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ENGINEERING SOLUTIONS FOR FIBER-REINFORCED CONCRETE STRUCTURES AND ANALYSIS OF THEIR STABILITY UNDER LEFT-HANDED BENDING CONDITIONS

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Abstract: The article examines innovative engineering solutions for fiber-reinforced concrete (fibroconcrete) structures, which are widely used in modern civil engineering, and analyzes the structural and operational characteristics of these materials. The functional advantages of fiber concrete, including its impact on moisture control and energy efficiency in ventilated facade systems, are noted. The material's high flexural-tensile strength, its ability to prevent cracking, and the increased impact and deformation resistance are also examined. At the microstructural level, the specific mechanisms of steel and synthetic fibers in crack control have been comparatively demonstrated.

Furthermore, a mathematical-analytical analysis of the stress-strain state of fiber-reinforced concrete elements under transverse bending conditions was conducted, and the material's mechanical behavior was evaluated based on the principles of the three-point bending test. In cases of lateral bending, the distribution of normal stresses, the shapes of the compressed zone (triangular and trapezoidal), and the trigonometric dependencies of the neutral axis position were determined, and it was mathematically substantiated that these processes are non-linear in contrast to classical material mechanics. As a result, the application of fiber concrete in both monolithic and combined hybrid systems significantly improves the structural safety and engineering efficiency of buildings.

Keywords: *fiber concrete, fiber-reinforced concrete, steel fibers, synthetic fibers, transverse bending, stress-strain*

Introduction. In modern civil engineering, fiber-reinforced concrete (FRC) materials are widely used in structures that require high strength, long-term durability, and resistance to cracking. Fibroconcrete is a composite material formed by the distribution of fibers (glass, steel, basalt, etc.) within a concrete matrix and has higher mechanical and performance properties compared to ordinary concrete. The main advantages of this material are high flexural and tensile strength, delayed crack development, increased energy absorption capacity, and improved deformation properties (Figure 1).

In modern construction engineering, the design of high-rise and multi-functional buildings considers not only structural strength but also operational quality and the efficiency of engineering systems as key criteria. In this regard, the application of fiber-reinforced concrete materials plays a crucial role in improving both the load-bearing and functional characteristics of building systems.

Fibroconcrete is a composite material created by the distribution of fibers within a concrete matrix, and these fibers enhance the material's integrity by restricting the development of micro and macro cracks. As a result, deformation in building elements is controlled, a more uniform distribution of stresses is ensured, and the overall stability of the structure is increased.

Figure 1. Comparison of plain concrete and fiber concrete: effect of the fibrous structure on crack resistance

The application of fiber concrete in a building's engineering systems is primarily seen in the following elements:

- floor slabs and covering systems,
- basement and foundation zones,
- facade and cladding panels,
- load-bearing walls subjected to seismic effects.

The use of fiber concrete in these elements not only increases mechanical strength but also positively affects the building's operating conditions. In particular, the application of fiber concrete panels in facade systems allows for the formation of an air gap between the structural layers. This air gap enhances the building's “breathing” ability, helping to reduce moisture and maintain a stable indoor environment. Thus, the facade structures, working in conjunction with the ventilation system, also increase energy efficiency.

At the same time, the low water permeability and high frost resistance of fiber concrete significantly increase the service life of building envelope systems. Additionally, the material's high energy-absorbing capacity reduces the risk of damage to structures during seismic and dynamic loads. These characteristics characterize fiber concrete not only as a traditional structural material but also as a functional engineering solution.

These macro-level advantages are directly related to the microstructural behavior of the material. In fiber-reinforced concrete systems, the delay of crack initiation and the restriction of their propagation constitute the primary mechanisms of energy absorption and deformation control. These mechanisms of microstructural-level crack control and energy dissipation form the basis for the effective application of fiber concrete in a building's engineering systems and are schematically depicted in Figure 2.

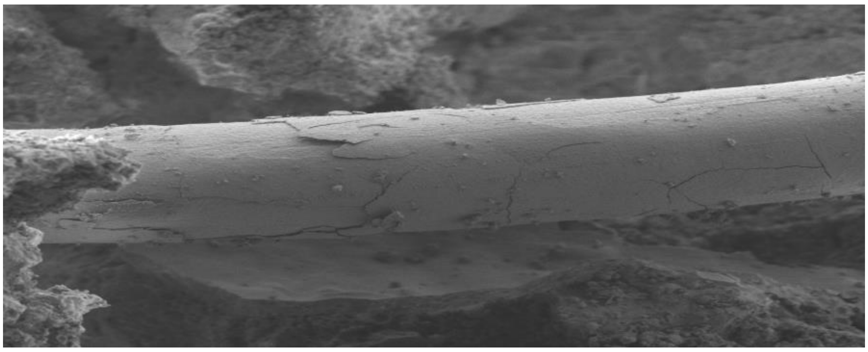

Figure 2. Schematic representation of how fibers prevent cracks in concrete at the microscale

Concrete is a widely used construction material with high compressive strength, but due to its brittle nature, it has low tensile strength. The flexural strength of concrete is one of the main indicators that characterizes its structural reliability and load-bearing capacity. However, because concrete's resistance to tensile stresses that occur during flexure is relatively low, fiber-reinforced concretes (fibroconcretes) are widely used to improve this characteristic.

Fiber concrete is a composite material obtained by distributing various types of fibers within the concrete matrix, primarily using steel and synthetic fibers. These fibers increase the concrete's flexural strength and resistance to plastic deformation by bridging cracks and redistributing internal stresses. Steel fibers are particularly known for their high effectiveness in increasing the mechanical properties of concrete, including its flexural strength. When concrete is subjected to bending, tensile stresses are created on one side of the element and compressive stresses on the other. In unreinforced concrete, tensile stresses cause cracks to form and propagate, leading to sudden failure. Steel fibers, with their high tensile strength and stiffness, effectively bridge these cracks, preventing their expansion.

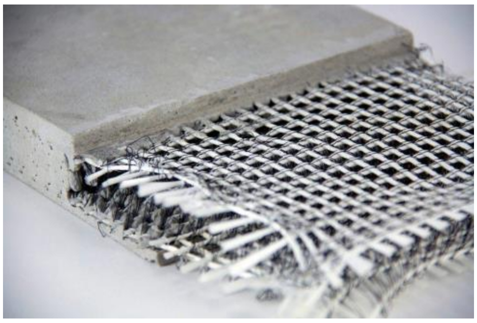

Figure 3. Fiber-reinforced fibrous concrete structure

Overall, steel and synthetic fibers perform distinct but complementary functions in improving the flexural behavior of concrete. While steel fibers are primarily superior in increasing post-crack strength and load-bearing capacity, synthetic fibers are more effective in restricting microcracks, homogeneously distributing stresses, and improving durability indicators. For this reason, the combined use of both fiber types (a hybrid fiber system) in modern fiber concrete technologies allows for a comprehensive improvement in both the mechanical and performance properties of concrete.

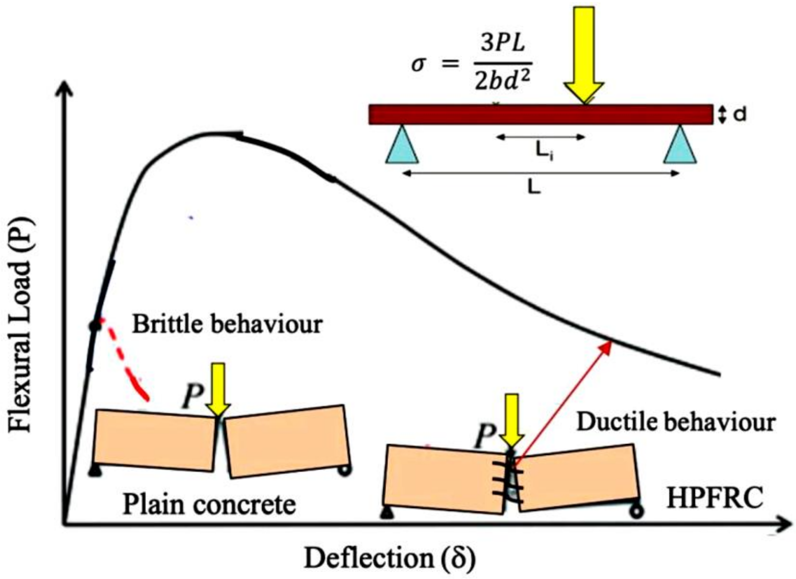

Figure 4. Schematic comparison of the flexural load–displacement behavior of plain concrete and fiber-reinforced concrete (fibrobeton)

The three-point bending test, as depicted in the figure, is used to evaluate the mechanical resistance of conventional materials and fiber-reinforced concrete under an external load. During this test, the specimen is placed on two supports, and a load is applied to its center. The specimen bends and eventually fails under the applied load. This method characterizes the material's flexural behavior and cracking properties.

The maximum flexural stress (σ), resulting from the load P applied to the center of the specimen (beam), is calculated using the following formula:

$$\sigma = \frac{3PL}{2bd^2} \tag{1}$$

Where: P – applied external load;
L – distance between supports (span length);
b – width of the specimen;
d – height of the specimen

This formula expresses the material's maximum tensile stress during bending. In other words, it indicates the level of stress the specimen can withstand until it breaks. This indicator is one of the main parameters that characterizes the material's resistance to bending.

In the behavior of fiber-reinforced concrete elements, this resistance becomes more complex, especially when the element is loaded in two planes simultaneously, i.e., under conditions of shear bending. For this reason, a theoretical analysis of the shear bending case is conducted to more accurately assess the stress state of such elements.

The occurrence of transverse bending is related to the fact that the plane of action of the external bending moment does not coincide with any plane containing the principal axis of inertia and the longitudinal axis of the element (the principal planes of inertia).

From the theory of material resistance, it is known that the equation of the neutral axis of a laterally buckled element is of the following form:

$$tg\alpha = \frac{I_x}{I_y} tg\beta \tag{2}$$

Where α - is the angle of inclination of the neutral axis with respect to the X-axis;
β - is the angle of inclination of the surface of the external torsional moment with respect to the Y-axis;
I_x and I_y - are the principal moments of inertia with respect to the X- and Y-axes, respectively

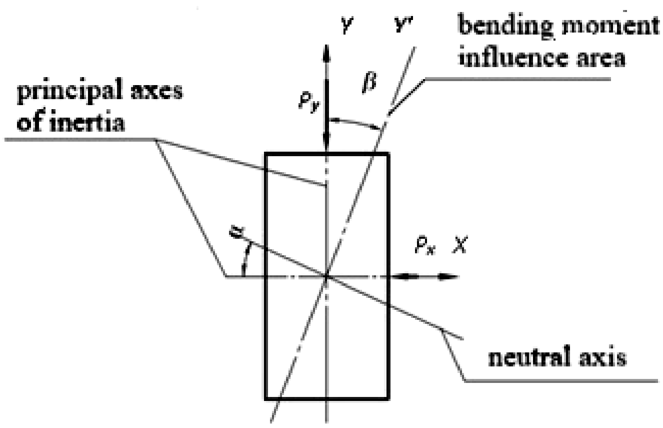

Figure 5. Schematic representation of the effect of oblique bending on ray propagation

According to equation (2), it is known that the angles α and β are equal only when the inertia moments I_x and I_y are equal. Thus, all principal axes of inertia are considered principal, and the element will be subjected to plane bending. It is thus evident that in a transversely loaded element, the neutral axis (zero line) is not perpendicular to the plane of bending, unlike in plane bending.

Equation (2), as applied in classical material mechanics, cannot be directly applied to fiber-concrete elements. This is because the equation considers only the elastic stage of the material. In the fiber concrete matrix, however, the stress-strain state becomes nonlinear during the loading process as the fibers take on tensile stresses within the crack, with the material's plastic deformation and effective stiffness operating dynamically.

As one of the types of a biaxial stress state, biaxial compression is a state of pure biaxial stress. The biaxial stress state of a structural element is considered in two main cases, depending on the application of external forces. In the first case, the loading vector is applied to the element at an angle β with respect to the X and Y axes (figure 6 a); in the second case, two different loading vectors (P_x and P_y) act on the element simultaneously (figure 6 b). When one of the vectors is zero, shear buckling occurs.

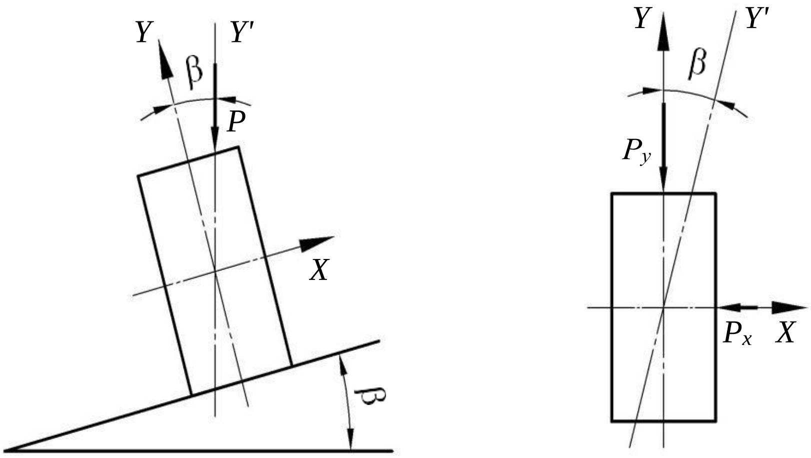

Figure 6. Possible working state of a structural element subjected to lateral bending:
Y' - The action surface or action plane of the external load P(a) is equal to the external load vectors P_x and P_y (b); β - is the inclination angle of the force surface

The projections of the external load P along the axes in the cross-section subjected to oblique bending are determined by the following trigonometric dependencies:

$$P_x = P \cdot cos\beta$$
$$P_y = P \cdot sin\beta \quad (3)$$

Here, β is the angle of inclination formed by the force plane with the vertical axis. This allows us to analyze the complex lateral bending as the sum of two in-plane bending moments (along the X and Y axes).

The shape of the compressed zone and the structural requirements in laterally loaded fiber concrete elements. The determination of the principal inertia planes in fiber concrete elements during the stress-strain stage presents challenges due to the presence of microcracks within the matrix and the influence of fiber placement. Therefore, in such elements, the surfaces of strength are considered as surfaces passing through the axes of symmetry of the element's cross-sectional figure and along the longitudinal axis

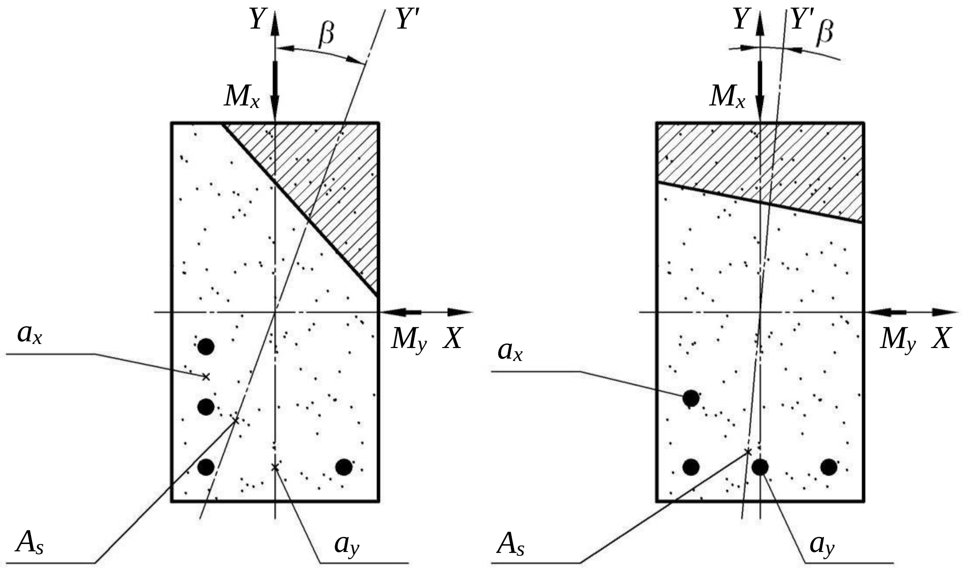

Figure 7. Types of shapes for the compressed zone in a transversely reinforced concrete element: triangular (a) and trapezoidal (b). Placement of the reinforcement in the cross-sectional area. Y' – area of influence of the external bending moment; β – angle of the Y' force surface with respect to the Y-axis; M_x and M_y - bending moments about the X and Y axes, respectively

The figure shows the shapes of the compressed zone (triangular and trapezoidal) and the placement of the combined reinforcement. This figure is directly related to the formula for calculating the normal stress at an arbitrary point in the section, σ_z.

$$\sigma_z = \frac{M_x}{\dot{I}_x} \cdot y + \frac{M_y}{\dot{I}_y} \cdot x \quad (4)$$

In fiber-reinforced concrete elements working under lateral bending (or in combined steel-fiber-reinforced concrete systems), the longitudinal reinforcement must be placed as follows:

– the center of gravity of the cross-section must be located in the reaction area of the external forces
– full use must be made of the stability and strength properties of all bars and the dispersed fibers within the concrete
– the determination of the maximum possible exits of the internal force couple must be ensured, taking into account the structural requirements specified in current regulatory documents.

Thus, longitudinal reinforcement with an area A_s to receive tensile forces is placed parallel to the width b and height h of the section (Figure 7).

It is recommended to position the vertical portions of the a_y area bars, which are placed parallel to the height h of the section, as close as possible to the most tensile angle. It is proposed to distribute the horizontal part of the a_x area reinforcement along the most tensile axis either uniformly along the entire width (*b*) or close to the most tensile corner of the section.

Conclusion

The analyses conducted show that fiber concrete has superior mechanical and performance properties compared to conventional concrete in modern construction structures. The distribution of fibers within the concrete matrix promotes the formation of cracks and their confinement, which results in increased flexural strength and deformability of the material. In engineering systems, its application, particularly in ventilated facade panels, provides an effective engineering solution for moisture control and energy efficiency.

While steel fibers primarily increase post-crack load-bearing capacity and structural stiffness, synthetic fibers play a more effective role in preventing microcracks and improving material homogeneity. The combined use of these two fiber types (hybrid systems) optimizes both the mechanical and performance characteristics of fiber-reinforced concrete.

The stress-strain state of fiber-concrete elements under biaxial bending, unlike in classical material mechanics, is nonlinear due to the microstructural effect of the fibers within the matrix. Based on the principles of the three-point bending test, the distribution of normal stresses and the position of the neutral axis, depending on the geometric shapes of the compressed zone (triangular or trapezoidal), have been determined by trigonometric dependencies. A hybrid combination of steel and synthetic fibers and the optimal grouping of longitudinal reinforcements in the most tensile zones of the cross-section provide an effective engineering solution.

Overall, the application of fiber concrete significantly increases the reliability, durability, and service life of structures, while the combination of engineering solutions with mathematical analysis allows for the more accurate and safe design of these types of elements.

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