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Methods of strengthening and repairing reinforced concrete beam and slab elements by increasing their cross-sections: a review and directions for further scientific research

Abstract. The article reviews scientific research on methods and ways of strengthening reinforced concrete beam and slab elements by increasing (building up) cross-sections. The main conclusions and directions for further scientific research into effective methods and ways for strengthening reinforced concrete beam and slab elements, carried out by increasing (building up) their cross-sections, which we have the opportunity to apply in the repair and reconstruction of prefabricated and monolithic reinforced concrete floors of buildings and structures, are substantiated. A classification of methods and methods of strengthening reinforced concrete beam elements by increasing their cross-sections is proposed.

Keywords: reinforced concrete beams and slabs, strengthening methods, cross-sections, bending and shearing, review, research directions

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Introduction.

At present, Ukraine faces an urgent need for the major repair, reconstruction, and restoration of buildings and structures incorporating reinforced concrete structural elements that have been damaged or destroyed as a result of emergency situations, military actions, and terrorist attacks.

One of the methods for strengthening existing reinforced concrete flexural structural elements, in accordance with the provisions of Clauses 6.3, 6.4.1, and 6.4.2 of the Ukrainian building standards DBN B V.3.1-2:2016 [1], is the enlargement of their cross-sections by means of additional reinforcing components.

The enlargement of cross-sections of reinforced concrete beam and slab elements may be carried out through: the installation of additional components fabricated from rolled structural and plate steel sections; the application of additional reinforced concrete or mortar layers, or fibre glass fabric sheets; or by employing a combined method incorporating components of different materials. Depending on the structural characteristics, conditions, and circumstances of the repair works, the strengthening of reinforced concrete element cross-sections may be performed using one of the following methods (see Fig. 1): exclusively along the upper face (compressed zone of the cross-section); exclusively along the lower face (tension zone of the cross-section); exclusively along the side faces of the cross-section; simultaneously along three faces of the cross-section, namely the lower face and two side faces; or simultaneously along the upper and lower faces of the cross-section (within the compressed and tension zones).

Therefore, when selecting a technique or method for strengthening a reinforced concrete flexural element, in accordance with the requirements of Clause 8.4.2 of DBN B V.3.1-2:2016 [1], it is necessary to take into account the following factors: the support conditions of beam or slab elements of floors and roofs; the possibility of increasing the overall structural depth of the element and the availability of space for the placement of strengthening components; the feasibility of carrying out the works without interrupting production processes or during scheduled technological breaks; and the technological capabilities associated with the fabrication and installation of strengthening elements.

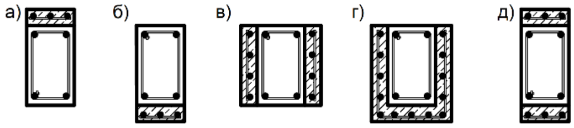

Figure 1 – Methods for strengthening the cross-section of a reinforced concrete beam element by enlarging its cross-section with an additional layer applied to one, two, or three faces thereof: (a) exclusively along the upper face (compressed zone of the cross-section); (b) exclusively along the lower face (tension zone of the cross-section); (c) exclusively along the side faces of the cross-section; (d) simultaneously along three faces of the cross-section, namely the lower face and two side faces; (e) simultaneously along the upper and lower faces of the cross-section (within the compressed and tension zones)

In order to select an effective method for strengthening reinforced concrete flexural elements through cross-sectional enlargement, it is necessary to conduct an analysis of previous scientific studies undertaken by researchers worldwide.

Problem statement

The aim of this study is to review scientific research devoted to experimental investigations and theoretical developments concerning the analysis and design of reinforced concrete beam and slab elements whose cross-sections have been strengthened through enlargement by means of additional reinforced concrete layers or longitudinal components fabricated from rolled steel sections, steel plates, reinforcing bars, and polymer fabric materials.

Review of the research sources and publications

A preliminary analysis of scientific studies has demonstrated that there exists a wide range of methods for enhancing the flexural and shear strength of reinforced concrete flexural elements through the enlargement of their cross-sections along the member length. External cross-sectional enlargement for the strengthening of reinforced concrete elements may be achieved using: steel components; additional concrete layers and reinforcing products; or composite combined enlargement employing various materials.

Therefore, in order to generalise the existing cases and variants of strengthening reinforced concrete flexural elements, directions for a comparative analysis of studies concerning strengthening methods were selected according to the location of the enlargement layer relative to the element cross-section, as presented in the Introduction and illustrated in Fig. 1.

1. Investigation of the Flexural and Shear Strength of Reinforced Concrete Flexural Structural Elements Strengthened by Increasing the Cross-Sectional Area within the Lower Tension Zone

The strengthening of reinforced concrete flexural structural elements by increasing the cross-sectional area within the lower tension zone is carried out in two principal ways: externally bonded reinforcement (EBR) applied beyond the lower face of the cross-section, and near-surface mounted reinforcement (NSM) installed within the cross-section in the vicinity of its lower face.

1.1. Strengthening of Reinforced Concrete Elements by Additional Longitudinal Steel Reinforcing Bars Positioned within the Cross-Sectional Depth over Part or the Entire Member Length

In studies [2–7], researchers Yaroslav V. Rymar, Zenovii Ya. Blikharskyi, Roman Ye. Khmil, Bohdan F. Kovalchuk, Petro F. Kholod, and Roman Yu. Tytarenko experimentally investigated reinforced concrete beams strengthened with additional reinforcing bars by directly welding them to the existing longitudinal reinforcement or by connecting them through welding using short reinforcing bar segments (“stitches”) placed at two to four locations along the specimen length. Figure 2 illustrates selected reinforced concrete beams during experimental testing on the test rig.

In study [2], the strengthening of reinforced concrete beams was carried out at load levels of $\eta = 0$, 0.3, 0.5, and 0.75 of the ultimate bending moment, corresponding to stress levels in the existing longitudinal reinforcement reaching the yield strength. The increase in load-bearing capacity of the strengthened reinforced concrete beams, compared with the reference specimens without strengthening, ranged from 30% to 45%. The load level applied during strengthening had a significant influence on the resulting bearing capacity of the beams: in the absence of loading, the load-bearing capacity was maximal, whereas under the maximum loading level during strengthening, its value was minimal [2].

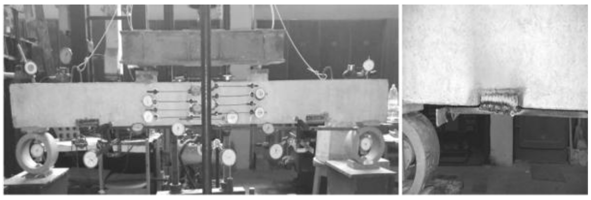

Figure 2 – View of a reinforced concrete beam from the series strengthened under load by means of short reinforcing bar segments (“stitches”), experimentally tested in study [6] by researchers Bohdan Kovalchuk, Yaroslav Rymar, Zenovii Blikharskyy, and Petro Kholod

In study [7], the strengthening of reinforced concrete beams at a loading level equal to one-half of the cracking moment ($\eta=0,5\times M_{cr}$) using additional reinforcement without prestressing increased their flexural strength by 89%, whereas the application of prestressed additional reinforcement resulted in an increase of 93%.

In the study conducted by B. A. Boiarchuk [8], two strengthening scenarios were considered: strengthening without предварительного loading, and strengthening under load corresponding to 0.6–0.7 of the ultimate load. Compared with unstrengthened specimens, all strengthening methods increased the load-bearing capacity by 30–60%, while the cracking resistance increased by approximately 30% [7, 8].

In study [9], researchers Akhtar Gul, Bashir Alam, Fayaz A. Khan, Yasir Irfan, and Khan Shezada presented the results of experimental investigations into the flexural strength of three reinforced concrete beam specimens strengthened within the tension zone by externally attached steel bars with a minimum reinforcement ratio. Two beams were strengthened by welding the external steel bars to the lower stirrup reinforcement bars (see Fig. 3), whereas one specimen without additional external strengthening was tested as a control specimen. All three beams were tested under positive bending using third-point loading in accordance with ASTM C78/C78M-10. The experimental results demonstrated that this strengthening technique enabled a significant increase in flexural strength together with improved crack distribution within the beam cross-sections.

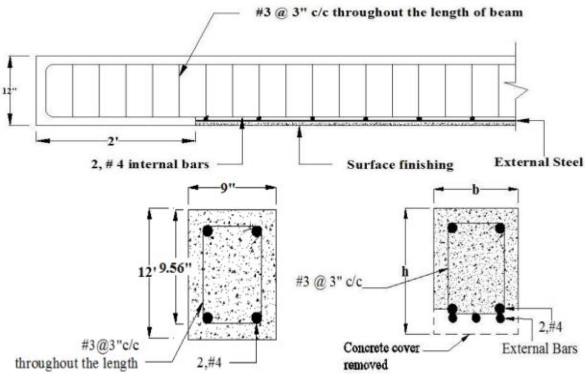

Figure 3 – View and cross-sectional dimensions of a reinforced concrete beam specimen strengthened by means of short reinforcing bar segments ("stitches"), experimentally tested in study [9] by A. Gul and el.

1.2. Strengthening of Reinforced Concrete Elements by Additional Longitudinal Glass-Fibre Reinforcing Bars Positioned within the Cross-Sectional Depth over Part or the Entire Member Length

Articles [10, 11] present the NSM method involving NSM composites, namely steel and carbon fibre-reinforced polymer (CFRP) bars used as reinforcement. Experimental and analytical investigations were conducted to examine the strength characteristics of reinforced concrete (RC) elements strengthened with NSM composites. The reinforcement arrangement of the beam specimens incorporating strengthening bars (NSM Bars), together with the testing scheme, is shown in Fig. 4.

The reinforcement of the beam cross-sections consisted of: two 12 mm diameter bars within the tension zone; two 10 mm diameter bars within the compression zone; and transverse reinforcement within the shear regions formed by 6 mm diameter stirrups spaced at s=50 mm, as illustrated in Fig. 4.

The compressive strength of the concrete after 28 days reached 40 MPa, as determined from tests on three concrete cubes measuring 100×100×100 mm.

The strengthening of the beam specimens was carried out using: high-strength steel bars with diameters of 6, 8, 10, 12, and 16 mm (manufactured by E Steel Sdn. Bhd., Klang, Malaysia) having a yield strength of 520 MPa and an ultimate tensile strength of 570 MPa, with an elastic modulus of 200 GPa for all bars; and ribbed carbon fibre-reinforced polymer (CFRP) bars with a diameter of 12 mm (manufactured by Haining Anjie Composite Material Co., Ltd., Haining, China), possessing a tensile strength of 1850 MPa and an elastic modulus of 124 GPa.

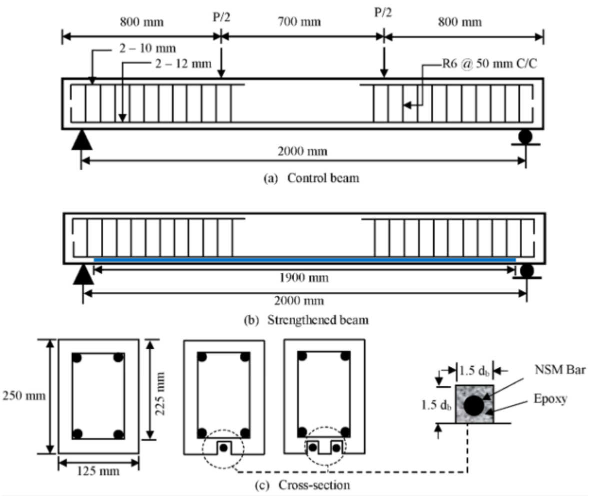

Figure 4 – Testing arrangement, dimensions, and reinforcement details of the cross-sections of beam specimens strengthened with NSM reinforcing bars (NSM Bars) [10, 11]

To anchor the reinforcing bars to the concrete substrate within the grooves formed along the beam length, Sikadur® 30 epoxy adhesive (produced by Sika Corporation, Lyndhurst, New Jersey, USA) was employed. Sikadur® 30 consists of two components, namely Component A and Component B. Component A is white in colour, whereas Component B is black. These two components were mixed in a 3:1 ratio until a uniform grey colour was achieved. The density of the mixed adhesive was 1.65 kg/L at 23°C. According to DIN EN 24624, the bond strength of the epoxy mixture was 21 MPa with steel and 4 MPa with concrete.

Based on the experimental investigations, the following parameters were evaluated: failure characteristics, yielding and ultimate strength, deflection, strain, and crack propagation behaviour of the beams. The test results demonstrated an increase in flexural strength at crack initiation of 69%, while at the ultimate load the increase reached 92% compared with the control beam specimen [10, 11].

In study [12], Hadeel S. Al-Ameedee and Hayder M. Al-Khafaji conducted experimental investigations on four reinforced concrete beams ($b\times h\times l$=150×300×1500 mm) subjected to bending, whose cross-sections were strengthened within the tension zone using different types of near-surface mounted (NSM) bars (see Fig. 5).

Three beams were strengthened using different NSM reinforcement elements (bars), namely carbon fibre-reinforced polymer (CFRP), glass fibre-reinforced polymer (GFRP), and steel, while one unstrengthened beam served as the control specimen. The specimens were tested under monotonic static loading in order to determine the effect of fibre-reinforced polymer (FRP) strengthening reinforcement.

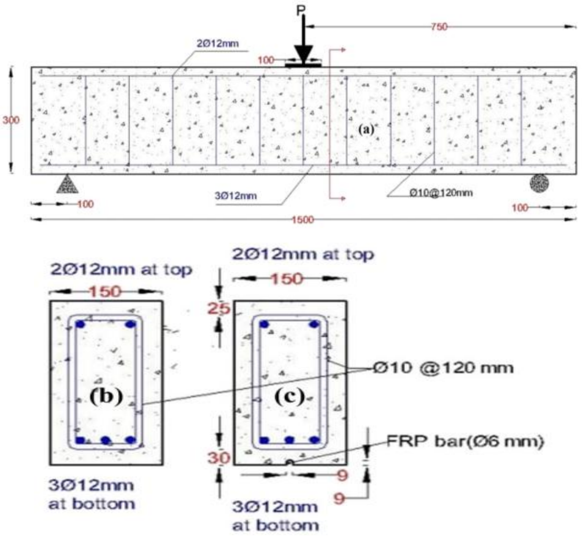

Figure 5 – Testing arrangement, dimensions, and reinforcement details of the cross-sections of beam specimens strengthened with NSM reinforcing bars (NSM Bars) [12]

The experimental results demonstrated [12] that the use of NSM-CFRP bars for strengthening reinforced concrete beams improves both their flexural capacity and stiffness.

Experimental investigations into the influence of additional reinforcement using polymer and steel bars installed within the cross-section near the lower face of reinforced concrete beams strengthened according to the NSM technique on flexural and shear strength were also carried out in studies [13–20], while numerical simulations of their stress–strain state were presented in studies [21, 22].

1.3. Strengthening of Reinforced Concrete Elements by Additional Longitudinal Components Fabricated from Rolled Structural Sections, Reinforcing Steel, Glass Fibre, or Other Composite Cross-Sections Installed beneath the Beam Cross-Section over Part or the Entire Member Length

Researchers M. Y. Alkhateeb and F. Hejazi, in study [23], proposed a novel strengthening scheme for reinforced concrete beams using carbon fibre-reinforced polymer (CFRP) bars secured by steel plates and anchor bolts, referred to as the Mechanical Anchorage System (MAS) (see Fig. 6). This system may additionally incorporate an external protective concrete jacket to protect the MAS components and CFRP bars.

The effectiveness of the proposed strengthening method was verified on eight beam specimens incorporating different configurations of additional reinforcement (see Figs. 7 and 8). The investigation evaluated the effectiveness of various design parameters, including the number of CFRP bars, the contribution of the Mechanical Anchorage System (MAS), and the concrete jacket (CJ), in terms of load-bearing capacity, crack development, failure mode, and ductility.

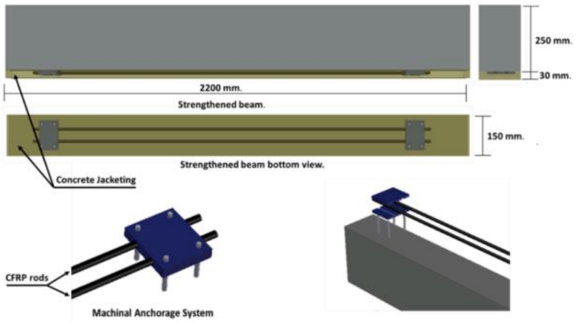

Figure 6 – Components of the beam strengthening system comprising steel plates and anchor bolts (MAS) together with carbon fibre-reinforced polymer (CFRP) bars [23]

The results demonstrated that the efficiency of the proposed strengthening system was achieved through an increase in the load-bearing capacity of the strengthened beams and the prevention of premature debonding of the CFRP bars [23].

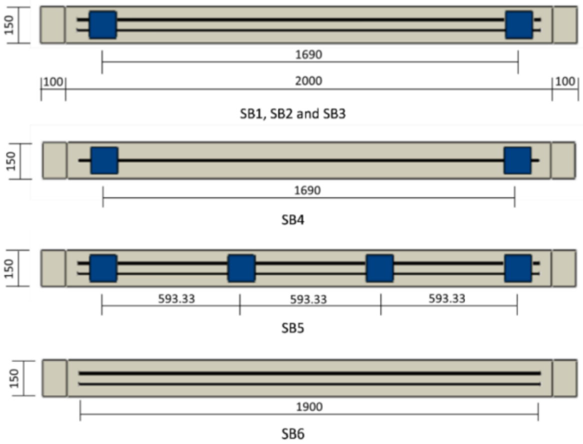

Figure 7 – Variants of structural solutions for additional strengthening of beams within the tension zone investigated in study [23]

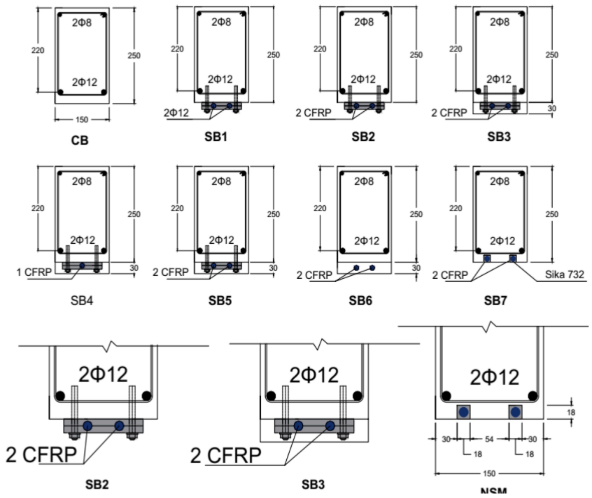

Figure 8 – Dimensions and reinforcement details of the cross-sections of beam specimens investigated in study [23]

In article [24], F. Oudah and R. El-Hacha investigated the strength behaviour of reinforced concrete (RC) beams strengthened using prestressed carbon fibre-reinforced polymer (CFRP) strips and bars installed near the surface (NSM) and anchored to the beams by means of steel anchorage devices. Eight RC beams were subjected to fatigue loading over 3 million cycles at a frequency of 2 Hz. Monitoring of strain values in the CFRP bars near the anchorage zones was performed using strain gauges, which provided reliable information regarding the magnitude of CFRP slippage at the ultimate stage.

The influence of increasing prestress levels on the slippage of the CFRP bars and the cracking of concrete within the anchorage zones was investigated. The experimental results revealed the occurrence of anchorage slippage in heavily prestressed beams, whereas only minor slippage was observed in beams prestressed to lower levels. An increase in both crack height and crack width within the anchorage regions was also observed with increasing prestress levels. Furthermore, the slip in reinforced concrete beams strengthened using NSM CFRP strips was lower than that in similar beams strengthened with NSM CFRP bars.

The strengthening of reinforced concrete flexural structural elements by increasing the cross-sectional area within the lower tension zone using sprengel tie-system elements arranged outside the lower face of the cross-section was proposed by M. H. Chekanovych in studies [25, 26]. The author proposed a strengthening configuration involving intensive prestressing of the tie reinforcement and tension members under external loading (see Fig. 9), which enables redistribution of internal forces within the beam, thereby increasing its load-bearing capacity and crack resistance while reducing deflection.

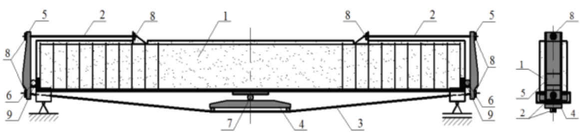

Figure 9 – General view of the strengthening system for a steel–reinforced concrete beam using a lever-and-rod mechanism [25]: 1 – beam to be strengthened; 2 – tension rods; 3 – tie member; 4 – crossbeam; 5 – double-arm levers; 6, 7 – rollers; 8 – fastening assembly with spherical washers; 9 – support block

2. Investigation of the Flexural and Shear Strength of Reinforced Concrete Flexural Structural Elements Strengthened by Increasing the Cross-Sectional Area on One or Both Sides of the Section

2.1. Strengthening of Reinforced Concrete Element Cross-Sections Using Steel Plates Installed on Both Sides along the Entire Member Length

Compared with other strengthening methods, the steel jacketing technique is not only less spatially demanding, simple to install, and lightweight, but is also less susceptible to debonding and delamination [27, 28]. The bolted side-plating (BSP) technique, namely the anchorage of steel plates to the side faces of reinforced concrete beams using bolts, represents one of the steel jacketing methods and is capable of increasing the flexural capacity of reinforced concrete beams without significant reduction in ductility due to the enhancement of both compressive and tensile reinforcement [29]. Furthermore, this technique may also improve the shear strength and stiffness of reinforced concrete beams, since the steel plates bolted to the side faces are located within the same plane as the shear force.

In study [27], researchers Ling-Zhi Li, Chang-Jiu Jiang, Ray Kai-Leung Su, and Sai-Huen Lo carried out experimental investigations on reinforced concrete beam specimens strengthened using steel plates and bolted connections (see Figs. 10 and 11) in order to examine the mechanism of shear force transfer through anchor bolts in BSP beams and to propose a practical method for assessing the influence of transverse partial interaction between components on the strengthening system of beams.

The authors of study [27] proposed a simplified piecewise-linear shear transfer model based on the principle of force superposition together with a simplified shear deformation model derived from previous numerical investigations.

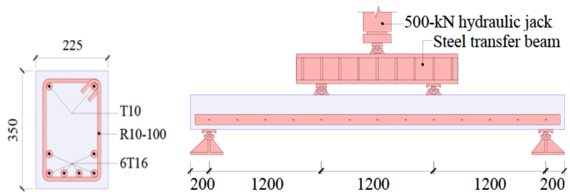

Figure 10 – Cross-section and experimental test setup of the beam specimens [27]

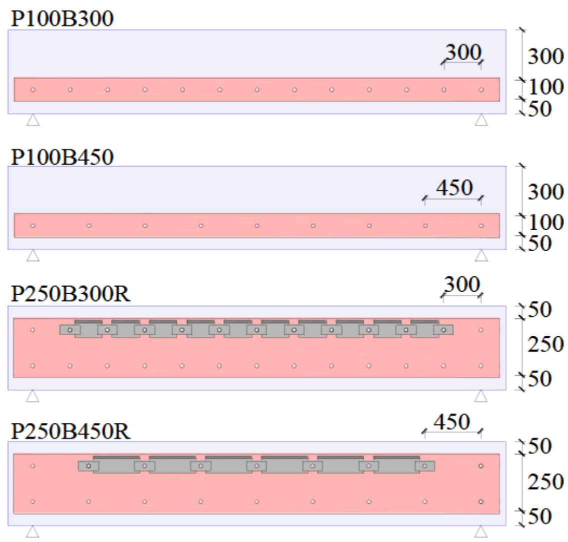

Figure 11 – General view of the specimens strengthened with steel plates and bolted connections in study [27]

The magnitude of the shear force was determined from force equilibrium conditions assuming compatible deformation (displacement) of the components within the composite beam cross-section.

A set of design equations was also derived for determining the flexural strength of BSP beams under several principal loading cases [27].

In article [28], Xin Liu et al. (2018) presented a review of previous experimental, theoretical, and numerical investigations [35] concerning the shear behaviour of reinforced concrete beams strengthened through cross-sectional enlargement using side steel plates and bolted connections (the BSP method). Fig. 12 illustrates the testing arrangement of the beam specimens investigated in study [28].

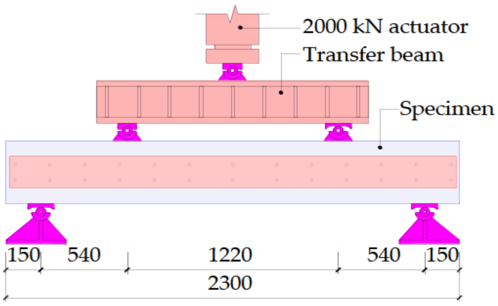

Figure 12 – Test arrangement of the beam specimens subjected to loading in a testing press for investigating the shear strength of their cross-sections in the study by Xin Liu et al. (2018) [28].

Figure 13 presents the variants of the beam specimens tested during the experimental investigations reported in study [28].

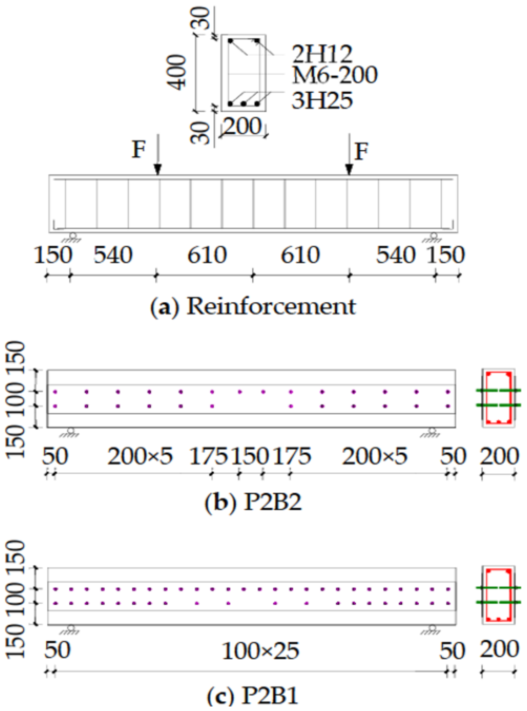

Figure 13a – Cross-sections of reinforced concrete beam specimens (dimensions in mm) and variants of their strengthening using side steel plates and bolted connections (BSP method) for investigating the shear strength of their cross-sections in the study by Xin Liu et al. (2018) [28].

The factors influencing the shear strength of the beam cross-sections were investigated in detail, namely: concrete strength; dimensions of the steel plate cross-section; bending and shear span lengths; longitudinal spacing between bolts; and the number of bolt rows. In addition, two possible theoretical models for evaluating the shear behaviour of beams strengthened using the BSP method were proposed, based on deformation compatibility and simplified transverse shear of the cross-sections.

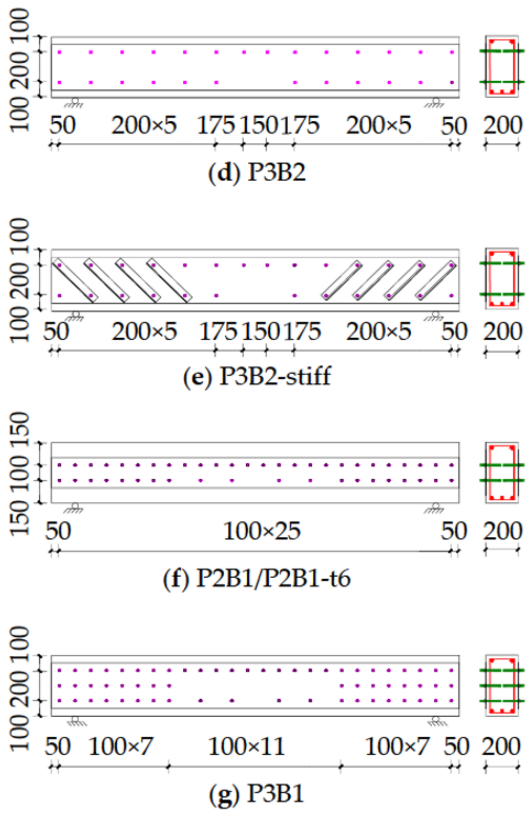

Figure 13b – Variants of strengthening reinforced concrete beam specimens using side steel plates and bolted connections (BSP method) (dimensions in mm) for investigating the shear strength of their cross-sections in the study by Xin Liu et al. (2018) [28].

In the comparative analysis of shear strength, the mean absolute discrepancy between the experimental test results and the predictions obtained using the two proposed theoretical models amounted to 2.7% and 5.9%, respectively [28].

In study [29], researchers Ling-Zhi Li, Xin Liu, Yi Luo, Mei-Ni Su, and Ji-Hua Zhu carried out investigations on five reinforced concrete beams, four of which were strengthened along both sides with steel plates (see Fig. 14) over the entire member length. The steel plates were anchored to the beams using bolted connections installed symmetrically within the compression and tension zones of the cross-sections at a spacing of u=280 mm.

The results of the investigations reported in study [29] demonstrated that the method of strengthening reinforced concrete beams using side steel plates and bolted connections (the BSP method) can significantly enhance their flexural strength and stiffness.

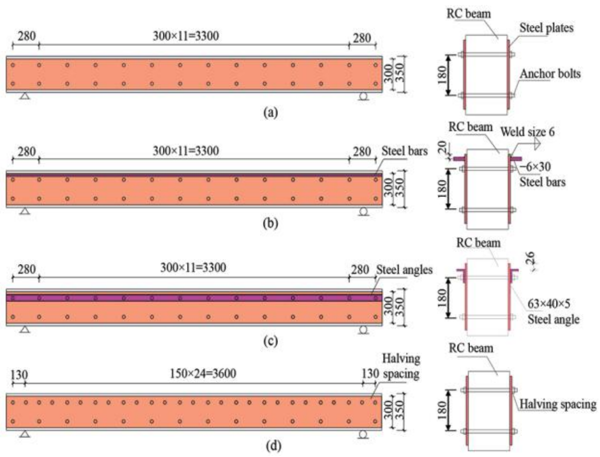

Figure 14 – General view and cross-sectional details of beams of the following series: (a) BSP-N; (b) BSP-B; (c) BSP-A; and (d) BSP, experimentally tested in study [29]

Furthermore, measures aimed at restraining buckling were shown to further improve the flexural capacity and ductility of the beams, while simultaneously suppressing local buckling and reducing relative slip at the steel-to-concrete interface.

A comparison between the theoretical predictions and experimental results confirmed the applicability and accuracy of the analytical calculation model proposed in the study.

3. Investigation of the Flexural and Shear Strength of Reinforced Concrete Flexural Structural Elements Strengthened by Increasing the Cross-Sectional Area along Two Side Faces and the Lower Face

In study [30], Min Sook Kim and Young Hak Lee carried out investigations aimed at evaluating the structural behaviour of reinforced concrete beams strengthened using prefabricated modular steel components installed in their design position by means of bolts and chemical anchors (see Fig. 15).

For this evaluation, a total of five specimens were fabricated, including one conventional reinforced concrete beam and four reinforced concrete beams strengthened with modular steel plates. The modelling of the beam strengthening method was performed taking into account realistic floor system conditions, in which slab elements bear on the upper face of the beams.

The concrete beams of all specimens were designed with a width of b=300 mm, a height of h=350 mm, and a length of l=4.5 m. The thicknesses of the modular structural components were as follows: the Z-shaped side plates had a thickness of t=2.5 mm, while the L-shaped bottom plates had a thickness of t=5 mm. The spacing between the chemical anchors and bolts was a=300 mm, arranged in a staggered (zigzag) pattern.

The thickness of the bottom plate and the number of vertical meshes were considered as experimental variables expected to influence the flexural behaviour, and these variables are illustrated in the relevant parts of Fig. 15. The depth of the newly formed beams was 100 and 150 mm, the thickness of the bottom plates was 5 and 10 mm, and the number of vertical meshes was 0, 2, and 4. For the specimen with two vertical meshes, the spacing between meshes was 200 mm, whereas for the specimen with four vertical meshes each mesh was installed at a spacing of 65 mm. An detailed specimen configurations corresponding to each variable are shown in Fig. 15.

The 28-day compressive strength of the concrete used in the experiment was 24 MPa. Deformed reinforcement bars with a diameter of 19 mm and a yield strength of 400 MPa were used for both tensile and compressive reinforcement. Structural steel plates with a yield strength of 275 MPa were employed. High-strength F10T M16 bolts with a diameter of 16 mm were used to connect the strengthening elements to the concrete beams.

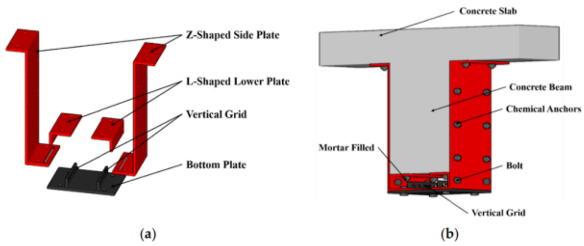

Figure 15 – Modular structural components used for strengthening the beam specimens in study [30]

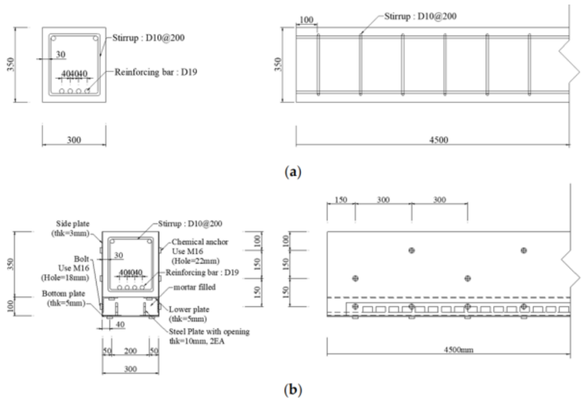

Figure 16 – Dimensions of the beam specimens tested in study [30]: (a) reinforced concrete beam specimen without strengthening; (b) reinforced concrete beam specimen strengthened with a steel jacket along the side faces and lower face

In this study, the slab portions (flanges) of the T-shaped cross-section served solely as a support area for fastening the steel plates by means of chemical anchors. Therefore, the flanges were not considered during the fabrication of the specimens, as illustrated in Fig. 16.

To evaluate the structural behaviour of the concrete beams retrofitted using the proposed components, five concrete beams with and without strengthening were experimentally tested. The proposed retrofitting method significantly increased both the ultimate load-carrying capacity and the ductility of the reinforced concrete beams.

The experimental results demonstrated [30] that the flexural performance of the existing reinforced concrete beams increased by approximately three times, the ductility increased by 2.5 times, and the energy dissipation capacity increased by seven times

4. Investigation of the flexural and shear strength of reinforced concrete flexural members strengthened by increasing the cross-sectional area in the upper compression zone

In the publication by E. Brühwiler and E. Denarié (2008) [31], three concepts for the application of an additional ultra-high-performance fibre-reinforced concrete (UHPFRC) layer to enlarge the cross-section of reinforced concrete beam members in the upper compression zone are presented (see Fig. 17). The first concept involves the application of an unreinforced UHPFRC layer serving solely as a protective overlay for the rehabilitation of the deteriorated concrete cover. The second concept combines the protective function with reinforcement embedded within the UHPFRC overlay, thereby enhancing the durability and structural performance of the rehabilitated concrete cover. The third concept incorporates both the protective function and the structural enlargement of the beam cross-section through the application of an additional reinforced UHPFRC layer on the compression face, thereby increasing the flexural stiffness and load-bearing capacity of the reinforced concrete member.

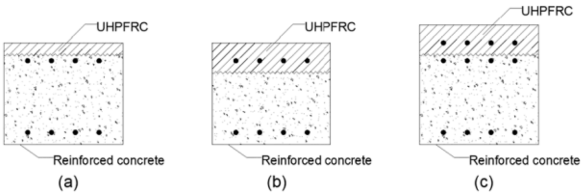

Figure 17 – Concepts and principles of a composite structural member in which the ultra-high-performance fibre-reinforced concrete (UHPFRC) layer serves as: (a) a protective layer without reinforcement; (b) a protective layer with embedded reinforcement; and (c) a strengthening layer providing both structural protection and enhanced load-bearing capacity [31].

5. Investigation of the flexural strength of reinforced concrete beam members strengthened by increasing the cross-sectional area at the top, along one or both side faces, and simultaneously along the two side faces and the bottom by means of an additional reinforced concrete layer

Studies [32–41] provide comprehensive reviews of the effectiveness of using Ultra-High-Performance Fibre-Reinforced Concrete (UHPFRC) for strengthening reinforced concrete beam and slab members.

In study [42], Huang et al. carried out a critical review of previous investigations [43–45] devoted to evaluating the influence of various strengthening techniques employing an additional UHPFRC layer on the shear and flexural performance of reinforced concrete members.

In study [43], a normal-strength concrete (NC) control beam and a high-strength concrete (HSC) control beam were compared with hybrid beams in which a portion of the conventional concrete was replaced by UHPFRC. The hybrid beams exhibited an increase in shear resistance of 60–110% (see Fig. 18a) compared with the control specimens, irrespective of the compressive strength of the parent concrete. The relationship between the steel fibre content and the increase in the shear resistance of the concrete beams is illustrated in Fig. 18b. In the specimen designation shown in Fig. 18a, the first and second letters identify the two concrete types used to produce the hybrid specimen, followed by the specimen configuration number. The subsequent numeral indicates the volumetric steel fibre content in the UHPFRC, while the final letter denotes the type of interface connection adopted between the two concrete layers.

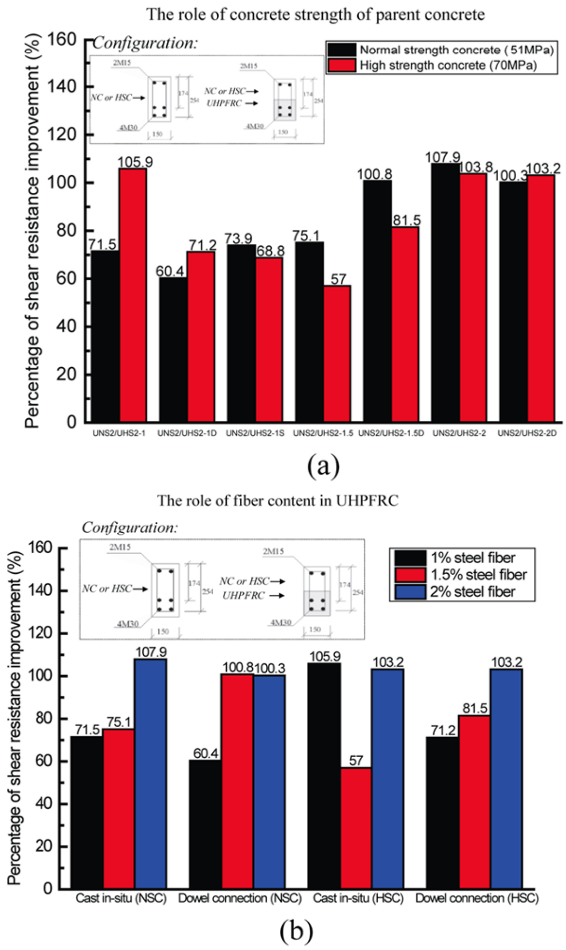

Figure 18 – Parametric analysis of the shear strengthening of reinforced concrete members using UHPFRC and the corresponding increase in shear resistance with changes in: (a) the compressive strength of the parent concrete; and (b) the steel fibre content of the UHPFRC layer [42–44].

The comparative analysis considered the influence of the following structural parameters on the performance of the strengthened reinforced concrete members:

- the compressive strength of the parent concrete of the reinforced concrete members (see Fig. 18a) and the steel fibre volume fraction (%) incorporated into the additional UHPFRC layer (see Fig. 18b);
- the location of the UHPFRC strengthening layer relative to the faces of the reinforced concrete member, together with the presence or absence of

reinforcement within the additional layer (see Figs. 19 and 20);

- the configuration of the interface connection (bond) between the additional UHPFRC layer and the parent normal-strength concrete (NSC) of the reinforced concrete member, and its influence on shear resistance (see Fig. 21);
- the variation in the shear span-to-effective depth ratio of reinforced concrete members strengthened using three different UHPFRC strengthening configurations, and its effect on their structural behaviour (see Fig. 22).

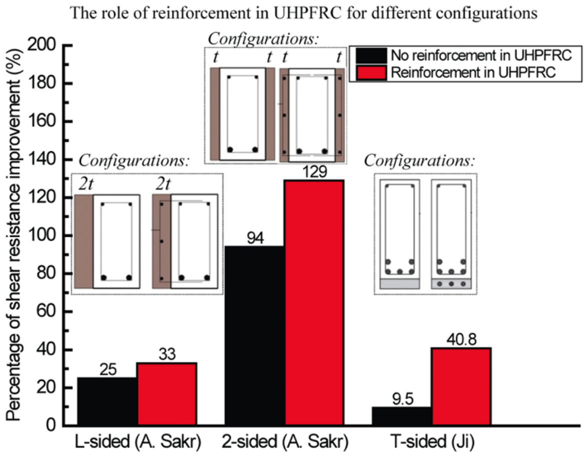

Figure 19 – Parametric analysis of the shear strengthening of reinforced concrete flexural members using UHPFRC and the corresponding increase in shear resistance with different strengthening configurations and reinforcement arrangements [42].

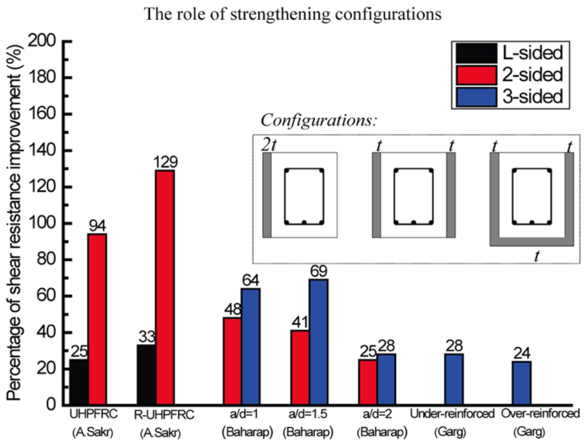

Figure 20 – Parametric analysis of the shear strength of reinforced concrete members strengthened with different UHPFRC layer configurations (one-sided, two-sided, and three-sided) as a function of the shear span-to-effective depth ratio (a/d) [42].

In study [46], Chalioris et al. investigated the repair and strengthening of damaged reinforced concrete beams by applying a three-sided reinforced concrete jacket made of self-compacting concrete (SCC). The authors found that the reinforced concrete jacket increased the load-bearing capacity of the tested beams by 35–50% compared with the damaged control specimens. Following strengthening, the failure mode changed from brittle shear failure to a more ductile flexural failure, while the strengthened members exhibited significantly improved deformability and crack resistance. The authors further emphasised that the use of self-compacting concrete is particularly advantageous for the rehabilitation of heavily reinforced structural members, as it ensures effective filling of the space between the existing reinforcement and the newly cast concrete jacket, thereby promoting adequate bond and composite action between the original and strengthening materials.

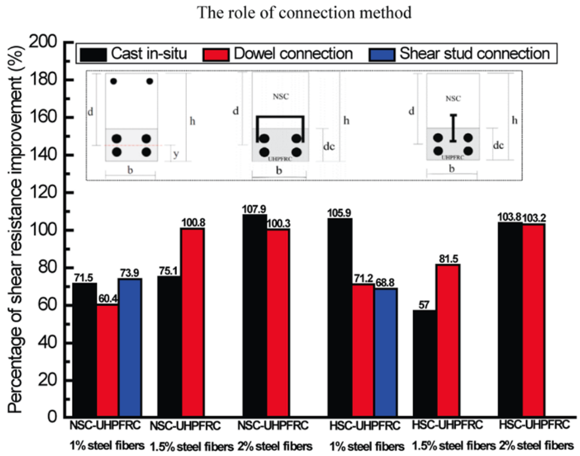

Figure 21 – Parametric analysis of the influence of the interface connection (bond) between the additional UHPFRC layer and the parent concrete of the strengthened reinforced concrete member on shear strength: (d) strengthening configuration; (e) interface connection type; and (f) shear span-to-effective depth ratio (a/d) [42].

Study [42] also analysed the effect of the shear span-to-effective depth ratio (a/d) on the shear strength of reinforced concrete members strengthened with a UHPFRC layer. The results showed that increasing the a/d ratio significantly reduced the shear resistance of the strengthened members, with the normalised shear strength decreasing from approximately 1.0 to 0.33 (see Fig. 20). These findings indicate that the effectiveness of UHPFRC strengthening is strongly influenced by the geometric characteristics of the structural member.

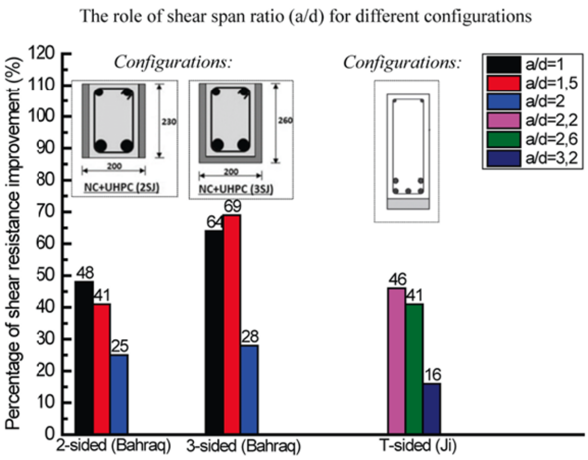

Figure 22 – Parametric analysis of the shear strengthening of reinforced concrete members with an additional UHPFRC layer as a function of the shear span-to-effective depth ratio (a/d) [42].

6. Strengthening of reinforced concrete members with additional longitudinal glass fibre-reinforced or other composite built-up elements installed below the beam cross-section over part or the entire span

6.1. Strengthening reinforced concrete beam and slab members with externally bonded glass fibre-reinforced polymer plates in the tension zone

In study [47], Gudonis et al. presented a comprehensive review of contemporary techniques for strengthening and reinforcing reinforced concrete structures using fibre-reinforced polymer (FRP) composites. The authors highlighted that the external strengthening of reinforced concrete beams and slabs using glass fibre-reinforced polymer (GFRP) and carbon fibre-reinforced polymer (CFRP) plates, sheets, or laminates represents one of the most promising approaches for upgrading existing structures owing to the high tensile strength, excellent corrosion resistance, and low self-weight of composite materials. Particular attention was devoted to the issue of bond failure between the FRP reinforcement and the concrete substrate, as debonding of the concrete cover or interfacial failure frequently governs the ultimate limit state of strengthened members. The authors further emphasised that the effectiveness of externally bonded FRP reinforcement depends primarily on the anchorage system, the quality of the concrete surface preparation, and the deformational characteristics of the composite material.

In study [48], Sakbana and Mashreib carried out a numerical investigation of the flexural behaviour of reinforced concrete beams strengthened with CFRP elements using the finite element method. The authors compared the effectiveness of externally bonded reinforcement (EBR) employing CFRP sheets with the near-surface mounted (NSM) technique, in which composite reinforcement is partially embedded within the concrete cover. The results demonstrated that CFRP strengthening increased the load-bearing capacity of the beams by 6.6% for the EBR system and by as much as 108.8% for the NSM system compared with the control specimens. The study also showed that increasing the thickness of the CFRP sheet from 0.11 mm to 0.50 mm enhanced the stiffness and flexural strength of the beam by approximately 48%, while increasing the length of the composite reinforcement further improved the load-bearing capacity of the strengthened member. Moreover, the authors reported that the NSM technique exhibited a lower tendency towards debonding and provided more efficient stress transfer between the concrete substrate and the CFRP reinforcement.

In study [49], Alkhrdaji et al. investigated the strengthening of cast-in-situ reinforced concrete bridge deck slabs using externally bonded FRP systems under full-scale field conditions. Experimental testing was performed on an existing bridge span in which one portion of the slab was strengthened using externally bonded FRP sheets, whereas another portion was reinforced using NSM CFRP bars. The results demonstrated that composite strengthening systems enable the upgrading of bridge structures with minimal disruption to traffic and service conditions while requiring comparatively low construction effort. The researchers also noted that the NSM system offers additional advantages, including improved anchorage, rapid installation, and reduced requirements for concrete surface preparation. Furthermore, the study confirmed that CFRP reinforcement provides an effective means of increasing the load-bearing capacity of existing bridge deck slabs originally designed in accordance with obsolete design standards.

6.2. Three-sided and side strengthening of reinforced concrete beams using external carbon fibre-reinforced polymer elements

In dissertation [50], Dias conducted a comprehensive experimental and analytical investigation into the shear strengthening of reinforced concrete beams by installing CFRP laminates into grooves cut within the concrete cover using the near-surface mounted (NSM) technique. The effectiveness of NSM strengthening was compared with conventional externally bonded CFRP reinforcement systems as well as with traditional steel stirrup strengthening. The results demonstrated that beams strengthened with embedded CFRP laminates exhibited more efficient utilisation of the composite material and superior shear resistance compared with externally bonded reinforcement (EBR) systems. The study also examined the influence of laminate orientation, transverse reinforcement ratio, concrete strength class, and the shear span-to-effective depth ratio on the efficiency of strengthening. The findings confirmed the considerable potential of the NSM technique for strengthening reinforced concrete beam members where an increase in shear load-bearing capacity is required.

Conclusions

One of the most effective techniques for strengthening reinforced concrete flexural members is the enlargement of their cross-sections through the application of an additional reinforced concrete layer. This method enhances the section modulus, stiffness, and load-bearing capacity of the structural member. Experimental investigations have demonstrated an increase in load-bearing capacity ranging from 30% to 90%, depending on the reinforcement arrangement, the thickness of the additional layer, and the quality of the bond between the existing and newly placed concrete. In particular, three-sided enlargement of the cross-sections of reinforced concrete beam members provides superior performance compared with other strengthening techniques. The maximum increase in flexural strength ranges from 81% to 120%, while crack resistance improves by 300%–500% relative to the reference specimens. Furthermore, the maximum increase in shear strength reaches 51%–80%, accompanied by an improvement in shear crack resistance of 121%–180%.

A hybrid strengthening technique for reinforced concrete beam and slab members, based on the simultaneous enlargement of the cross-sections in both the tension and compression zones, has demonstrated significantly higher efficiency than conventional strengthening methods because it combines two or more technological techniques and structural approaches. Previous studies have shown that, compared with individual strengthening schemes, the hybrid technique increases the flexural load-bearing capacity of reinforced concrete slab elements by more than 100–120% without reducing their ductility. In contrast, individual strengthening methods, involving reinforcement applied only to the upper or lower surface or only to one or both side faces of the cross-section, increase flexural strength by only 40–60% compared with the corresponding reference structural element.

The literature review revealed that, despite the considerable number of published studies devoted to the strengthening of reinforced concrete members, relatively little attention has been paid to the simultaneous strengthening of reinforced concrete beam elements by enlarging their cross-sections in both the compression and tension zones (see Fig. 1e). Furthermore, the provisions of Clause 6.3.5 of the current Ukrainian building code DBN B V.3.1-2:2016 [1] do not include a combined strengthening scheme for beam and slab structural members involving the simultaneous strengthening of both the compression and tension zones of the cross-section. Consequently, to facilitate the widespread implementation of this strengthening technique in engineering design practice, it is necessary to develop a design methodology for evaluating the flexural strength of reinforced concrete beam and slab members strengthened by the simultaneous enlargement of their cross-sections in both the compression and tension zones. Such a methodology should enable the determination of the optimum parameters of the additional tensile reinforcement as a function of the thickness of the additional reinforced concrete layer (d), the member span (L), and the cross-sectional depth (h), while accounting for the existing reinforcement area of the reinforced concrete member prior to strengthening.

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Способи підсилення і ремонту залізобетонних балкових і плитних елементів шляхом нарощування їх поперечних перерізів: огляд та напрямки подальших наукових досліджень

Аннотація. В результаті довготривалої експлуатації залізобетонні балкові елементи збірних і монолітних перекриттів будівель і споруд зазнають старіння, зношення, часткового чи повного руйнування під впливом агресивного середовища, статичних і динамічних навантажень вибухового типу. Під впливом агресивного середовища з підвищеною вологістю і перепадом температур, який характеризується циклічним заморожуванням та відтаюванням, наявністю хімічно активних сполук в рідині і повітрі, які безпосередньо контактують з конструкцією, в елементах виникають пошкодження у вигляді: появи і розвитку вздовж робочої арматури поздовжніх тріщин шириною розкриття, що перевищує гранично допустиму величину; локальних і точкових руйнувань захисного шару бетону і корозію стальної арматури. Випадкова або непередбачена дія позапроектного статичного чи динамічного навантаження вибухового типу, також можуть призвести до перевантаження і появи ознак значного фізичного зносу і зрілої форми видимого руйнування залізобетонних балкових конструктивних елементів, таких як: залишкові деформації у вигляді прогинів, величина яких перевищує гранично допустиму величину; локальні руйнування бетону у стиснутій зоні перерізів у вигляді точкових дрібних тріщин, відділень шарів і частинок бетону один від одного на зовнішній поверхні, їх розшарувань і випадення; поява і розвиток силових тріщин в перерізах у зоні згину і зрізу балкового елементу, ширина розкриття яких перевищує гранично допустиму величину. В п. 6.3 норм ДБН Б В.3.1-2:2016 [1] приведені основні методи і способи підсилення залізобетонних балкових елементів, одним із варіантів яких є метод їх підсилення шляхом часткового збільшення площі їх поперечних перерізів ззовні за допомогою: додаткового залізобетонного шару нарощування; додаткових стальних елементів із прокатних профілів, пластин і арматурних стержнів; додаткових елементів із полос полімерних матеріалів, армованих волокнами, та арматурних стержнів.
В статті проведено огляд наукових досліджень, які присвячені методам і способам підсилення залізобетонних балкових елементів шляхом збільшення (нарощування) поперечних перерізів. Обгрунтовані основні висновки і напрямки подальших наукових досліджень ефективних методів і способів підсилення залізобетонних балкових елементів, що здійснюються шляхом збільшення (нарощування) їх поперечних перерізів, які маємо можливість застосувати при ремонті та реконструкції збірних і монолітних залізобетонних перекриттів будівель і споруд. Запропонована класифікація методів і способів підсилення залізобетонних балкових елементів шляхом збільшення (нарощування) їх поперечних перерізів.

Ключові слова: залізобетонні балки та плити, методи підсилення, поперечні перерізи, згин і зсув, огляд, напрями досліджень

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