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Influence of the percentage of reinforcement by unstressed rebar on the deformability of pre-stressed RC beams

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Abstract
This article presents the materials of deformability studies of pre-stressed steel-concrete beams reinforced with a package of reinforcement with different ratio of tape and rebar in the pure bending moment zone. The aim of the research was determination of the reinforcement percentage influence, for pre-stressed reinforced concrete beams reinforced with a package of reinforcement on their deformability. Also, the aim was to evaluate the effectiveness of using pre-stressed rebar in combined reinforcement. The practical significance of the experimental research is to study the deformability in pre-stressed bending elements with external tape and rebar reinforcement, taking into account the influence of different ratios of reinforcement areas within the combined reinforcement and development of proposals for such structures` calculation and design. The scientific novelty of the research is in obtaining the deformability characteristics of reinforced concrete beams reinforced with a package of reinforcement (tape and steel bars with periodic profile) with different ratios in the case of static loads` action.

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1. Introduction

Reinforced concrete unstressed and prestressed constructions are widely used in construction and studied by scientists (Azizov et al., 2019; Karpiuk et al., 2019; Kovalchuk et al., 2021). Research is also performed using mathematical models and approximate engineering calculations (Blikharskyy et al., 2021; Kotes et al., 2020; Kos et al, 2019; Pavlikov et al., 2019).

Tape reinforcement in reinforced concrete structures was originally used as sheet insulation or formwork. Steel sheet was not taken into account in the calculations. As insulation, tape reinforcement was used in the construction of an underground overpass under the Cologne Canal in Germany, in reinforced concrete panels in France, England, the United States, metro construction in Austria, the Czech Republic, and Hungary. Similar type of construction was used in the construction of underground structures in the United States, Canada, France, and Japan.

For today, great amount of works are dedicated to analysis of influence of reinforcement corrosion on RC structures (Kotes et al., 2018,). Therefore the number of articles is dedicated to usage of modern materials in order to ensure reliable RC structures` exploitation (Khmil et al, 2021a). Due to the depletion of their resources, many structures need to be restored and strengthened (Lipinski, 2017; Nikolic et al., 2020; Turba and Solodkyy; 2021). According to modern technologies, a lot of RC structures are strengthened with the use of various composite materials (Vatulia et al., 2019; Vavrus and Kotes, 2019), reinforced concrete jacketing (Khmil et al., 2021b), external steel sheets, etc. It is necessary to develop structures, which would be reliably used for a long time. Therefore, the development of new constructions is an urgent issue.

The design of modern buildings nowadays has the tendency towards the possibility of free planning or, if necessary, the open free space creation inside the building (Kramarchuk et al., 2019; Ulewicz and Ulewicz, 2020). Therefore, constant improvement of design solutions is required. Nowadays concrete and steel remain the most optimal and widely used materials (Blikharskyy et el., 2020; Dziuba et al., 2018; Lipisnki and Ulewicz, 2021). In order to save the consumption of steel in reinforced concrete structures nowadays are increasingly used pre-stressed reinforced concrete structures, as well as in some cases steel-concrete structures (Vatulia et al, 2018). One of the disadvantages of such structures is the prestress loss of compressive forces after formwork dismantling. In order to reduce such losses and maximize the level of the initial stresses sometimes altogether with pre-stressed steel bars unstressed rebar are arranged, which partially perceive pre-stressing forces. This combination of reinforcement is called the package of reinforcement.

Concentrated location of the tape reinforcement on the outer face of the section increases its moment of inertia and the shoulder of the inner pair of forces, if comparing with conventional reinforced concrete with the same rebar percentage. Therefore, the load-bearing capacity and rigidity of structures are increased, which enables to decrease steel consumption at the same section height compared to similar reinforced concrete structures. However, such placement of external reinforcement has the disadvantage of low corrosion resistance in the case of improper and untimely care of such structures.

The use of a package of reinforcement, which contains pre-stressed external tape reinforcement and unstressed steel bars allows to reduce the percentage of reinforcement of reinforced concrete structures, simultaneously ensuring their strength and deformability.

2. Research methodology

For implementation of the study tasks and objectives, three reinforced concrete beams with combined reinforcement of different ratio of unstressed rebar were developed and constructed, namely (Bobalo et al., 2021):

- Beam B-1 – total reinforcement ratio 2.97%, including the unstressed rebar- 0.65%;
- Beam B-2 - total reinforcement ratio 3.51%, including the unstressed rebar- 1.16%;
- Beam B-3 - total reinforcement ratio 4.02%, including the unstressed rebar- 1.75%;

Following goals could be identified:

- check of regularities and revealing of deformation specifics of bended reinforced concrete structures;
- verification of stress - strain states` principles for bended structures;
- comparison of theoretical and obtained data I order to assess the behavior of bended structures, predicting the possible behavior of elements with similar reinforcement and identifying specifics of their work.

Experimental investigation was conducted on experimental models - samples of beams with cross-sectional dimensions of 270×135 mm and span 2700 mm. The total length of the samples is 3000 mm. The dimensions are taken in order to provide the reinforcement percentage within 2.9÷4.02%. Tape reinforcement used had the periodic profile with a cross section of 105×6 mm, with tensile strength of 450MPa.

The concrete from which the test specimens were made was used within classes C40/50-C45/55. This class of concrete is selected based on the results of the preliminary calculation, provided that the bearing capacity of the samples is determined by the yield stress of the stretched reinforcement without destroying of the compressed zone concrete.

In all experimental beams was used tape reinforcement made of 16G2AF steel of periodic profile with cross reefs, recommended by UkrNDIM, main parameters of which were developed at Lviv Polytechnic National University.

The A400C class rebar were strengthened by hooding on the power stand. Reinforcement was stretched out mechanically by means of hydraulic jacks with stress control by means of dynamometers and a manometer. Steel bars of class A400C of the stretched zone was strengthened until the strength limit of tape reinforcement fyd = 450 MPa was reached. Rebar of the compressed zone was strengthened until the maximum limit defined by normative documents was reached: fyd = 540 MPa (DBN V.2.6-98, 2011).

The study of pre-stressing of reinforced concrete beams with a package of reinforcement was performed in two stages:

- compression by prestressing force with holding during 7-90 days under the action of this force;
- short-term bending test.

Physic-mechanical characteristics of tape steel (yield strength, tensile strength and modulus of elasticity) were determined by testing of specially made samples, according to regulations, on a rupture machine of R-20 mark with simultaneous recording of tensile force - deformation diagram.

Physic-mechanical characteristics of concrete (strength, modulus of elasticity, concrete class) were determined by testing of cubes with 100 mm edge and a prism with 400 mm length and 100×100 mm cross section, respectively, on a hydraulic press with a capacity of 250 tons.

For realization of tasks and objectives of the study three beams were developed and manufactured, the characteristics of the materials of the prototypes are given in Table 1.

The presence of pre-stressed reinforcement in the upper zone of the beams is provided for perception of tensile forces of reverse bending, as well as crack resistance of this zone when transmitting forces from pre-stretching of tape reinforcement. It should be noted, that transfer of pre-tensioning force to concrete was performed 28 days after concreting.

For experimental beams was used the tape reinforcement of constant cross-section along the entire length of the beams, whereas steel bars of different diameters were not laid on the entire length of the beams. Steel bars in all beams was unstressed with the length of 1850, 2050, 2150 mm for beams B-1, B-2, B3, respectively. Steel bars were freely placed on the top of the tape pre-stressed reinforcement. In order to reduce the material consumption steel bars were spaced along the length of the beam in different directions from the symmetry axis by: 150 mm (beam B-1) and 125 mm (beams B-2, B-3). Anchoring of tape reinforcement is provided by its adhesion to concrete and use of transverse anchor steel bars.

In each of the beams in the upper compressed zone, one longitudinal bar of Ø16 A400C class was designed. Transverse reinforcement was taken of Ø8A400C class and placed along the length of the beam in the form of collars with the spacing indicated below. In the zone of pure bending in all beams the collar spacing was taking according to structural assumptions equal to 180 mm. In the zone of transverse forces` action, depending on the bearing capacity of the beam, the spacing of collars was- 135 mm (B-1), 110 mm (beam B-2), 80 mm (beam B-3). Three pairs of transverse rods with 50 mm spacing were placed on the supports in all beams. Schemes of frameworks of experimental samples are given on Fig. 1.

Table 1. Characteristics of test samples of materials

Beam marking	B-1	B-2	B-3
Parameters of cross secton: Width b, mm	135		
Parameters of cross secton: Height h, mm	270		
Parameters of cross secton: Area A, cm^2	364.5		
Parameters of cross secton: Concrete class (design)	C40/50		C45/55
Heavy-weight concrete			
$f_{ck, prism}$, MPa	36.97	39.14	40.65
E_{cd}×10^3, MPa	38.94	39.25	39.07
Reinforcement of stretched zone-tape (longitudinal)			
B_s×t_s, mm	105×6		
f_{yk}, MPa	450		
E_s×10^5, MPa	2.1		
Class	16G2AF		
b_s×t_s, cm	10.5×0.6		
A_s, cm^2	6.3		
ρ, of tape, %	1.77		
Reinforcement of stretched zone- rebar (longitudinal)			
∅', mm	2 ∅12	2 ∅16	3 ∅16
f_{yk}', MPa	450		
E_s×10^5, MPa	2.0		
Class	A400C		
∅, mm	2 ∅12	2 ∅16	3 ∅16
A_s, cm^2	2.26	4.02	6.03
ρ, of rebar, %	0.65	1.16	1.75
$\sum\rho$, %	2.45	2.99	3.57
Reinforcement of compressed zone- rebar (longitudinal)			
∅, mm	1 ∅16		
f_{yk}, MPa	540		
E_s×10^5, MPa	2.1		
Class	A400C		
∅, mm	1 ∅16		
A_s, cm^2	2.011		
Total ratio of rebar reinforcement			
ρ, total %	2.97	3.51	4.02
Transversal steel bars			
∅, mm	8		
f_{ywd}, MPa	355		
E_{sw}×10^5, MPa	2.0		
Class	A400C		
∅, mm	1 ∅8		
A_{sw}, cm^2	0.503		
Spacing , mm	180 (50)		

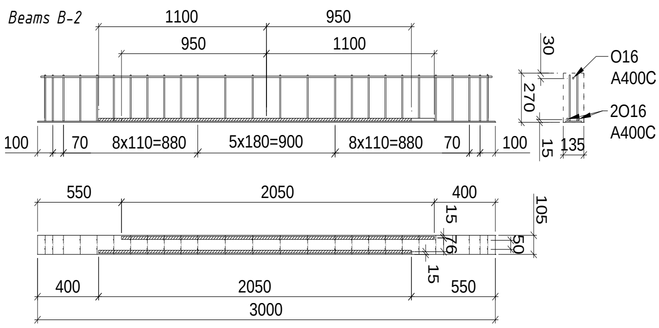

Fig. 1. The construction of investigation beams

3. Main assumptions and results

The design values of deflections were calculated as for statically determined elements with constant cross section, which work according to the beam scheme. Namely, actual design values were calculated by the formula:

$$f = \frac{1}{r} k_m l^2 \tag{1}$$

The experimental values of deflections were determined from the indicators` readings, as well as according to the curvature. The experimental curvature was determined by the average concrete deformations of the upper face of the beam ε_b and tape reinforcement ε_s, which were measured by strain gauges.

$$\frac{1}{r} = \frac{\varepsilon_s + \varepsilon_b}{d}, \tag{2}$$

Also, on the basis of indicators` readings in the assumption that the axis of a beam within the pure bending zone is close to a circle:

$$\frac{1}{r} = \frac{1}{\frac{l^2}{8\Delta w} + \frac{\Delta w}{2}} \tag{3}$$

where: Δw – difference in indicators` readings under the load application point and in the middle of the beam.

According to the recommendations of (DBN V.2.6-98, 2011) the design values of deflections are determined at the initial stages of loading as for a continuous elastic-plastic body. When the stage of crack formation is exceeded these values should be determined as for elements with cracks in the stretched zone taking into account negative values of bending due to transverse compressive forces.

Shear and bend deformations were taken into account when calculating deflections according to the norms. The deflection caused by the bending moment was calculated with use of equation:

$$w_M = \sum_{i=1}^{l} M_{xl} (1/r)_{xp} \Delta l \tag{4}$$

where: M_{xl} – bending moment in the section x from the unit load action, $(1/r)_{xp}$ – curvature of the element in the section x from the applied load. Similarly, the deflection from shear deformation:

$$w_Q = \sum_{i=1}^{l} Q_{xl} \gamma_{xp} \Delta l \tag{5}$$

where: Q_{xl} – transverse force in the section x from the unit load, γ_{xp} - shear deformation in the section x from the applied load.

Deflections of experimental beams are presented as graphs on Fig. 2-4. The graphs show that at loads, which do not reach the moment of crack formation, the deflections increase proportionally to the load. The regions of the graphs that correspond to this stage of the samples` deformation are almost rectilinear.

In the stretched zone after the formation of cracks with load increasing, the increments of deflections begin to exceed the increments of the load, which is expressed by the curvature of the graphs towards the deflection accretion. At the last stage of beams` work as could be seen from Fig. 2, the increments of deflections are much larger than the increments of the load.

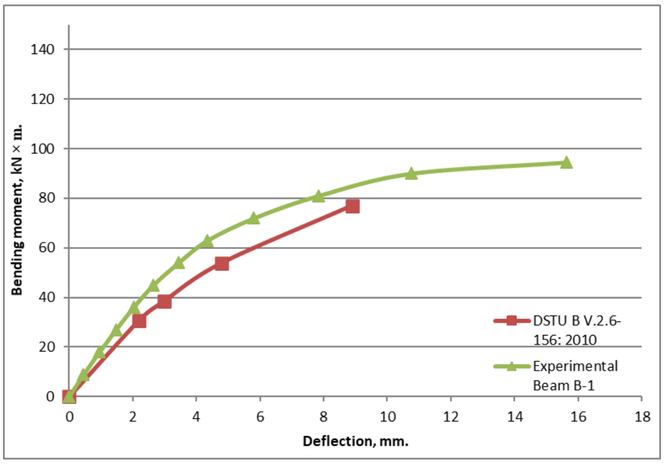

Fig. 2. Deflection of beam B-1

As could be seen from Fig. 2, 3, 4, the reaching of yield stress by the tape reinforcement is accompanied by a further increase in the deflection. The higher the percentage of tape reinforcement, the sharper the increase in deflections can be observed after the yield point. This tendency could be explained by the difference between the loads, which are perceived by the tape and rebar reinforcement.

The limit value of deflection is assumed to be equal to 1/250 of the span of the beam, according to (DBN V.2.6-98, 2011), which namely was equal to 9.6 mm.

As could be seen from the graphs the usage of unstressed steel bars helps to reduce the deflections of the tested beams by 1.1 ÷1.3 times (Table 2). In the beam B-1, where steel bars of 2∅12 A400C are used, as well as in the beams B-2 (2∅16 A400C), B-3 (3∅16 A400C) could be identified the gradual decrease in deflections.

With further loading of the test beams (more than 0.7 Mdr2), the accretion in deflections increased significantly, this region of the test specimens` performance corresponds to the "fluidity of the reinforcement".

According to the results of experimental investigation, it could be concluded that with increase of unstressed steel bars` percentage in combination with constant percentage of prestressed tape reinforcement no change in the deflections was identified. Further increase in the diameter and number of rebar in the beam has small effect and almost has no influence on the reduction of deflections. Increase of the percentage of unstressed rebar ratio reduces the initial strain decrease and the loss of compressive forces.

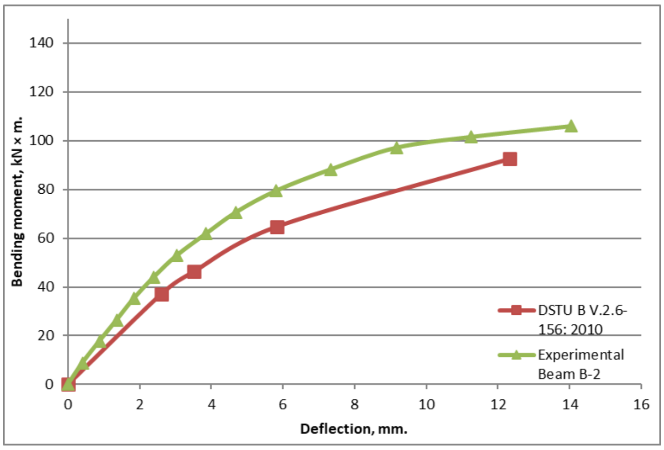

Fig. 3. Deflection of beam B-2

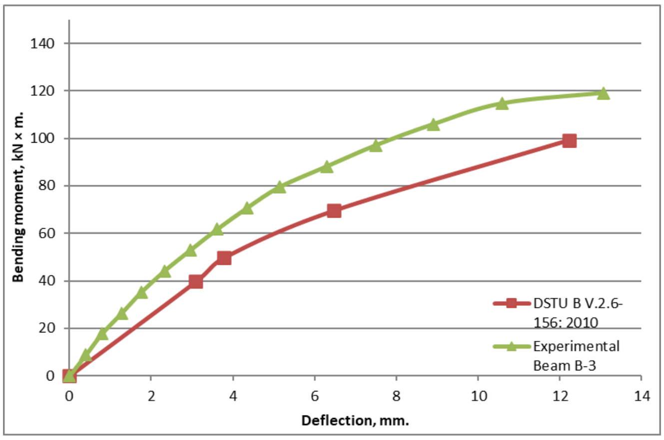

Fig. 4. Deflection of beam B-3

Numerical experimental and theoretical values of deflections are given in Table 2.

Table 2. Numerical experimental and theoretical values of deflections

Beam marking	$\rho_{rebar}/\rho_{total}$ %	Experimental f^d_1, mm	DSTU B V.2.6-156: 2010 f^{DBN}_1 mm	%	Experimental f^d_2, mm	DSTU B V.2.6-156: 2010 f^{DBN}_2 mm	%
		0.4 M_{dr1}			0.7 M_{dr2}		
B-1	26.9	2.15	2.38	9.7	4.31	4.8	10.2
B-2	39.6	2.29	2.60	11.9	5.14	5.84	11.9
B-3	49.7	2.58	3.1	16.8	5.66	6.46	12.4

The use of equations 4.3; 4.4 of the valid (DBN V.2.6-98, 2011), which allow to set the initial deformation of the reinforcement, enables estimation with sufficient accuracy of prestressed reinforced concrete beams` deflections, reinforced with a package of reinforcement. The difference between experimental and theoretical values of deflections calculated according to this normative document was within 9.7-16.8%.

4. Conclusions

Reinforcement of concrete beams with the package of reinforcement with an increase of unstressed steel bars ratio in combination with constant pre-stressed tape reinforcement ratio does not change the samples` deflections. Increase of the diameter and number of unstressed steel bars in the beam has small effect and does not affect the reduction of deflections. Increase of the unstressed rebar ratio in reinforced concrete beams reinforced with a package of reinforcement reduces only the decrease in initial deformations and loss of compressive forces.

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无应力钢筋配筋率对预应力钢筋混凝土梁变形能力的影响

關鍵詞
预应力
加强
钢筋混凝土梁
实际尺寸样品
实验结果

摘要

本文介绍了在纯弯矩区用不同带筋比的钢筋包加固的预应力钢-混凝土梁的变形性研究材料。研究的目的是确定钢筋百分比影响，对于用钢筋包加固的预应力钢筋混凝土梁对其变形能力的影响。此外，目的是评估在组合钢筋中使用预应力钢筋的有效性。实验研究的实际意义是研究外带钢筋和钢筋预应力弯曲构件的变形能力，同时考虑组合钢筋内不同配筋面积比例的影响，并制定此类结构的建议。计算和设计。该研究的科学新颖之处在于获得了在静载荷作用情况下用不同比例的钢筋（具有周期性剖面的胶带和钢筋）加固的钢筋混凝土梁的变形特性。