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
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STRENGTHENING OF RC SLABS WITH PRESTRESSED AND NON-PRESTRESSED NSM CFRP STRIPS

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A b s t r a c t

This paper presents the results of an experimental tests carried out on reinforced concrete (RC) slabs strengthened in flexure with prestressed near surface mounted (NSM) carbon fiber reinforced polymer (CFRP) strips. The main aim of the test was to define effectiveness of strengthening with narrow CFRP strips glued into slits made in a concrete cover in aspect of an influence of an internal steel reinforcement ratio. In order to improve serviceability limit state conditions of pre-tensioning of the NSM reinforcement has been proposed. According to the authors knowledge a number of studies on the pretensioned NSM FRPs is quite small. Until now only few laboratories all over the world have undertaken the subject of flexural strengthening with pre-tensioned strips and obtained very promising results. The innovation of this study is a novel prestressing device adapted to tension narrow CFRP strips proposed by the authors. The experimental program contained two RC slabs reinforced with different internal steel reinforcements. Obtained results indicated high effectiveness of this technique with flexural enhancement of 73 and 134% compared to non-strengthened specimens respectively with higher and lower steel reinforcement ratio. Introducing pre-tensioning of the CFRP strips upgrades the service conditions with decrease of existing deflections and reduction of crack width. Outcomes of the study presented herein motivated authors for further research and developed novel experimental program based on preloaded specimens to analyse the effect of prestressing on service conditions.

S t r e s z c z e n i e

W pracy przedstawiono wyniki badań żelbetowych płyt wzmocnionych na zginanie naprężonymi taśmami kompozytowymi (CFRP – carbon fiber reinforced polymer) wklejonymi w podłużne bruzdy wycięte w betonowej otulinie (technika NSM – near surface mounted). Głównym celem badań było określenie wpływu stalowego stopnia zbrojenia podłużnego na efektywność wzmocnień przy użyciu cienkich, kompozytowych taśm. W celu poprawy warunków w stanie granicznym użytkowania zaproponowano wstępne naprężenie zbrojenia kompozytowego. Opierając się na wiedzy autorów, badania wzmocnień elementów żelbetowych przy użyciu naprężonych kompozytów, szczególnie wklejonych w betonową otulinę są dość rzadkie. Do tej pory kilka ośrodków badawczych na całym świecie podjęło tą tematykę. Innowacyjnym aspektem jest zastosowanie autorskiego systemu przystosowanego do naciągu wąskich kompozytowych taśm. Przeprowadzone badania obejmowały dwie żelbetowy płyty różniące się stopniem wewnętrznego zbrojenia stalowego. Wyniki badań potwierdziły wysoką efektywność wzmocnienia techniką NSM. Zaobserwowano wzrost nośności płyt wynoszący 73% i 134% odpowiednio z mniejszym i większym stopniem zbrojenia stalowego w porównaniu do odpowiadających im elementów niewzmocnionych. Wprowadzenie wstępnego naciągu taśm CFRP doprowadziło do zmniejszenia ugięć oraz szerokości rozwarcia rys. Otrzymane rezultaty skłoniły autorów do kontynuacji badań i przeprowadzenie testów elementów wytężonych przed wzmocnieniem.

K e y w o r d s : **CFRP strips; Flexural strengthening; NSM, Pre-tensioning NSM; RC slabs.**

1. INTRODUCTION

Rehabilitation of existing concrete structures is a developing field. Engineers deal with a problem of extending a service lifetime and effective strengthening of deteriorated RC structural elements of buildings and bridges due to material decay, design errors, changes of a static scheme, increased service loads and unforeseen factors. Generally, repairing deteriorated construction with conventional methods takes a long time. A novelty in civil engineering is usage of fibre reinforced polymers (FRP) instead of steel. Composite materials are used with notable effectiveness to increase the flexural load carrying capacity of reinforced concrete members.

Two basic methods of strengthening using FRP materials have been distinguished – externally bonded (EB) and near surface mounted (NSM). Use of FRP materials as external reinforcement (EB) like unidirectional strips, sheets or fabrics made by fibres arranged in one or two different directions applied on the concrete surface of strengthened RC member has increased extensively over the past decade. A number of researchers investigated debonding of externally bonded FRP materials from the concrete surface as the most popular failure mode, which limited the FRP strength utilization until 35%. Furthermore, the externally bonded reinforcement may be affected for inevitable agents such as fire or other negative external factors. Numerous applications of EB FRP reinforcement on existing RC elements have been successfully executed until now. To provide protection and to delay the failure caused by FRP debonding a new technique involving FRP strips or rods embedded in pre-cut grooves made in the concrete cover of the strengthened member has been proposed. In the near surface mounted technique a higher tensile FRP stress can be achieved due to higher bond strength. It is a result of increasing the bond area between the FRP material, an adjacent epoxy and the concrete surface. The NSM strengthening technique is one of the most recent and promising technique of rehabilitation RC structures.

A drawback in NSM method is the curtailment the cross-section of FRP materials caused by thickness of the concrete cover. Experimental tests confirmed a significant influence of longitudinal steel reinforcement ratio on the strengthening efficiency with NSM FRP reinforcement [1]. The increase in the steel reinforcement ratio caused decrease in the strengthening effectiveness. Passive methods of strengthening using FRP reinforcement do not withdraw the existing deflections or cracks of the strengthened structure. It means no influence on the service limit state on existing deformations of RC members. To avoid this disadvantage, FRP reinforcement needs to be pre-tensioned. FRP prestressing increases utilization of FRP materials and the steel yielding loads.

Numerous commercial systems for pre-tensioning FRP laminates in the EBR technique have been very common. Prestressing of the RC members with NSM technique is more complex due to a lack of space in the grooves required for mounting the anchorage system and a small cross-section of the FRP strip. In addition gripping the material (strips/bars) during the pre-stressing phase without damaging the fibres which are sensitive on the transversal stress is difficult to achieve. To overcome above problems, many research have focused on discovering the most effective anchorage system for NSM FRP prestressing [2, 3]. No commercial system is dedicated to pre-tension the NSM FRP strips. More recent tests on pre-stressing FRPs with NSM systems are mainly for laboratory investigation and are non-practical for the field applications.

The scope of presented in the paper experimental program conducted at Lodz University of Technology was to assess the influence of steel reinforcement ratio on the effectiveness of NSM technique. Moreover, the accuracy of the innovative system [4] proposed by the authors to tension NSM CFRP strips was investigated in details.

2. EXPERIMENTAL STUDY

2.1. Specimens and test configuration

The pilot experimental program consisted of two RC slabs, namely NSM12 and NSM16, strengthened in flexure with CFRP strips mounted in grooves made in the concrete cover. The main aim of the test was to combine the original NSM technique with its pre-tensioning. Each slab was strengthened with three carbon FRP strips – one pre-tensioned in the mid-cross section and two non-active bonded into the outer grooves cut symmetrically with 150 mm spacing. The cross-section of FRP strip was 2.5 mm wide and 15 mm high, what provided composite reinforcement ratio equal to $\rho_f = 0.10\%$. Both full scale slabs with 6000 mm clear span had rectangular cross-section of 220 mm height and 500 width. Experimental parameter includes only a difference in the longitudinal steel reinforcement ratio. The bottom tensile steel reinforcement consisted of four steel bars with a nominal diameter of 12 mm ($\rho_s = 0.49\%$) in NSM12 slab and four bars with a diameter of 16 mm (ρ_s = 0.87%) in NSM16 slab. Four bars with a diameter equal to 8 mm were used as a compressive longitudinal steel reinforcement in both specimens. Rectangular stirrups made of 8 mm diameter bars were placed at 150 mm spacing along the member length. Stirrups did not occur in the pure bending moment region. The concrete cover at the bottom reinforcement was equal to 28 mm. The pre-tensioning strain in the middle strip in both slabs was assumed to be equal ε_{fp} = 0.006, corresponding to 35% of the ultimate tensile CFRP strain. The slabs were simply supported and tested under static six point bending introduced by four hydraulic jacks with the maximum capacity of 100 kN each at 1200 mm spacing (Fig. 1a). To achieve steady loading on the slab width, the force from each actuator was transferred to the concrete member through a steel crossbeam with a length equal to the slab's width.

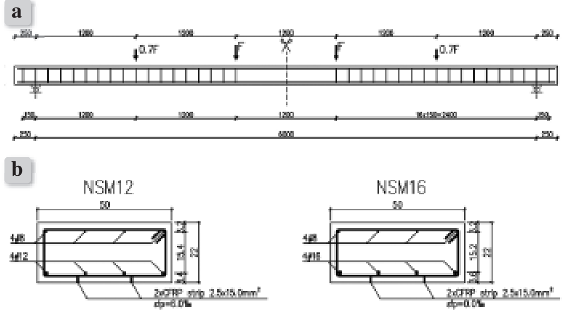

Figure 1.
(a) Static scheme; (b) Geometry, steel reinforcement and strengthening configuration

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 from 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. The tensile characteristics of steel bars used as the internal reinforcement are presented in Tab. 1. 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}) (Tab. 1). Strength properties according to manufacturer are shown in brackets.

Table 1.
Properties of steel, concrete and CFRP strip

Material		8	12	16
Steel	E_S [GPa]	191.2	191.3	198.0
	f_y [MPa]	486.0	595.0	595.0
	f_u [MPa]	690.0	672.0	672.0
Concrete		NSM12	NSM16	
	f_{ck} [MPa]	46.0	53.9	
	$f_{c,cube}$ [MPa]	44.9	59.5	
	$f_{ct,sp}$ [MPa]	3.95	4.30	
	E_{cm} [GPa]	25.3	24.0	
CFRP	E_f [GPa]	170.4 (160*)		
	f_{fu} [MPa]	2551 (2800*)		
	ε_{fu} [‰]	13.6 (17*)		

2.3. Strengthening technique

Installation of the NSM prestressing system and CFRP strips is shown in Fig. 2 and Fig. 3. Rectangular grooves approximately of 6 mm wide and 19 mm deep were cut longitudinally in the concrete cover in upside down position. At the ends of the middle groove, where the strips were anchored, the concrete cover was removed resulting formation of the "pockets" of 110 mm width and 310 mm length. Next, on the each side of the pocket four bolt anchors were mounted. Slabs were rotated 180 degrees and moved to the test standing. Grooves were cleaned with compressed air and CFRP strips were cleaned by acetone. Strengthening the slabs had two phases. First included the assembly of prestressing NSM system into the slab and mounting CFRP strip into the groove. In second phase epoxy adhesive was produced according to the supplier recommendations. The length of the strips was different. Passive strips were longer and measured 5500 mm, tensioned CFRP strip length was equal to 5350 mm due to a space needed for the installation of prestressing NSM system. Strengthening process took place in the ceiling position which represented strengthening of the existing structural members. Slabs were strengthened under their dead load, which corresponded to preloading level of 14% of non-strengthened element for NSM12 slab and 25% of non-strengthened element for NSM16 slab. The releasing of the prestressing force was applied in two steps. After the strains in the CFRP strip reached the expected values, two isolated sections at the ends of the strips equalled to 300 mm were heated to accelerate the adhesive curing. When the epoxy adhesive achieved desirable strength a decrease in the prestressing force was performed and the strains in the sections of reduction decreased to the average value of 0.003. In the middle section of the CFRP strip, between the heating sections, the strains remained on the same level equalled to values before the reduction of prestressing. After the epoxy reached required strength the NSM prestress system was dismantling. Second step consisted of mounting passive CFRP strips into the grooves.

Figure 2.
CFRP strip mounted in the groove

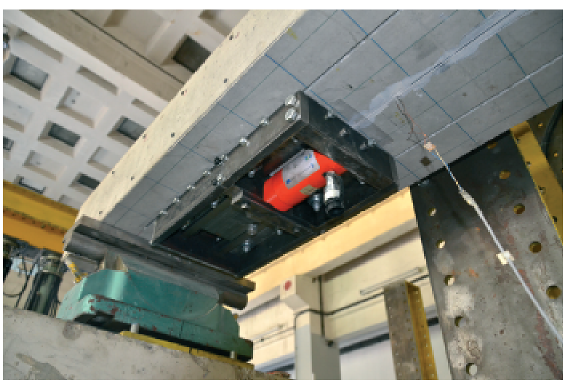

Figure 3.
NSM pre-stressing system

2.4. Instrumentation

Both specimens were instrumented to measure deflections, strain in the concrete at the tensile and compressive steel reinforcement level, strain in the longitudinal steel reinforcement and strain in the CFRP strips. Vertical displacements were recorded at the midspan and on both sides of each load point by nine voltage differential transducers LVDTs with the range of 50 mm and 100 mm settled on the independent suspension frame (Fig. 4a). Furthermore, the concrete strains were recorded by five LVDTs transducers in the compressive and thirteen in the tensile zone (range 10 mm and 20 mm) mounted on side of the slab at the level of the top and the bottom longitudinal steel reinforcement (Fig. 4b). Strains along the CFRP strips and at a midspan of the longitudinal steel reinforcement were monitored by strain gauges. Nine strain gauges were mounted on the side and three on the bottom of strip – one at midspan and two symmetrically on sides with 300 mm spacing (Fig. 4c). All readings were registered up to failure by a data acquisition system with 1 second intervals.

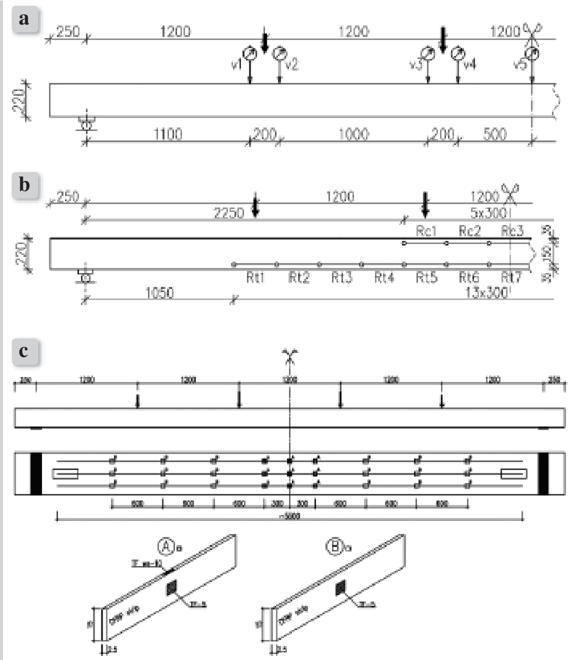

Figure 4.
Arrangement of displacement transducers and strain gauges: (a) Vertical displacement transducers (LVDTs), (b) Transducers for concrete strain measurements, (c) Strain gauges location on CFRP strips

3. TEST RESULTS

3.1. Failure modes

In both specimens failure due to rupture of the CFRP strips occurred (Fig. 5), what confirmed a full utilization of the tensile strength of the CFRP strips, irrespectively prestressed or non-prestressed. In NSM16 slab concrete crushing in compression zone also occurred (Fig. 6). Pre-tensioned strips fractured as first in NSM12 and NSM16 member. Further increase in loading was accompanied by rupture of passive strips. Infringements of CFRP reinforcement protruded inside the groove in the midspan section and distanced around 30 cm from loading points. No longitudinal cracking in the concrete along the groove, at the level of the bottom steel or at epoxy-concrete interface was observed after the process of tensioning the strip and removal of the NSM pre-stressing system. This confirms good stress transfer between pre-tensioned strip, epoxy and a concrete substrate caused by reduction of prestress force at the ending sections of the strips. No peeling of prestressed FRP reinforcement was observed what proves the assumption that no mechanical anchorage at the ends of the CFRP prestressed strips is necessary. Moreover, the prestress loses recorded between the time of disassembly the prestressing system and the time of testing were very small and considered negligible. It should be noticed that no slip or debonding at the entire length of the pre-tensioned strip has appeared proving full adhesion (bond) between concrete, epoxy and additional reinforcement.

Figure 5.
Rupture of the passive CFRP strip

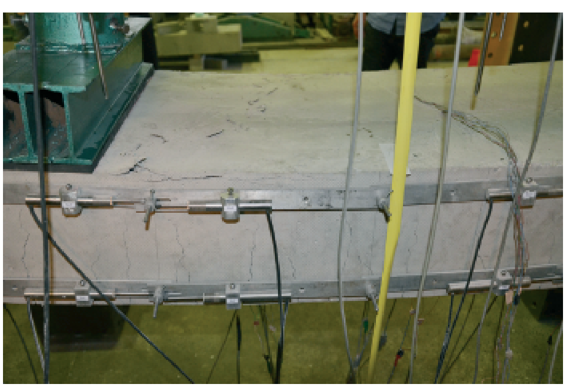

Figure 6.
Concrete crushing in NSM16 slab

The initial CFRP prestressing strains (ε_{fp}), cracking moment (M_{cr}), steel yielding moment (M_y), ultimate bending moment (M_u), increase in the load bearing capacity of the slabs compared to the non-strengthened elements (the strengthening effectiveness ratio) (ΔM_u), bending moment corresponding to a deflection equal to $L/200$ (M_{vdop}), and a deflection (V_f), dedicated to ultimate bending moment (M_u) are summarized in Table 2.

3.2. CFRP Strains

Strains were monitored during pre-tensioning of the CFRP strips and loading. Application of strain measurement allowed to assess the average prestress loses equalled 0.004 between the time of dismantling the NSM prestressing system and the test day. After the heating process the system was locked for minimum 24 hours. Finally, on the test day, the preliminary strain values in CFRP strains stabilized at the level of $\varepsilon_{fp12} = 0.0056$ and $\varepsilon_{fpu16} = 0.0062$, respectively in NSM12 and NSM16 slab. The strains in the sections with reduction of tensile force at the ends of the strips attained values of 0.0036 and 0.0035 in the NSM12 specimen and 0.0029 and 0.0032 in the NSM16 member. This reduction did not allow the slippage after disassembly of the NSM prestressing system and avoided cracking the concrete along the slit at the ends of the strip caused by the concentration of the lateral stress. The preliminary strain and stress obtained in the CFRP strips are presented in Table 3. The maximum registered CRFP strain during the tests in the passive strips indicated values of 0.0147 and 0.0149 for the NSM12 specimen, while CFRP strain in the NSM16 slab reached values of 0.01537 and 0.01707. Prestressed strips ruptured when the total CFRP strain ($\varepsilon_{f,tot}$) attained values of 0.0186 and 0.01624 respectively in NSM12 and NSM16 specimens. The total CFRP strain is calculated as a sum of the CFRP initial prestressing strain and the maximum strain registered during the test

Table 2.
Summary of test results

Specimen	M_{cr} [kNm]	ΔM_{cr} [%]	M_y [kNm]	ΔM_y [%]	M_u [kNm]	ΔM_u [%]	M_{vdop} [kNm]	ΔM_{vdop} [%]	V_{Mmax} [mm]
B12*	13.0	-	46.5		46.5	-	24.0		-
NSM12	27.0	108	70.0	50	110.2	134	39.5	65	258
B16*	15.0	-	84.0		84.7	-	35.5		-
NSM16	33.0	120	100.0	19	146.9	73	57.0	61	250

Table 3.
Average prestressing stresses and strains in the CFRP strips at midspan section

Specimen	Assumed pre-tensionig level		Pre-tensioning CFRP level before adhesive curing		Effective CFRP prestressing level before testing		
	Stress [MPa]	Strain ‰	Stress [MPa]	Strain ‰	Stress [MPa]	Strain ‰	Strain reduction [%]
NSM12	960	6.0	976	6.1	896	5.6	32.9
NSM16	960	6.0	1080	6.3	992	6.2	36.5

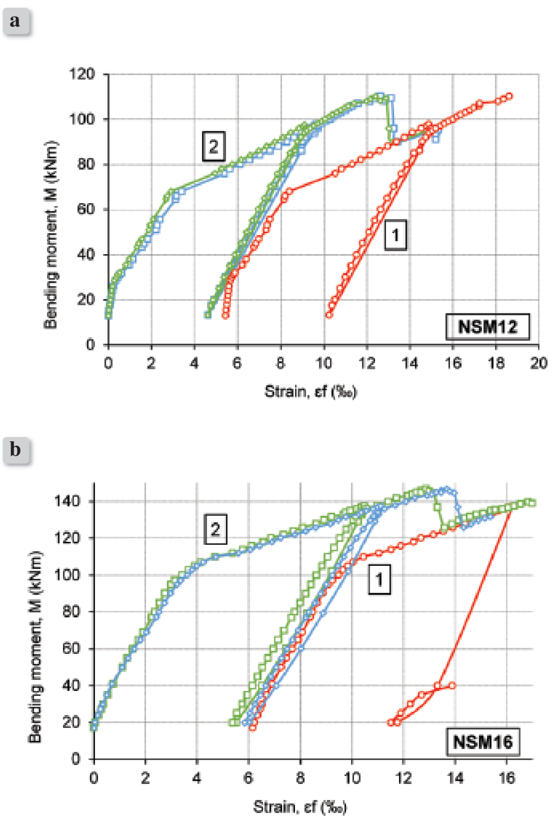

Figure 7.
Bending moment versus strains in CFRP strips in NSM12 slab 1 – prestressed, 2 – non-prestressed: (a) NSM12 slab; (b) NSM16 slab

$\varepsilon_{f,tot} = \varepsilon_{fp} + \varepsilon_{f,test}$. Fig. 7(a) and Fig. 7(b) shows the comparison between the maximum CFRP strain as a function of the bending moment at the midspan.

3.3. Vertical displacement

After prestressing of the CFRP strip a reduction of the deflection in both slabs obtained values of 1.9 mm and 2.2 mm in NSM12 and NSM16, respectively. Slabs demonstrated large pliability in the full range of loading what was reflected in vertical displacements causing the reduction of loads during the testing procedure due to the end of actuators range. The vertical displacements at the midspan corresponding to the ultimate load reached 258 mm in the NSM12 specimen and 250 mm in NSM16 slab. After the fracture of the CFRP strips, midspan deflections increased despite the load decrease, alike in NSM12 and NSM16 slabs (Fig. 9a and 9b). The bending moment versus curvature relation presented in Fig. 10a and 10b was linear until concrete cracking, then linear at shallower slope until the steel yielded. After the rupture of the CFRP strips, several drops in the bending moment values were perceived. However, the deflections raised constantly. Strengthening with one prestressed and two non-prestressed CFRP strips caused the increase in the value of the bending moment corresponding to the acceptable deflection in the serviceability limit state ($L/200 = 30$ mm) equaled 60% (NSM12) and 65% (NSM16) compared to bending moment of non-strengthened specimens. A practical adaptation of the strengthening using presented prestressed NSM technique tends to be very promising especially for the preloaded RC elements. This beneficial influence had been confirmed earlier in the tests of RC slabs strengthened with externally bonded prestressed CFRP laminates (EBR – externally bonded reinforcement) under different preloading level before the strengthening, [3].

3.4. Analysis of test results

Prestressing the embedded CFRP reinforcement enhanced the overall performance of the slabs by increasing cracking, yielding and ultimate loads. The effectiveness of strengthening ratio was calculated using the equation (1) defined as the quotient of the increase in the ultimate bending moment registered in the strengthened specimen (M_u-M_{u0}) compared to non-strengthened specimen to the ultimate bending moment of the non-strengthened slab (M_{u0}):

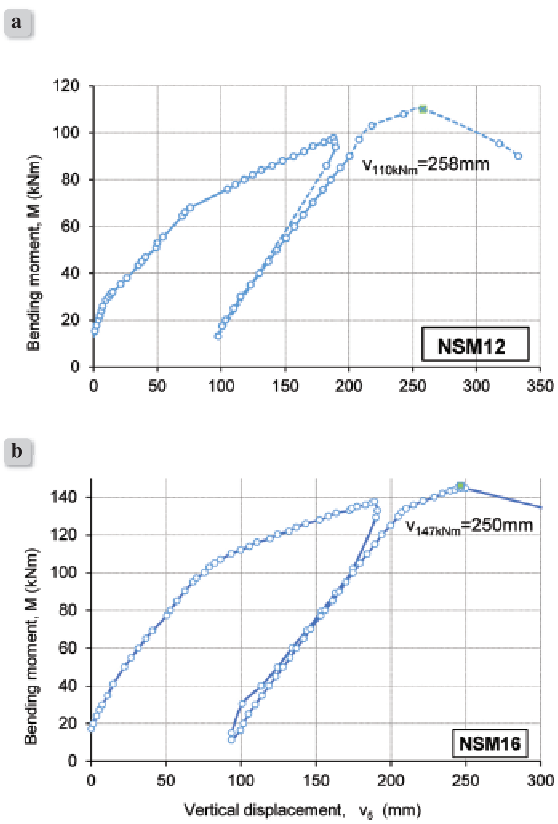

Figure 8.
Bending moment versus midspan deflection curve: (a) NSM12 slab; (B) NSM16 slab

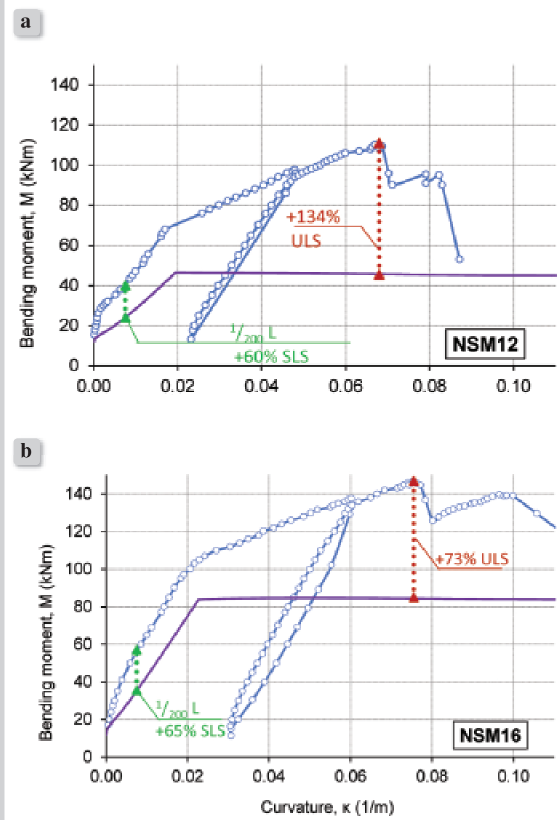

Figure 9.
Bending moment versus curvature curve: (a) NSM12 slab; (b) NSM16 slab

$$\Delta M_u = \frac{M_u - M_{ux0}}{M_{u0}} \quad (1)$$

The curvature of the slabs was determined based on the average tensile strains in the compression and tensile zones, calculated from the formula:

$$\kappa = \frac{\varepsilon_t - \varepsilon_c}{h^{'}} \quad (2)$$

where: ε_t – average concrete strain in tension zone, [‰]; ε_c – average concrete strain in compression zone [‰]; h' – vertical distance between compressive and tensile strain measurement.

The capacity of the reference elements (M_{u0}) was signified analytically with the several assumptions made in the concrete theory: plane cross-section remain plane, transfer of the tensile stress in the cracked concrete (tension stiffening), model considers only normal stresses in section, experimental adopted stress-strain relationships of materials – concrete and steel. The value of the external load is defined according to the equilibrium condition of generalized forces in the cross-section. The value of the bending moment, for the non-strengthened, specimens when the maximum strains of either used material is achieved is the value corresponding to the load carrying capacity of the non-strengthened specimen.

The test results clearly show the significant influence of the internal steel reinforcement ratio on strengthening effectiveness with the prestressed CFRP strips. This fact was also proved in the tests conducted on the RC beams strengthened with non-prestressed CFRP strips, [1]. The analysis of the tests results are summarized in Table 2, which shows the influence of the tested parameters on the strengthening effectiveness. The strengthening delayed cracking of the concrete, which indicated the increase in the cracking moment about 108% and 120% corresponding to reference specimens, respectively in NSM12 and NSM16 slabs (Table 2). Significant differences in bending moment corresponding to yielding of the longitudinal steel reinforcement (ΔM_y) equal to 50%

and 19% were caused by strong influence of internal steel reinforcement ratio (ρ_{sl}) equalled to 0.49% and 0.87% in NSM12 and NSM16 element, respectively. Similar influence of the longitudinal steel reinforcement ratio in the strengthened specimens on the ultimate bending moment confirmed increments compared to non-strengthened specimens. The increase of the steel reinforcement ratio (ρ_{sl}) from 0.49% in NSM12 slab to 0.87% in NSM16 slab caused the decrease in the strengthening effectiveness from 73% to 134% (Table 2).

4. CONCLUSIONS

Flexural strengthening of RC structures using carbon FRP laminates demonstrated high efficiency confirmed by the high strengthening ratios of the NSM12 and NSM16 specimens equalled to 134% and 73% compared to the calculated non-strengthened slabs. The effectiveness decreased by increase in the steel reinforcement ratio. Both specimens failed due to fracture of CFRP strips after yielding of the steel longitudinal reinforcement what means that proposed strengthening technique allows to fully utilize the composite tensile strength. No slip or debonding was observed what has proved the achievement of full action between CFRP strips, adhesive and surrounding concrete. Laboratory tests confirmed that mechanical anchors at the ends of the pre-tensioned strips were not necessary. Flexural strengthening of reinforced concrete slabs with CFRP strips using pre-tensioned NSM technique is very effective in the ultimate limit state and serviceability limit state. By inducing pre-stressing in the CFRP strips, the NSM technique significantly enhanced the performance of the slabs by affecting the overall performance by decreasing deflections and crack widths and increasing the cracking, yielding and the ultimate bending moment.

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