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Studies of multilayer bent reinforced concrete structures of rectangular cross section review

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Reducing the use of cement and reducing the weight of concrete in bending reinforced concrete elements is an important task in modern construction. To solve this problem, various methods are being implemented, including the use of both removable and non-removable void formers, and the combination of several materials (e.g., heavy in the compressed zone and light in the tensile zone of concrete) for their mutually beneficial joint operation. The paper provides an overview of several experimental and theoretical studies in these areas, which substantiate the possibility and feasibility of reducing the strength of concrete in the tensile zone of bending reinforced concrete structures, and as a result, reducing the consumption of cement for the preparation of concrete mix for structures, without prestressing the latter. The use of two- and multi-layer elements reduces the dead weight of structures, improves sound and thermal insulation properties, which leads to savings in materials, labor and financial resources. The right choice of material for each layer allows for the creation of structures with high performance characteristics.

Keywords: test, experiment, reinforced concrete, bending, multilayer.

Огляд досліджень багатошарових згинаних залізобетонних конструкцій прямокутного поперечного перерізу

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Зменшення використання цементу та зниження ваги бетону у згинальних залізобетонних елементах є важливим завданням у сучасному будівництві. Для його вирішення впроваджуються різні методи, зокрема використання як знімних, так і незнімних пустото утворювачів, поєднання декількох матеріалів для взаємовигідної їх сумісної роботи. Хоча у нормативних документах зазначено, що бетон в розтягнутій зоні не працює, попри це, бетон у розтягнутій зоні традиційно приймають того ж класу міцності, що й у стиснутій зоні елемента. Однак систематизований огляд досліджень можливості заміни розтягнутого бетону у таких конструкціях на більш дешевий матеріал, наприклад бетон меншого класу по міцності чи із пористими заповнювачами, не виконаний. Метою роботи є огляд експериментальних і теоретичних досліджень, що обґрунтовують можливість та доцільність зменшення міцності бетону в розтягнутій зоні згинальних залізобетонних конструкцій, і як результат зменшення витрат цементу на приготування бетонної суміші для конструкцій, без попереднього напруження останніх. Глуховський В.Д. і Пахомов В.А. вперше науково обґрунтували застосування шлаколужного цементу замість портландцементу для виробництва розтягнутої частини залізобетонних конструкцій. Байков В.М. та Сігалов Е.Є. розробили ряд прикладів, в яких наведено економічне обґрунтування застосування бетонів меншого класу у розтягнутій зоні. Дослідники Національного університету «Львівська політехніка» Рутковська І.З., Рутковський З.М., Вознюк Л.І., Марущак А. провели експериментальні дослідження тришарових балок, виготовлених у двох серіях: у першій серії середній шар складався з керамзитобетону, у другій – із пінобетону. Науковці з В'єтнаму T.Q.K. Lam, T.M.D. Do, V.T. Ngo, T.T.N. Nguyen, D.Q. Pham експериментальним шляхом та методом чисельного моделювання дослідили зміну класу бетону у шарах тришарових сталефібробетонних балок. Слід відзначити, що багатошарові згинані залізобетонні конструкції із бетоном меншого класу утворюються також у під час підсилення. Так Мазурак А., Ковалик І. та інші наводять результати експериментальних випробувань залізобетонних конструкцій, підсилених торкретуванням.

Ключові слова: випробування, експеримент, залізобетон, згинання, багатошаровість.

Introduction

Reducing the use of cement and reducing the weight of concrete in bending reinforced concrete elements is an important task in modern construction [1]. Various methods are being implemented to solve this problem, including the use of both removable and non-removable void fillers made of cardboard-polyethylene, asbestos cement or plastics with various cross-sectional shapes: round, square, vertical, elliptical or oval [2]. Slag and fly ash concretes are also used, and optimising the size and ratio of crushed stone to sand helps to achieve this goal [3-4]. Another option is to replace stretched concrete in such structures with a cheaper material, such as concrete of a lower strength class or with porous aggregates. Therefore, the review and systematisation of the results of experimental studies of multilayer bent reinforced concrete structures is an urgent issue.

Review of the research sources and publications

The growing volume of reconstruction and modernisation of buildings requires efficient and cost-effective structural solutions. The idea of multilayered structures has a long history, but its development has been significantly accelerated by its use in aviation and aerospace, where lightweight and durable materials are required [5]. Today, multilayer reinforced concrete structures are becoming increasingly common in construction. The use of lightweight concrete with porous aggregates helps to create energy-efficient solutions. The use of two- and multi-layer elements with porous aggregates can significantly improve sound and thermal insulation characteristics, as well as reduce the dead weight of structures, which leads to savings in materials, labour and financial resources [6]. However, the right choice of material for each layer allows for the creation of structures with high performance characteristics.

In their research [7], scientists propose using ash, ground slag, metallurgical waste, slag-alkali concrete, chemical additives (potash, liquid glass, plasticisers), aggregates and void fillers, as well as improving the composition of concrete mixtures and their heat treatment to reduce concrete and cement consumption.

Publication [8] describes a method for the production of precast concrete slabs with oval cavities, which is aimed at reducing the consumption of concrete and cement during their manufacture. However, this method has not gained popularity in mass production due to the destruction of the walls of the oval holes when the punches are removed from the newly formed slab.

Baikov V.M. and Sigalov E.E. noted that with a nominal span of 6 m, the most economical in terms of concrete consumption are slabs with oval cavities, the thickness of the concrete layer of which is 92 mm, compared to 120 mm for slabs with round cavities. At the same time, the production of such panels is accompanied by technological difficulties: after the removal of the void formers, the walls of the channels in newly formed products sometimes collapse. For this reason, boards with round cavities are standardised for production. Further development of technologies allows us to move to more economical designs.

Glukhovsky V.D. and Pakhomov V.A. were the first to scientifically substantiate the use of slag cement instead of Portland cement for the production of concrete and reinforced concrete structures.

Current regulations [5] define cement consumption rates for the manufacture of concrete and reinforced concrete products. The regulated amount of cement per 1 m³ of concrete must ensure the design properties, such as compressive strength class, density grade, frost resistance and water resistance.

An interesting method of reducing concrete consumption in the production of floor slabs is the use of non-removable plastic void formers of various shapes (washer, spherical, box) [2; 9], as well as stone materials. This method can reduce concrete consumption by up to 30 % compared to solid slabs.

Definition of unsolved aspects of the problem

Thus, the creation of resource-saving reinforced concrete structures involves the search for new types of them from one material or in combination of several materials for their joint mutually beneficial operation, reduction of their cost while ensuring the same bearing capacity, increase of manufacturing manufacturability, etc. It should be noted that in calculations of the total bearing capacity of a structure, stretched concrete is not taken into account, but only increases its weight and, consequently, the cost of manufacturing. However, a systematic review of studies on the possibility of replacing stretched concrete in such structures with a cheaper material, such as concrete of a lower strength class or with porous aggregates, has not been carried out. Also, the impact of physical and mechanical characteristics of the layers, their thickness and the method of reinforcement on the strength and deformation properties of such structures remains insufficiently investigated. The design of such structures is difficult due to the imperfection of theoretical calculations for the limit states.

Problem statement

The purpose of the paper is to review experimental and theoretical studies that substantiate the possibility and feasibility of reducing the strength of concrete in the tensile zone of bending reinforced concrete structures, and as a result, reducing the consumption of cement for the preparation of concrete mix for structures without prestressing the latter.

Basic material and results

Baikov V.M. and Sigalov E.E. note that in sections perpendicular to the longitudinal axis of elements (under bending, off-centre compression or tension), at a stage close to destructive loads, the same stress-strain state is characteristic under conditions of a two-digit stress diagram. In calculating the strength of elements, the forces perceived by a section perpendicular to the longitudinal axis of the element are determined by the calculated material resistances, taking into account the coefficients of working conditions [10].

The following assumptions are used: concrete in the tensile zone is inactive, i.e., its resistance f_{ctk} is zero;

concrete in the compressed zone has a rectangular stress diagram with a design resistance f_{ck}; longitudinal reinforcement operates within the design stresses $\sigma_s \leq f_{yd}$, and in the compressed zone, reinforcement is subjected to stresses f_{ck}.

Nevertheless, concrete in the tensile zone is traditionally assumed to be of the same strength class as in the compressed zone of the element. The authors also note that the load-carrying capacity of the element is ensured by various combinations of cross-sectional dimensions and the number of reinforcement bars. The cost of reinforced concrete elements is close to the optimum under the conditions:

μ=1-2% at x/h_0=0.3-0.4 for beams;

μ=0.3-0.6% at x/h_0=0.1-0.15 for slabs.

To reduce cement consumption, it is proposed in [11] to use concrete of reduced strength in the lower (tensile) zone of the element.

Examples of calculations of the economic efficiency of using concrete of a lower strength class in the tensile zone of beams according to [11].

Example 1: Precast concrete beam without prestressing, dimensions 6(L)×0.5(h)×0.2(b) m. The concrete used was C16/20 class with cement grade 400, the cement consumption per beam was 340 kg/m³ with a yield strength of 80%. The volume of concrete in the beam was V_b=6×0.5×0.2=0.6 m³, and the cement consumption was 0.6×340=204 kg. After replacing the concrete in the tensile zone with C8/10 concrete, the cement consumption is reduced to 0.446 m³×235 = 104.9 kg. In the compressed zone, the cement consumption is 0.6 - 0.446 m³ × 340 = 53.76 kg. The total cement consumption after the changes is 158.66 kg, which is 22.23% less.

Example 2: A monolithic reinforced concrete slab with a thickness of 24 cm. Concrete volume per 1 m²: 0.24 m3. Initial cement consumption: 370 kg/m³ × 0.24 = 88.8 kg. After replacing the concrete in the tensile zone with C8/10 class, the cement consumption is reduced to 49 + 11.66 = 60.66 kg, which is 31.7% less.

Example 3: Precast concrete slab with dimensions of 630×150×22 cm with voids. Initial cement consumption for C20/25 concrete: 547.83 kg. After replacing the concrete in the tensile zone with C8/10 class, the cement consumption decreased by 33.5%.

It should be noted that multilayer bent reinforced concrete structures with concrete of a lower class are also formed during reinforcement. Thus, A. Mazurak, I. Kovalyk, V. Mykhaylechko, P. Ambrozyak [12] describe the methodology for experimental studies of reinforced concrete elements reinforced with shotcrete at different levels of loading. The aim of the study is to evaluate the bearing capacity, deformability, and crack resistance of reinforced concrete elements reinforced by different methods, taking into account the technological features of reinforcement. Additionally, a methodology for experimental testing of reinforced concrete beams has been developed, taking into account the residual stresses before their reinforcement. The design and calculation of the experimental beams were based on the analysis of literature sources, current standards, and previous experience in conducting similar studies. To test the methodology, three series of reinforced concrete beams with dimensions of 2300 × 200 × 80 mm and a working span of 2100 mm were manufactured. The beams were reinforced using different technological schemes depending on the series (see Fig. 1): on one side, on both sides and with a U-shaped cage from below and on both sides simultaneously.

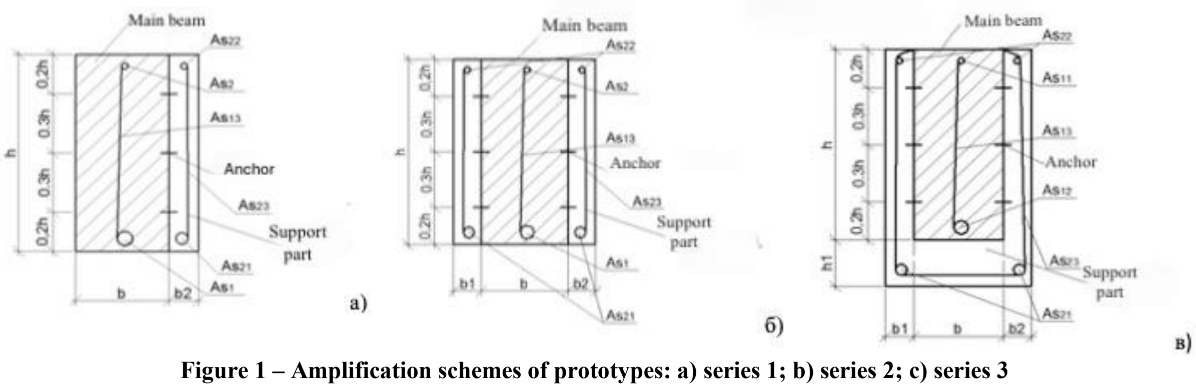

Figure 1 – Amplification schemes of prototypes: a) series 1; b) series 2; c) series 3

To determine the main characteristics, such as bearing capacity, deformability and crack resistance, as well as to assess the effect of the load level on the stress-strain state of the reinforced specimens, bending tests were carried out under short-term concentrated load. The prestressing load levels for the beams reinforced by the shotcrete method were 0, 0.32, 0.45, and 0.63 of the destructive load under conditions of reinforcement yield.

The loading process was carried out in two stages:

1. Before strengthening - the specimens were loaded on a bench in one-third of the section span using weights, springs and a threaded device. Load control was carried out using pre-calibrated springs, threaded tighteners and a lever wrench with a dynamometer. The load was increased gradually ($\Delta F < 0.05\ F_{max}$) with a holding time of 25 min at each step.

2. After strengthening, the beams were tested on a test bench using a hydraulic jack (250 kN) and a distribution beam. The forces were monitored using dynamometers located on the beam supports. The loading was also carried out gradually: before the appearance of cracks with an increase of $\Delta F < 0.05\ F_{max}$, and after

their appearance - by $\Delta F < 0.1\ F_{max}$, with a holding time of 20 min.

To record the deformations, we used:
- clock-type indicators (accuracy 0.01 mm) for measuring deflections of beams;
- micro-indicators (accuracy 0.001 mm) to determine the deformations of concrete and reinforcement;
- electric strain gauges (50 mm base) to measure stresses in the zone of maximum bending moment;
- MPB-2 microscope for recording the moment of crack formation and determining their width.

To improve visual control over the development of cracks, the surface of the beams was painted with water-based paint or putty. The test results were recorded in the relevant journals.

The authors A. Mazurak, I. Kovalyk, P. Ambrozyak, V. Mykhaylechko, [13] proposed methodology made it possible to evaluate the bearing capacity, crack resistance and deformability of reinforced concrete beams reinforced by shotcrete, i.e. two-layer reinforced concrete beams, taking into account the residual stresses before the moment of reinforcement.

Researchers of Lviv Polytechnic National University I.Z. Rutkovska, Z.M. Rutkovskyi, L.I. Vozniuk, A. Marushchak [14] conducted experimental studies of three-layer structures. A methodology for studying three-layer reinforced concrete beams manufactured in two series was proposed. In the first series, the middle layer consisted of expanded clay concrete, and in the second - of foam concrete. Control cubes and prisms were tested to assess the properties of the materials. The beams were mounted on two supports, one movable and one fixed, and the load was applied by two concentrated forces located on the upper face in one-third of the span. The loading process was carried out in gradual stages. To prevent deformations in the areas of concentrated load and supports, distributing steel plates were used on a layer of cement-sand mortar. During the experiment, the moment of crack formation and development were monitored.

The purpose of this experimental study was to improve the methodology for assessing the stress-strain state of three-layer reinforced concrete structures. For this purpose, two series of three-layer reinforced concrete beams (four in each), as well as 12 concrete prisms and 12 control cubes were manufactured (see Fig. 2). The test specimens had dimensions of 1200 × 90 × 120 mm. All beams were reinforced with longitudinal reinforcement of A400C class and transverse reinforcement of Bp1200 class, with a transverse reinforcement spacing of 50 mm. The middle layer of the first series consisted of expanded clay concrete, the second of foam concrete, while the outer layers were made of heavy concrete. The thickness of the inner layer was 40 mm, the upper layer was 30 mm, and the lower layer was 50 mm.

The spatial frame of the reinforcement was made by resistance welding. The concrete mix was made of M500 cement, quartz sand and granite crushed stone. The prismatic strength and initial elastic modulus were determined using a 2PG-100 press, with measurements made on specimens of different sizes. Concrete deformations were recorded with micro-indicators with an accuracy of 0.001 mm. The control tests confirmed that the average prismatic strength of expanded clay concrete was 4.88 MPa, foam concrete - 5.03 MPa, and heavy concrete - 15.28 MPa.

The beams were concreted in batches at the factory and underwent a standard manufacturing cycle, including moulding, compaction and heat treatment. After being transported to the laboratory, they were stored at a temperature of 8-10 °C until the test. The beams were loaded in gradual stages, with control measurements made at each stage of loading. To ensure the accuracy of deflection measurements, used clock-type indicators with a division price of 0.01 mm and for deformations used electric strain gauges.

The results of the experiments showed the effectiveness of the improved methodology for the study of three-layer reinforced concrete beams. The data obtained allow us to better understand the stress distribution, the process of crack formation and development, as well as the behaviour of structures under load. The research results open up new prospects for the further development of multilayer reinforced concrete structures in construction.

а) б) в)

Figure 2 – Fracture pattern of prism samples: a) heavy concrete; b) foam concrete; c) expanded clay concrete

Other researchers - A.V. Mazurak, V.M. Kalitovsky, M.Y. Yukhym, T.A. Mazurak [15] - conducted experimental studies of reinforced concrete beams made and reinforced with shotcrete (see Fig. 3). The main objective of this study is to develop a methodology for assessing the parameters, deformation characteristics, crack resistance and bonding strength of new and old concrete when reinforcing bending reinforced concrete structures with shotcrete. The design and calculation of the experimental beams were performed in accordance with the current regulatory requirements for standard reinforced concrete elements.

The basic shotcrete mixture tested on the test specimens was prepared by dry mixing and had the following composition by weight: sand - 22%, screenings - 9%, crushed stone of 2-5 mm fraction - 20%, crushed stone of 5-10 mm fraction - 25%, cement - 24%. To improve the characteristics, a plasticising admixture silol latex was added in the amount of 0.15% by weight of cement.

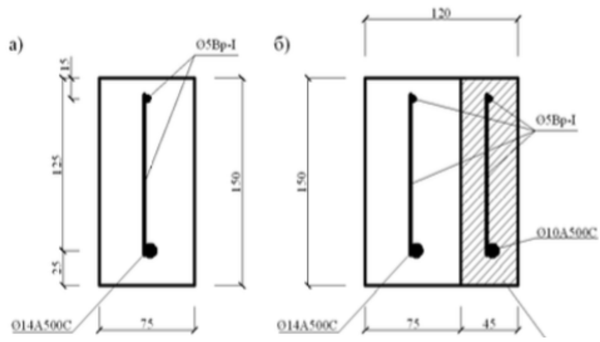

Figure 3 – Scheme of construction of experimental beams: a) beams B-1-1-1, B-1-1-2, B-1-2-1, B-1-2-2, B-1-2-1t, B-1-2-2t; b) reinforced beams with shotcrete B-1-1-1pt, B-1-1-2pt

The compressive and tensile strengths of the concrete specimens during bending were determined in accordance with the standard. The tests were carried out on 40×40×160 mm specimens and 600×600 mm shotcrete slabs. The experimental beams were manufactured in the laboratory of Lviv Regional Scientific and Technical Centre of 'DerzhdorNDI', and the materials were tested in the laboratories of 'DerzhdorNDI', Karpenko Physical Engineering Institute of the National Academy of Sciences of Ukraine and Lviv National Agricultural University.

The research series included eight experimental beams with dimensions of 1650×150×75(150) mm. Four of them (B-1-1-1, B-1-1-2, B-1-2-1, B-1-2-2) were manufactured in the traditional way, and two (B-1-1-1pt, B-1-1-2pt) were reinforced with shotcrete. Two more beams (B-1-2-1t, B-1-2-2t) were manufactured using shotcrete technology with subsequent cutting into separate elements.

To determine the parameters of strength, deformation capacity and crack resistance, the beams were tested in bending by applying two concentrated loads to the upper edge in one-third of the span. The tests were performed on the 220th day after concreting. The working span was 1500 mm, and the loads were applied in stages with a 15-minute dwell time at each stage to stabilise the deformations.

The force was applied using a 250 kN hydraulic jack and a distribution beam. The load was monitored using a reference dynamometer and two ring dynamometers located on the beam supports.

Deflections were recorded using three 0.01 mm precision clock-type indicators mounted on a special metal frame. Concrete deformations were determined by micro-indicators with a division price of 0.001 mm, mounted on the side faces of the beams. Reinforcement deformations were monitored using micro-indicators mounted on special holders attached to the reinforcing bars by resistance welding.

Crack formation was recorded using an MPB-2 microscope. The determination of the moment of crack formation was supplemented by the readings of strain gauges that recorded sudden changes in deformation.

Conclusions according to [16]. The developed methodology makes it possible to evaluate the strength characteristics of concrete, shotcrete, and reinforced concrete beams reinforced by the shotcrete method. It helped to determine the main parameters of strength, crack resistance and deformability of structures in the zones of maximum bending moment. However, further research and improvement of methods for analysing their stress-strain state are needed to gain a deeper understanding of the performance of multilayer structures.

Scientists from Vietnam (Faculty of Civil Engineering, Western Construction University (MTU) T.Q.K. Lam, T.M.D. Do, V.T. Ngo, T.T.N. Nguyen, D.Q. Pham [17] in a scientific article in an international scientific journal investigated the change in concrete class in the layers of three-layer steel fibre-reinforced concrete beams (see Fig. 4). Beams with a cross-section of 150×300 mm, a total span length of 2200 mm and a working length of 2000 mm were studied, where the middle layer consisted of ordinary concrete. All beam specimens were tested under two-point loads. The study modelled three-layer concrete beams with different concrete layers, with and without steel fibres, taking into account the nonlinearity of the material.

However, this study focuses only on the change in concrete class in the layers, but does not take into account parameters such as the number of reinforcing bars, reinforcement diameter, steel fibre content in concrete, changes in layer thickness, etc.

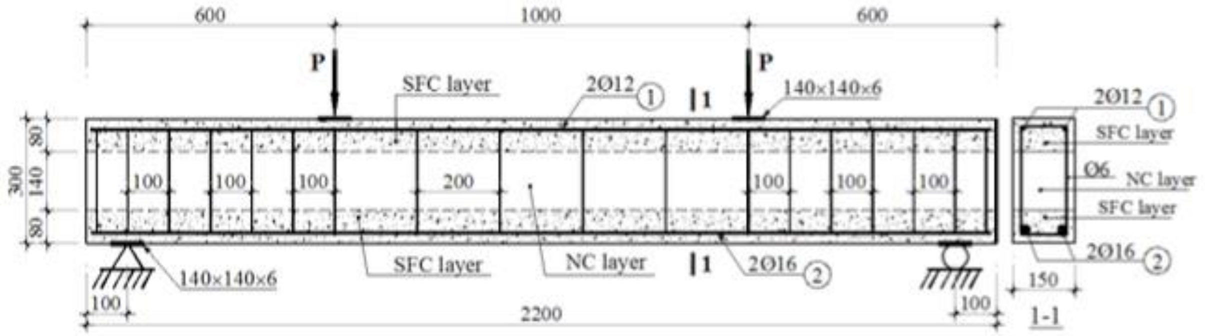

Figure 4 – Structural solution for a three-layer concrete beam model

The results of the study characterise the stress-strain state, crack formation and development, load-compression stress diagrams, load-tensile stress diagrams, and load-vertical displacement in three-layer beams with a change in concrete class. Also, the scheme of crack formation and development in three-layer concrete beams was determined, the load at which cracking begins and the load at which the beams collapse were determined. The relationships between the load, compressive stress, tensile stress, and vertical displacement in the middle of the three-layer beams were established. The study showed that these three-layer concrete beams crack earlier in cases 2 and 3, but the failure of the beams in case 3 occurs at 67 kN, which is the lowest value, and in case 6 - at 116 kN, which is the highest value.

Paper [18] also presents the results of numerical modelling in the ANSYS software package, which includes the analysis of the stress-strain state and crack formation of steel fibre-reinforced concrete layers of three-layer reinforced concrete beams. The advantage of the research is the use of a real concrete work diagram in the numerical modelling of structures (see Fig. 5). Figure 6 shows a diagram of crack formation between the finite elements of stretched concrete.

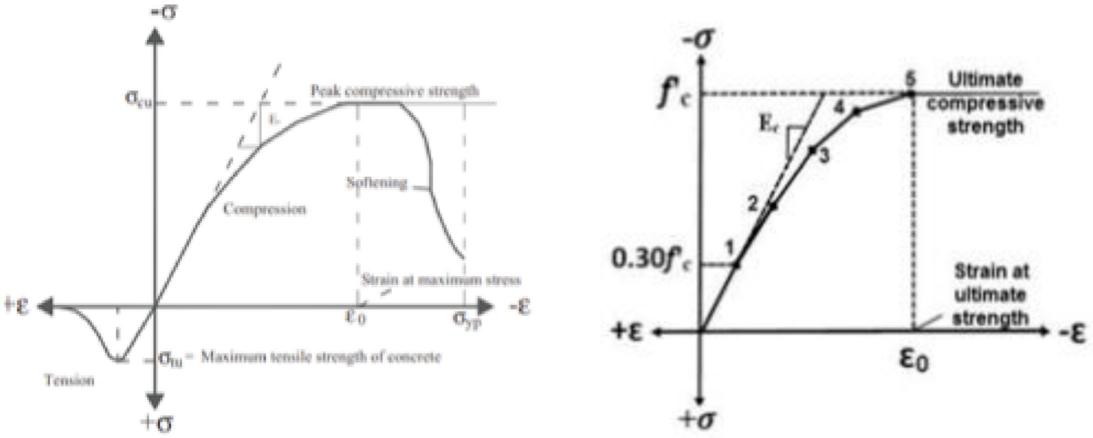

Figure 5 – Typical uniaxial compression and tension diagram for concrete

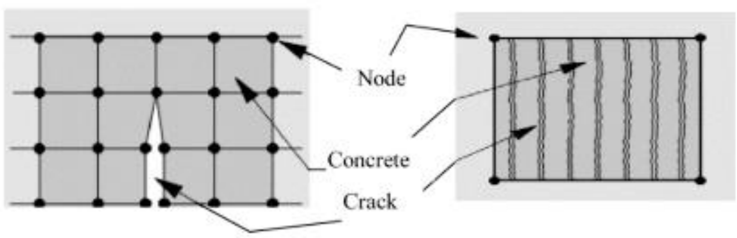

Figure 6 – Model of crack formation in concrete

Finite element model of a reinforced concrete beam with steel fiber reinforcement in ANSYS show in Fig. 9. Element types used in this model. *Concrete:* concrete modeling element: the SOLID65 element is a specialized material simulation for concrete. It can model concrete reinforcement, including cracking and compression effects, and allows the definition of non-linear material properties. This is a 3D element with 8 nodes (see Fig. 7, a). In SOLID65, the content of steel fibers can be specified as a constant percentage of concrete reinforcement. *Steel reinforcement:* Steel bar element: the BEAM188 element is used for modeling beam reinforcement. It is based on Timoshenko beam theory and consists of 2 nodes, each having 6 degrees of freedom (Fig. 7, b and 8).

The analysis of multilayer steel fibre-reinforced concrete beams using experimental and numerical methods (see Figs. 9) shows the need for further study of other parameters that affect the performance of three-layer beams. Based on the results of the study [21-22], the following conclusions were drawn: the analysis of changes in the concrete grade in the layers shows that the value of the compressive stress is the lowest in case 1. Cases 3 and 6 have higher tensile stress values than the other cases considered. The change in vertical deflection in the centre of the span between the cases is very small. Bearing capacity of the beam: the earliest damage is observed in case 3, while the latest damage is observed in case 6. In cases 5 and 6, the effect of steel fibres on the change in concrete grade in the layers of three-layer concrete beams is very significant; the use of steel fibres in the layers of three-layer concrete beams is necessary. In cases 1 and 3, the effect of the presence or absence of steel fibres is minimal.

In the scientific article ‘Experimental study of pre-stressed two-layer reinforced concrete beams’, the authors: Yakov Iskhakov, Yuri Rybakov, Klaus Holschechmacher, Stefan Keseberg [23] discussed the issue of researching a series of experiments on the study of double-layer beams (DLB). As part of this series, the concept of the DBG was developed, high-strength concrete with metal fibres (HSCF) was tested as a material, and simple braced and double-span beams were tested.

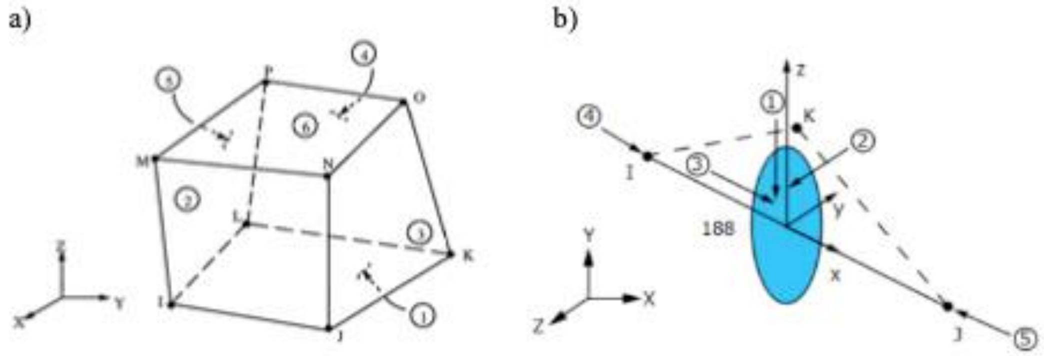

Figure 7 – Types of beam elements: a) Solid65 element, b) beam188 element

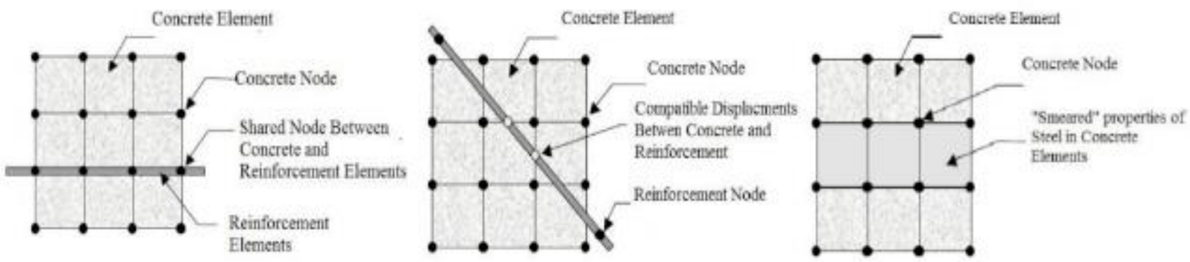

Figure 8 – Model of steel fibres in concrete

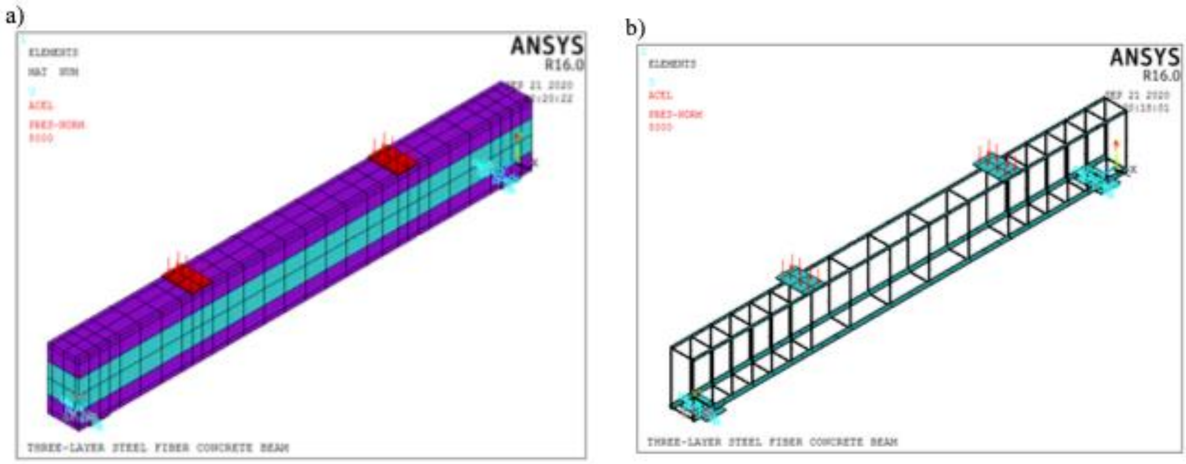

Figure 9 – Three-layer model of concrete beam in ANSYS: a) model of a three-layer concrete beam, b) modelling of steel bars in concrete beams.

In the scientific article ‘Experimental study of prestressed two-layer reinforced concrete beams’, the authors: Yakov Iskhakov, Yuri Rybakov, Klaus Holschechmacher, Stefan Keseberg [23] discussed the issue of researching a series of experiments on the study of double-layer beams (DLB). As part of this series, the concept of the DBG was developed, high-strength concrete with metal fibres (HSCF) was tested as a material, and simple braced and double-span beams were tested. The current study focuses on the testing of full-scale prestressed simple braced beams (SSBs). The aim of the study is to investigate the bending behaviour of the PPSSB under a four-point loading scheme and compare it with non-prestressed beams (see Figure 10).

As in the previous stages of the study, the interaction of concrete layers in the HFRPB was studied to confirm the effectiveness of such beams in real long-span reinforced concrete structures.

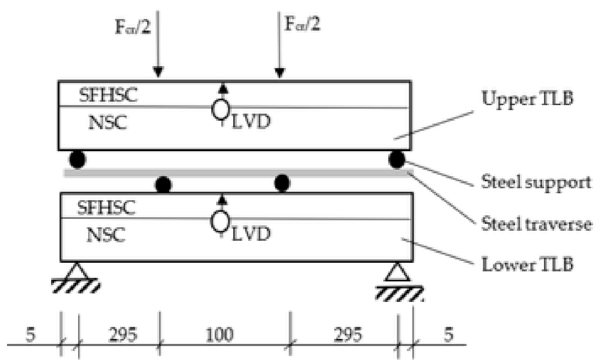

Figure 10 – Dimensions and loading pattern of the investigated double-layer reinforced concrete beams (DLRB)

No delamination between the HSMF and conventional concrete (CC) layers was observed up to the ultimate state, indicating a reliable interaction between the layers. The obtained results allow us to recommend the

HSCF for further research of full-scale reinforced concrete elements with larger spans (9-12 m) and their practical application as efficient and economical bending elements.

Conclusions from [15]: continuing the previous research on non-prestressed DLRBs, this work is devoted to the study of prestressed DLRBs (PPDLRBs). The study is aimed at testing simple support beams with an optimum steel fibre content under a four-point loading scheme from the initial stage to failure, and comparing the results with those of previous studies of non-prestressed beams. The interaction of the concrete layers in the prestressed concrete beams was studied to confirm the effectiveness of such beams in real structures.

The following aspects were considered for the studied PCSBs: crack initiation and development, vertical deflections, transverse deformations, vertical and horizontal shear deformations between layers, and the behaviour of prestressed ropes.

The appearance of bending cracks in the WB layer was observed at 75 kN, which is approximately twice the value for the unstressed SSBs. At subsequent loading stages, the cracks developed to the interface between the layers, but no cracks were observed in the HFBF layer. The bearing capacity of the prestressed beams is approximately 20% higher than that of the DSBs. Similar to the DSBs, the PPDSSBs showed good interaction between the HFBF and reinforced concrete layers. The maximum transverse strains in the HSMF layer of the PPDSS were twice as high as those in the DSB, which demonstrates the possibility of nonlinear deformation in concrete. This is especially important for DSBs with a compressed layer of high-strength concrete.

The maximum vertical shear strains in the linear range of the PPDSS and DSB are similar, but the ultimate shear strains in the PPDSS are about 70% higher and the bearing capacity is 20% higher compared to the DSB.

At the stages with insignificant cracking, the horizontal shear strains between the layers in the PPDSC are insignificant, which confirms the perfect interaction between the layers of the HMF and the concrete. The maximum horizontal shear strains between the layers in the PPDSC are approximately twice as high as in the DSB, which corresponds to the increase in transverse strains in the compressed layer of the PPDSC.

In all the studied PPDSCs, no cracks between the HFBF and WB layers were observed up to the limit state, which indicates proper interaction of the layers. The obtained results allow us to recommend the PPBF for further research of full-scale elements with a larger span (9-12 m) and their practical application as efficient and economical continuous bending elements.

The above-mentioned authors [11] also considered the issue and covered it in an article in an international scientific journal: Methodology and Experimental Investigation of Linear Creep in Double-Layer Reinforced Concrete Beams.

This article presents the first stage of the experimental study of creep in double-layer reinforced concrete beams. The main focus is on the methodology of testing beams under long-term loading in order to investigate the real effect of linear creep. The beams under study consisted of ordinary strength concrete (OSC) in the tensile zone and high strength steel fibre concrete (HSCF) in the compressed zone.

The specimens were subjected to bending under a four-point loading scheme at loads of 70% and 85% of their bearing capacity. The load was applied using special reinforcing devices. The experiment at this stage lasted 90 days. Deflections were measured in the middle of the span of each specimen. During the first 24 hours after the load was applied, deflections were recorded every 10 seconds, and then every hour.

During the tests, no cracks were observed near the supports or between the layers of BZM and SFRP. Cracks appeared only within the clean bending zone. Load-deflection curves were obtained and analysed. The maximum deflection in the middle of the span in the studied beams was less than 1/250 of the beam span length, which indicates the safety of the structure and the beam being in an elastic state with linear creep. The results obtained are the basis for the second stage of the experimental study, which will focus on the effect of nonlinear creep in such beams.

Thus, the paper presents the results of an experimental study of linear creep in two-layer reinforced concrete beams. A methodology for testing creep of reinforced concrete beams was developed. Special amplifying devices with lever systems were used to apply a long-term load to the test specimens. The experimental results showed that the previously proposed algorithm can be used to evaluate the effect of linear creep in two-layer reinforced concrete beams. The maximum deflection in the middle of the span of the tested beams was less than 1/250 of the span length, which indicates the safety of the structure and the beams being in an elastic state under the action of linear creep. The results obtained are the basis for the next stage of the experimental study, which will be devoted to the study of the effect of nonlinear creep in such beams.

Conclusions

Thus, reducing the use of cement and reducing the weight of concrete in bending reinforced concrete elements is an important task in modern construction. To solve this problem, various methods are being implemented, including the use of both removable and non-removable void formers, and the combination of several materials (e.g., heavy in the compressed zone and light in the tensile zone of concrete) for their mutually beneficial joint operation. The paper provides an overview of several experimental and theoretical studies in these areas, which substantiate the possibility and feasibility of reducing the strength of concrete in the tensile zone of bending reinforced concrete structures, and as a result, reducing the consumption of cement for the preparation of concrete mix for structures, without pre-stressing the latter. The use of two- and multi-layer elements with porous aggregates can significantly improve sound and thermal insulation characteristics, as well as reduce the dead weight of structures, which leads to savings in materials, labour and financial resources. The right choice of material for each layer allows us to create structures with high performance characteristics.

References

1. Shmukler V.S. (2005). Evolutionist approach in rationalization of building structures Shmukler. *ISEC-03. Third International structural Engineering and construction Conference, Shunan (Japan)*

2. Мельник І.В., Сорохтей В.М., Кузик О.О. (2010). Монолітні плоскі залізобетонні перекриття з пінополістирольними вставками. *Вісн. Львів. терит. від-ня Акад. буд-ва України, 5* (10), 146-153.

3. Шмуклер В.С., Бугаєвський С.А., Нікулін В.Б., Ямкова Т.І. (2015). Вплив якісного та кількісного складу компонентів бетону на технологічні властивості само ущільнювальної бетонної суміші. *Зб. наук. пр. "Ресурсоекономні матеріали, конструкції, будівлі та споруди", 31*, 168-175.

4. Демчина Б.Г., Литвиняк О.Я., Давидюк О.В. (2011). Дослідження збірно-монолітних залізобетонних плит перекриття з використанням пінобетону. *Будівельні конструкції: міжвідомчий науково-технічний збірник наукових праць (будівництво), 74*: в 2-х книгах. Книга 1. 160–166.

5. Sohel K.M.A., Richard Liew J.Y. (2011). Steel-Concrete-Steel sandwich slabs with lightweight core - *Static performance. Engineering Structures*, 33(3), 981-992. [Електронний ресурс] - Режим доступу: http://www.sciencedirect.com/science/article/pii/S0141029610004918?via%3Dihub

6. Shams, A., Horstmann, M., Hegger, J. (2014). Experimental investigations on Textile-Reinforced Concrete (TRC) sandwich sections. *Composite Structures*, *118*, 643–653. [Електронний ресурс] - Режим доступу: http://linkinghub.elsevier.com/retrieve/pii/S0263822314003791

7. Lai T., Connor J.J., Veneziano D. (2020). Structural behavior of BubbleDeck slabs and their applicatiob to lightweight bridge decks. *Massachusetts Institute of Technology*; June 2020

8. Литвиняк О.Я. (2012). Дослідження на згин при монтажі та експлуатації збірно-монолітних залізобетонних плит перекриття з використанням пінобетону. *Науковий вісник будівництва: збірник наукових праць Харківського національного університету будівництва та архітектури, 69*, 153-160.

9. Шаленний В.Т., Щегула Р.В. (2022). Порівняльна ефективність монолітних перекриттів із вкладишами з картону, пластмаси та місцевих кам'яних матеріалів. *Будівництво та техногенна безпека. 24(76).* 63-70.

10. Бабій І.М, Коломійчук В.Г. (2019). Ефективні попередньо напружені монолітні залізобетонні перекриття з використанням незнімних вкладишів-порожниноутворювачів. *Бетон та залізобетон в Україні. 2.* 13-18.

11. Пушкарьов Б.А. (2023). Спосіб зниження витрат цементу під час виготовлення згинаних залізобетонних конструкцій без попереднього напруження. *Будівництво та техногенна безпека. 29(81),* 81-86.

1. Shmukler V.S. (2005). Evolutionist approach in rationalization of building structures Shmukler. *ISEC-03. Third International structural Engineering and construction Conference, Shunan (Japan)*

2. Melnyk I.V., Sorokhtey V.M. & Kuzyk O.O. (2010). Monolithic flat reinforced concrete slabs with expanded polystyrene inserts. *Bulletin of the Lviv Territorial Branch of the Academy of Civil Engineering of Ukraine, 5* (10), 146-153.

3. Shmukler V.S., Bugayevsky S.A., Nikulin V.B. & Yamkova T.I. (2015). Influence of the qualitative and quantitative composition of concrete components on the technological properties of self-compacting concrete mix. *Collection of scientific papers "Resource-efficient materials, structures, buildings and structures", 31*, 168-175.

4. Demchina B.G., Litviniak O.Y. & Davydiuk O.V. (2011). Investigation of precast monolithic reinforced concrete slabs using foam concrete. *Building structures: interdepartmental scientific and technical collection of scientific papers (construction), 74*: in 2 books. Book 1. 160-166.

5. Sohel K.M.A. & Richard Liew J.Y. (2011). Steel-Concrete-Steel sandwich slabs with lightweight core - *Static performance. Engineering Structures*, 33(3), 981-992. [Electronic resource] - Access mode: http://www.sciencedirect.com/science/article/pii/S0141029610004918?via%3Dihub

6. Shams, A., Horstmann, M. & Hegger, J. (2014). Experimental investigations on Textile-Reinforced Concrete (TRC) sandwich sections. *Composite Structures*, *118*, 643–653. [Electronic resource] - Access mode: http://linkinghub.elsevier.com/retrieve/pii/S0263822314003791

7. Lai T., Connor J.J. & Veneziano D. (2020). Structural behavior of BubbleDeck slabs and their applicatiob to lightweight bridge decks. *Massachusetts Institute of Technology*; June 2020

8. Litviniak O.Y. (2012). Bending tests during installation and operation of precast concrete slabs using foam concrete. *Scientific Bulletin of Construction: Collection of scientific papers of Kharkiv National University of Construction and Architecture, 69*, 153-160.

9. Shalenny V.T. & Shchegula R.V. (2022). Comparative efficiency of monolithic ceilings with liners made of cardboard, plastic and local stone materials. *Construction and technogenic safety. 24(76).* 63-70.

10. Babiy I.M. & Kolomiychuk V.G. (2019). Efficient prestressed monolithic reinforced concrete slabs using non-removable ones. hollow-forming inserts. *Concrete and reinforced concrete in Ukraine 2,* 13-18.

11. Pushkarev B.A. (2023). Method for reducing cement consumption when manufacturing flexible reinforced concrete structures without pre-stressin. *Construction and technogenic safety. 29(81),* 81-86.

12. Мазурак А., Ковалик І., Михайлечко В., Амброзяк П. (2015). Методика експериментальних досліджень залізобетонних елементів, підсилених торкретуванням, за різних рівнів навантажень. *Вісник Львівського національного аграрного університету Архітектура і сільськогосподарське будівництво 16,* 48-54.

13. Мазурак А.В., Калітовський В.М., Ковалик І.В. (2011). Методика експериментальних досліджень підсилених залізобетонних елементів за різних рівнів навантажень. *Вісник Лвівського національного аграрного університету: архітектура і сільськогосподарське будівництво. 12.* 83 – 88.

14. Рутковська І.З., Рутковський З.М., Вознюк Л.І., Марущак А. (2008). Експериментальні дослідження тришарових конструкцій. *Вісник Національного університету "Львівська політехніка". 627.* 179-182.

15. Мазурак А.В., Калітовський В.М., Юхим М.Я., Мазурак Т.А. (2009). Методика експериментальних досліджень залізобетонних балок, виготовлених і підсилених торкретуванням. *Дороги і мости. Київ, Випуск 11.* 226-232.

16. Артюх В.Г., Санников І.В. (2007). Торкрет – бетон у цивільних будинках, що реконструюються. *Будівництво України, 3.* 11-13.

17. T.Q.K. Lam, T.M.D. Do, V.T. Ngo, T.T.N. Nguyen, D.Q. Pham. (2020). Concrete grade change in the layers of three-layer steel fibre reinforced concrete beams. *Journal of Achievements in Materials and Manufacturing Engineering, 102(1),* 16-29.

18. V.T. Ngo, T.Q. Khai Lam, T.M. Dung Do, T.C. Nguyen. (2019). Nano concrete aggregation with steel fibers:A problem to enhance the tensile strength of concrete, *E3S Web of Conferences 135,* 03001. https://doi.org/10.1051/e3sconf/201913503001

19. Wang, C., Shen, Y., Yang, R. & Wen, Z. (2017). Ductility and Ultimate Capacity of Prestressed Steel Reinforced Concrete Beams. *Hindawi Mathematical Problems in Engineering*, 6, 1467940. https://doi.org/10.1155/2017/1467940

20. V.T. Ngo, T.Q.K. Lam, T.M.D. Do, T.C. Nguyen. (2020). Increased plasticity of nano concrete with steel fibers, *Magazine of Civil Engineering 93/1* 27-34. https://doi.org/10.18720/MCE.93.3

21. T.Q. Khai Lam, D.D. Thi My, V.T. Ngo, T. Chuc Nguyen, T. Phuoc Huynh. (2020). Numerical simulation and experiment on steel fiber concrete beams. *Journal Physics: Conference Series 1425* 012007. https://doi.org/10.1088/1742-6596/1425/1/012007.

22. T.M.D. Do, T.Q.K. Lam. (2021). Design parameters of steel fiber concrete beams. *Magazine of Civil Engineering* 102/2.

23. I. Iskhakov, K. Holschemacher, S. Kaeseberg, Y. Ribakov. (2025). Methodology and Experimental Investigation of Linear Creep Behavior in Two-Layer Reinforced Concrete Beams. *Appl. Sci., 15(7),* 3456. https://doi.org/10.3390/app15073456

12. Mazurak A., Kovalyk I., Mihaylechko V. & Ambroziak P. Methods. (2015). Experimental experimental study concrete elements reinforced concrete spraying atdifferent levels of load. *Bulletin of the Lviv National Agrarian University. Architecture and Agricultural Construction, 16,* 48–54.

13. Mazurak A.V., Kalitovskiy V.M. & Kovalyk I.V. (2011). Methodology of experimental research on strengthened reinforced concrete elements under different load levels. *Bulletin of the Lviv National Agrarian University. Architecture and Agricultural Construction, 12,* 83–88.

14. Rutkovska I.Z., Rutkovskyi Z.M. & Voznyuk L.I., Marushchak A. (2008). Experimental studies of three-layer structures. *Bulletin of the National University "Lviv Polytechnic", 627,* 179–182.

15. Mazurak A., Kalitovsky V., Yuhim M. & Mazurak T. (2009). Technique of experimental research of reinforced beams manufactured and reinforced by guniting. *Roads and bridges. Kyiv,11.* 226-232.

16. Artiukh V.H. & Sannikov I.V. (2007). Shotcrete in renovated civil buildings. *Construction of Ukraine, 3,* 11–13.

17. T.Q.K. Lam, T.M.D. Do, V.T. Ngo, T.T.N. Nguyen & D.Q. Pham. (2020). Concrete grade change in the layers of three-layer steel fibre reinforced concrete beams. *Journal of Achievements in Materials and Manufacturing Engineering, 102(1),* 16-29.

18. V.T. Ngo, T.Q. Khai Lam, T.M. Dung Do & T.C. Nguyen. (2019). Nano concrete aggregation with steel fibers:A problem to enhance the tensile strength of concrete, *E3S Web of Conferences 135,* 03001. https://doi.org/10.1051/e3sconf/201913503001

19. Wang, C., Shen, Y., Yang, R. & Wen, Z. (2017). Ductility and Ultimate Capacity of Prestressed Steel Reinforced Concrete Beams. *Hindawi Mathematical Problems in Engineering*, 6, 1467940. https://doi.org/10.1155/2017/1467940

20. V.T. Ngo, T.Q.K. Lam, T.M.D. Do, T.C. Nguyen. (2020). Increased plasticity of nano concrete with steel fibers, *Magazine of Civil Engineering 93/1* 27-34. https://doi.org/10.18720/MCE.93.3

21. T.Q. Khai Lam, D.D. Thi My, V.T. Ngo & T. Chuc Nguyen, T. Phuoc Huynh. (2020). Numerical simulation and experiment on steel fiber concrete beams. *Journal Physics: Conference Series 1425* 012007. https://doi.org/10.1088/1742-6596/1425/1/012007.

22. T.M.D. Do & T.Q.K. Lam. (2021). Design parameters of steel fiber concrete beams. *Magazine of Civil Engineering* 102/2.

23. I. Iskhakov, K. Holschemacher, S. Kaeseberg & Y. Ribakov. (2025). Methodology and Experimental Investigation of Linear Creep Behavior in Two-Layer Reinforced Concrete Beams. *Appl. Sci., 15(7),*3456. https://doi.org/10.3390/app15073456