A R C H I T E C T U R E C I V I L E N G I N E E R I N G E N V I R O N M E N T
The Silesian University of Technology No. 2/2009

TESTING OF RC BEAMS WITH CFRP STRIPES ON BEAM SIDE SURFACES

Witold WOŁOWICKI [a], Lech APANAS [b]

[a] Prof.; Faculty of Building and Environmental Engineering, Poznan University of Technology, ul. Piotrowo 5, 61-138 Poznań, Poland
E-mail address: *witold.wolowicki@put.poznan.pl*

[b] MSc; Faculty of Building and Environmental Engineering, Poznan University of Technology, ul. Piotrowo 5, 61-138 Poznań, Poland
E-mail address: *lech.apanas@put.poznan.pl*

Received: 02.02.2009; Revised: 16.03.2009; Accepted: 02.04.2009

Abstract
The paper presents description of experimental testing of RC beams strengthened with CFRP stripes glued to beam sides. Test results are presented and discussed. The aims of testing were: identification of mechanism of failure of such beams, assessment of interaction of CFRP stripes and concrete with possibility of stripes lamination included as well as assessment of effectiveness of strengthening. Testing concerned nine concrete beams (including seven strengthened) and four RC beams (all strengthened). Tested RC beams failed due to loss of bearing capacity of compression zone in concrete. Stripes glued to beam sides were not torn away prior to beams failure, effectiveness of strengthening was proved to be sufficient. Stripes had beneficial influence on layout and width of cracks – large number of crack resulted in their small widths. Stripes enhanced range of linear loading-deflection relationship. This alteration was caused by yielding of reinforcement and beyond-elastic strain of concrete or reinforcement and plastic stiffening.

Streszczenie
Artykuł zawiera opis podjętych badań eksperymentalnych belek żelbetowych wzmocnionych poprzez przyklejenie taśm do boków belek oraz przedstawia i omawia ich wyniki. Celem prowadzonych badań było: określenie mechanizmu zniszczenia tak wzmocnionych belek, ocena współpracy taśm węglowych z betonem, w tym możliwości rozwarstwienia taśm oraz określenie skuteczności wzmocnienia. Badania przeprowadzono na 9 belkach betonowych (w tym 7 wzmocnionych) oraz 4 wzmocnionych belkach żelbetowych. Badane belki żelbetowe uległy zniszczeniu wskutek wyczerpania nośności strefy ściskanej betonu, taśmy przyklejone do boków belek nie ulegały oderwaniu aż do chwili zniszczenia belek, skuteczność wzmocnienia okazała się wystarczająca. Taśmy miały korzystny wpływ na układ i rozwartość rys – przy dużej liczbie rys ograniczały ich rozwartość. Taśmy zwiększały zakres liniowej zależności obciążenia – ugięcia. Zmianę tej zależności powodowało uplastycznienie zbrojenia oraz odkształcenia pozasprężyste betonu lub zbrojenia po wzmocnieniu plastycznym.

Keywords: **Strengthening; CFRP stripes; RC beams; Experimental testing; Anchorage; Failure mechanism.**

1. INTRODUCTION

Strengthening of RC structures involves more and more composites, especially stripes glued to concrete. In case of members in flexure stripes are being glued to bottom surface (in tensile zone) of beams and rarely, in addition, to side surfaces [1]. Stripes glued to beam bottom surfaces are the subject of numerous tests [2, 3, 4, 5]. Respective computational procedures are available. Gluing stripes to side surfaces does not seem to attract similar interest. However, this type of attachment of strengthening stripes:

– enables stripes gluing to the beam very ends, that enlarge anchorage length,
– decreases probability of strip damage as result of vehicle collision with strengthened viaduct girder,
– makes stripes application (gluing) easier.

As it was mentioned descriptions and failure analyses of the case of CFRP stripes glued to the beam bottom surface are numerous. The mechanism, simply speaking, relies on failure initiation near stripe end, due to stripe tearing away from concrete or, more frequently, due to stripe with concrete cover being torn away together. Practically it is impossible to get failure mechanism due to loss of bearing capacity of concrete, reinforcing steel or carbon stripes in midspan.

It is authors' opinion that, analysing reasons for CFRP stripes tearing away from concrete, one should take into account impact of material weakening within concrete cover. Reinforcement layer creates horizontal plane that separates concrete cover from the rest of beam concrete. Therefore lamination is possible just at this level, especially because concrete cover strength, due to technological difficulties, is smaller than the strength of the beam concrete above reinforcement layer.

Such weakening of concrete cover should not be experienced over side beam surfaces. So it may be suggested that gluing stripes to beam side surfaces provides better anchorage and limits, so called, lamination. To verify this experimental testing of beam with stripes glued to their side surfaces was taken up.

The aims of testing were: identification of mechanism of failure of such beams, assessment of interaction of CFRP stripes and concrete with possibility of stripes lamination included as well as assessment of effectiveness of strengthening. In addition an experimental attempt was made to find out if, in case of stripes glued to beam side surfaces, lamination of stripe due to variable stress over its width (eccentrical tension in stripe) and limited ability of matrix to carry out transverse strain, is possible.

Testing have covered so far three series of beams: one consisting of concrete beams and two consisting of RC beams.

2. DESCRIPTION OF TESTS

The first series of test was pilot series. It consisted of nine non-reinforced beams of 0.7 m length and of 0.15×0.15 m rectangular cross-section. The rest of series concerned RC beams: two in the second series and two in the third series. In both cases beams were 3.1 m long and 0.20×0.10 m in rectangular cross-section (Fig. 1).

RC beams were of variable degree of reinforcement, steel grade (plain and ribbed) and variable spacing of stirrups (from 0.05 to 0.15 m) that were 4.5 mm in diameter. The stripes Sika CarboDur XS of width ranging from 1.0 do 5.0 cm, thickness of 1.4 mm and elastic modulus of 165 GPa were used as strengthening material. Change of stripe width was done by longitudinal cutting.

Beams were simply supported (Fig. 1), and loading was applied by means of hydraulic jack – in the case of concrete beams – or numerically controlled SCHENCK jack – in case of RC beams.

During testing reaction at supports, vertical displacements and, only for RC beams, angles of rotation at supports as well as strain of stripes and concrete were investigated. Moreover cracks development at subsequent levels of loading as well as failure loading was registered.

Among the beams of series I:

– two were tested with no strengthening (beams: I-2, I-9),
– one was tested after strengthening with 10 cm wide and 56 cm long stripe glued to the bottom surface (beam I-3),
– two were tested after strengthening with pair of 5 cm wide stripes glued to the side surfaces (beams: I-1, I-4),

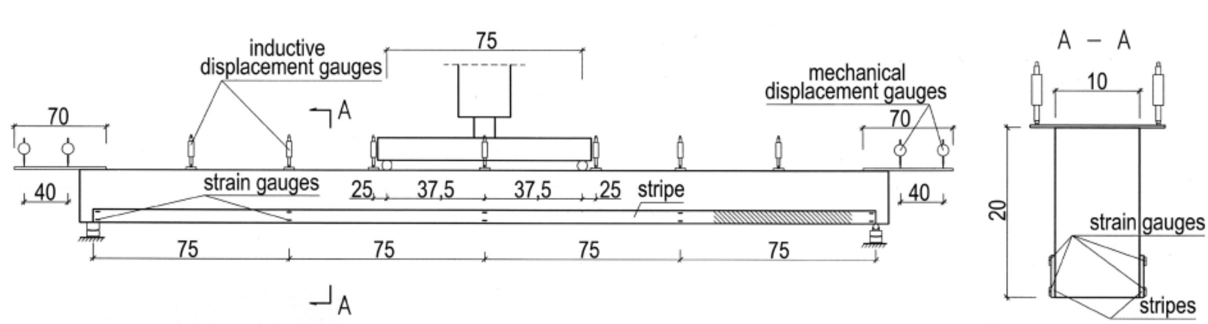

Figure 1.
Test scheme – series II and III

Table 1.

Beam no.	Type of bars	Degree of reinforcement	Bearing capacity without strengthening [kNm]	Bearing capacity after strengthening [kNm]	Degree of strengthening
II-1	ribbed	0.0195	15.1	19.9	1.32
II-2	plain	0.0114	6.5	19.0	2.92

– two were tested after strengthening with pair of 3, 2 cm wide stripes glued to the side surfaces (beams: I-5, I-6),

– two were tested after strengthening with pair of 1.65 cm wide stripes glued to the side surfaces (beams: I-7, I-8).

The width of stripes glued to side surfaces varied from 1/3 to 1/9 of beam height.

All beams were loaded in a single cycle up to failure. Load increased with magnitude of 0.1 kN/s. After completing a 2.5 kN step, loading increment was set to zero and beam displacements were recorded. During whole process of loading stripes behaviour and cracks pattern were observed.

Series II consisted of two RC beams strengthened with CFRP stripes of various widths, glued to beams side surfaces.

The beam II-1 was strengthened with 3 cm wide stripes glued over the whole beam length and the beam II-2 – with 5 cm wide stripes glued over 3 m of the beam length, i.e. between support axes. In the first case the stripe width equals 0.15 of the beam depth and in the second – 0.25 respectively. In the beam II-1 the degree of reinforcement was 0.0195 (ribbed bars), and in the beam II-2 – 0.0114 (plain bars).

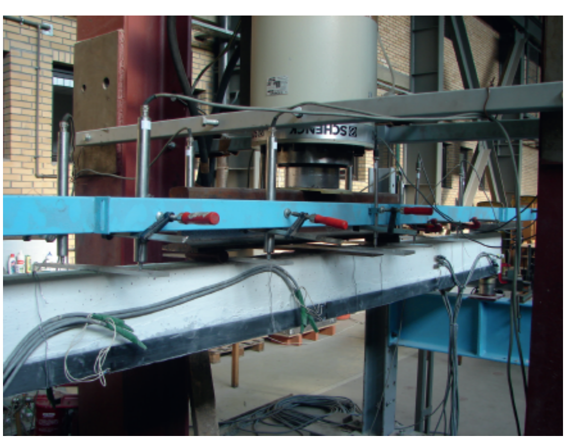

Figure 2.
Location of gauges, supporting system and method of loading

Figs. 1 and 2 show location of gauges, supporting system and method of loading.

The beams were loaded twice: first up to ultimate loading computed for non-strengthened RC beam and then, in single cycle, up to failure. After each loading step, of about 1/10 of ultimate loading for non-strengthened beam, all monitored data was recorded. Behaviour of stripes and cracks development was observed.

Load bearing capacity of strengthened beams was computed with the assumption of gluing stripes to beam bottom surface [6], taking stripe width as total width of actual stripes glued to beam side surfaces. The applied equations did not take into account the decrease of internal force lever arm due to gluing the stripes to beam side surfaces. Table 1 presents computed bearing capacities of beams.

Series III consisted of two RC beams strengthened with CFRP stripes of various widths glued to beams side surfaces.

The beam III-1 was strengthened with 3 cm wide stripes, and the beam III-2 – with 2 cm wide stripes, glued over whole beams length. Layout of gauges, supporting system and loading method were as in the case of the second series of beams. In addition, in case of the series, concrete strains on beam top surface, within the zone of constant bending moment, were recorded. For the beams of this series the attempt of experimental assessment of effectiveness of stripe anchorage was done.

Beams were loaded three times: twice up to 80% of computed ultimate loading of strengthened beam, and then, in one cycle, up to failure. After the first cycle the stripe length was reduced down to 2.8 m, by their transverse cutting on each end at the offset of 10 cm from supports axes towards midspan, and after the second cycle – down to 2.7 m, by cutting off further 5 cm. Loading steps, range of recorded data and recording procedures, observation of behaviour of

Table 2.

Beam no.	Type of bars	Degree of reinforcement	Bearing capacity without strengthening [kNm]	Bearing capacity after strengthening [kNm]	Degree of strengthening
III-1	plain	0.0086	5.2	16.5	3.17
III-2	plain	0.0267	13.9	17.8	1.28

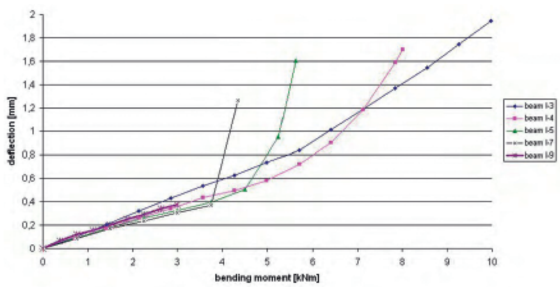

Figure 3.
Deflections of beams I-3, I-4, I-5, I-7, I-9

Figure 4.
Failure of beam II-1

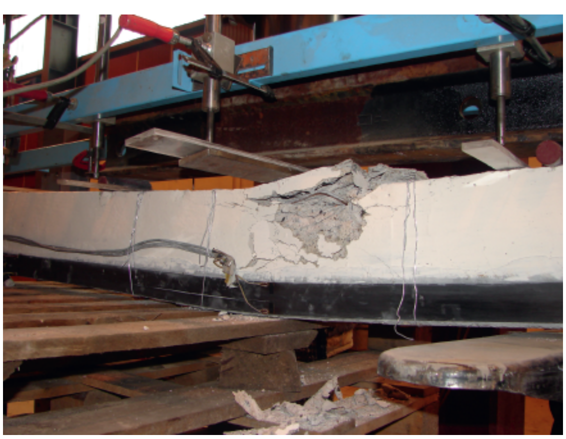

Figure 5.
Failure of beam II-2

stripes and cracks development were as for beams of the second series. Table 2 presents computed bearing capacities of beams.

3. TEST RESULTS

3.1. Test results of series I

Concrete beams non-strengthened with stripes failed suddenly in the midspan due to cracking and simultaneous loss of bearing capacity of tensile zone.

Observations of beams strengthened with stripes glued to beam side surfaces lead to conclusion that stripe tearing away that was always the direct reason for failure, was initiated in the midspan where the visible crack appeared above stripe, and – with load increase – spread towards supports. The crack character was, in addition, dependent on shear force, of course. Stripe tearing away was located in concrete or between stripe and glue. In no case was the stripe laminated. Deflection – loading relationship for non-strengthened beams was practically linear. Strengthened beams were, after crack appearance, able to carry loads and deflection increase.

Fig. 3 shows an example of deflection-bending moment curie for beams I-3, I-4, I-5, I-7 and I-9. Value of bending moment at failure for strengthened beams was definitely bigger than for non-strengthened beams. The biggest bearing capacity was recorded for beam strengthened at its bottom surface (I-3), while for beams with stripes glued to beam side surfaces bearing capacity decreased with increasing width of glued stripes.

3.2. Test results of series II

Both beams tested in this series failed due to loss of bearing capacity of compression zone (Fig. 4, 5). Stripes glued to beam side surfaces did not tear away, even in case of beam II-2, where stripes were not extended beyond supports axes. The actual degree of reinforcement for the beam II-1 was 2.30 (computed – 1.32), and for the beam II-2 – 4.22 (computed – 2.93).

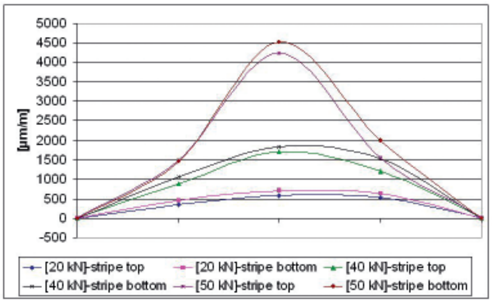

Figure 6.
Comparison of stresses in top and bottom strip fibre. The beam II-1. Stripes of 3 cm width.

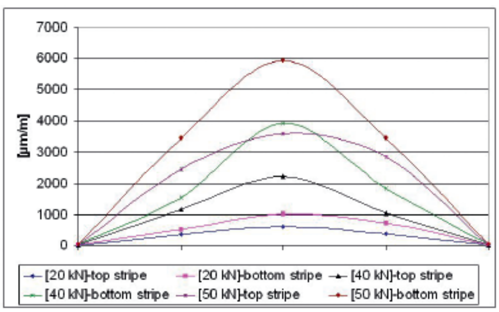

Figure 7.
Comparison of stresses in top and bottom strip fibre. The beam nr II-2. Stripes of 5 cm width

Figure 8.
Cracked beam II-1

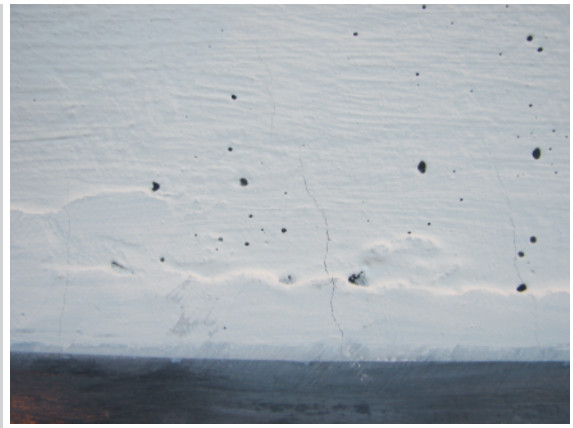

Figure 9.
Cracked beam II-2

Stripes underwent eccentrical tension what caused variation of stresses across their width (in vertical direction). In case of the beam II-1, of 3 cm width, lamination did not occur and variation of stresses between top and bottom stripe fibres did not exceed 10% (Fig. 6). In case of the beam II-5, of 5 cm width, lamination occurred and variation of stresses between top and bottom stripe fibres exceeded 50% (Fig. 7). Lamination of stripes became visible after beam failure (Fig. 5).

In the cycle leading to failure, crack development was clearly influenced by strengthening stripes. First cracks above stripes were observed at loading exceeding significantly non-strengthened beam bearing capacity. The cracks were hard to notice with small spacing and concentrated at loaded cross-sections. Cracked regions widened towards midspan and supports with loading increase. At 65-70% of ultimate loading the cracked region covered half of beam length, and crack width did not exceed 0.05 mm. Fig. 8 shows the beam II-1 midspan, where at 84% of ultimate loading (47 kN), the two cracks spaced by 10 cm, increased their width up to 0.1 mm. Near ultimate loading inclined cracks appeared, and cracks in the midspan kept widening significantly up to failure. Cracks in the beam II-2 with lower degree of reinforcement appeared and developed at a bit lower stress levels. Fig. 9 shows a fragment of beam with characteristic inclined cracks at 45 kN load level, i.e. 88% of ultimate loading.

On the basis of recorded strains in stripes (Fig. 10) and computations, one may assume that loading – strain relationship consists of two straight lines with bend in between relating to yielding of reinforcement (redistribution of internal forces at cross-section).

Relationship deflection – loading for the beam II-2

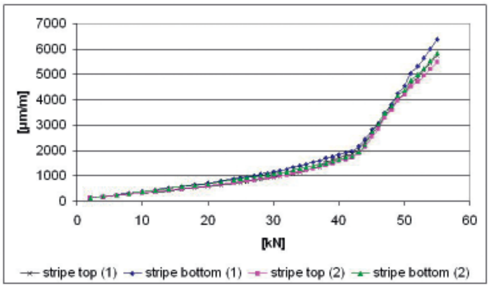

Figure 10.
Increase of stresses in the midspan of the beam II-1

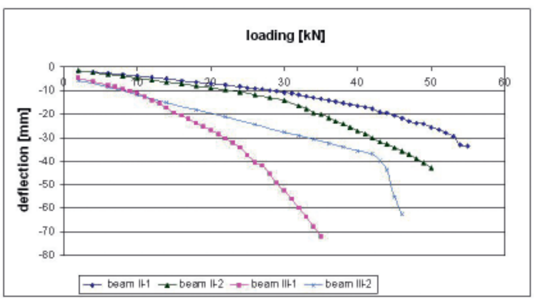

Figure 11.
Comparison of deflections of beams II-1, II-2, III-1, III-2

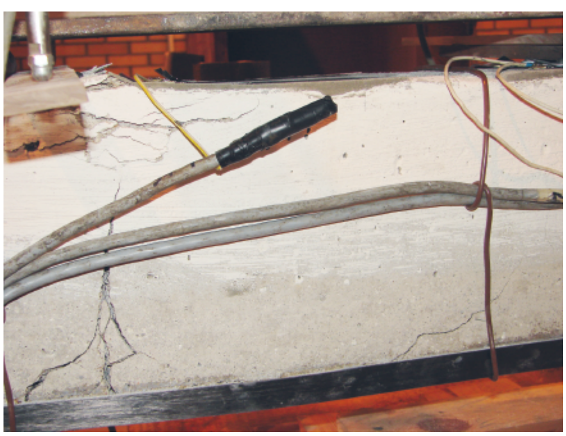

Figure 12.
Failure of beam III-2

had similar character (Fig. 11). However, in the beam II-1 (reinforced with ribbed bars) the deflection – loading relationship is clearly non-linear.

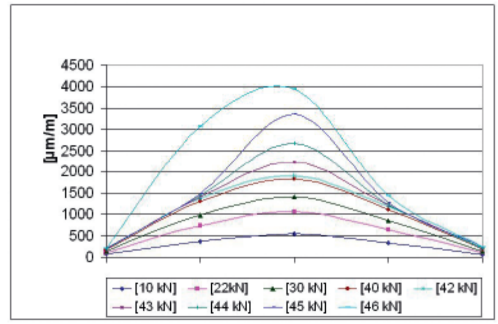

Figure 13.
Strains in stripe, beam III-2

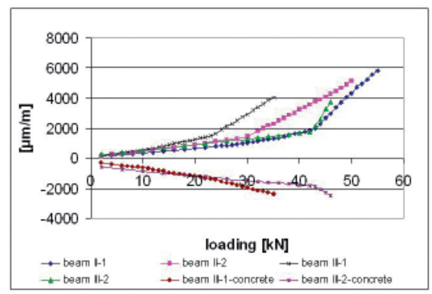

Figure 14.
Stress increase in resultant strip and in concrete in midspan of beams of series II and III

3.3. Test results of series III

Both beams tested in this series failed similarly to beams of series II, due to prove by recordings strains in concrete and loss of bearing capacity of compression zone. Fig. 12 shows failure region of beam III-2. Stripes glued to beam side surfaces did not tear away despite of being ended 15 cm away from support axes (on each end) towards midspan. Actual degree of reinforcement In case of beam III-1 was 3.73 (computed – 3.17), and in case of beam III-2 – 1.78 (computed – 1.28).

The beam III-1, with stripes of 3 cm width, lamination did not occur, and variation of stresses between top and bottom stripe fibres did not exceed 15%.

During loading development of cracks similar to the one described for series II beams was observed. It could be seen that spacing and width of cracks were influenced by stripe width and degree of reinforcement.

Fig. 13 shows variation of average strain in stripes on beam III-2 together with increase of loading and in Fig. 14 average stress in stripes in midspan for all beams of series II and III were compared.

Table 3.

Beam no.	Type of bars	Degree of rein-force-ment	Strain at yielding	Strain at loading – strain dia-gram bend
II-1	ribbed	0.0195	0.00183	0.00184
II-2	plain	0.0114	0.00156	0.00144
III-1	plain	0.0086	0.00156	0.00150
III-2	plain	0.0267	0.00137	0.00173

As can be seen in Fig. 14 stress increase in stripes is nearly linear with diagram bend due to reinforcement yielding, as in the case of the beams of series II, used for comparison. Diagram bend appeared earlier in beams with weaker reinforcement. Table 3 brings together stripe strains (one should resume that they are close to reinforcement strain), at which diagram bend occurred, and strains at reinforcement yielding recorded during reinforcing bars tests.

Fig. 14 shows increase of concrete strains up to failure, recorded on plan surface, in the midspan of beams III-1 and III-2. Strain increase in nearly linear way (especially in strongly reinforced beam III-2), with clear diagram bend relating to yielding of reinforcement. Bends of loading – concrete/stripe strain diagrams are related to each other respectively.

4. CONCLUSION

On the basis of preliminary experimental test results with stripes glued to beam side surfaces one may conclude that:

– tested beam failed due to loss of bearing capacity of concrete compression zone, in another way than documented so far in literature – tearing away of stripe glued to beam bottom surface near support,

– stripes glued to beam side surfaces did not tear away up to beam failure, however, some of them ended 15 cm (0,75 of beam depth) away from support axes (towards midspan),

– beams with stripes 3 cm or less wide (0.15 of beam depth or less) lamination of stripes due to eccentrical tension did not occur,

– in the beam with 5 cm wide stripes (0.25 of beam depth), lamination occurred, and revealed itself after beam failure and at results analysis stage; it did not influence effectiveness of strengthening,

– effectiveness of strengthening turned out to be fully sufficient and it was significantly bigger (from 18 to 74%) than the computed ones according to the procedure [6],

– strengthening stripes had clear influence on cracks layout development – cracks visible above stripes were located closely (up to 5 cm), and their width was small (0.05 mm), at 0.7 of ultimate loading,

– increase of stress in stripes and in concrete compression zone were of nearly linear character with loading – stain diagram bend, caused yielding of reinforcement, that occur earlier for weakly reinforced beams.

On the basis of so far carried out tests one may recognize that gluing stripes to beam side surfaces provides better anchorage than in case of stripes glued to beam bottom surfaces and leads to more predictable failure mechanism, such as loss of bearing capacity of concrete compression zone.

Presented method of beam strengthening seems to be simpler in practical application and more effective than the one described for example in [7], i.e. method of gluing stripes into concrete cover.

REFERENCES

[1] *Kwasza W., Saliczuk L., Sobko J., Panczenko A.*; Rekonstrukcja mostu drogowego ze wzmocnieniem belek przez przyklejenie elementów kompozytowych z włókien węglowych. (Reconstruction of roadway bridge by means of beam strengthening with gluing composite members of carbon fibre). Problemy naukowo-badawcze budownictwa, Tom II – Konstrukcje budowlane i Inżynierskie, Wydawnictwo Politechniki Białostockiej, Białystok 2007; p.593-600 (in Polish)

[2] *Łagoda M.*; Wzmacnianie mostów przez doklejanie elementów. (Strengthening of bridges with gluing members). Politechnika Krakowska, Seria Inżynieria Lądowa, Monografia 322, Kraków 2005 (in Polish)

[3] *Kamińska M. E., Kotynia R.*; Doświadczalne badania żelbetowych belek wzmocnionych taśmami CFRP. (Experimental tests of RC beams strengthened with CFRP stripes). Zeszyt 9, Wydawnictwo Katedry Budownictwa Betonowego Politechniki Łódzkiej, Łódź 2000 (in Polish)

[4] *Cichocki M., Lewandowski R.*; Badania zarysowanych

belek teowych wzmocnionych taśmami kompozytowymi z włókien węglowych CFRP. (Tests of cracked T-beams strengthened with composite CFRP stripes). IX Seminarium „Współczesne metody wzmacniania i przebudowy mostów", Instytut Inżynierii Lądowej Politechniki Poznańskiej, ZMRP Oddział Wielkopolski, Poznań, 8-9.06.1999 (in Polish)

[5] *Kmita A.*; Experimental investigation into behaviour of CFRP composite-strengthened RC beam under cyclic loading. Archives of Civil and Mechanical Engineering, Quarterly Vol.VII, No.2, Polish Academy of Sciences, Wrocław University of Technology, Wrocław 2007

[6] FIB Bulletin 14 (CEB-FIB), Externally bonded FRP reinforcement for RC structures, Switzerland, Lousanne 2001

[7] *Blaschko M., Zilch K.*; Rehabilitation of concrete structures with CFRP stripes glued into slits. Proceedings of the 12th International Conference of Composite Materials, Paris 1999