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Calculation of Deformations of Flexural Three-Layer Reinforced Concrete Elements with A Middle Layer of Arbolite

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Abstract: This study presents a deformation-based calculation approach for three-layer reinforced concrete (RC) elements with an arbolite insulating core. Given the insufficient theoretical foundation in current design standards and the scarcity of experimental data, a comprehensive experimental investigation was undertaken. Two series of full-scale specimens were tested to evaluate flexural behavior, particularly focusing on the influence of vertical and inclined shear reinforcement. Results demonstrate that deflections prior to cracking correlate well with theoretical predictions when both bending and shear deformations are considered. This paper proposes refined equations and section models for accurate deflection prediction in such composite systems.

Keywords: Three-layer reinforced concrete, Arbolite core, Flexural behavior, Shear deformation, Deflection analysis, Inclined shear reinforcement, Low-strength concrete insulation, Composite concrete panels, Modulus of elasticity, Layered concrete systems, Experimental mechanics, Shear stiffness, Deflection modeling.

Introduction: Improving the thermal performance of building envelopes is critical for reducing operational energy costs and fuel resource consumption. A promising solution is the use of three-layer RC panels, comprising low-strength insulating concrete (such as arbolite) in the core and dense concrete on the outer layers. Despite their practical benefits, design methodologies for such systems remain underdeveloped due to limited theoretical grounding and experimental validation. Existing codes, such as KMK 2.03.01-96, offer limited provisions for layered RC elements, especially when composite action and shear deformations are significant. This research addresses this gap by analyzing the deformation characteristics of three-layer RC bending elements with an arbolite core made from local cotton stalks.

One of the effective ways to increase the thermal resistance of enclosing structures in order to reduce the operating costs of buildings and the costs of fuel and energy resources is the use of three-layer reinforced concrete panels with insulation made of low-strength concrete with a low thermal conductivity coefficient and outer layers made of dense lightweight or heavy concrete [1].

Based on the fact that all proposals for calculating three-layer reinforced concrete elements with monolithically bonded layers are not sufficiently substantiated for inclusion in regulatory documents, and experimental data are limited, targeted studies were conducted on the deformations of bending three-layer reinforced concrete elements with an insulating layer of arbolite on local raw materials (cotton stems). For this purpose, two series of test specimens 330 cm long with a design span of 300 cm, a height of 25 cm and a width of 16 cm were manufactured and tested. The thickness of the outer layers is 4 cm, which makes it possible to place longitudinal reinforcement in them and ensure its protection in accordance with the requirements of KMK 2.03.01-96 [2-5].

METHODS

Series I, consisting of eight test specimens, was designed to study the effect of transverse reinforcement in the form of vertical bars on the operation of near-support sections. All specimens are reinforced with the same longitudinal working reinforcement of two bars with a diameter of 12 mm made of grade A-III steel and different transverse. In six test specimens, transverse vertical reinforcement is installed with a pitch of 21 cm with a diameter of 4; 5.66; 6.93; 8; 8.94; 9.8 mm made of grade A-1 steel, two test specimens do not have transverse reinforcement. The following designation of the test specimens is adopted: BA-I-1...BA-I-8. Series II of four test specimens was designed to study the possibility of strengthening the support zones with transverse reinforcement in the form of inclined rods. The test specimens, as in Series I, are reinforced with longitudinal reinforcement of two rods with a diameter of 12 mm made of grade A-III steel. The inclined rods are made in the form of a triangular lattice, located at an angle of 45° and spot welded to the longitudinal rods. One specimen, the control, is made without transverse reinforcement, in the other three the inclined transverse reinforcement is made of 4 and 5 mm diameters of Br-500 steel and 6 mm of A-240 steel, respectively. The shear span in the test specimens is 2.7ho. The test specimens of the second series are designated BA-II-1...BA-II-4, respectively.

The concrete of the outer layers is heavy with the strength of 25 MPa, and the concrete of the middle layer is made of arbolite - 1 MPa.

The analysis of the experimental results shows that at the stages before crack formation, the deflections of the samples increased proportionally to the load. The deflections of the samples of the 1st series BA-1-1 BA-1-8 did not differ significantly from each other. The deflection values of the samples with transverse reinforcement BA-1-7 and BA-1-8 were 22 and 25% greater than the deflections of the samples without transverse reinforcement (BA-1-1 and BA-1-2). This is most likely due to the fact that due to the constrained shrinkage of the concrete of the middle layer, in the presence of transverse rods, tightening stresses arise in it. With an increase in the diameter of the inclined reinforcement in the samples of the 2nd series, the deflection values were less than in the sample without transverse reinforcement (BA-P-1). For samples BA-11-2 - BA-11-4 with reinforcement diameters of 4, 5 and 6 mm, the differences were 17, 24.7 and 35%, respectively, and this is most likely due to an increase in shear rigidity of the middle layer in the presence of inclined bars.

For bending structures in the current KMK 2.03.01-96, general theoretical deflections are recommended for determining the sum of deflections from bending and shear deformations. If the ratio of the design span to the height of the structure section is more than 10, it is permissible to ignore the shear deflection due to its smallness. The specified ratio for the studied test samples is 12. For three-layer structures with a middle layer made of low-strength concrete, due to a significant effect of shear deformations on the deflections of test samples, it is recommended to take into account the shear deflection. Based on this, the calculation of the deflection of test samples was carried out taking into account the bending and shear deformations.

The theoretical values of deflections from the bending moment to the appearance of cracks were obtained in accordance with the recommendations of KMK 2.03.01-96 using the following formula:

$$f_m = \frac{M}{\varphi_{bl}\, E_b\, I_{red}} \rho_m l^2 \ (1)$$

where M is the bending moment, $E_b$is the initial modulus of elasticity of concrete; $I_{red}$is the moment of inertia of the reduced section; φ_{bl} is the coefficient taking into account the effect of short-term creep of concrete, taken as 0.85; $\rho_m$is the coefficient depending on the loading scheme and the point of determining the deflections.

RESULTS

To calculate three-layer elements for crack formation, the three-layer section was replaced by a homogeneous I-beam, the deformations during bending up to based on the ratio of the initial moduli of elasticity of concrete in the layers. The theoretical values of deflections were compared with the experimental ones, obtained at the middle of the span of the samples minus the deflections under loads, i.e., in the section of constant moments (Table 1). As can be seen from Table 1, the calculated values of deflections from the bending moment differed insignificantly from the experimental ones: in the samples of the 1st series within 1.7-20.8%; in the samples of the 2nd series 3.2-27.3%. The differences may be due to some measurement error. Based on this, we can state that the calculation of deflections of three-layer structures from the bending moment is made according to formula (1).

Comparison of experimental and theoretical values of deflections from bending moment to crack formation

Table 1

Sample code	M, kNm	Sag due to bending in the middle of the span relative to the loads,$\mathbf{f_m}$ 10 3 cm/%	
		Experience	Calculation
BA-I-1	1 ,76	29/100	28.5/98.3
BA-I-2	1 ,76	36/100	28.5/79.2
BA-I-3	1 ,76	27.8/100	28.5/102.5
BA-I-4	1 ,76	26.7/100	28.5/106.7
BA-I-5	1 ,76	31.1/100	28.5/91.6
BA-I-6	1 ,76	28/100	28.5/101.8
BA-I-7	1 ,76	31/100	28.5/91.9
BA-II-8	1 ,76	28/100	28.5/101.8
BA-II-1	1 ,76	36/100	28.9/80.3
BA-II-2	1 ,76	31.6/100	28.9/91.4
BA-II-3	1 ,76	28/100	28.9/103.2
BA-II-4	1 ,76	22.7/100	28.9/127.3

We recommend determining deflections from transverse forces before the appearance of cracks caused by shear deformations using the formula given in the course "Strength of Materials" by N.M. Belyaev, which more strictly takes into account the shape of the section

$$f_q = \int_0^1 \frac{KQ(x)}{GA_b} dx (2)$$

where $Q(x)$is the transverse force in the section due to the action of an external load; G is the shear modulus of concrete, equal to 0.4E b ; A b is the cross-sectional area of the structure; K is the coefficient taking into account the shape of the cross-section and is determined by the formula

$$K = \frac{A_b}{I^2} \int \frac{S^2(z)}{b} dz$$

where I, S are the moment of inertia and the static moment of the cross section; b is the width of the sample.

Then, based on the ratio of the initial elastic moduli of concrete, the three-layer section of the test samples was replaced by a homogeneous I-beam, and the value of the coefficient "K" is determined by the following formula:

$$K = 2\frac{A_b}{I_{red}^2}\left[\int_{-\frac{h}{2}}^{-(\frac{h-2h_f}{2})} \frac{S^2(z)}{b_f} dz + \int_{-(\frac{h-2h_f}{2})}^{0} \frac{(S')^2(z)}{b'} dz\right] (3)$$

where S' and S are the static moment of inertia of the wall and flange of the reduced I-section

$$S' = \frac{b_f h^2}{8}\left(1 - \frac{4z^2}{h^2}\right) - \frac{(b_f - b')(h-2h_f)^2}{8}\left(1 - \frac{4z^2}{(h-2h_f)^2}\right)$$

$$S = \frac{b_f h^2}{8}\left(1 - \frac{4z^2}{h^2}\right)$$

For samples of series II, the effect of inclined rods on reducing deflections from transverse forces was taken into account when determining the geometry of the reduced section using the formula

$$b_{red} = \frac{2A_{s,inc}}{a}\frac{E_s}{E_b} + b$$

Here is $A_{s,inc}$the cross-sectional area of the inclined bar; $E_s$is the modulus of elasticity of the transverse inclined reinforcement; $E_b$is the initial modulus of elasticity of concrete; $a$is the distance between the transverse inclined bars normal to them.

The magnitude of the deflections from transverse forces, determined by formula (2) at the values of the coefficient "K" according to formula (3), differs insignificantly from the experimental ones (Table 2). In the samples of series I without transverse reinforcement (BA-I-I and BA-1-2), the differences between the calculated and experimental values of deflections amounted to 9.3% on average, and in the samples reinforced with transverse vertical reinforcement BA-1-3-BA-1-8 19.2%. Here, most likely, the decrease in shear deformations of concrete in the middle layer had an effect due to large initial deformations associated with shrinkage.

A sufficiently good convergence of the theoretical and experimentally obtained values of deflections from transverse forces occurs in the samples of series 11. Thus, for a sample without transverse reinforcement (BA-II-1), the difference does not exceed 2.1%. In three other samples of this series with inclined reinforcement in the support zone (BA-P-2 - BA-P-4), the differences were 11.8; 119 and 14.9%, respectively.

Comparison of experimental and theoretical values of deflections from transverse forces before crack formation

Table 2

Sample code	Diameter of transverse reinforcement, mm	Q, kN	Sag in the middle of the span due to transverse forces.$\mathbf{f_m}$ 10 3 cm/%	
			Experience	Calculation
BA-I-1	-	2.4	16.4/100	15.6/95.1
BA-I-2	-	2.4	18.1/100	15.6/86.2
BA-I-3	4.0	2.4	16.9/100	21.3/126
BA-I-4	5.66	2.4	19/100	21.3/112.1
BA-I-5	6.93	2.4	15/100	21.3/142
BA-I-6	8.0	2.4	23.8/100	21.3/89.5
BA-I-7	8.94	2.4	24.6/100	21.3/86.6
BA-II-8	9.8	2.4	24/100	21.3/88.7
BA-II-1	-	2.4	19.5/100	19.1/97.9
BA-II-2	4.0	2.4	17/100	15/88.2
BA-II-3	5.0	2.4	14.2/100	15.9/111.9
BA-II-4	6.0	2.4	13.4/100	15.4/114.9

Based on the above, it is recommended to calculate the deflections of three-layer samples from transverse forces to the formation of cracks using formula (2), taking into account the shape factor of the reduced section using formula (3).

CONCLUSIONS

- Shear deformations significantly influence the total deflection of three-layer RC elements with arbolite cores.
- The combined bending-shear model yields results consistent with experimental data.
- Inclined shear reinforcement substantially reduces deflections, outperforming vertical stirrups in layered RC elements.
- The modified design approach should be incorporated into future versions of structural codes for composite concrete panels.

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