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Effectiveness of using fiber-reinforced concrete in columns with external corner reinfocement

Abstract. This article examines the effectiveness of using concrete reinforced with basalt and steel fibers in columns with external corner reinforcement. Concrete columns with external corner reinforcement are quite reliable in service, as they can withstand significant loads for extended periods under ultimate conditions. This is made possible by the fact that the concrete in a column with external corner reinforcement operates under a volumetric stress state, as the stirrups prevent its free movement (stirrup effect). At the same time, concrete operating under a complex stress state increases its strength and prevents the stirrups from losing stability. To this end, in the first stage, a calculation was performed for a column made of ordinary concrete with a cross-section of 25 × 25 cm, a length of 4.8 m, and 50 × 50 × 5 mm angles, fastened with 8 mm diameter clamps spaced 200 mm apart, using C20/25 concrete. In the next stage of the study, cross-sections were selected using concrete with steel and basalt fibers at various thicknesses of the metal angles. To calculate fiber-reinforced concrete columns, we use the methodology proposed in [1], in which, instead of the prismatic strength of concrete, we will consider the reduced prismatic strength of fiber-reinforced concrete. Based on the calculations performed, it can be concluded that adding steel or basalt fibers to the concrete of a column significantly affects its dimensions, weight, and cost.

Keywords: fiber-reinforced concrete, reinforced concrete, column, load-bearing capacity, corner reinforcement.

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Introduction.

Columns with a square cross-section and external corner reinforcement offer several advantages over traditional reinforced concrete columns. Using such structures instead of reinforced concrete ones is cost-effective. The economic benefit is achieved through the rational combination of external corner reinforcement and a concrete core. Such columns utilize the best properties of each of these components while simultaneously eliminating their shortcomings. Columns with external corner reinforcement are quite reliable in service, as they exhibit high ductility at the ultimate limit state. This property prevents the possibility of an instantaneous loss of load-bearing capacity. At the ultimate limit state, they can withstand significant loads for an extended period. When a load is applied simultaneously to the concrete and the external corners, the latter prevents the development of transverse deformations in the concrete core. This creates a cage effect, causing the concrete to operate under a volumetric stress state, in which it tends to increase its strength. In turn, the concrete core prevents the loss of local stability at the corners of the external reinforcement. Ultimately, these two factors result in an increase in the overall load-bearing capacity of such columns. One way to increase the cost-effectiveness of columns with external corner reinforcement is the use of dispersed-reinforced concrete.

Review of the research sources and publications

The works of Chikhladze E.D., Yermak E.M., Gasii G.M., Petrov A.M., Khalifa E. S. [1–4], and other researchers are devoted to experimental and theoretical studies of columns with external corner reinforcement.

The works of Krus Y.O. [15], Romashko V.M. [16], and other researchers are devoted to the study of the concrete deformation process under complex stress conditions. The issue of using fibers in fiber-reinforced concrete was examined by Surianinov M.G. [11], Kuznetsova I.O. [17], and other scientists [5–8].

Definition of unsolved aspects of the problem

The lack of information in recent publications regarding the use of fiber-reinforced concrete in columns with external corner reinforcement led to the conclusion that it is advisable to conduct research on the application of steel and basalt fibers in such structures.

Problem statement

Based on an analysis of recent studies, the following objectives have been formulated: to examine the methodology for calculating concrete columns with external corner reinforcement; to analyze the types of fibers that are suitable for use in concrete columns; to perform calculations for columns with external corner reinforcement using fiber-reinforced concrete; and to conduct a comparative analysis of these results.

The purpose of this article is to determine the economic efficiency of using fiber-reinforced concrete in columns with external corner reinforcement.

Basic material and results

We will perform the design of columns with external corner reinforcement in accordance with the methodology proposed in [1]. The load-bearing capacity under axial and eccentric compression is determined numerically by iteratively scanning through the deformed states of the element. Each deformed state is defined by the curvature as Eq. 1.

$$\mathrm{K} = \mathrm{K}_0 \cdot I \; ; \qquad (1)$$

where K_0 is the curvature step,

I is the strain state number.

The value of the curvature step is determined by the magnitude of the applied longitudinal force according to the equation:

$$\mathrm{K}_0 = 1.4 - \frac{N}{abR_b}\frac{10^{-4}}{a} \; ; \qquad (2)$$

where N is the longitudinal force,

R_b is the prismatic strength of the concrete.

Linearization of the nonlinear part of the problem is performed through a process of successive approximations, with the variable deformation parameters being the secant modulus of deformation of the concrete and the transverse deformation coefficient at each point of the finite-difference grid.

This solution allows us to obtain the relationship between the bending moment and curvature and to perform a longitudinal bending analysis. To do this, consider a straight reinforced concrete bar of length l, hinged at both ends, loaded by centrally applied forces F and equal bending moments M_0 directed in opposite directions (Fig. 1).

The differential equation for a curved rod axis is given by:

$$K_i = F(M_i) = \frac{M_i}{D_i} \; ; \qquad (3)$$

where D_i is the bending stiffness;

M_i is the bending moment at any cross-section of the rod, which is determined by the equation:

$$M_i = F\left(e_0 + Y_i\right) + M_0 \; ; \qquad (4)$$

where e_0 is the random eccentricity;

Y_i is the deflection function;

M_0 is the bending moment, determined by the equation:

$$M_0 = F\left(e - e_0\right) \; ; \qquad (5)$$

where F is the axial force;

e is the specified eccentricity.

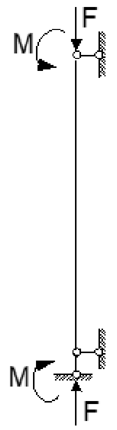

Figure 1 – Schematic diagram of the rod

The curvature of the cross-section is determined by the following equation:

$$K_i = \frac{\partial^2 Y_i}{\partial x^2} \qquad (6)$$

Equation (6) is solved using the finite difference method. The objective is to find the bending moment M_0 that, for a given beam, would induce the maximum allowable moment in the most critical cross-section (mid-span), as determined by the calculation of a reinforced concrete element of unit length. In the first approximation, the deflection is assumed to be zero. The magnitude of deflections at the mesh nodes is refined in an iterative process that continues until the required accuracy is achieved.

To determine the economic efficiency of using dispersed-reinforced concrete in columns with external corner reinforcement, we will first calculate a column made of ordinary concrete. Consider a column of a multi-story building where, for rigid connections between beams and columns in precast floor slabs, the height of the floor is taken as $l_o = l$. In our calculation, $l_o = l \approx 4.8$ m, with the cross-sectional dimensions of the concrete core being 25 × 25 cm (Fig. 2), and the angle bars 50 × 50 × 5 mm (DSTU 2251:2018 “Hot-rolled steel angle bars with equal flanges. Assortment”), fastened with 8-mm-diameter clamps spaced 200 mm apart (the diameter and spacing of the clamps were selected based on the results of experimental studies [1]), where we use standard C20/25 concrete.

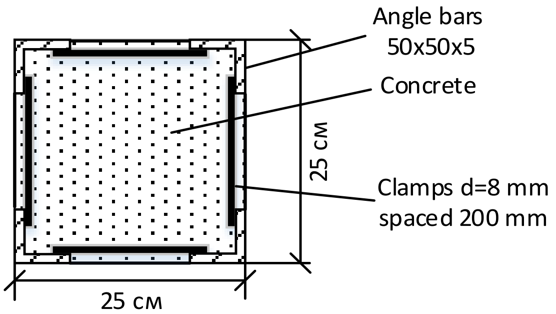

Figure 2 – Cross-section of the column

After performing the calculation according to [1], which considers the column’s flexibility and the hoop effect, we obtain a column bearing capacity of N =1,788 kN.

In the next step, we will analyze the types of fibers that are suitable for use in columns. Fiber-reinforced concrete is a modern composite building material formed by introducing dispersed fibers of various origins and geometries into a concrete matrix. Unlike traditional reinforced concrete, fiber-reinforced concrete provides three-dimensional reinforcement of the material, which contributes to increased crack resistance, deformability, and energy absorption capacity. Thanks to these properties, fiber-reinforced concrete has become widely used in global construction practice and has also become the subject of active scientific research in Ukraine.

A significant portion of domestic scientific works is devoted to studying the strength and deformation characteristics of fiber-reinforced concrete. In the works of M. Vygnanets, the behavior of steel-fiber-reinforced concrete under short-term compression was investigated, taking into account different volume contents of steel fibers [9]. The author established that the introduction of fibers leads to an increase in ultimate strains and a change in the failure mode of the specimens from brittle to more ductile. At the same time, increasing the fiber content beyond the optimal value is not always accompanied by a proportional increase in strength, which indicates the need to optimize the mixture composition.

Similar results have been obtained in studies by other Ukrainian researchers, which show that fiber significantly affects the modulus of elasticity, ultimate strains, and residual load-bearing capacity of the material after cracking [10]. The use of steel and basalt fibers proves to be particularly effective in critical structures operating in the zone of plastic deformation. Studies [11, 12, 13] propose the optimal composition and size of the fibers.

To determine the economic efficiency of columns with external corner reinforcement, we will compare columns with the same load-bearing capacity using ordinary concrete, concrete with steel fiber, and concrete with basalt fiber with different corner thicknesses.

For all columns, we use the following concrete mix, which corresponds to class C20/25: Portland cement M400 – 437.5 kg/m^3, 5–10 mm crushed stone – 1158.12 kg/m^3, river sand – 552.6 kg/m^3, water – 210 L/m^3. Water content was determined using Mironov’s chart, assuming a concrete mix slump of 5 cm. For concrete with steel fiber, “Chilyabinka” fiber was used, added to the concrete at a rate of 32.536 kg/m^3 of concrete [13]. For concrete with basalt fiber, basalt fibers 12 mm in length were used, introduced at a rate of 0.2% of the cement mass [13].

To calculate fiber-reinforced concrete columns, we use the method proposed in [1], in which, instead of the prismatic strength of concrete, we will consider the reduced prismatic strength of fiber-reinforced concrete [14], which is: for concrete with steel fiber, R_c = 30.1 MPa, and for concrete with basalt fiber, R_c = 26.2 MPa. The results of the theoretical calculations are summarized in Tables 1 and 2.

The cost of the column consisted of the cost of the angle iron (https://stroyryad.com.ua/cat/kutyk-katanyi), the cost of concrete (https://betonplus.com.ua/kupit-beton/), the cost of steel fiber (https://metizy-94.com.ua/home/fibre.html), and the cost of basalt fiber (https://abud.com.ua/fibra-bazaltova-12-mm). We will refer to this cost as approximate, since the cost of manufacturing the column is not included; only the cost of the component elements of the corner column is accounted for. However, this is sufficient for theoretical research.

The theoretical calculations presented in Table 1 show that, for the same load-bearing capacity, the addition of steel fibers to the column core significantly affects the cost of the column compared to concrete without fibers. For example, reducing the thickness of the corner to 3 mm reduces the column size by 12.8%. The total cost of the column decreases by 21.6%, while the cost of the concrete increases by 18.6% and the cost of the flange decreases by 32.2%. At the same time, the weight of the column decreases by 25.6%. With the same corner thickness (5 mm), the cost of the column does not change significantly, but the column size decreases by 17.2%, and the weight decreases by 27.9%. When the flange thickness is increased to 6 mm, the cost of the column increases by 15.3% due to a 20.2% increase in the cost of the flange, but the column dimensions decrease by 19.6% and the weight decreases by 32.2%.

Table 1 – Comparison table for columns made of steel-fiber-reinforced concrete based on the thickness of the angles

	Corner thickness, mm				**Standard column**
	3	4	5	6	
Load-bearing capacity, kH	1781	1786	1787	1784	**1788**
Column size, cm	21.8x21.8	21.3x21.3	20.7x20.7	20.1x20.1	**25x25**
Angle size, mm	50x50x3	50x50x4	50x50x5	50x50x6	**50x50x5**
Column concrete area, m²	0.046	0.044	0.041	0.038	**0.06**
Column cost, UAH	2833.3	3042.2	3673.6	4168,3	**3614.8**
Concrete cost, UAH	894.1	853.4	812.8	731.5	**754**
Angle cost, UAH	1939.2	2188.8	2860.8	3436.8	**2860.8**
Column weight, kg	528.54	523.2	512.38	481.8	**710.38**

Table 2 – Comparison table for columns made of concrete reinforced with basalt fiber, by corner thickness

	Corner thickness, mm				**Standard column**
	3	4	5	6	
Load-bearing capacity, kH	1792	1783	1775	1779	**1788**
Column size, cm	23.4x23.4	22.7x22.7	22x22	21.4x21.4	**25x25**
Angle size, mm	50x50x3	50x50x4	50x50x5	50x50x6	**50x50x5**
Column concrete area, m²	0.054	0.050	0.046	0.043	**0.06**
Column cost, UAH	2608.1	2852.44	3469.1	3989.8	**3614.8**
Concrete cost, UAH	668.9	663.64	608.34	553.03	**754**
Angle cost, UAH	1939.2	2188.8	2860.8	3436.8	**2860.8**
Column weight, kg	614.78	586.56	556.38	525.8	**710.38**

According to the analysis in Table 2, the addition of basalt fiber also significantly affects the dimensions, weight, and overall cost of the column compared to a concrete core without fiber. Thus, with the same load-bearing capacity and a corner thickness of 3 mm, the column size decreases by 6.4%, the column cost decreases by 27.8%, while the cost of concrete decreases by 11.3% and the cost of the corner decreases by 32.2%. The column's weight decreases by 13.5%. With the same corner thickness (5 mm), the column's cost decreases by 4.0%, the column's size decreases by 12.0%, and the weight decreases by 21.7%. With a flange thickness of 6 mm, the cost of the column increases by 10.4% due to a 20.1% increase in the cost of the flange, but the column dimensions decrease by 14.4% and the weight decreases by 26.0%.

Conclusions

Based on the theoretical calculations performed, it can be concluded that the use of fiber-reinforced concrete columns (with both steel and basalt fibers) provides nearly the same load-bearing capacity as conventional columns, while achieving material savings and reducing the structure's weight.

For steel-fiber-reinforced concrete columns, a significant weight reduction of up to ~32% is observed; as the corner thickness increases, the cost rises, but the concrete area and the structure's mass decrease. The option with a 5 mm corner appears to be the most rational, as it provides nearly maximum load-bearing capacity with a significant weight reduction and an acceptable cost.

In columns made of basalt fiber-reinforced concrete, the weight is less than that of a conventional column but greater than that of steel fiber-reinforced concrete counterparts. The cost in most cases is lower than or comparable to that of a conventional column. The option with a 5 mm angle bar can be considered optimal, as it offers the best balance between cost, mass, and load-bearing capacity.

If the priority is minimal structural weight and high efficiency, it is more appropriate to use steel-fiber-reinforced concrete columns.

If cost-effectiveness is more important while maintaining sufficient load-bearing capacity, basalt fiber-reinforced concrete columns are more appropriate.

In both cases, the most balanced solution is to use a 5 mm thick angle.

To confirm the results obtained, experimental studies are planned.

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Ефективність використання фібробетону в колонах із зовнішнім кутиковим армуванням

Аннотація. Колони квадратного поперечного перерізу із зовнішнім кутиковим армуванням мають низку переваг порівняно з традиційними залізобетонними. Застосування таких конструкцій замість залізобетонних є економічно вигідним. Економічний ефект досягається завдяки раціональному поєднанню зовнішнього кутикового армування та бетонного ядра. При прикладенні навантаження до бетону та зовнішніх кутиків одночасно, останні перешкоджають розвитку поперечних деформацій у бетонному ядрі. Таким чином, створюється ефект обойми, що призводить до того, що бетон працює в умовах об'ємного напруженого стану, в якому він має властивість підвищувати свою міцність. У свою чергу, бетонне ядро перешкоджає втраті локальної стійкості кутиками зовнішнього армування. Одним із способів збільшення економічної ефективності колон із зовнішнім кутиковим армуванням є використання дисперсно армованих бетонів. Для визначення економічної ефективності використання дисперсно-армованих бетонів в колонах із зовнішнім кутиковим армуванням в першу чергу розрахуємо колону зі звичайним бетоном. Розглянемо колону з розмірами поперечного перерізу бетонного ядра 25 х 25 см, довжиною 4.8 м, кутиками 50х505х5 мм, скріпленими хомутами діаметром 8 мм з кроком 200 мм. На наступному етапі порівняємо колони з однаковою несучою здатністю при використанні звичайного бетону, бетону зі сталевою фіброю та бетону з базальтовою фіброю з різною товщиною кутиків. Для всіх колон використовуємо наступний склад бетону, який відповідає класу С20/25.

Проаналізувавши теоретичні розрахунки можна зробити наступні висновки: сталефібробетонні колони доцільніше використовувати, якщо пріоритетом є мінімальна маса конструкції, а базальтофібробетонні – якщо важливішим є економічність при збереженні достатньої несучої здатності. У обох випадках найбільш збалансованим рішенням є використання кутика товщиною 5 мм.

Ключові слова: фібробетон, сталебетон, колона, несуча здатність, кутикове армування.

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