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EFFECTIVENESS OF STRENGTHENING OF REINFORCED CONCRETE BEAMS WITH THE USE OF COMPOSITE MATERIALS

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Wide spread of RC structures in construction projects indicates the necessity of their service life prolongation. Perspective possibility to increase strength of RC structures is use of external composite tapes. The article presents theoretical research on the effectiveness of strengthening of RC bended elements with the use of composite tapes. Work also includes comparative analysis on the basis of calculations, according to normative regulations. With the use of developed algorithm parameters of stress-strain state and deformability of RC beams, strengthened with composite tapes were obtained. Study identified, that the most critical parameter was the steel bars` strain and yield point. Interesting finding of the study is the no-linearity of the strength growth of the studied elements with the increase of additional reinforcement amount. Consistent literature review was conducted, which identified the necessity to take into account different external factors and failure mode.

Keywords: RC beams, stress-strain state, CFRP reinforcement, theoretical calculation, strengthening, effectiveness

Introduction

Reinforced concrete structures during the past decades have reached the increasingly wide application in numerous engineering projects. However, there are the number of reasons, which cause challenges for their exploitation: environmentally induced degradation, not sufficient design strength, lack of maintenance, accidental events, poor level of construction, etc. (DebMallik P., 2004; Blikharskyy et al., 2021(a, b, c)). All the listed above factors lead to deterioration of existing RC structures and buildings and enormous economic and technical consequences. As the RC structures are the most common, prolongation of their service life has become the issue of specific importance recent times. Panchacharam and Belarbi in their study have noted, that replacement of an existing structure, as it could be inappropriate, cost-consuming and in some cases even impossible (Panchacharam and Belarbi, 2002).

In engineering practice, strengthening of RC structures could be performed in the various ways: epoxy bonded steel plates, additional rebar, concrete cages etc. (DebMallik P., 2004). However, as the most of conventional strengthening methods may be problematic, the innovative methods with the use of composite strengthening materials were developed.

External strengthening with the use of various composite bands and liners, based on carbon, aramid and fiberglass have found their wide application in construction practice and is effectively used during almost 40 years (Borysiuk et al., 2019, Kramarchuk et al., 2020). Although the technology of strengthening by gluing of external reinforcement to the surface of critical zones has the long application history, there are still the number of specific factors, which need to be considered for each particular situation (Kvasha, 2008).

Borysiuk et al highlights the lack of accurate calculation methods which could be adapted to the codes of practice and would consider all possible loading effects. Therefore, it is really necessary to provide further research on operation of bending reinforced concrete elements, strengthened with composite materials, taking into account structures operation history before strengthening, which would help to develop such calculation algorithm (Borysiuk et al., 2019).

According to Zhu et al. (Zhu et al., 2020), one of the most perspective and promising techniques for strengthening of reinforced concrete structures is external bonding of additional FRP reinforcement. Reasons to use composite materials include high immunity to corrosion, high strength/weight ratio, comparatively easy application, reduction in labor costs and time. In addition, such materials are characterized with increased tensile strength, consistent stiffness, large deformation capacity and wide range of available forms, dimension and sizes (DebMallik P., 2004). However, the effectiveness of such strengthening mechanisms is strongly dependent on specifics of their stress-strain state and load distribution. Thus, the effective load transfer at the interface between the FRP and the concrete should be controlled, as well as various failure models should be taken into consideration (Zhu et al., 2020). Retrofitting of concrete structures with externally bonded FRP laminates are the reason of formation of specific failure modes, including the following: debonding in the concrete surface layer, at the FRP concrete interface or within the adhesive layer, as well as fracture of the additional reinforcement (Smith and Teng 2002; Teng et al., 2003). As was noted in the number of studies, FRP-strengthening ensures significant increase in post-cracking stiffness, as well as in strength of structural elements, subjected to flexure and shear (Panchacharam and Belarbi, 2002).

Experimental research on externally retrofitted beams has shown that the most common failure mode was interfacial crack induced debonding failure. Thus, sustainable anchoring of CFRP tapes is highly important (Gideon and Alagusundaramoorthy, 2018).

Composite materials for strengthening are mainly used in the form of uni-directional thin tapes with thickness below 1 mm and flexible fabrics, with fibers of different directions (with thickness of fibers between 0.13 and 0.36 mm) (DebMallik P., 2004).

The number of studies were dedicated to development of theoretical basis for calculation methodology. For instance, in the work of Borysiuk et al. (2008) are proposed general assumptions for evaluation of the normal section strength, rigidity and crack resistance of RC beams strengthened by CFRP composite materials. Interesting results were obtained by Panchacharam and Belarbi, who on the basis of theoretical and experimental investigations confirmed, that external bonding of GFRP sheets can significantly increase both the cracking and the ultimate torsional capacity. Authors also noted rather good agreement between theoretical and experimental results (Panchacharam and Belarbi, 2002).

Effect of strengthening strongly depends on the fiber orientation and direction, as well as cross-sectional area of composite reinforcement (Panchacharam and Belarbi, 2002). In addition, spacing of CFRP-tapes could also have certain effect on strengthening efficiency (Abdul Halim et al., 2020).

Article of Abdul Halim et al is also interesting, because the quasi-static loading case was investigated according to energy dissipation criteria (Abdul Halim et al., 2020). According to another experimental investigation increase in spacing of CFRP stirrups reduces strengthening effect. Authors also noted improvement in deflection characteristics of CFRP-wrapped samples, compared to conventional RCC beams (Rahul Raja et al., 2018).

Maazoun et al analyzed the great number of scientific publications, which generally indicated the benefits of FRP under blast loading. Authors admitted increase in strength and reduction in damage levels (Maazoun et al., 2017).

The positive effect of FRP-composite reinforcement on cyclic response of reinforced concrete structure was noted in the number of recent investigations (Saljoughian and Mostofinejad, 2020; Xu and Huang, 2020; Petkune et al., 2018). Within the recent studies, additional attention is required to the article of Karpiuk et al, who established the effect of various parameters of the load-bearing capacity of beams, strengthened with composite materials. Qualitive and quantitive deformation picture, as well as tendency of crack formation and failure process was presented. Corresponding reliable experimental-statistical dependences were presented and approved (Karpiuk et al., 2020).

Limited research was conducted on the issue of prestressed additional reinforcement and its efficiency for RC beams. Although, Atutis et al have noticed reductions of deflections and opening of normal cracks, the information on the bearing capacity of oblique beam sections is still insufficient (Atutis et al., 2018).

Rather interesting proposition was presented in article of Li et al for usage of sea sand as alternative material for designing beams with external composite reinforcement (Li et al., 2018).

However, it is necessary to admit, that the use of composites includes certain challenges. In technical report fib TG 9.3, the following specific is noted: linear elastic behavior up to failure, whereas no yielding or plastic deformation could be seen. Therefore, the structures tend to less ductile behavior, which should be taken into account at the design stage. Additional disadvantage is rather high cost of the material, which is on the other hand is not so obvious, when comparison is made on cost/strength ratio basis. Engineer should also take into account such factors as incompatible thermal expansion coefficients of some FRP materials with concrete, low resistance to high temperatures. Therefore, the design of such structures should be performed with consideration of various additional parameters and ensure consistent load-bearing capacity and reliability.

Target of this article

The aims of this work include theoretical research on the effectiveness of strengthening of reinforced concrete bended elements with the use of composite materials. The article includes comparative analysis on the basis of theoretical calculations, according to valid normative regulations.

Materials and Methods

This section includes the methodology of theoretical calculation of reinforced concrete bent elements strengthened with composite materials. Calculation of stress-strain state parameters stresses of reinforced concrete section subjected to action of bending moments according are conducted according to recommendations of Sika ZNT–219–2167.13-001. According to the main concepts of regulatory documents on the design of concrete and reinforced concrete structures DBN V.2.6-98:2009, two equilibrium forms of reinforced concrete section and corresponding equations could be formulated.

For the first form of equilibrium (in the case of compressed section, see Fig. 1, *b*):

$$\frac{b\cdot f_{cd}}{\bar{\aleph}}\cdot\sum_{k=1}^{5}\frac{\alpha_k}{k+1}\cdot\left(\frac{\varepsilon_{c(1)}^{k+1}-\varepsilon_{c(2)}^{k+1}}{\varepsilon_{c1}^{k+1}}\right)+\sum_{i=1}^{n}\sigma_{si}A_{si}+\sum_{i=1}^{n}\sigma_{fi}A_{fi}=0. \tag{1}$$

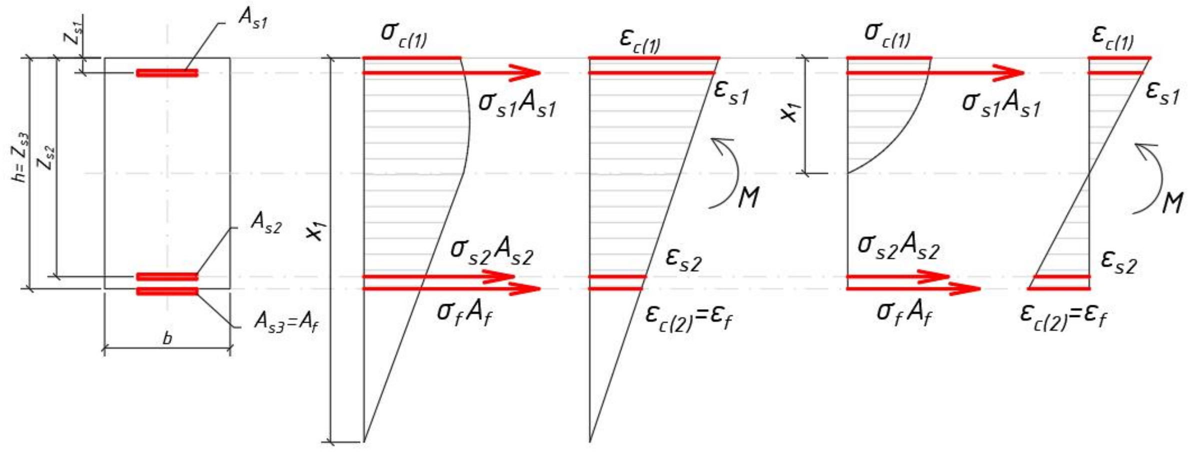
$$\frac{b\cdot f_{cd}}{\bar{\aleph}^2}\cdot\sum_{k=1}^{5}\frac{\alpha_k}{k+2}\cdot\left(\frac{\varepsilon_{c(1)}^{k+2}-\varepsilon_{c(2)}^{k+2}}{\varepsilon_{c1}^{k+2}}\right)+\sum_{i=1}^{n}\sigma_{si}A_{si}\cdot(x_1-z_{si})+\sum_{i=1}^{n}\sigma_{fi}A_{fi}\cdot(x_1-z_{fi})=M\ . \tag{2}$$

For the second form of equilibrium (in the case of compressed section, see Fig. 1, c):

$$\frac{b\cdot f_{cd}}{\bar{\aleph}}\cdot\sum_{k=1}^{5}\frac{\alpha_k}{k+1}\gamma^{k+1}+\sum_{i=1}^{n}\sigma_{si}A_{si}+\sum_{i=1}^{n}\sigma_{fi}A_{fi}=0. \tag{3}$$

$$\frac{b\cdot f_{cd}}{\bar{\aleph}^2}\cdot\sum_{k=1}^{5}\frac{\alpha_k}{k+2}\gamma^{k+2}+\sum_{i=1}^{n}\sigma_{si}A_{si}\cdot(x_1-z_{si})+\sum_{i=1}^{n}\sigma_{fi}A_{fi}\cdot(x_1-z_{fi})=M, \tag{4}$$

where b – the width of the section; $\varepsilon_{c(1)}$ – the deformations of the compressed fiber of concrete; $\varepsilon_{c(2)}$ – the average deformations of the stretched concrete fiber; $\aleph$ – the value of the curvature of the bent axis; $\bar{\aleph}=\aleph/\varepsilon_{c1}$ – the relative curvature of the bent axis; $\gamma=\varepsilon_{c(1)}/\varepsilon_{c1}$ – the ratio of deformations; $x_1=\varepsilon_{c(1)}/\aleph$ – the height of the compressed zone; z_{si} – the distance from the *i*-th layer of reinforcement to the most compressed face of the cross-section; z_{fi} – the distance from the *i*-th layer of composite reinforcement to the most compressed face of the cross-section; *M* – the value of the bending moment in the cross-section; σ_{si} – the stress in the *i*-th layer of reinforcement; σ_{fi} – the stress in the i-th layer of composite reinforcement; A_{si}, A_{fi} – the cross-sectional area of *i*-th layer of steel and composite reinforcement; respectively.



a *b* *c* *d* *e*

Fig. 1. Scheme of stresses and deformations in reinforced concrete section:
a – cross section of RC element; b – stress diagram in the case of the 1st form of equilibrium; c – diagram of deformations in the case of the 1st form of equilibrium; d – stress diagram for the 2nd form of equilibrium; e – diagram of deformations for the 2nd form of equilibrium

The stress in an arbitrary layer of reinforcement of ordinary and composite unstressed and prestressed reinforcement can be determined by the formulas:

$$\sigma_s = \varepsilon_s \cdot E_s, \tag{5}$$

$$\sigma_f = \varepsilon_f \cdot E_f, \tag{6}$$

where E_s, E_f are the values of the modulus of elasticity of steel and composite reinforcement, respectively, and deformations can determined with the use of formulas:

$$\varepsilon_{si} = \aleph \cdot (x_1 - z_{si}) + \varepsilon_{si,0}, \tag{7}$$

$$\varepsilon_{fi} = \aleph \cdot (x_1 - z_{fi}) + \varepsilon_{fi,0}, \tag{8}$$

where $\varepsilon_{si,0}, \varepsilon_{fi,0}$ are the values of the initial (before the application of external forces) deformations in the i-th layer of steel and composite reinforcement, respectively.

Formulas (1)–(2) and (3)–(4) are systems of equations with two unknowns solved in iterative way, with the use of gradual approximations method and control of the exhaustion criteria of the bearing capacity at each stage. At the same time, the deformation approach is used to calculate the bearing capacity, in accordance with the recommendations of valid normative regulations DBN V.2.6-98:2009. The block diagram of the calculation algorithm is shown in Fig. 2.

Following initial characteristics of materials could be accepted:

1. On the first stage deformations of the concrete are assumed equal to $\varepsilon_{c(1)} = \Delta\varepsilon_{c(1)}^{(0)} = 0{,}1\varepsilon_{cu1}$ $\varepsilon_{c(2)}^{(0)} = 0$.
2. After that values of $\aleph$, $\bar{\aleph}$, γ, x_1, σ_{si} could be calculated with the use of formulas:

$$\aleph = \frac{1}{\rho} = \frac{\varepsilon_{c(1)} - \varepsilon_{c(2)}}{h}, \tag{9}$$

$$\bar{\aleph} = \frac{\aleph}{\varepsilon_{c1}}, \tag{10}$$

$$\gamma = \frac{\varepsilon_{c(1)}}{\varepsilon_{c1}}, \tag{11}$$

$$x_1 = \frac{\varepsilon_{c(1)}}{\aleph}, \tag{12}$$

$$\sigma_{si} = \varepsilon_{si} \cdot E_{si} = E_{si} \cdot \aleph(x_1 - Z_{si}). \tag{13}$$

3. For the second form of equilibrium, we determine the force *N* can be calculated, taking the coefficients α_k, according to Appendix D of DBN V.2.6-98:2009, with the use of equation:

$$\frac{b \cdot f_{cd}}{\aleph} \cdot \sum_{k=1}^{5} \frac{\alpha_k}{k+1} \gamma^{k+1} + \sum_{i=1}^{n} \sigma_{si} A_{si} - N = 0. \tag{14}$$

Since for the case of bending *N=0*, the further calculation is performed in the iterative way with gradual increasing of the stretched face deformations. First $\varepsilon_{c(2)}^{(0)} = 0.01\varepsilon_{cu1}$ is accepted, after that the steps 2 and 3 are repeated. We perform this cycle of the algorithm until *N≈0* is reached with the accuracy, which is appropriate for the engineering purposes.

4. After the determined deformations are substituted into equation (4), an expression is obtained for determining the bending moment corresponding to the first point on the state diagram for the reinforced concrete section:

$$M = \frac{b \cdot f_{cd}}{\aleph^2} \cdot \sum_{k=1}^{5} \frac{\alpha_k}{k+2} \left(\frac{\varepsilon_{c(1)}^{k+2} - \varepsilon_{c(2)}^{k+2}}{\varepsilon_{c1}^{k+2}} \right) + \sum_{i=1}^{n} \sigma_{si} A_{si} \cdot (x_1 - z_{si}). \tag{15}$$

5. The following points of the state diagram are obtained by repeating the steps 2–4 of the algorithm and increasing the deformations of the compressed concrete fiber:

$$\varepsilon_{c(1)}^{(2)} = \varepsilon_{c(1)}^{(1)} + \Delta\varepsilon_{c(1)}. \tag{16}$$

The deformations of the stretched concrete $\varepsilon_{c(2)}^{(2)}$ are assumed equal to those, defined at step 3. The calculations are repeated until the level *N≈0* is reached with the required accuracy.

During the calculation, the stress level in all layers of the reinforcement should not exceed the value:

$$\sigma_{si} \le f_{yk}. \tag{17}$$

Results and discussion

With the use of described above algorithm parameters of the stress-strain state and deformability of reinforced concrete beams, strengthened with composite tapes were obtained. For theoretical research following initial parameters of the samples were accepted:

The effective span of the beam was *l*=1.9 m; the cross-section sizes were *h*×*b*=200×100 mm Distances from the compressed and stretched steel bars to the most compressed face of the cross-section are equal to $z_{s1} = 30$ mm, $z_{s2} = 170$ mm, respectively. Distance from the composite reinforcement to the most compressed face $z_f = 200$ mm. (Fig. 1, *a*).

During the research were considered the beams, manufactured from concrete of class C25/30 with parameters according to DBN V.2.6-98:2009:

$f_{ck} = 22$ MPa, $\varepsilon_{c1,ck} = 0.00176$, $\varepsilon_{cu1,ck} = 0.00355$, $E_{cm} = 32.5$ GPa.

Coefficients of polynoms are taken according to recommendations of normative regulations of DBN V.2.6-98:2009.

Beam is reinforced with 1Ø20 A500S steel bar in the stretched zone and 2Ø8 A500S steel bars in the compressed zone. Parameters of reinforcement are the following: $f_{yk} = 500$ MPa, $\varepsilon_{ud} = 0.02, E_s = 210$ GPa, according to DSTU B V.2.6-156:2010.

Characteristics of carbon tapes Sika CarboDur S are accepted according to recommendations of Sika (ZNT–219–2167.13-001): $f_{fk} = 3000$ MPa, $\varepsilon_{fu} = 0.013$, $E_f = 160$ GPa.

Theoretical analysis was performed for three sample models:

- Beam-1-0– unstrengthened control sample with no additional composite reinforcement;
- Beam-2-25– sample, strengthened with composite tape of 1.2 mm thickness and 25 mm width;
- Beam-3-50– sample, strengthened with composite tape of 1.2 mm thickness and 50 mm width.

After iterative calculations results the following results were obtained for stress-strain state (see Table 1).

For more clear representation of results, diagrams, which describe stress-strain state of the samples are given on Figs. 2 and 3.

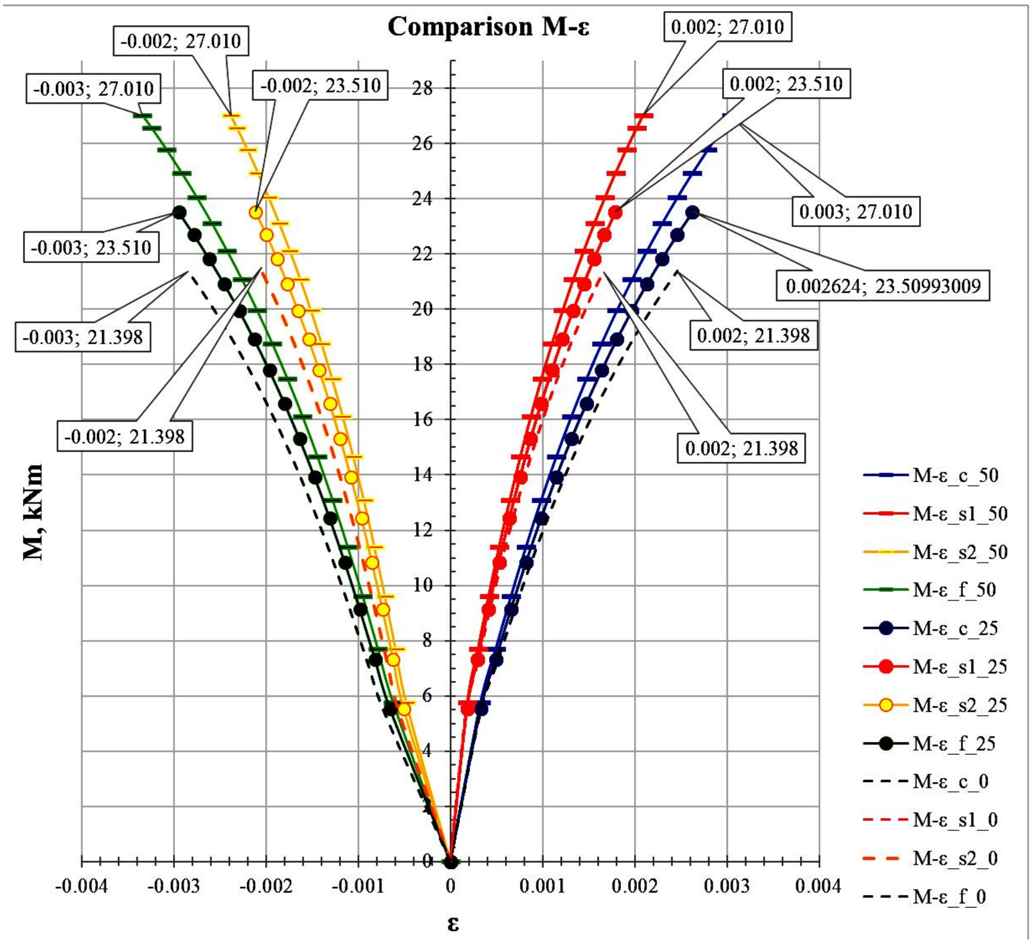


Fig. 2. M-ε diagrams for studied samples: M-ε_i_0 – for unstrengthened sample – Beam-1-0; M-ε_i_25 – for sample Beam-2-25, M-ε_i_50 – for sample Beam-3-50

Elements, subjected to bending has significant positive effect on their performance. Strengthening of RC beam with 25 mm width carbon tape increased its load-bearing capacity by 9.87 %, whereas the use of 50 mm width composite tape resulted in 26.23 % growth in value of maximum bending moment *M* (see Table 1).

Table 1

Parameters of stress-strain state of investigated samples

Sample	Beam-1-0	Beam-2-25	Beam-3-50
Maximum bending moment M_{max}, kNm	21.398	23.51	27.010
Maximum strain of the most compressed fiber of the concrete ε_c	0.002	0.0026	0.002
Maximum strain of the stretched steel bar ε_{s1}	0.002	0.003	0.002
Maximum strain of carbon tape ε_f	0.003	0.003	0.003
Strengthening effect, %	0	9.87	26.23

According to results of calculations it could be concluded, that strengthening of reinforced concrete Important specific of the limit state of all the samples, is that the most critical parameter was the strain of the stretched steel bars. Thus, it could be assumed, that the yield point of steel reinforcement determined the limit state of all the beams. Therefore, additional strengthening of the bearing capacity of the stretched zone of the beam would be appropriate.

It is important to note, that the increase of strength of the studied elements was non-linear. Therefore, it could be recommended to use higher cross-sectional area of additional composite reinforcement, due to obvious economical effect.

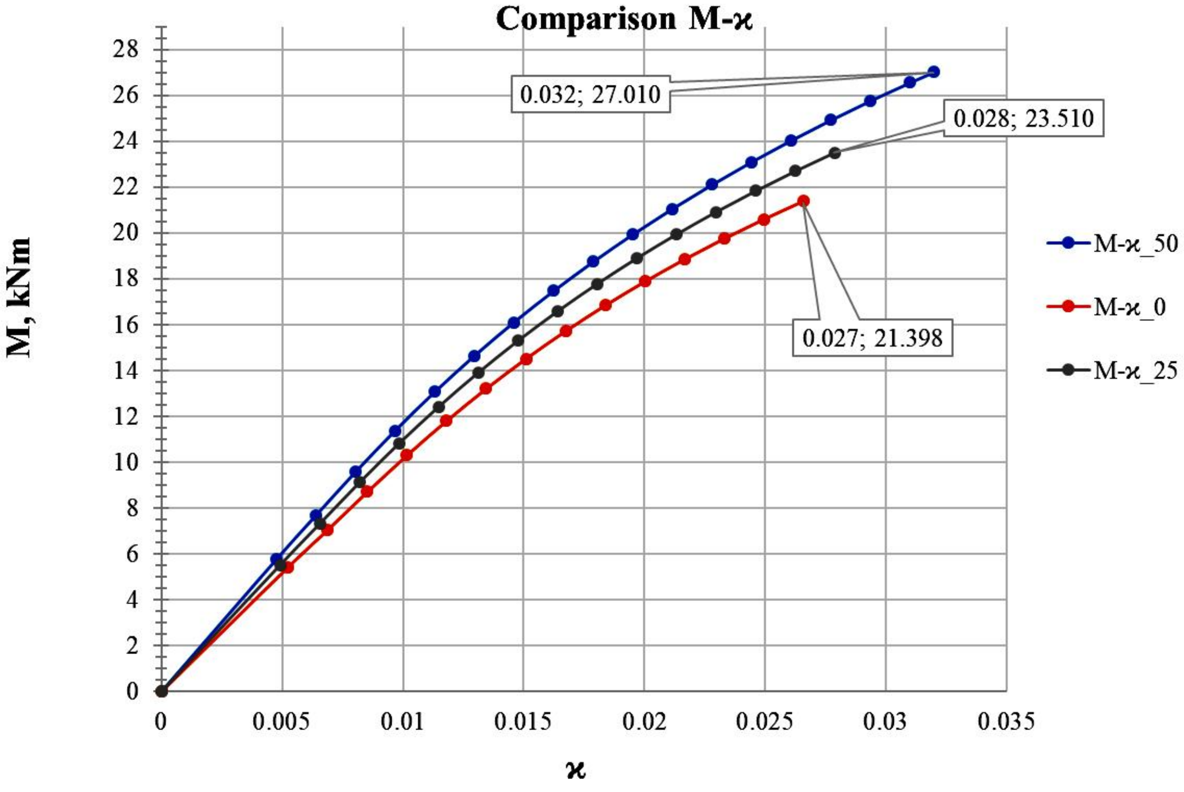


Fig. 3. M-χ diagrams for studied samples: M-χ _0 – for unstrengthened sample – Beam-1-0; M-χ _25 – for sample Beam-2-25, M-χ _50 – for sample Beam-3-50

Conclusions

The article presents the calculation algorithm, which enables to determine the qualitive and quantitive picture of performance of the RC beam with additional external tape reinforcement. According to calculations it could be concluded, that the use of composite reinforcement in the form of carbon tape is highly effective way for increasing of RC structures load-bearing capacity. Obvious non-linearity was observed as the specific feature of the work of the beam under applied loading. In addition, it was seen, that the highest performance of reinforced concrete elements could be obtained for higher cross-sectional area of additional composite reinforcement.

Thorough theoretical research and literature review have identified the necessity for implementation of specific strength models, which take into consideration individual loading and failure cases. The study of reinforced concrete structures with external composite reinforcement should include various experimental factors of load-bearing capacity individually and in interaction with each other.

Prospects for further research

The lack of experimental and theoretical studies, as well as recently increased interest to composite materials confirm the necessity of further investigation of this issue. Composites need to be considered in the context of their advantages and disadvantages, rather than just as blind replacement of steel. Their positive features should be evaluated against potential challenges of their implementation. Final decision on the design stage has to be made with consideration of wide range of external factors: stress-strain parameters, durability and technological constructability.

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ЕФЕКТИВНІСТЬ ПІДСИЛЕННЯ ЗАЛІЗОБЕТОННИХ БАЛОК З ВИКОРИСТАННЯМ КОМПОЗИТНИХ МАТЕРІАЛІВ

Широке поширення залізобетонних конструкцій у будівництві вказує на необхідність максимального продовження терміну їхньої служби. Серед найбільш поширених і перспективних можливостей підвищення несучої здатності залізобетонних конструкцій є використання зовнішньої композиційної арматури. У статті представлені теоретичні дослідження ефективності методів підсилення залізобетонних згинаних елементів з використанням композитних матеріалів. Ця робота також містить порівняльний аналіз на основі теоретичних розрахунків, розроблених згідно з положеннями чинних нормативних документів. З використанням розробленого алгоритму отримано параметри напружено-деформованого стану та деформативності залізобетонних балок, зміцнених композитними стрічками. Описана технологія підсилення залізобетонних елементів, що піддаються згину, суттєво позитивно впливає на їх експлуатаційні характеристики. Дослідження виявило, що найбільш критичним параметром була деформація розтягнутої сталевої арматури, а граничний стан усіх балок визначався межею текучості сталевої арматури. Цікавим висновком дослідження є нелінійність зростання міцності досліджуваних елементів при збільшенні кількості додаткового композитного армування. Крім того, було проведено ґрунтовні теоретичні дослідження та огляд літератури, які визначили необхідність урахування різних зовнішніх факторів на конструктивні характеристики та характер руйнування. Незважаючи на широке використання композитного армування в сучасній інженерній практиці і присвячені цьому питанню багаторічні дослідження науковців різних країн, наразі досі є низка погано висвітлених аспектів роботи таких конструкцій під навантаженням. Необхідність подальшого дослідження цього питання можна підтвердити недостатнім рівнем експериментальних і теоретичних досліджень, а також підвищеним останнім часом інтересом до композиційних матеріалів.

Ключові слова: залізобетонні балки, напружено-деформований стан, армування карбованими стрічками, теоретичний розрахунок, підсилення, ефективність.