First Middle East Conference on Smart Monitoring,
Assessment and Rehabilitation of Civil Structures
8 – 10 February 2011, Dubai, UAE

SMAR 2011

Application of Prestressed Near Surface Mounted Carbon Fibre Reinforced Polymer (PNSM).

Alois Vorwagner[1], Stefan L. Burtscher[2], Günter Grass[3] and Clemens Freund[4]

[1] Vienna University of Technology, Vienna, Austria
[2] Technische Versuchs- und Forschungsanstalt GmbH, Vienna University of Technology, Vienna, Austria
[3] Sika Austria GmbH, Bludenz, Austria
[4]Vienna University of Technology, Vienna, Austria

ABSTRACT: Carbon fibre reinforced polymers (CFRP) are often used for strengthening. In most applications the CFRP-reinforcements are externally bonded (EBR) to the structure. An improvement can be achieved by near surface mounted CFRP (NSM), due to the better bond behavior. Further refinements can be obtained by prestressing, e.g.: utilization of high strength, activation of dead loads and much lower deflections, without losing ductility by approaching the ultimate load (if appropriately designed).

This paper will demonstrate a perfect application of prestressed NSM tendons. The key point is to define the minimum distance of the stressed strips according to the concrete strength and prestressing level. Therefore additional pull out tests with different prestressing levels were performed. The application of prestressed NSM is shown in full scale tests with a span of 10 m, where 6 T- beams were loaded under different conditions. The results confirm that the bond anchorage handles the usage of PNSM application with very narrow distances and demonstrates a perfect strengthening system.

1 INTRODUCTION

Carbon fibre reinforced polymers (CFRP) are often used for strengthening. In most applications the CFRP-reinforcements are externally bonded (EBR) to the structure. An improvement can be achieved by near surface mounted CFRP (NSM), due to the better bond behavior. Further refinements can be obtained by prestressing, e.g.: utilization of the high strength, activation of dead loads and much lower deflections, without losing ductility by approaching the ultimate load (if appropriately designed). The advantage of a delayed cracking of concrete and yielding of the steel reinforcement leads to lower crack widths, higher durability and an increase in the serviceability load.

In order to apply the prestressing force, a special anchorage is designed based on the Composite Wedge principle as seen in Burtscher (2008). The wedge anchor enables a simple and fast application of the prestressing force and weighs only 8 kg. The wedge anchorage is only used for prestressing actions and will be removed afterwards. Permanent anchoring ist established by the so called “bond anchorage”. For that purpose the ends were fixed to the structure by epoxy adhesive. So the strengthening components are free from corrosive materials and thus durability is enhanced. The efficiency of the developed systems and the prestressed strips was examined experimentally for plates, strengthened with one prestressed lamella for different prestressing levels (30% -50% $f_{u\,FRP}$) in prior investigations as seen in Vorwagner et al. (2010).

2 ANCHORAGE OF PRESTRESSING FORCE

2.1 Load introduction

The key point for the application of prestressed FRP strips is to anchor the prestressing force. As seen in a strut and tie model for example in Figure 1 the diagonal strut is supported by the tension reinforcement and the stirrups. If reinforcement is additionally applied on the bottom face of the structure the stirrups do not encompass the adhered strips. So the vertical tension component has to be sustained by the concrete tensile strength only. The ultimate load is a function of the concrete strength, the width b_w and activated tension region. If the vertical force component is higher than the concrete strength the strip force cannot be supported by the cross section. In an investigation of NSM strengthened beams this failure mode was called offset rupture, and if the force reaches a critical level external stirrups can take the vertical tension force as seen in Blaschko (2001) and DIBT (2009).

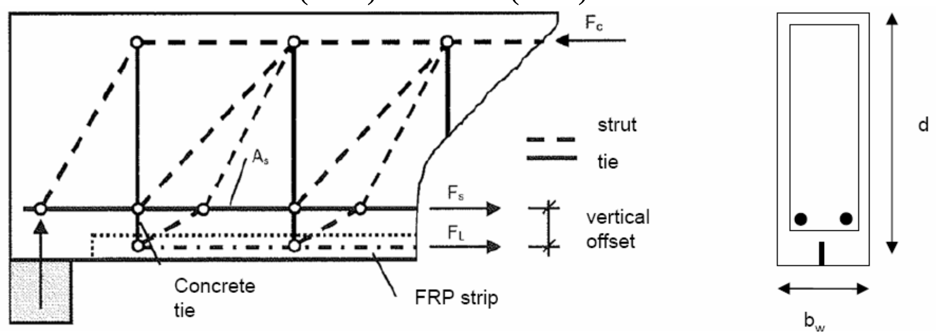

Figure 1: Extended strut and tie model for strengthened cross section Schäfer (1996).

For prestressed strips, external stirrups are not very practical and for example in plates additional stirrups cannot be applied. The axial strip distance is therefore a ruling parameter. The strip distances and prestressing level have to be defined economically and in order to avoid offset failure. The crucial point is the introduction of the load P_0 after prestressing action. The permanent anchorage is applied by the bond anchorage, as seen in previous investigations Vorwagner et al. (2010).

A new approach is to adhere the strip in a transmission bonding. The adhesion runs along a ramp starting form 0 height at the free end to the full strip height, as seen in Figure 2.

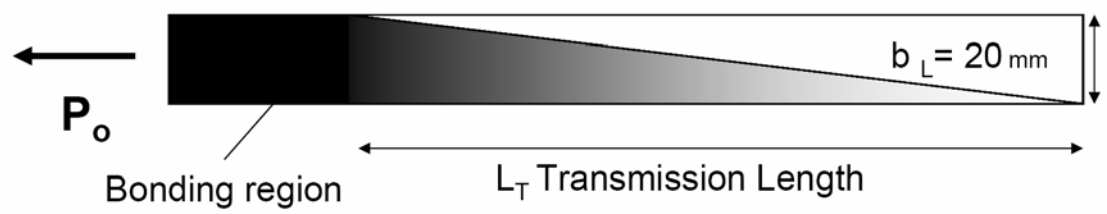

Figure 2: Transmission bonding of the strip

A numerical analysis shows the effect of the transmission bonding. The material parameters for the investigation are given in Table 1. For a concrete section with an edge distance e_r = 37,5 mm and a transmission length L_t=350,0 mm the load distribution is illustrated in Figure 3.

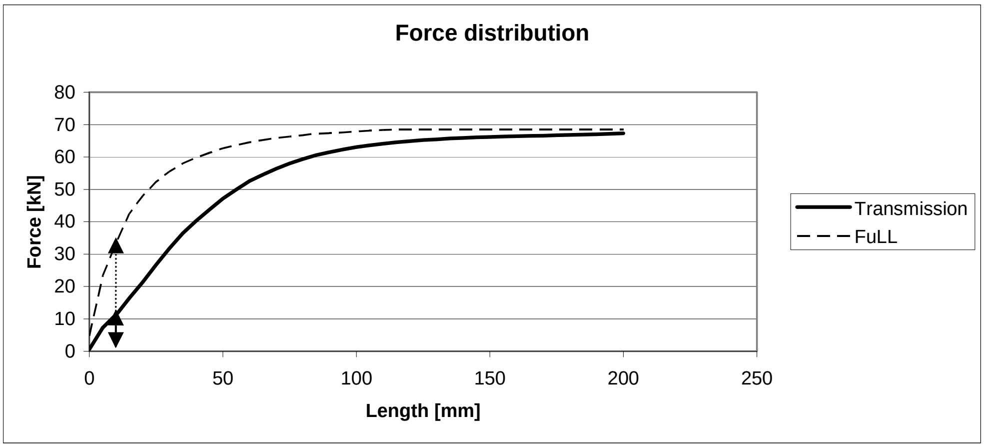

Figure 3: Load and stress distribution of FE - analysis

Close to the free end the strip force is reduced to approximately 30 % compared to full adhesion. In further investigations the transmission length was doubled, but it had no strong impact on the force distribution. A ramp in the adhesion causes shear stress in the CFRP Strip. For a longer transmission length the shear stress over the strip width (b_L) is higher. To investigate the effect of the transmission length and to define an economic prestressing level according to the strip distance, several pull out test have been carried out.

Table 1: Material Parameters

		Cross-Section		E Modul	Strength	Ultimate Strain
		dxb	[cm²]	[MPa]	[MPa]	[‰]
CFRP A_L	1 Strip	20x2,5 mm	0,5	168.000	f_u: 2772	16,5
STEEL A_{s1}		4 DM 10	3,12	194.300	f_y: 583	174
STEEL A_{s2}		6 DM 16	12,05	194.300	f_y:583	174
CONCRETE A_c		16x40x12 cm	928	~30.000	f_{cm}: 33/ f_{ck}=25	3,5

2.2 Pull out test

Different configurations were examined in the pull out tests. Various prestressing levels, the transmission bonding and edge distances were the investigated parameters. The idea behind the transmission anchorage was distribute the load transfer along the strip and not concentrate the load transfer to the strip end. In Figure 4 the test set up is presented. First the strips were prestressed, next they were glued to the concrete. After curing of the epoxy resin the prestressing was released from one side (free end). From the other side the CFRP strip was loaded by a hydraulic actuator. To determine the load capacity of the system, the strip was loaded until failure $F_{u\,exp}$ which meant shear failure in the concrete in all cases.

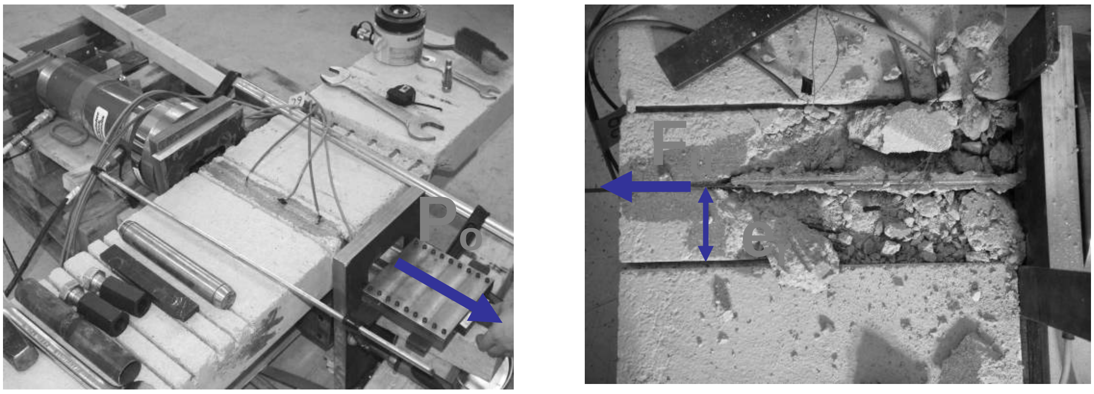

Figure 4: Test Set up pull out test left e_r =36 mm, concrete failure right for e_r 75 mm,

The distance from the edge e_r (See Figure 4) amounted to 36 and 75 mm and the prestressing level(P_0)varied from 30 kN (22% $f_{u\ FRP}$) to 56 kN (42% $f_{u\ FRP}$). The results are given in Table 2. As seen below, the bearing capacity of the system (F_u—P_0) is for the distance e_r=36 mm ranging from 30 to 44 kN. The concrete strength was low in order to simulate old structures and is given in Table 1.

Table 2: Results Pull Out Test

Spec.	Edge dist.	Prest.	Trans. L	Ultimate		Failure	Failure
	e_r	*Po*	L_T	$F_{u\ exp}$	$F_{u\ exp}$ -P_o	*Prestress.*	*Ultimate*
	[mm]	[kN]	[cm]	[kN]	[kN]		
1	36	0	-	36,1	36,1	-	Conc.
2	36	30	-	74,8	44,8	OK	Conc.
3	36	38	-	76,1	38,1	OK	Conc.
4	36	43,5	30	69,9	26,4	FRP	Conc.
6	36	52,6	30	82,8	30,2	FRP	Conc.
7	36	56,2	10	95,5	39,3	Conc.	Conc.
5	75	0	-	59,5	59,5	-	Conc.
8	75	0	10	53,8	53,8	-	Conc.
9	75	0	30	57,5	57,5	-	Conc.

For the transmission bonding in specimens 4 and 6 the shear stress in the lamella was too high and an interlaminar failure appeared after release of the prestressing load. When the transmission length was reduced to 10 cm, the concrete failed by releasing the prestressing force, see specimen 7. A prestressing force of P_0= 38 kN could be anchored to the groove without transmission bonding (specimen 3).

But a prestressing level of 38 kN, which means 28 % of $f_{u\ FRP}$ is not very effective. By using the transmission bonding the prestressing force could not be significantly increased. In specimen 4 the prestressing force was 5 kN higher than without transmission (specimen 3) and first fibre cracks appeared as seen in Figure 5. For a prestressing force of 52,6 kN (spec. 6) the strip failed over a long distance but could still anchor additional 30,2 kN. If the transmission length is reduced to 10 cm, the concrete fails at a P_0= 56,18 kN (40% $f_{u\ FRP}$ spec. 7) for an edge distance of 36 mm.

As a matter of fact the transmission length does not benefit significantly. To reach an economic prestressing level of 40% $f_{u\ FRP,}$ the edge distance has to be increased. For the non prestressed strips the pull out force was increased from 36,11 kN (spec.1) to 59,5 kN (spec.5), which means an amplification factor of 1,65. Which leads to a feasable prestressing force of 38*1,65=62,7 kN.

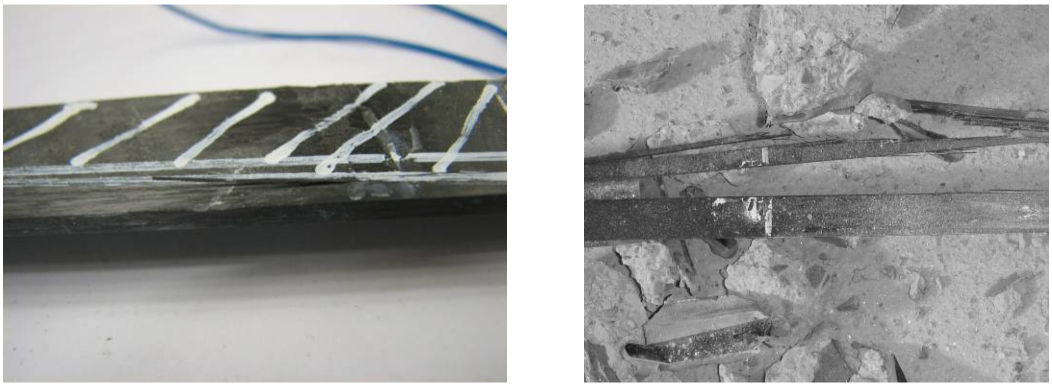

Figure 5: FRP failure: left specimen 4 P_0 = 43kN right specimen 6 P_0 = 53 kN

For the final approach the prestressing force was chosen with 56 kN or 40 % of $f_{u\ FRP}$. The edge distances were 80 mm, or 4 x the strip height at the concrete FRP dimensions. 6 prestressed strips can be anchored per meter. According to the approvals of DIBT (2009) for b_w= 16 cm, 3 strips are feasible for NSM application.

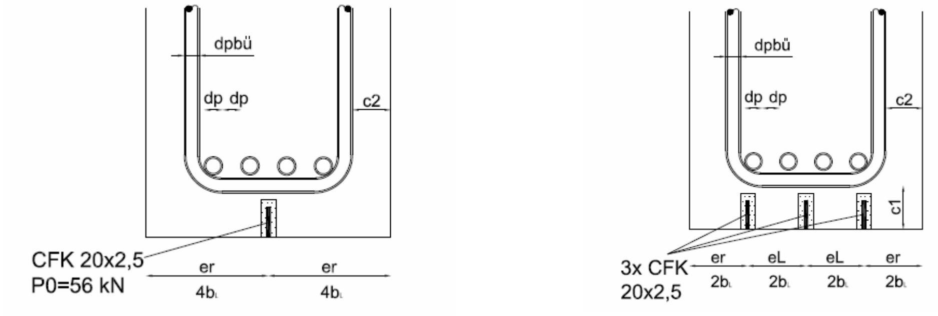

Figure 6: Strip application left the prestressed and right NSM application.

3 FULL SCALE TEST

To demonstrate the usage of prestressed NSM application a test series of 6 T- beams with a length of 10,4 m was designed. The prestressing force was applied by hydraulic jacks and by application of the composite wedges. The strip was bonded to the structure in prestressed state. After the curing time of 48 h the prestressing force was released and the wedges were removed. 50cm of the strips were not glued during prestressing. For the permanent anchoring these ends, which are free from tension are bonded with epoxy to the structure. In this paper this is called "bond anchorage".

The T- beams were designed in such a way, that the strip rupture is achieved at ultimate load. To avoid shear failure the beams were designed in such a manner, that the shear force at ultimate load was in the range of the shear bearing V_{Rcm} without shear reinforcement according to EC 2 for plates. According to the code for beams a minimum shear reinforcement has to be installed. Also in this configuration the concrete tie as seen in the strut and tie model in Figure 1 should be able to take the additional tension force.

$$V_{Rcm} = \left[\frac{0,18}{1,00} \cdot k \cdot \left(100 \cdot \rho_L \cdot f_{cm}\right)^{1/3} + 0,15 \cdot \sigma_{cp} \right] \cdot bw \cdot d \qquad \textbf{(1)}$$

Debonding of the concrete cover is also effected by the reinforcement, thus very narrow distances of rebars were chosen to test a critical situation for debonding. The test setup is shown in Figure 7. The cross section was turned upside down for a better handling during the experiments. The beams were loaded in 2 different configurations with a low shear force (a1 = 4.00m) and a high shear force (a1= 2,60 m). Also 2 reference beams were tested: Beam 1 was not strengthened and beam 2 was strengthened with 3 strips without prestressing (NSM) according to the rules in the approvals DIBT (2009). Beams 4 to 6 were prestressed at 56 kN.

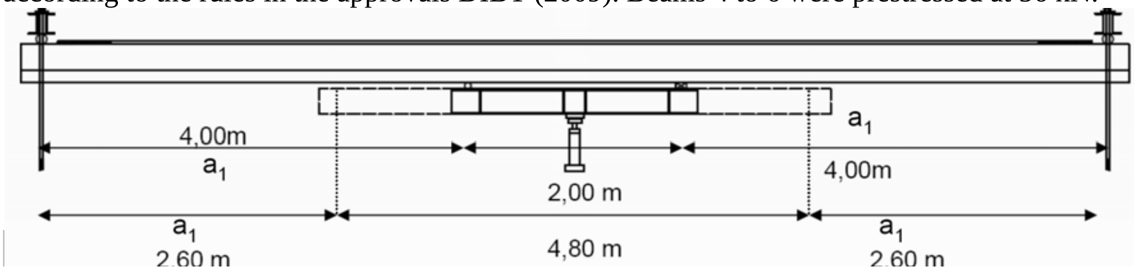

Figure 7: 4 point bending test

Due to the high bending of the beam, chip rupture occurred in all tensioned beams. The fibre cracks can be noticed over a length of ca. 2 m including the example in Figure 8. The maximum load is not affected by the prestressing level, also the total numbers of cracks, but the cracks appear at higher loading, and the deflection and crack width is lesser than for non prestressed beams. Strip rupture starts with small fibre cracks until the whole strip fails.

Figure 8: Strip rupture at maximum load for Beam 5

The explosion of the concrete cover and a very high deflection of beam 2 is presented in Figure 9. Debonding started at the loading point which is the maximum shear and moment region. The debonding effects occurred without prior warning.

Figure 9: Debonding of concrete cover of beam 2, strengthened with 3 untensioned strips.

4 RESULTS

In Figure 10 the moment curvature diagram are shown for the reference beam 1 (non strengthened), beam 2 (3x NSM) and for prestressed beam 4 and beam 6. Beam 1 was stopped after reaching the yielding load of reinforcement to avoid great deflection. Prestressing of 1 strip causes the same yielding moment (when the reinforcement started to yield) as when 3 untensioned strips are used. The prestressed system is still ductile, for example in beam 6 the deflection at ultimate load is amounted to 313 mm or 1/32 of the span. Strip rupture due to high bending was the failure mode for all prestressed beams. At low load levels influence of the dead load can be seen, which were caused by the installation of the specimens. Initially the beam was supported at the inner loading points only and dead weight was acting. When the beam touch the supports the system changes. This system change is not considered in the calculation.

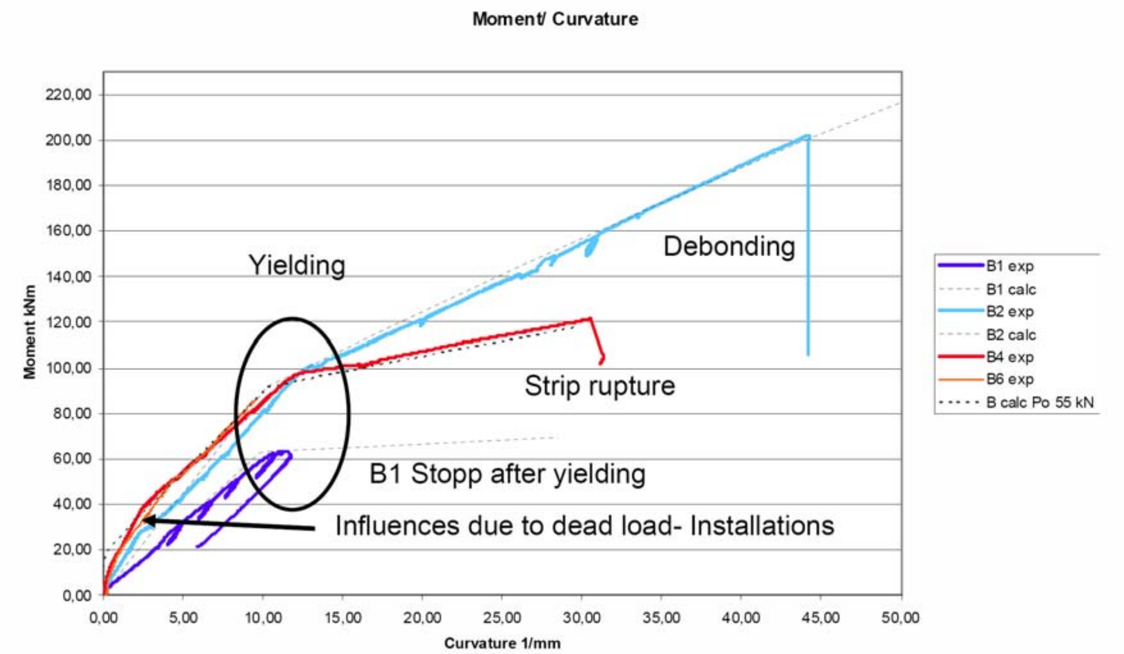

Figure 10: Moment Curvature diagram

The results of the 4 point bending tests are given in Table 3. The yielding moment My is listed for all beams, and compared to beam 1, an amplification factor of 1,54 can be achieved by prestressing. For the ultimate load the factor is 1,94 for prestressing with 1 strip and 3,18 for 3 strips. The results match the calculated parameters very well. But debonding occurred at around 94% of the calculated ultimate load for beam 2. As seen in Table 3, the maximum shear force V_{max} (54,84) is exceeding V_{Rcm}.(51 kN). Beam 6 was loaded near the support to generate a higher shear force. Due to prestressing and the defined edge distance e_r no debonding occurs and the beam can be loaded with a shear force up to V_{Rcm}.

Table 3: Results 4 Point Bending Tests

Beam	Prest.		Distance	Deadload	Moment			Ultimate			Failure
	Po	*er*	a1	*G*	Mg	My	Mu	$F_{u\ exp}$	V_{max}	V_{Rcm}	*Ultimate*
	[kN]	[mm]	[m]	[kN]	[kNm]	[kNm]	[kNm]	[kN]	[kN]		
B1	0,00	-	4,00	23,77	20,17	62,78		21,31	20,25	44,8	-
B2	0,00	40,0	4,00	23,70	20,10	100,36	201,17	90,54	54,84	51,0	Deb.
B4	54,67	80,0	4,00	25,90	21,97	95,97	120,59	49,31	35,11	52,0	Strip R
B5	54,41	80,0	4,00	25,90	21,97	96,44	121,45	49,73	35,32	52,0	Strip R
B6	56,05	80,0	2,60	24,50	9,23	97,30	123,40	87,81	50,50	52,0	Strip R

5 CONCLUSION

Prestressing of near surface mounted CFRP strips is an effective strengthening method. The pull-out tests define a prestressing level of 1120 N/mm². The transmission bonding was not very effective, because fibre cracks occur due to shear stresses in fibre direction. For economical reasons it is better to have a higher prestressing force than to fix more strips with a lower stressing level. Thus the distance from the edges was chosen 4x the lamella width.

The tendons can be stressed fast and simple by using the composite wedge method. The “bond anchorage” enables a simple and durable permanent fixing of the strip, the whole strengthening system consists of non corrosive materials.

All prestressed beams have shown strip rupture due to high bending. Crack widths and deflections can be reduced, and the system is still very ductile.

The main advantages of this system are: activation of dead loads, full utilization of CFRP and the increase of the yielding point of the reinforcement. To reach this yielding point with non tensioned strips, 3 strips are needed instead of a prestressed one.

Future approaches will be numerical investigation of prestressed NSM applications.

The authors would like to express their gratitude to Austrian Research Promotion Agency (FFG GesmbH, Vienna) and Sika Austria GmbH for the financial support and the good cooperation.

Blaschko, M. 2001. *Zum Tragverhalten von Betonbauteilen mit in Schlitze eingeklebte CFK-Lamellen*. München: Berichte aus dem Konstruktiven Ingenieurbau. Technische Universität München.

Burtscher S.L. 2008. Wedge anchorage for CFRP strips. Journal for Composites in Construction Engineering, ASCE, Vol 12, No. 4: 446-453.

DIBT, Deutsches Institut für Bautechnik. 2009. *Verstärken von Stahlbetonbauteilen durch in Schlitze eingeklebte Kohlefaserlamellen „Carboplus“*. Allgemeine bauaufsichtliche Zulassung. Berlin. Antragsteller: Bilfinger Berger AG.

Schäfer, H.G. 1996. *Verstärken von Betonbauteilen – Sachstandsbericht*. Deutscher Ausschuss für Stahlbeton, Heft 467. Berlin: Beuth Verlag.

Vorwagner A., Burscher S.L., Grass G. and Kollegger J. 2010. Verstärkung mit vorgespannten eingeschlitzten Lamellen. Beton und Stahlbetonbau, Vol. 105, Verlag Ernst und Sohn: 9 -18