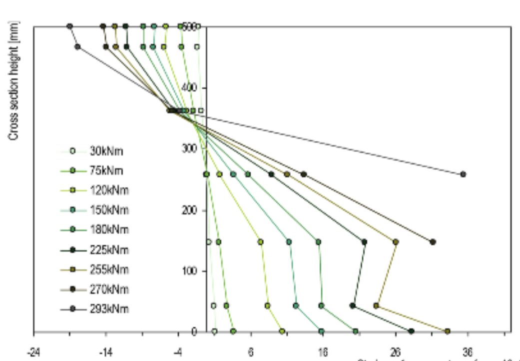

Figure16.
Strain distribution on the concrete surface in the cross-section.

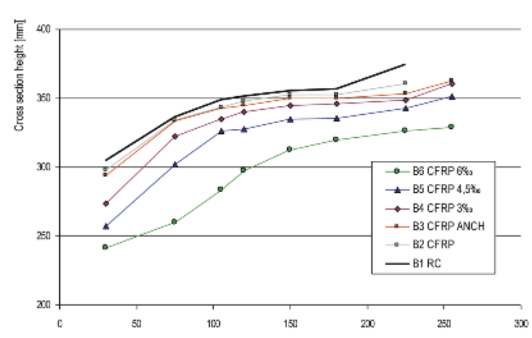

Figure 17.
Changes in localization of the neutral axis for all beams with total height 500 mm

was effective in reducing the extent of crack formation and width of cracks for all prestressed beams. The increase of the compressive zone resulted from the presence of the initial strain evoked by the prestress. The initial strain consisted of compressive strain coming from the compressive force and strain coming from the bending moment evoked by the eccentricity of the compressive force.

The height of compressive zone in case of both beams with passive strengthening – with and without anchorages – was insignificantly higher then for non-strengthened beam (B1). The glued strip without prestressing did not have a significant influence on the vertical range of cracks, thus also on the localization of the neutral axis.

3.4. Behaviour of tested beams at failure

Different ways of failure in the tested elements were observed. Therefore, several stages of beams failure could be distinguished. In majority it depended on the connection of strips, in particular on the presence of anchorages at the end of strips.

Excessive deformation was noted for non-strengthened beam (B1). A rapid increase in deflection took place after the yielding of the steel reinforcement. The beam deformed so much that there was a danger of damage to the test facility and before the concrete failed in compression the test had to be broken. The beam was used as a reference and the bending moment at failure corresponded to that excessive deformation (Fig. 18).

The beam with passive strengthening without anchorages failed in form of total delamination of the CFRP strip (B2). The final failure stage followed directly the local delamination of the strip under the load application points. In general, the start of delamination was practically equivalent to the failure of the element (Fig. 19). Partially debonded strip was unable to carry much more loading and a very rapid increase of deformation took place. The presence of the strip assured a small reserve in load capacity and allowed for certain additional loading of the beam. The load at reaching the steel yield limit was about 30% higher than that for the non-strengthened beam. In practice, the process of delamination occurs rapidly and causes very sudden damage of the element.

The most complicated mode of failure was observed for all beams with strips anchored at the end. This concerned the beam with passive strengthening with anchorages (B3) and all prestressed beams (B4÷B6). Local crushing of concrete in the compressive zone occurred for all those beams. Various changes in behaviour were observed during the test. The first change corresponded with a rapid increase of deflection for relatively small increase of load. This was connected with yielding of the internal reinforcement. The next point of change was recognized as the start of CFRP strip delamination. The final stage occurred just before failure of beams due to the total CFRP strip delamination. Delaminated strips worked further as a tendon, fixed to the concrete by means of steel plates. In each case delamination took place in the layer of concrete cover and was followed by friction action between the hardened glue on the strip and concrete surface. This caused the strip to work like a partially-bonded tendon, with some concrete still glued to its surface and maintaining contract with the remainder of the beam through some aggregate interlocking remaining effective. The anchorages in beam (B3) and prestressed beams

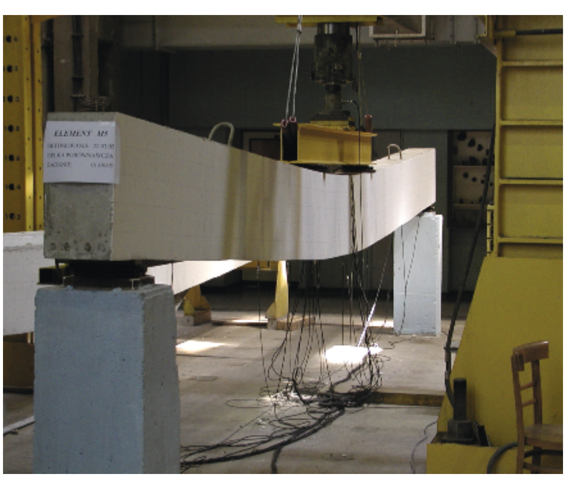

Figure 18.
Deformation of non-strengthened beam (B1)

Figure 19.
Delamination of CFRP strip in the beam (B2)

(B4÷B6) prevented premature debonding mechanisms and allowed for further element loading, even after complete delamination of CFRP strip (Fig. 20, 21, 22). The accompanying crushing of the compressive zone is shown in Fig. 23.

It should be emphasized, that in practice in case of partial debonding or delamination of strip, caused by temporary overloading of strengthened beam, is possible to re-glue debonded part of anchored strip again. For the strip without anchorages, as for the beam (B2), the beginning of delamination is equivalent to the failure of the beam.

It has been stated, that the application of prestress to concrete beams could significantly delay the cracking moment and moment required to cause steel reinforcement yielding in the strengthened beams. The strengthening by pre-tensioned CFRP strips caused the significant increase of the load-carrying capacity of the beams. The difference in increasing of the capacity for prestressed beams amounted from 61% for the beam (B4) to 66% for the beam (B6) compared with the capacity of the non-strengthened beam. The load capacity slightly only increased with increasing prestressing force. Unfortunately, the differences between the ultimate loads for the prestressed beams (B4÷B6) and for the non-prestressed beam with anchorages (B3) were about 17% only. This is not sufficient to recommend that this could be always taken into account for the design purposes, because is not adequate to the value of introduced work.

To compare the behaviour of tested elements and to clarify the influence of strengthening methods, the values of characteristic load for all occurring failure stages were summarized in Table 6.

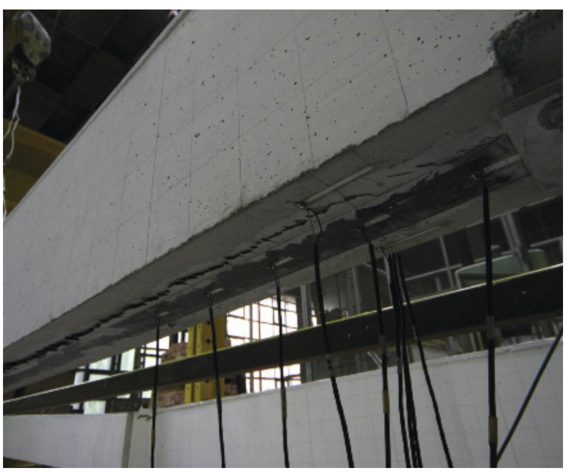

Figure 20.
Process of delamination for the beam (B3) with anchored strip

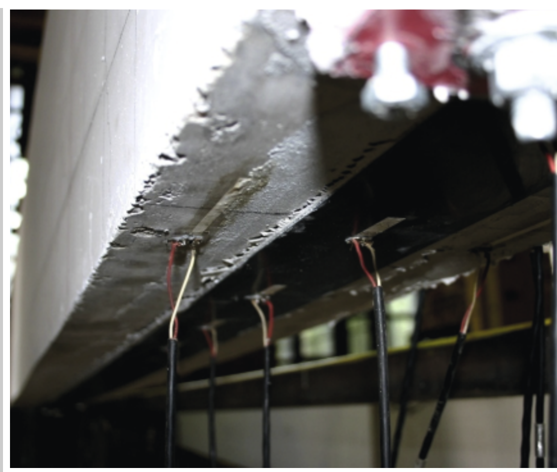

Figure 22.
Process of delamination in the prestressed beam (B6)(B4)

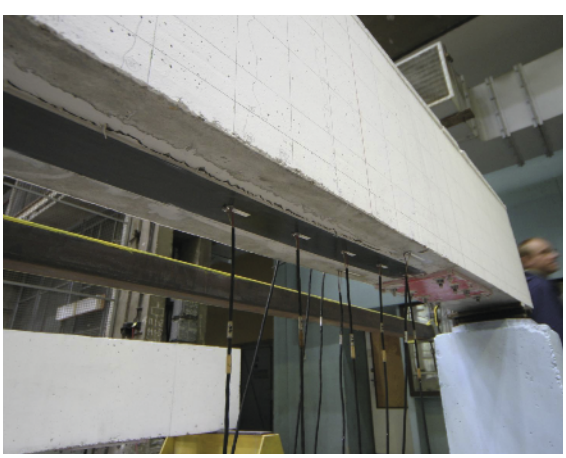

Figure 21.
Delamination of pre-tensioned strip in the prestressed beam (B4)

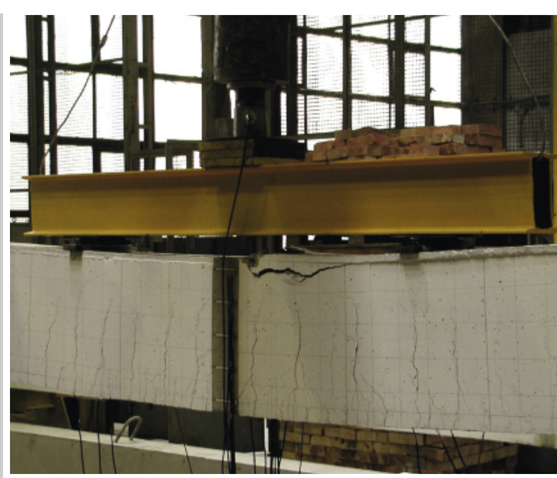

Figure 23.
Damage of concrete in compression zone in the beam (B4)

Table 6.
The values of load at the characteristic stages up to failure in particular beams

Beams	Registered bending moment [kNm]			
	Selected permissible deflection of 30 mm	Rapid increase of deformation (yielding of the steel)	Beginning of the CFRP strip delamination	Final failure of the beam
B1 RC	161	188	-	190
B2 CFRP	165	213	-	249
B3 CFRP ANCH	165	217	250	261
B4 CFRP 3‰	180	240	270*/265**	302***
B5 CFRP 4.5‰	195	255	285*/270**	306***
B6 CFRP 6‰	210	263	302*/287**	312***

* load level recorded just before the beginning of delamination

** load level recorded in the moment of distribution of the strain in the delaminated strip

*** load level recorded only in the hydraulic jack, without measurement of other data (deflection, strain)

4. CONCLUSIONS

The comparison of the efficiency of strengthening method using CFRP laminates based on the tests carried out at the Department of Structural Engineering of the Silesian University of Technology. The six tested beams differed from each other in the following aspects: passive or active strengthening, stabilization of the free ends of the CFRP strips and the intensity of the prestressing. All other factors, like material properties, internal steel reinforcement, or scheme of testing, were provided as invariable. Because of a limited number of six elements in tests only some main tendencies in behaviour of strengthened elements were investigated. The results of presented investigation should be analysed mainly from qualitative point of view. Taking into account the above limitations the following conclusions can be formulated:

- All strengthening methods caused the increase of the load-bearing capacity at bending. In case of both beams with passive strengthening the ultimate load increased 31÷37% when compared with the non-strengthened reference element, while the ultimate loads for beams with active strengthening were about 60% higher than for the reference beam.
- Pre-tensioning of the CFRP strips allowed utilization of the properties of materials to the higher degree, that is: the compressive strength in concrete, yield limit in steel reinforcement, and ultimate strains in CFRP strips. The usage of the CFRP strips in active form appeared more effective in about 17% as regards load-bearing capacity of beams in comparison with beams with passive strengthening using the same strips.
- Prestressing enhanced the serviceability feature of the strengthened elements compared with non-strengthened beams, as well as beams with passive strengthening. There was recorded a significant increase of the flexural stiffness of beams and, in consequence, the smaller deflections and reduction of cracking. Prestressing of the strengthening strips significantly increased the bending moment at the appearance of first cracks.
- Serious positive effects of the prestressing were observed already at the smallest value of prestressing force. The benefits from use of the active strengthening of beams are much more important from the serviceability point of view than from the load capacity increase.
- The introduction of the anchorages at the ends of the strip – in passive and active strengthening alike – had a significant influence on the safety of the strengthened structure. The failure process followed in many stages with distinct warning in form of delamination of the CFRP strips.
- Based on the ultimate strain in the strips (12÷14‰) the increase of the initial strip pre-strain over 6‰ couldn't be efficient. For the 6‰ initial strain used at prestressing the remaining strain capacity could safely be 4÷5‰ only. This means that only limited additional loads can be applied. Proper selection of the prestressing level depends on the ratio between the existing loads at prestressing, and required loads after strengthening.

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