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Preloading effect on strengthening efficiency of RC beams strengthened with NSM strips

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ABSTRACT: FRPs (fiber reinforced polymers) gained major popularity and have been extensively used in civil engineering over the past decade. Many tests carried out on reinforced concrete members strengthened in flexure with NSM (near surface mounted) technique proved high strengthening efficiency indicating NSM strengthening as one of the most promising and recent methods of rehabilitation of RC structures. The paper concerns the issue of strengthening of reinforced concrete members with pretensioned CFRP (carbon fiber reinforced polymer) strips. The experimental investigation concerned six concrete beams strengthened in flexure with narrow carbon strips glued in the grooves made in the concrete cover called NSM method. A practical and unique aspect of the program focuses on the analysis of the effect of preloading on the strengthening efficiency of RC beams strengthened with pretensioned carbon fiber reinforced polymer laminates. Although the preloading is one of the most important parameters to be accounted for while designing strengthening of existing concrete structures, this aspect has been investigated very rarely. The main division of the tested members was made according to the strengthening configuration. The beams of series A were strengthened with complex strengthening - one pretensioned and two nonpretensioned strips, while the beams of series B were strengthened with two pretensioned composites. Two levels of preloading were investigated: the first one as the beam's self-weight corresponding to 25% and 14% of the longitudinal yield strength of nonstrengthened beam and the second one corresponding to 60% of the yield strength of nonstrengthened beam. Moreover, the influence of the conventional steel reinforcement ratio on the strengthening efficiency is analyzed in the paper.

1 INTRODUCTION

Many studies proved high efficiency of the near surface mounted method in flexural strengthening of RC members. Strengthening of RC members with pretensioned carbon fiber reinforced polymers (CFRP) is the most effective way to increase their load capacity and to improve their serviceability limit state. Although passive strengthening increases flexural capacity of RC members, it does not influence the cracking load and the deflections under service loads. Prestressing leads to reduction of the width of a crack, delays opening of the new ones and decreases the existing deflections. The review of available literature on flexural strengthening of RC members strengthened with passive and pretensioned NSM method yields high effectiveness of strengthening. Moreover, experimental tests conducted up to now have indicated strong dependency between strengthening effectiveness and longitudinal steel reinforcement ratio Badawi et al. (2009). The NSM method prevents premature FRP debonding and leads to the full utilization of FRP tensile strength unlike EB method, which indicates FRP debonding as the most common failure mode Hajihashemi et al. (2011) and El-Hacha et al. (2016).

This experimental investigation shows the achievement of a novel NSM prestressing system for tension of the narrow FRP strips embedded in the concrete cover. This patented pretensioning system for NSM CFRP strips was implemented just on the member. All the components of the system are mounted directly on the concrete surface and no additional space beyond the strengthened member is needed. The scope of the experimental program conducted in the laboratory of the Department of Concrete Structures at Lodz University of Technology was to evaluate the strengthening efficiency of prestressing NSM method. The study focused on assessing the influence of the CFRP reinforcement ratio on the strengthening effectiveness. Moreover, the effect of the steel reinforcement ratio and a number of pretensioned strips were also investigated. The accuracy of the novel prestressing system proposed by the author's for pretensioning of the NSM CFRP strips was investigated in detail.

2 EXPERIMENTAL PROGRAM

2.1 Test Specimens

The experimental research consisted of six specimens in total. The RC beams with cross-section of 500 x 220 mm were divided into two series: A and B, depending on a number of CFRP strips. Single span simply supported beams were tested in the static six point loading loaded by four hydraulic jacks, each at 1200 mm spacing (Figure 1). In Series A, which consisted of two beams (NSM12A and NSM16A), complex strengthening was proposed with combination of one active and two passive CFRP strips. Series B included four specimens (NSM12B, NSM16B, NSM12B-L and NSM16B-L), each strengthened with two pretensioned CFRP strips. The bottom tensile steel reinforcement consisted of four steel bars with a nominal diameter of 12 mm (ρ_s=0.49%) in the NSM12A, NSM12B and NSM12B-L beams, and four bars with a diameter of 16 mm (ρ_s=0.87%) in the NSM16A, NSM16B, NSM16B-L beams.

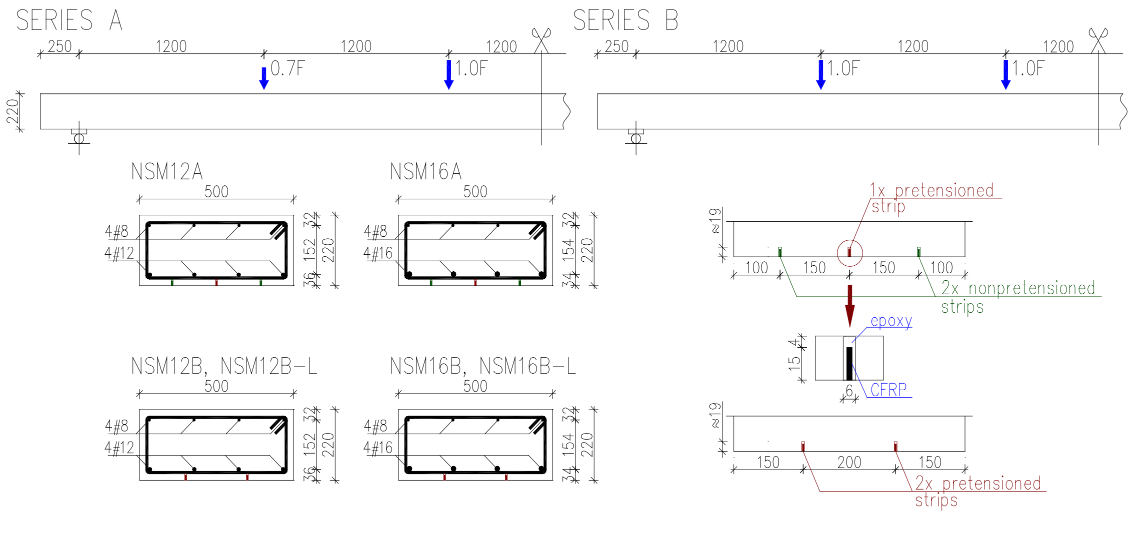


Figure 1. Static schemes, specimens cross sections and strengthening arrangement

The cross-section of the CFRP strip was 2.5 mm wide and 15 mm high, which provided the overall composite reinforcement ratio equal to ρ_f=0.10% and ρ_f=0.07%, in series A and B respectively. The pretensioning strain of the CFRP strips was assumed as ε_{fp}=6‰, corresponding to 35% of the ultimate tensile CFRP strength.

The beams were strengthened at two preloading levels. The first one, represented by self-weight only, corresponded to the preloading level of 25% of the yield strength of the nonstrengthened member (M_{u0}) for NSM12A and NSM12B beams and 14% for NSM16A and NSM16B beams. The second preloading level corresponding to 60% of the yield strength of nonstrengthened beam (M_{u0}) reflected to initial preloading of existing concrete structures before their strengthening (Table 1).

Table 1. Summary of investigated parameters and preloading bending moments

Specimen	Tensile steel reinforcement	Number of CFRP strips	Number of pretensioned CFRP strips	M_{u0} [kNm]	Preloading moment M_p [kNm]	Preloading ratio M_p/M_{u0} [%]
NSM12A	4ϕ12	3	1	46.5	13.5	25
NSM16A	4ϕ16	3	1	84.7	15.0	14
NSM12B	4ϕ12	2	2	46.5	13.5	25
NSM16B	4ϕ16	2	2	84.7	15.0	14
NSM12B-L	4ϕ12	2	2	46.5	27.90	60
NSM16B-L	4ϕ16	2	2	84.7	50.90	60

2.2 *Material Properties*

The average compressive strength of concrete (f_c) and the modulus of elasticity (E_{cm}) were defined at the day of testing in uniaxial compression tests on the cylinder samples of 150 x 300 mm and in tension and compression on the cubic samples of 150 x 150 x 150 mm, cured at the same conditions as the tested beams. The tensile characteristics of longitudinal steel bars are presented in Table 2. The average experimental values of the strength characteristics of CFRP strips contained: tensile strength (f_{fu}), elastic modulus (E_f) and ultimate strain (ε_{fu}). Strength properties according to the manufacturer are shown in brackets (Table 2).

Table 2. Strength characteristics of materials

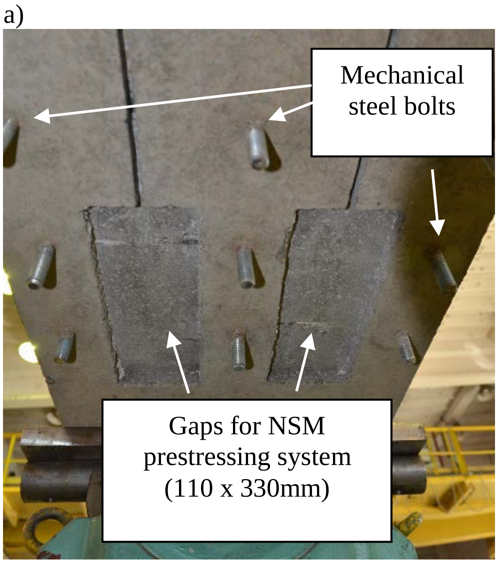
Material			Series A				Series B			
			NSM12		NSM16		NSM12		NSM16	
			8	12	8	16	8	12	8	16
Steel	E_s	[GPa]	186.1	191.3	196.5	198.0	205.5	214.0	205.5	204.9
	f_y	[MPa]	416.2	539.6	555.8	595.0	554.9	563.4	554.9	578.3
	f_u	[MPa]	734.1	627.5	646.0	672.0	608.9	651.7	608.9	693.8
Concrete	f_{ck}	[MPa]	46.0		53.9		51.0		52.0	
	$f_{c,cube}$	[MPa]	44.9		59.5		60.0		60.1	
	$f_{ct,sp}$	[MPa]	3.95		4.30		4.5		4.1	
	E_{cm}	[GPa]	25.3		24.0		25.8		24.3	
FRP	E_f	[GPa]	160*							
	f_{fu}	[MPa]	2800*							
	ε_{fu}	[%]	17*							

* values proved by the manufacturer.

2.3 *Strengthening technique*

The beams were strengthened in the test stand in ceiling position with CFRP laminates bonded to the concrete with two part epoxy adhesive. Prior to strengthening, three groves in beams series A and two grooves in beams series B of 6 mm x 19 mm cross-section were cut using diamond saw blade. Grooves prepared for pretensioned laminates were ended with the rectangular gaps of 110 mm x 300 mm cross-section and depth of 19 mm (Figure 2). After preparing the grooves, steel bolts were installed on the bottom of the beam for the NSM prestressing system. After the CFRP strips were mounted in the NSM prestressing system two hydraulic jacks were mounted at both CFRP ends (Figure 3). In series A, strengthened with one pretensioned CFRP strip, after pretensioning middle CFRP strip, the prestress force was anchored and blocked and the two isolated sections at each end of the CFRP of 300 mm long were heated to accelerate adhesive curing. When the epoxy adhesive reached desirable strength the prestressing force was unblocked and reduced causing the decrease of 3‰ in the CFRP strains between heating sections and NSM prestressing system. Between the heating sections, CFRP strains reminded at the primary level. This had intended to proper transfer of the prestressing force at the time of unblocking and releasing the prestressing force. The prestress force was then blocked again. Blocking was removed after 12 hours and the NSM prestressing system was removed, and the CFRP strip remained without any anchors. Two non pretensioned CFRP strips were mounted in the outer grooves. In beams of series B, strengthened with two pretensioned CFRP strips, CFRP strips were sequentially installed and pretensioned. After unblocking the prestressing force and removal of NSM prestressing system of first pretensioned laminate, second laminate was tensioned. In this Series reduction of prestressing force was not applied and the strains were constant at the full length of laminate.

a)



b)

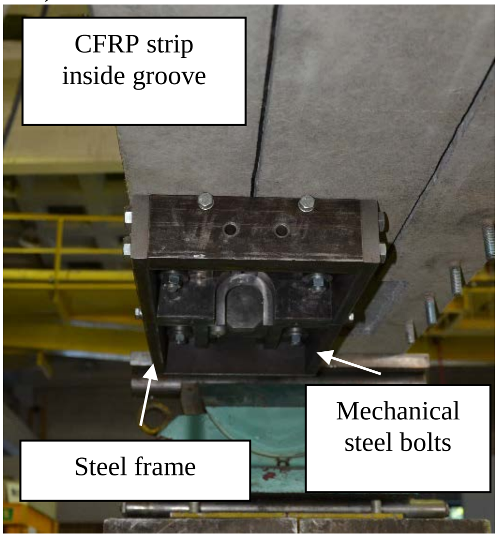


Figure 2. Strengthening of series B specimens: (a) View on the bottom of beam of NSM12B before CFRP strips installation, (b) Frame of NSM prestressing system mounted on the bottom of the beam.

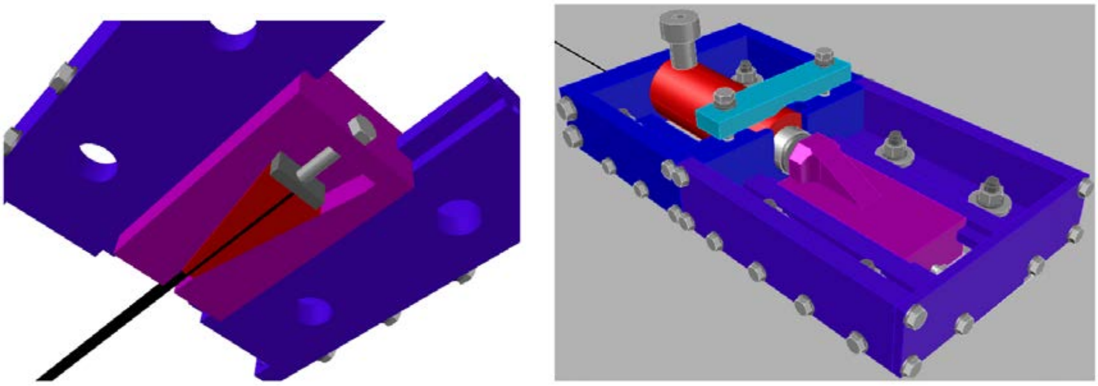


Figure 3. Pretensioning system for NSM strips (Patent P 4O7 898).

2.4 *Instrumentation*

To estimate the CFRP strain distribution along the composites, twelve strain gauges were mounted on each strip. The CFRP strain gauges arrangement along the length of the strip is shown in Figure 4. To estimate the beam vertical displacement, nine 50 mm linear variable differential transformers (LVDTs) were located at the beams midspan and at either side of loading points, as shown in Figure 5(a). Furthermore, concrete strains were registered using LVDTs transducers. 13 gauges (20 mm) in the tension zone and 5 gauges (10 mm) in the compression zone were arranged over 300 mm gauge length as shown in Figure 5(b).

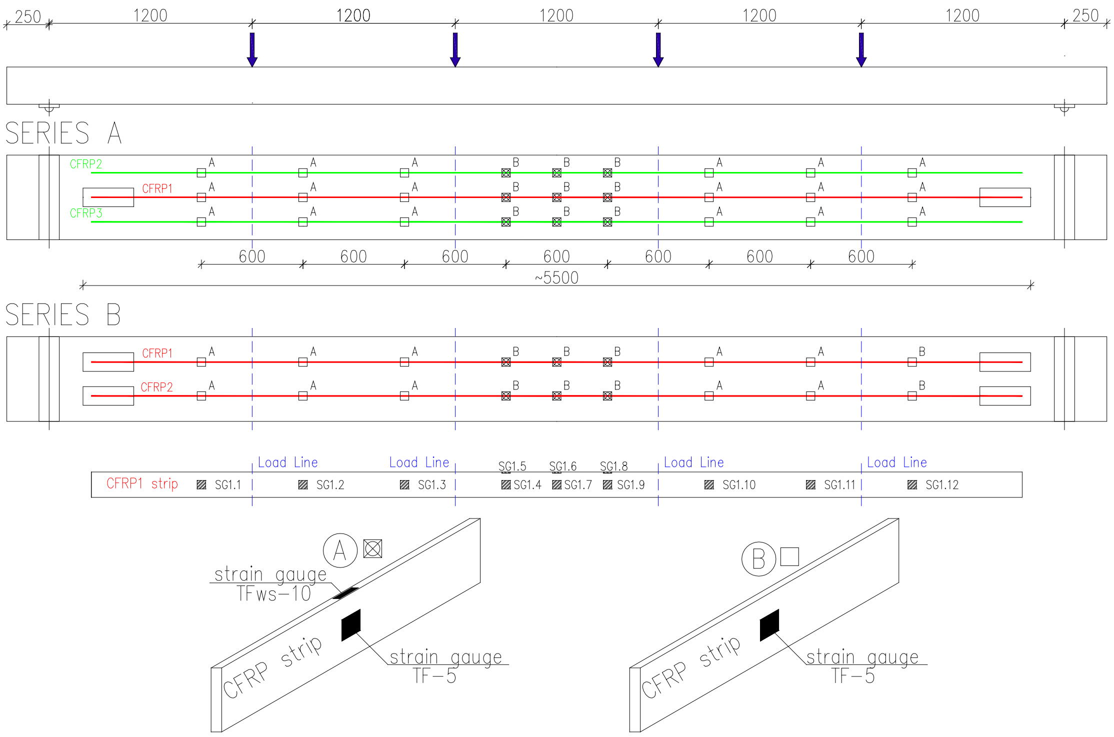


Figure 4 . Strain gauges on the CFRP strips (A–bottom and lateral side, B–lateral side)

a) b)

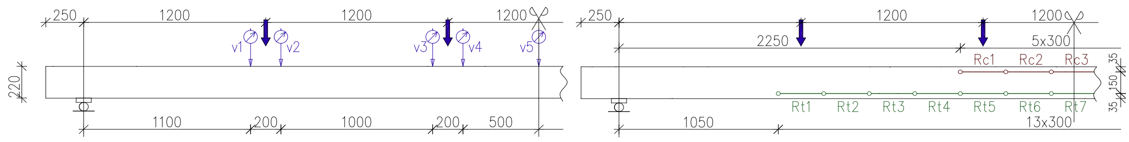


Figure 5. Location of gauges: (a) vertical LVDTs, (b) LVDTs for concrete strain measurements

3 TEST RESULTS

3.1 Failure Modes

Independently of a series, steel and composite reinforcement ratio and preloading level, all beams failed due to rupture of the CFRP strips (Fig. 6(a)). The CFRP rupture was accompanied by a loud noise. Composite rupture confirmed full utilization of CFRP tensile strength, both pretensioned and nontensioned. Fracture of all three (one pretensioned and two passive) CFRP strips occurred in beams of series A. The pretensioned strip ruptured as first in both members. Further increase in loading led to the rupture of the remaining two passive strips. At least one of the pretensioned strips fractured in both specimens of series B. Moreover, the concrete crushing in compression occurred in beam NSM16A with higher reinforcement ratio (Fig. 6(b)).

a) b)

Figure 6. The failure of specimens: (a) The rupture of the passive CFRP strip in NSM12A, (b) The concrete crashing in NSM16A

3.2 Crack pattern

Cracking of concrete in all tested beams was monitored during full range of loading. In general, crack patterns are similar in all tested beams regardless of the preloading level which is visible in Figure 7. Slight differences are caused by different composite reinforcement ratio of each series, especially by the number of pretensioned CFRP strips. Specimens strengthened with two pretensioned laminates demonstrated fewer cracks than beams strengthened with one pretensioned CFRP strip. No longitudinal cracking in the concrete along the groove, at the level of the bottom steel or at epoxy-concrete interface was observed. The crack pattern on the bottom surface of the beams exhibited typical crack pattern for the NSM method named “fishbone” (Figure 8 a, b). This confirms good stress transfer between pretensioned strips and a concrete substrate.

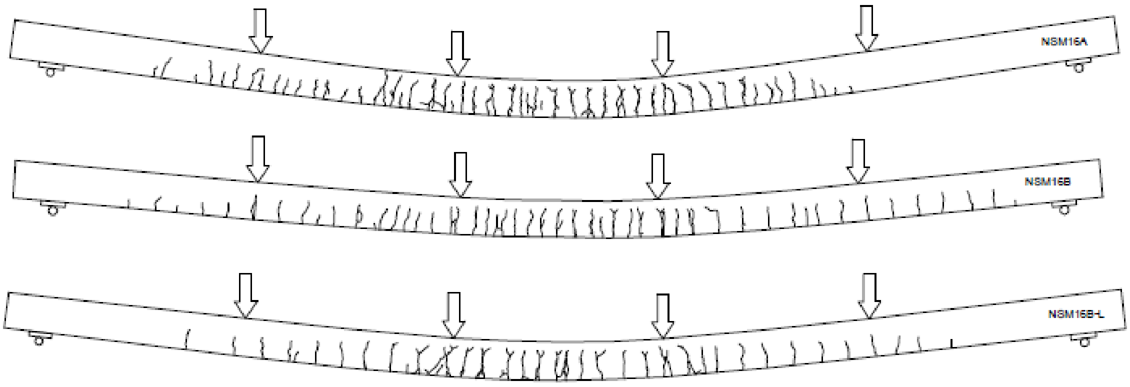


Figure 7. Comparison of crack pattern of beams with higher steel reinforcement ratio (NSM16A, NSM16B, NSM 16B-L).

a) b)

Figure 8. Crack pattern on the bottom surface of beams series B: (a) NSM12B, (b) NSM12BL.

4 THE ANALYSIS OF TEST RESULTS

The beams failure modes, values of bending moments corresponding to concrete cracking (M_{cr}), steel yielding (M_y) and ultimate (M_u) observed in the tests, and the increase in the cracking (ΔM_{cr}), yielding (ΔM_y) and ultimate (ΔM_u) bending moments in comparison with nonstrengthened beams are shown in Table 3. The values of bending moments of reference – nonstrengthend specimens corresponding to cracking (M_{cr0}), yielding (M_{y0}) and ultimate (M_{u0}), were calculated using the nonlinear analytical model. The model considers only normal stresses in the cross-section and the initially plane sections remain plane in the full range of loading, as a result strain compatibility is enforced in the cross-section. The adopted model includes the transfer of the tensile stresses in cracked concrete - tension stiffening principle (Czkwianianc and Kamińska, 1993)

The strengthening ratio identified as the measure of the strengthening effectiveness is defined as the difference between the ultimate bending moment of the strengthened (M_u) and non-strengthened (M_{u0}) beams over the ultimate bending moment of the nonstrengthened member (M_{u0}) as follows: (1):

$$\Delta M_u = \frac{M_u - M_{u0}}{M_{u0}} \tag{1}$$

Table 3. Summary of the test results

Specimen	Failure mode	M_P/M_{u0} [%]	M_{cr0} [kNm]	M_{cr} [kNm]	ΔM_{cr} [%]	M_{y0} [kNm]	M_y [kNm]	ΔM_y [%]	M_{u0} [kNm]	M_u [%]	ΔM_u [%]
NSM12A	R	25	13.0	22.0	69.2	46.5	70.0	50.5	46.7	110.2	135.0
NSM12B	R	14	13.0	26.0	100.0	49.5	61.5	24.0	49.7	97.0	95.2
NSM12B-L	R	60	13.0	-	-	49.5	58.5	18.0	49.7	98.0	97.0
NSM16A	R+CC	25	15.0	27.3	82.0	85.2	100.0	18.0	86.0	146.9	70.8
NSM16B	R	14	15.0	29.0	93.3	83.0	98.0	18.1	83.3	130.0	56.1
NSM16B-L	R	60	15.0	-	-	83.0	100.1	21.0	83.3	133.0	59.7

R – rupture of CFRP strip, CC – concrete crushing

The strengthening efficiency is strongly dependent on the internal steel reinforcement ratio. Beams with lower steel reinforcement ratio demonstrated major strength increase in flexure, reaching values within the range of 97% - 135% , whilst specimens with higher reinforcement ratio demonstrated the strength increase in the range of 56% - 70.8%. In members of series A strengthened with three CFRP strips, the increase in bending moment was higher (135% NSM12A), when compared with corresponding beams of series B (95.2% NSM16B and 97.0% NSM16B-L) strengthened with two CFRP strips. The beams prestressed with CFRP strips induced significant increment in the cracking moment reaching values from 69.2% (NSM12A) to 100.0% (NSM12B) compared with the reference beam, and delayed the steel yielding as shown in Table 3. In specimens strengthened with three pretensioned CFRP strips, the increase of steel yielding moment reached 18.0% and 50.5% for NSM16A and NSM12A beams. However, in specimens strengthened with two pretensioned CFRP strips steel, yielding moment increased within the range of 18.0 – 24.0%. Pretensioning of CFRP strips resulted in the decrease of existing deflections within the range of 1.8 – 6.6 mm in beams strengthened under lower preloading level (self-weight only). The decrease of existing deflections in specimens strengthened under higher preloading level of 7.7 mm in specimen NSM12B-L and 5.2 mm in NSM16B-L beam were observed.

Figure 9 shows the deflection of specimens in the full range of loading. The higher preloading level did not influence the flexural behavior of the tested specimens (NSM12B-L and NSM16B-L). After a decrease of existing deflections in specimens NSM12B-L and NSM16B-L, the slope of the bending moment vs deflection curve during further loading of beams NSM12B-L and NSM16B-L did not differ from the beams strengthened under lower preloading level. The dashed vertical line visible in the curves determines the allowable specimens' deflection in terms of serviceability limit state, determined as L/200=30 mm (L-span). The increase in the bending moment corresponding to deflection equal to 30 mm increased within the range of 70% - 83% in specimens of series A and 44% - 69% in specimens of series B. This confirms a beneficial influence of pretensioning on the overall flexural behavior and stiffness of the beam specimens which are initially preloaded. Pretensioning the laminates in specimens strengthened under self-weight led to increase in the bending moment at the time of obtaining the allowable deflection equal to 30 mm. The maximum registered CFRP strain in specimens of series A was18.6‰ and 17.1‰ in the pretensioned laminates and from 14.9‰ to 17.9‰ in passive laminates. In beams of series B the ultimate registered CFRP strains ranged from 14.7‰ to 18.3‰.

a) Series A b) Series B

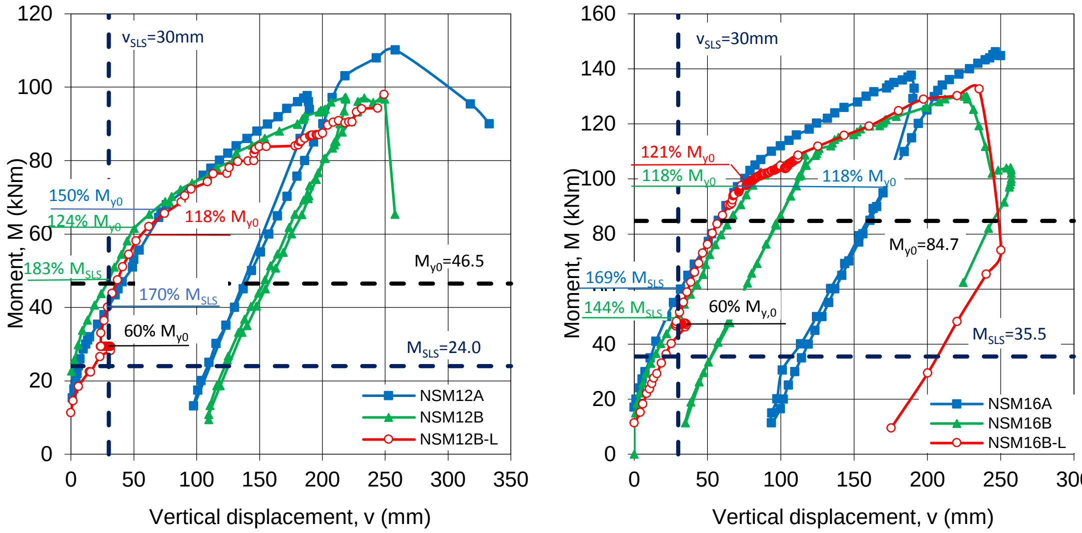


Figure 9. Bending moment vs vertical displacements curves

5 CONCLUSIONS

The research provided several important conclusions concerning the factors influencing the strengthening efficiency of reinforced concrete members strengthened with pretensioned CFRP strips. The high efficiency of the prestressing technique for flexural strengthening with NSM FRP composites was confirmed by high strengthening ratio, which ranged from 56.1% to 135.0%. The strengthening ratio is shown to be inversely proportional to the steel reinforcement ratio. A different preloading history for beams NSM12B-L and NSM16B-L did not affect the flexural behavior of this specimens during strengthening and loading. Pretensioning of the composite reinforcement strongly influences the serviceability limit states conditions: deflections and cracking. It was proved by the increase of bending moment corresponding to allowable deflection in the serviceability limit state amounting to 70%. This also applies to members strongly loaded before strengthening. Moreover, considering the increase in the beams flexural strength, it is overall composite reinforcement ratio rather than number of pretensioned strips that shows critical influence. The results of the tests indicated high efficiency of the novel prestressing system invented by the authors, which makes it possible to apply NSM CFRP without any anchorage systems.

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