Study of bonding zone composite reinforced structures

K E Nikitin 1, D I Zhukov 2, V S Moskovtseva 1

1Unique buildings and structures Department, South-West State University, 94, 50-let Octyabrya st., Kursk 305040, Russia
2Reinforced concrete and masonry structures Department, Moscow state (National research) state university of civil engineering, 26, Yaroslavskoye Shosse, Moscow 129337, Russia

E-mail: niksbox@mail.ru

Abstract. A bonding zone between elements of layered composite concrete structure was investigated. Results of stress-strain state, nonlinear deformation, and crack resistance of this zone are presented. The bonding zone simulation was performed using the developed methodology based on the finite element method. The problem was solved in a nonlinear formulation using elements with nonlinear material properties and one-side contact elements. A fragment of a layered structure made of two concretes with different strength and under the action of shear forces was considered. Based on the available experimental data, shear stiffness of the bonding zone was calculated. The simulation of the deformation process for the composite structure was performed taking into account its nonlinear deformation and consideration of the cracking process up to the moment of its complete failure. The obtained results of are compared with experimental data. The necessity of using the actual strength and deformation characteristics of the shear of the bonding zone when modeling the deformation process and evaluating the ultimate breaking load is shown.

1. Introduction

The use of reinforced concrete multilayer composite structures over the past two or three decades has substantially increased. This is a result of using of three-layer building envelopes for thermal protection, and especially it’s connected with the ever increasing number of reconstructions, the need for strengthening individual structural elements by their building-up or growing, including the use of rigid reinforcement. At the same time, the specificity of deformation of such structures, despite of a large amount of studies in this field (see, for example, [1-15]), are not taken into account strictly enough. The current codes for reinforced concrete structures [16,17] do not consider the specifics of nonlinear deformation with the crack formation and sequential disconnection in the bonding zone (also known as the interelement concentration zone [18]), but they only approximate estimates of deformability and strength. Moreover, there are no standardized deformation curves for the bonding zones between elements of composite concrete and reinforced concrete structures.

Goals of this work were to develop a numerical nonlinear deformation model of bonding zone between elements of layered and composite reinforced concrete structures made of concretes of different strengths (for example, a composite beam or a layered wall panel), to determine the deformation properties of bonding zones and to compare the results with available experimental data.
2. Materials and methods
The object of our study is a fragment of a plane-stressed layered composite structure consisting of two concrete prisms connected by a bonding zone of thickness $t$ and formed by layer-by-layer concreting (figure 1). The upper prism is made of heavy-weight concrete of class B20 (according with Russian building codes), and has a cross-section of 100 X100 mm and a length of 590 mm. The lower prism is made of lightweight concrete of class B5 with 1200 kg/m$^3$ density and has a cross section of 200 x 100 mm with a length of 600 mm.

The choice of the object for study was determined by the fact that an experiment was conducted for such structure [19].

Deformation process simulating of structure was performed with the finite element method in the Lira-SAPR software package. Elements with nonlinear material properties and nonlinear elements representing contact and sliding between nodes were used to build the model of the composite structure.

A regular mesh of plane stress state rectangular finite elements was used to create a design model of the structure. Orthotropic linear elements were used as elements that simulate the bonding zone, for which it is possible to specify the shear modulus independently of the modules of linear deformations.

Multilinear stress-strain relationships diagrams were used to describe the plasticity of concretes. Parameters of diagrams were taken from the Russian building codes [16]. The boundary conditions of free support of the structure on the lower surface were modeled by one-sided contact elements (see figure 1) so that they correspond to the experimental scheme as much as possible. The necessity of using such elements is demonstrated by the results of the calculations performed (see figure 2), which show that the position of contact zone of the structure and the base is significantly shifted in the process of nonlinear deformation.

The structure was loaded with a continuous load ‘$p$’, on the area shown in figure 1. Nodes of this area was coupled to impose equal displacement in the direction of x-axis. This allowed us to simulate the application of the load from a hard stamp, just as it was in experiments [19]. During loading, the cracking process was simulated. For this purpose, at each loading step, the material strength was checked based on the stress values calculated at the center of the finite element. The criterion for the appearance of a crack in the element was the achievement by the shear stresses of their limiting value.

After the appearance of the crack, the element was removed, and a special one-sided contact finite element (a gap element) with Coulomb friction in the tangential direction was installed in the place between the edges of the crack. This element simulates the flow of forces in the direction across the crack in the case of compression, and the friction of the crack edges against each other when they contact. Under the action of tensile forces in the direction across the crack, there is no interaction between the crack edges due to one-sided activity of this element.
The results of the calculations performed with those elements show the rationality of their using in the model. So, with their use, in the process of loading the structure with a crack, both areas on which edges of crack was contacted each others and areas where they have no contact were found (see figure 2).

Step by step loading was carried out until the appearance of a through crack or forming significant areas of destroyed elements that make impossible to pass forces to the structure or its interaction with the constraints.

3. Results and discussion

It is known [18] that the bonding zone of the layered composite structure has different deformation behavior from the deformation behavior of the materials of the connected elements. Therefore, the value of the shear modulus of this zone was calculated at the first stage of research.

For this purpose, an iterative calculation was performed, during which the value of the shear modulus of the finite elements located in the bonding zone was adjusted. At the same time, we don't change linear modulus of deformation. It was taken equal to the linear modulus of deformation of the materials from which the elements of the composite structure are made.

In the process of changing the shear modulus, the values of shear strain $\gamma$ in the middle of the bonding zone (in section 2 of figure 3) were calculated and compared with the values obtained in the experiment [19]. When the displacement values converged, the achieved value of the shear modulus was taken as the deformation characteristic of the bonding zone. The shear modulus was determined under relatively small load values (2.6 kN), at which the deformation process is close to linear.

The location of checking of shear deformations was chosen so that it is farthest from the zones of stress concentration - areas of application of load and fixing of the structure (according to the Saint-Venant's principle) - see figure 4.
As a result, a shear modulus of 400 MPa was obtained for the simulated structure. This value is much less than the shear modulus of concrete elements from which the considered composite structure was made: 3167 MPa for B5 and 11460 MPa for B20.

![Figure 4. Isofield of tangent stresses $\tau_{xz}$ (P=2.6 kN)](image)

At the second stage of research, for the considered composite structure, the process of its deformation was simulated taking into account the cracking process. During loading, up to the moment of ultimate failure, the values of shear strains were checked in three sections along the length of the bonding zone (figure 3). A value of the ultimate shear strength was taken according to the following formula [20]:

$$R_{uh} = \frac{R_c \cdot R_{bt}}{3}$$

where $R_c$ is the compressive strength of concrete; $R_{bt}$ is the tensile strength of concrete.

The analysis of these data shows the excess of the load-bearing capacity of the composite structure (ultimate failure load about 20 kN) in comparison with the values obtained as a result of the experiment (ultimate failure load 13-14 kN).

In addition, the type of structural failure obtained as the result of numerical simulation differs significantly from that observed in the experiment. Thus, as a result of step-by-step loading, it was found that the structure break occurs as a result of concrete crushing near the area of application of the load. Moreover, a horizontal crack along the bonding zone is formed from the side of the concrete with less strength (B5), and has a limited length. A through crack is not formed along the junction of elements of the composite structure. This indicates that the approach is erroneous when the strength characteristics of the bonding zone are equated with the strength characteristics of the connected elements.

At the last stage of the research, the average values of stresses along the contact zone at the time of failure, obtained in the experiment [19], were taken as the shear strength of the simulated bonding zone of the composite structure. They averaged 0.235 MPa, which is significantly lower than the shear strength for concrete B5 (0.8 MPa).

At this stage, the results of numerical simulation of the deformation process taking into account crack process showed a better agreement with the results of the experiment. Thus, the obtained deformation curves are closer to the experimental ones (see figure 5(b)). At the same time, the present difference in the values of strains is primarily a result of the constancy of the shear modulus of the bonding zone taken in the model, while it should progressively decrease, as the experimental diagram shows.
Figure 5. Deformation curves obtained from numerical simulation (---) and experimental results (-- --) without (a) and with (b) the real failure load of the bonding zone.

The type of cracking and failure process obtained as a result calculation of the simulated structure fully matches the ones observed in the experiment. Thus, the failure of a composite structure occurs as a result of the formation of a through longitudinal crack passing through the bonding zone between elements. In this case, breakage in the connected elements does not happen.
The calculated value of the failure load (10.2 kN) is slightly lower than that recorded in the experiment (14 kN). This is probably the effect of a number of errors related to the applied strength criterion, the numerical method of calculation, as well as the difference between the actual deformation characteristics of concrete and the standard values we have accepted [16].

But at the same time, the value of the failure load obtained as a result of the calculation is slightly lower than the experimental one, and gives the safety margin, which allows us to conclude that it is possible to use the proposed methodology for estimating the structural strength.

4. Conclusions
A technique was developed for finite element modelling of the stress-strain state and the cracking process of the bonding zone composite reinforced structures.

The shear stiffness of the bonding zone is numerically determined taking into account the stress pattern in the structure.

The necessity of using reduced shear strength characteristics and the shear modulus of bonding zone instead of the characteristics of the contacting elements in the simulation of the deformation process and assessing the ultimate load is shown.

The results obtained with the developed calculation methodology demonstrate their adequate agreement with the experimental data. This allows us to recommend it for nonlinear calculations of layered composite concrete structure.

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