Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2024.62.3884

UDC 624.012.4-183.2:624.94.012.45:624.042.65

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Review of multilayer reinforced concrete beams with rectangular cross section experimental-theoretical studies

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One of the options for reducing cement consumption for the preparation of concrete for bent reinforced concrete structures is the use of two-layer beams with higher strength concrete in the compressed zone and lower strength concrete in the tensile zone, which saves cement without losing structural strength. Experimental tests and theoretical calculations of concrete deformations in the compressed zone of five series of concrete beams with cross-sectional dimensions of b×h = 100×160 mm and a total length of 1500 mm were compared; compressed zone concrete of class C20/25; tensile zone concrete of class C12/15; reinforcement in the tensile zone - 2Ø12 mm of class A400C. The beams differed in the thickness of the concrete layers in the compressed and tensile zones. As a result of the comparison, it was found that the average value of the ratio of theoretical to experimental results was 15.1%; the mathematical expectation of this ratio was 0.856; the coefficient of variation of the ratio was 9.3%, which indicates a fairly high correlation of results.

Keywords: test, experiment, theoretical research, reinforced concrete, bending, two-layer.

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Introduction

The development of the range of building structures involves both the search for fundamentally new types of elements made of one material or in combination of several materials for their joint mutually beneficial operation and the improvement of existing building products, namely, reducing their weight while ensuring the same load-bearing capacity, increasing the manufacturability of production, etc. This issue is even more acute in bending reinforced concrete structures, as stretched concrete is not taken into account in the calculation of the overall bearing capacity of the structure, but only increases its weight and, consequently, the cost of manufacturing. *That is why replacing stretched concrete in such structures with a cheaper material, such as concrete of a lower strength class or with porous aggregates, is an urgent problem.*

Review of the research sources and publications

In their works, the researchers 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 [1] describes a method for the production of precast concrete floor 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.

Work [2], led by V.S. Shmukler, indicates that for 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 cavity fillers, the channel walls in newly formed products sometimes collapse. For this reason, boards with round cavities were adopted as the standard. Further development of technologies will allow us to move to more economical designs.

Demchyna B.G., Litviniak O.Y. and Davydiuk O.V. [3-4] were the first to scientifically substantiate the use of foam concrete in precast concrete slabs.

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 voiding agents of various shapes (washer, spherical, box) [6-7], as well as stone materials [8]. This method can reduce concrete consumption by up to 30 % compared to solid slabs.

Definition of unsolved aspects of the problem

Definition of unsolved aspects of the problem

Thus, the creation of resource-saving building structures involves the search for new types of them made of one material or in combination of several materials for their mutually beneficial operation, reducing their cost while ensuring the same load-bearing capacity, increasing the manufacturability of production, etc. It should be noted that in calculations of the total bearing capacity of a structure, stretched concrete is not taken into account [9], but only increases its weight and, consequently, the cost of manufacturing. However, a systematic review of the results of both experimental and theoretical studies of 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 performed.

Problem statement

The aim of this paper is to review the results of experimental and theoretical studies of concrete reinforced beams of rectangular cross-section and to compare them.

Basic material and results

To obtain experimental data on the performance of concrete reinforced beams of rectangular cross-section [10-11], the following specimens were made (see Table 1 and Figure 1):

1. concrete beam: concrete of compressed zone of class C20/25 - 80 mm, concrete of tensile zone of class C12/15 - 80 mm (sample B-1 - 3 pieces);
2. concrete beam: concrete of compressed zone of class C20/25 - 40 mm, concrete of tensile zone of class C12/15 - 120 mm (sample B-2 - 3 pieces);
3. concrete beam: concrete of the compressed zone of class C20/25 - 120 mm, concrete of the tensile zone of class C12/15 - 40 mm (sample B-3 - 3 pieces);
4. concrete beam: concrete of compressed zone of class C20/25 - 55 mm, concrete of tensile zone of class C12/15 - 105 mm (sample B-4 - 3 pieces);
5. concrete beam: concrete of compressed zone of class C20/25 - 105 mm, concrete of tensile zone of class C12/15 - 55 mm (sample B-5 - 3 pieces);
6. beam made of solid concrete of class C20/25 (sample B-6 - 3 pieces);
7. beam made of solid concrete of class C12/15 (sample B-7 - 3 pieces);
8. concrete prisms and cubes for determination of physical and mechanical properties of concrete;
9. reinforcing bars for determination of physical and mechanical characteristics of reinforcement.

Table 1 - Ratio of concrete heights of concrete reinforced beams of rectangular cross-section

Grade of beams	B-1	B-2	B-3	B-4	B-5
Ratio of height (mm) of concrete classes C20/25 to C12/15	80/80 $h_{C20/25}/h_{C12/15}=1$	40/120 $h_{C20/25}/h_{C12/15}=0,33$	120/40 $h_{C20/25}/h_{C12/15}=3$	55/105 $h_{C20/25}/h_{C12/15}=0,5$	105/55 $h_{C20/25}/h_{C12/15}=2$

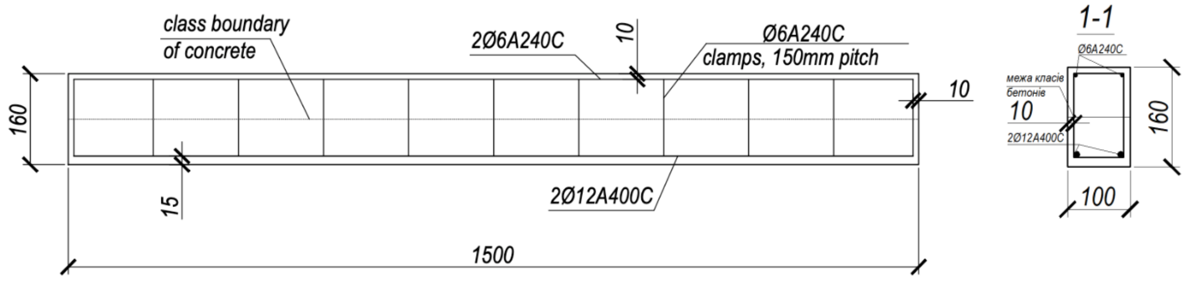

Figure 1 – Formwork drawing of experimental beams

The concrete mix was made using M500 cement from Balakleya Cement and Slate Plant, 10-20 mm granite crushed stone from Kremenchuk quarry and quartz sand with a particle size distribution of 1.0. The composition of the lightweight concrete was as follows: cement - 400 kg, sand - 655 kg, crushed stone - 1130 kg, water-cement ratio (w/c) was 0.55. The concrete mixture was mixed in a 50-litre electrically driven concrete mixer.

To measure the relative deformations of the beams in the zone of maximum bending moments, wire strain gauges 2PKB-20-200KhB with a base of 20 mm on the reinforcing bars and a base of 50 mm on the concrete surface were used (see Fig. 2). To measure the deflections, we used clock-type indicators (division price of 0.1 mm).

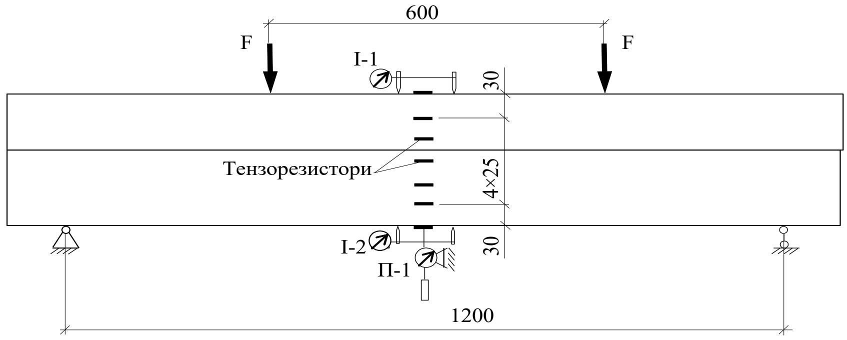

Figure 2 – Scheme of loading during experimental testing of concrete beams and placement of measuring instruments

In the study of the stress-strain state of bending elements with normal cross-sections, the deformations in the fibres furthest from the neutral layer (the most stretched and the most compressed) are of decisive importance, since they can be used to judge the bearing capacity of the structure under study. As a result of measuring the deformations in the outermost fibres of the cross-section of the studied bi-concrete reinforced beams of rectangular cross-section, measured using electrotensor resistors, graphs of the dependence of deformations on the bending moment of the samples of five series were obtained.

The theoretical determination of the strength of sections normal to the longitudinal axis of reinforced concrete beams can be carried out similarly to the calculation of the strength of conventional reinforced concrete beams [12]. In addition, in the practice of building structures construction, it is rarely necessary to accurately describe the stress-strain state of an element. Usually, it is sufficient to determine the bearing capacity of the element and the maximum deflection with the required accuracy. the assessment of the strength of the normal section of reinforced concrete beams is presented on the basis of a joint solution of the equilibrium equation of longitudinal forces in accordance with the scheme of internal forces arising in the cross section.

The hypotheses underlying the theoretical calculations of strength and deformability of concrete reinforced beams are as follows:

• concrete reinforced beams operate reliably under various loading patterns and conditions;

• at all stages of loading, the joint operation of two layers of concrete and the working reinforcement of the complex beam is ensured;

• when composite beams operate in the elastic stage, the hypothesis of flat sections is valid, and the horizontal layers do not press on each other, i.e. there are no compression deformations and they do not affect the stress-strain state of the structure.

Figure 3 shows a comparison of the development of deformations in the most compressed (upper) fibre of five series of concrete beams in the middle of the span, obtained as a result of experimental tests and calculated theoretically on the basis of a joint solution of the equilibrium equation of longitudinal forces arising in the cross-section of the beams. The graphs in Figure 3 show that all specimens, regardless of the value of the ratio of the height of the higher class concrete to the lower class, were elastic at the initial stages of loading in both the compressed and tensile zones of the bending element cross-section. The appearance of plastic deformations was observed at loads of 60-65% of the destructive load; the bending moment was 5.7-6.3 kNm.

The calculated deviations of the theoretical from the experimental results of determining the deformations of the compressed zone of concrete are recorded on the graphs in Figure 3 for each degree of loading of each series of tested specimens in percent. Table 2 shows the average values of these deviations for each series of beams. A graphical comparison of the deviations presented in Table 2 is shown in Figure 4. The average value of the deviation of theoretical from experimental results for beams of all series is 15.1%.

In order to assess how well the theoretical model for determining deformations based on the joint solution of the equilibrium equation of longitudinal forces arising in the cross-section of beams agrees with the reality represented by experimental data, statistical processing of the results was performed: the mathematical expectation and the coefficient of variation of the ratio of theoretical results to experimental ones were calculated (see Figure 5).

Statistical processing is essentially a test of the reliability of the theoretical model and the identification of potential deviations. The tasks of statistical processing are as follows:

– *assessment of the accuracy of the theoretical model:* the mathematical expectation (mean) of the ratios can show whether the theoretical values overestimate or underestimate the experimental values. The calculated mean value of the mathematical expectation of the ratio is 0.856, which indicates that the theoretical model slightly underestimates the experimental values;

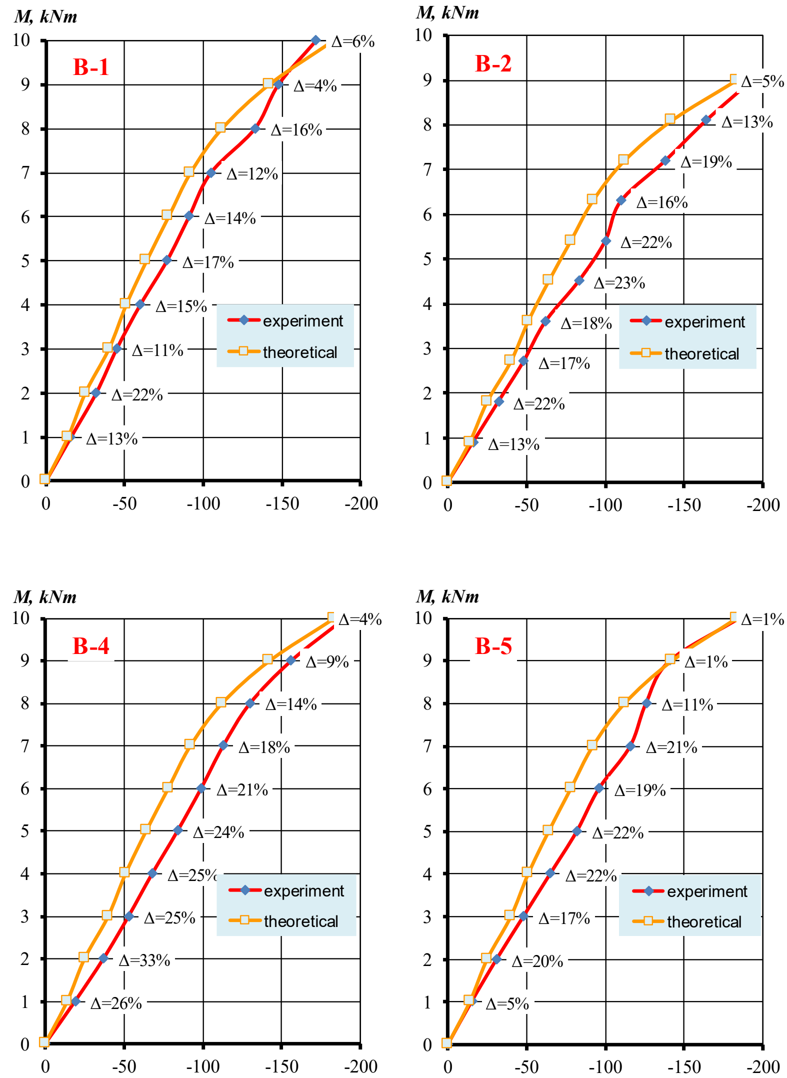

Table 2

Average deviations of theoretical calculations from experimental test data

Series number	Δ, %
B-1	13,0
B-2	16,7
B-3	12,0
B-4	19,8
B-5	13,9

Figure 3 – Comparison of the development of deformations in the most compressed (upper) fibre of five series of concrete beams obtained as a result of experimental tests and calculated theoretically on the basis of a joint solution of the equilibrium equation of longitudinal forces

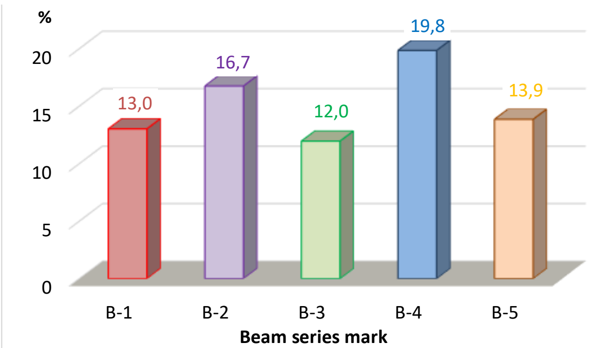

Figure 4 – Comparison of deviations of theoretical calculations from experimental tests

– *detection of systematic deviations:* if the mathematical expectation of the ratio differs from 1.0, this indicates a systematic error in the theoretical model. The applied theoretical model consistently underestimates the experimental data, as described above;

– *to determine whether the theoretical model is too simple*: if the mathematical expectation of the ratios differs significantly from 1.0, this may indicate that the model does not take into account important factors that affect the experimental data. In our case, there were no significant deviations, which indicates that all important factors of the experimental tests are taken into account in the theoretical model;

– *determining whether the theoretical model is too complex:* in some cases, an overly complex model can be 'overtrained' on experimental data, leading to poor predictions on new data. In our case, no overly complex aspects were found in the theoretical model;

– *selection of model parameters:* mathematical expectation calculations can be used to select the parameters of a theoretical model that give the best fit to experimental data;

– *model improvement:* analysis of deviations from mathematical expectation can help identify the causes of deviations and improve the theoretical model.

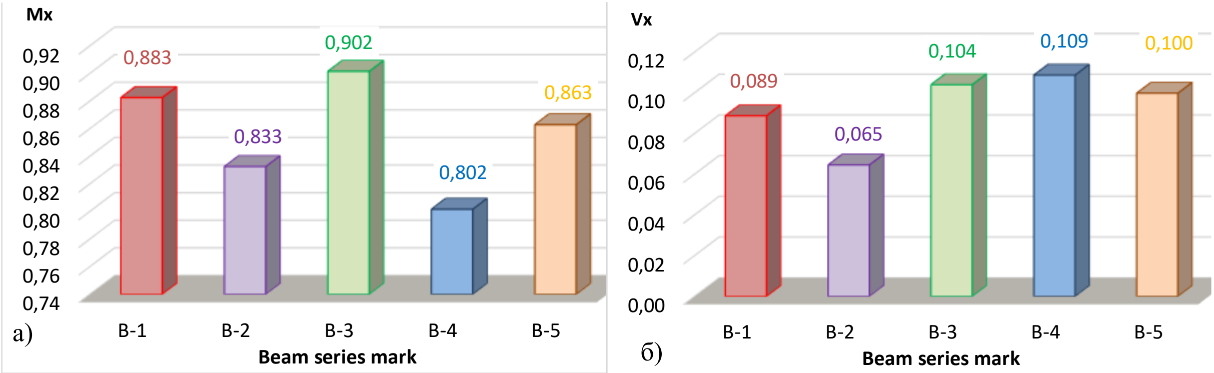

Figure 5 – Comparison of mathematical expectation (a) and coefficient of variation (b) ratio of theoretical results to experimental ones

Conclusions

The results of experimental studies confirm the feasibility of using bi-concrete beams in construction practice to ensure the economic and technical efficiency of load-bearing structures. The effective ratio of layers with different concrete characteristics reduces cement consumption for the preparation of the concrete mix. The efficiency of bi-concrete beams is based on the rational distribution of materials: concrete with higher strength is used in the compressed zone, while less durable concrete is used in the tensile zone, which saves resources without losing structural strength.

The average value of the deviation of the theoretical deviation of the longitudinal forces arising in the cross-section of the beams from the experimental results of determining the deformations of the compressed zone of concrete calculated for all five series of beams based on a joint solution of the equilibrium equation of the longitudinal forces arising in the cross-section of the beams is 15.1%. The average value of the mathematical expectation of the ratio of theoretical to experimental results of all five series of beams is 0.856; the average value of the coefficient of variation of this ratio is 9.3%.

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Порівняння експериментально-теоретичних досліджень згинаних бібетонних армованих балок прямокутного поперечного перерізу

Одним з варіантів зменшення витрат цементу для приготування бетону згинаних залізобетонних конструкцій є застосування двошарових балок із раціональним розподілом матеріалів: бетон з вищою міцністю застосовують в стиснутій зоні, тоді як менш міцний бетон використовується в розтягнутій зоні, що й забезпечує економію цементу без втрати міцності конструкції. У статті наведено конструкцію та методику виготовлення експериментально досліджених п'яти серій зразків бібетонних балок загальною кількістю 15 штук із розмірами поперечного перерізу – $b \times h$ = 100×160 мм; загальна довжина балок – 1500 мм; відстань між опорами L = 1200 мм; бетон стиснутої зони класу С20/25; бетон розтягнутої зони класу С12/15; армування в розтягнутій зоні – 2Ø12мм класу А400С. Балки відрізнялися товщиною шарів бетону стиснутої та розтягнутої зон. У результаті порівняння експериментальних випробувань та теоретичних розрахунків деформацій бетону стиснутої зони встановлено, що середнє значення відхилення теоретичних від експериментальних результатів рівне 15,1%; математичне сподівання відношення теоретичних від експериментальних результатів становить 0,856; коефіцієнт варіації відношення – 9,3%, що свідчить про достатньо високу кореляцію результатів експериментальних випробувань та теоретичних розрахунків.

Ключові слова: випробування, експеримент, теоретичні розрахунки, залізобетон, згинання, двошаровість.

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