Structural simulation modeling of the fiber-reinforced concrete composite

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Abstract. The quantitative estimation of concrete structural elements influence on its strength characteristics is an actual task requiring application of computer technologies. Separate models for several scale levels to study the strength properties of fiber-reinforced concrete were developed in this article. Herein, the results of the material behavior study at a low level were used in the modeling of higher-level structures. Three alternative values of the elastic modulus were obtained for several compositions by different methods and compared with experimental data. The results of this research can be used for directional regulation of the concrete composites properties.

1. Introduction

Mathematical description of the composite structure’s influence on its mechanical and strength properties is one of the most effective ways to optimize its composition. At the same time, improving the construction production efficiency is inextricably linked with the creation and development of new advanced building materials, such as fiber-reinforced concrete. Therefore, structural-simulation modeling (SSM) is one of the most effective tools, which is suitable for the description of the similar complex structured systems.

The author offers a generalizing model of fine-grained concrete structure, which can be used to study the heterogeneity of stress distribution in the material volume in the paper [1]. This phenomenon can be explained by a large difference in the values of the cement stone elastic modulus and fine aggregate according to the author. The author created a flat model of cement-sand composite microstructure on three scale levels in order to calculate it. At the same time, the author's program "PoreSolution", implementing the Monte Carlo method, was used to place the structural elements of the model within a given area. An experiment on static compression of a flat concrete model for developed geometrical and finite element models was simulated. The studies [1] performing have allowed to obtain the strength and deformation regularities in the behavior of cement-sand compositions depending on their composition. This article presents the results of studies that continue and develop the above approach.

2. Conducting of the computational experiment

In mathematical modeling of the concrete compositions behavior, it is impossible to take into account the elements contained of a large sizes range – from pores measured in several nanometers to grains of large aggregate reaching tens of millimeters in size. So, separate mathematical models for each scale level were used to study the mechanical properties of fiber-reinforced concrete. Two scale levels were...
taken into account: mesostructure, in the form of cement-sand composition, and macrostructure, represented by coarse-grained concrete and fiber-reinforced concrete.

2.1. Cement-sand composition model

The concept of “probabilistic-geometric concentration” proposed in [2] was used to create a structural-simulation model of cement-sand composition. A pores distribution and sand grains by size, porosity and arrangement of pores and solid phases in model space were considered as a major probability factors that define the geometry model. The design model plane is taken in the square form with dimensions of 50 x 50 mm. Structural components which considered in the model are as follows: the matrix (cement stone), grains of sand (1-5 mm), pores (sizes range from 0.8 mm to 1.7 mm), the contact area between the grains of the filler and the matrix (thickness 0.2 mm). The form of pores and grains of sand is conditionally accepted as circles for simplification of a finite-element grid construction. The contact area is simulated as an annular shell around each grain of sand.

The modulus of elasticity ($E$) and Poisson's ratio ($\mu$) of quartz sand are adopted on the basis of literature data and are equal to: $E = 72.8$ GPa, $\mu=0.167$. The values of the elasticity modulus and Poisson's ratio of the contact zone are assumed to be equal 10.6 GPa and 0.30 (according to estimates obtained in the work [3]). The above values were recalculated for use in two-dimensional formulation [4] in order to prepare for the calculation:

$$E_2 = \frac{E_3}{(1-\mu_3^2)},$$  

(1)

$$\mu_2 = \frac{\mu_3}{(1-\mu_3)}$$  

(2)

The values of elasticity modulus and Poisson's ratio of cement stone for ten calculated compositions (P1...P10) are taken from the results of experiments carried out in [1]. Figure 1 shows a typical geometric scheme of the composition for P1, built by the macro-program in the language APDL (ANSYS Mechanical). Each time you run the program, it implements a new packaging option that does not repeat the previously built layouts. The conditions of fastening and loading were taken in accordance with Figure 2.

![Figure 1](image1.jpg)

**Figure 1.** Geometric model of the cement-sand composition: 1 – cement matrix; 2 – pore; 3 – sand particle; 4 – contact area.

![Figure 2](image2.jpg)

**Figure 2.** Boundary conditions of the calculation scheme.
The following two types of finite elements were selected to build the mesh in the ANSYS library: PLANE 182 and PLANE 183. According to the results of preliminary calculations on two corresponding meshes (with the same partition step, but with different types of finite elements) in one case, the result was noticeably overestimated relative to the experimental value, in the other – slightly understated. After the final selection of the finite element type (PLANE183), a second preliminary calculation was carried out, also on two finite element meshes, but with a different partition step (0.2 mm and 0.4 mm). Based on the obtained results, it can be concluded that the 0.2 mm mesh pitch gives a slightly more accurate result. The enlarged fragment of this mesh is shown in Figure 3.

![Figure 3](image.png)

**Figure 3.** The enlarged fragment of the finite-element model.

In preparation for the strength calculations’ main series for each composition (P1..P10) it was formed on three models with different distribution of structural components in the plane of the model, but with the same percentage, with one type of finite element (PLANE 183), and with one partition step (0.2 mm). The results were averaged for each composition. Then the summary tables 1 and 2 were made, where the values of the elasticity modulus and Poisson’s coefficients specified in [1] \((E^*_{\text{exp}}, E^*_{\text{the}}, \mu^*_{\text{the}})\) and received as a result of the executed calculations \((E_{\text{calc}}, E_{\text{int}}, E_{\text{eq}}, \mu_{\text{calc}})\).

### Table 1. Comparison of elastic modulus.

| Composition | Sand, % | Pores, % | 3D | 2D | 3D | 2D | 3D | 2D | 2D | 2D |
|-------------|---------|----------|-----|-----|-----|-----|-----|-----|-----|-----|
| P1          | 47.4    | 19.86    | 22.41| 25.2| 23.7| 21.465| 20.259| 23.550| 42.358|
| P2          | 48.9    | 19.09    | 23.95| 25.0| 23.5| 21.987| 20.752| 23.960| 43.241|
| P3          | 52.3    | 17.68    | 32.01| 33.2| 31.4| 26.622| 25.127| 27.270| 46.475|
| P4          | 49.1    | 18.13    | 25.34| 25.8| 24.4| 21.754| 20.532| 24.049| 43.844|
| P5          | 53.2    | 20.25    | 22.03| 24.1| 22.8| 20.182| 19.105| 23.209| 44.834|
| P6          | 55.3    | 17.65    | 27.81| 28.7| 27.2| 22.936| 21.712| 24.789| 47.107|
| P7          | 56.1    | 17.21    | 30.56| 31.5| 29.8| 25.460| 24.101| 27.075| 47.875|
| P8          | 55.4    | 19.62    | 20.60| 22.2| 21.0| 19.920| 18.857| 22.399| 45.921|
| P9          | 58.3    | 20.05    | 22.44| 24.7| 23.4| 19.084| 18.066| 22.827| 47.337|
| P10         | 66.1    | 18.70    | 19.02| 21.5| 20.2| 16.807| 15.910| 19.324| 50.766|
Table 2. Comparison of Poisson's ratio.

| Composition | Sand, % | Pores, % | Poisson's ratio | $\mu_{\text{the}}$ | $\mu_{\text{calc}}$ |
|-------------|---------|---------|----------------|------------------|------------------|
|             |         |         | $\mu_{\text{2D}}$ | $\mu_{\text{3D}}$ | $\mu_{\text{2D}}$ | $\mu_{\text{3D}}$ |
| P1          | 47.4    | 19.86   | 0.31            | 0.24             | 0.31            | 0.237            |
| P2          | 48.9    | 19.09   | 0.31            | 0.24             | 0.31            | 0.237            |
| P3          | 52.3    | 17.68   | 0.30            | 0.23             | 0.31            | 0.237            |
| P4          | 49.1    | 18.13   | 0.30            | 0.23             | 0.31            | 0.237            |
| P5          | 53.2    | 20.25   | 0.30            | 0.23             | 0.30            | 0.231            |
| P6          | 55.3    | 17.65   | 0.30            | 0.23             | 0.30            | 0.231            |
| P7          | 56.1    | 17.21   | 0.30            | 0.23             | 0.30            | 0.231            |
| P8          | 55.4    | 19.62   | 0.30            | 0.23             | 0.30            | 0.231            |
| P9          | 58.3    | 20.05   | 0.29            | 0.22             | 0.30            | 0.231            |
| P10         | 66.1    | 18.70   | 0.29            | 0.22             | 0.30            | 0.231            |

Several approaches were used to obtain the values of the elastic modulus and Poisson's ratio based on the results of the computational experiment. According to GOST 24452-80, elasticity modulus is defined as the ratio of voltage increment from zero to the external load level equal to 30% from the damage (20 MPa according [1]), to the increment of elastic-instantaneous relative deformation of the sample. The Poisson ratio is calculated as the ratio of the elastic-instantaneous relative transverse strain to the longitudinal strain of the specimen. Thus, devices for measurement of concrete sample deformations in the form of a cube shall be established on four free sides. In accordance with the indication (in the transition to the plane problem), the results of calculation in ANSYS (values of the elastic deformations) was determined in the nodes located on the free right edge of the model. According to the obtained data, the average values of longitudinal and transverse strain on the face were calculated. The calculated values of the elastic modulus $E_{\text{calc}}$ and Poisson's ratio $\mu_{\text{calc}}$ were determined. Figure 4 shows the distribution fields of elastic longitudinal deformation for the composition P3, which provided the highest value among all the simulated compositions.

![Elastic longitudinal deformation of the composite composition P3.](image)

The second approach to the calculation of the elastic modulus is based on the calculation of the obtained data integral value on the stress-strain state in each node of the model. The value of the elastic modulus was defined as the ratio of the normal stress in the node to the elastic longitudinal
deformation in the same node: \( E_{int} = \frac{\sigma_{yi}}{\varepsilon_{yi}} \). Then the integral modulus of elasticity was determined as the average value for all nodes: \( E_{int} = \sum E_{int} \).

The equivalent modulus of elasticity \( E_{eq} \) takes into account the degree of structure components influence on the elastic properties of the composite and is calculated by the following expression:

\[
\sigma_{eq} = \sum_{m=1}^{N} (k_mE_m)
\]

This value sums the shares of the individual phases “contribution” to the strength of the model in proportion to the volume occupied by them in the structure of the model. It is obvious that the equivalent modulus of elasticity differs markedly from the actual absolute value of the resulting modulus of elasticity. Therefore, at the following scale levels this value was not taken into account.

The obtained results of the mechanical properties allow us to conclude, that a consistent increase in the percentage of sand in the composition to 50-55% leads to an increase in the value of the elastic modulus, but with a further increase in the reinforcement of the cement stone with a small filler. There is a significant decrease in the elastic characteristics of the material.

2.2. Coarse-grained and fiber-reinforced concrete model

At the next scale level, the modeling ideology remains the same, but the contact zone is not taken into account to simplify the finite element grid creating. Thus, the concrete composition was accepted consisting of two phases: cement-sand composition (with elastic characteristics obtained at the previous scale level) and a large aggregate in the form of regular polygons (with the number of sides from 3 to 6). Crushed grains were taken with a diameter of 5...25 mm; pores in the size range from 1.7 to 5.0 mm. In accordance with the proposed method, coarse-grained concrete of four compositions’ numerical models were developed, reflecting the basic parameters of the structure of real compositions. The flat model is also chosen in the square form with dimensions of 200x200 mm, the location and orientation of the crushed stone grains in the model space were assigned randomly (figure 5). The conditions of fastening and loading of the model are identical to those indicated earlier (figure 2).

**Figure 5.** Geometric model of the coarse-grained composition.

**Figure 6.** Finite-element model of the coarse-grained composition.

By analogy with coarse-grained concrete, the fiber-concrete composition was also adopted consisting of two phases: cement-sand composition (with elastic characteristics obtained at the previous scale level) and reinforcing fibers in the form of finely chopped fibers with a diameter of
0.3 mm and a fiber length of 22 mm. In accordance with the described technique have been developed the numerical model for fiber-reinforced concrete composite four samples. Thus, for each composition has been examined in two options of the percentage of fibers $\eta$: 0.5 and 1%. The flat model was also chosen in the form of a square with dimensions of 200x200 mm, the location and orientation of the fibers in the space of the model were assigned randomly. The obtained results are presented in figures 7 and 8.

![Graph 1](image1)

**Figure 7.** Comparison of values for the coarse-grained composition models.

![Graph 2](image2)

**Figure 8.** Comparison of values for the fiber-reinforced composition models.

### 3. Conclusion

The calculated values of the elastic modulus were less than the experimental values by 10...15% at all scale levels. The results of coarse-grained concrete and fiber-reinforced concrete models calculations indicate that it is necessary to take into account the contact zone between the reinforcing element and the matrix at the level of macrostructure. Otherwise, the effect of fiber reinforcement is hardly noticeable and the elastic characteristics of the fiber-reinforced concrete do not differ from the corresponding characteristics of non-reinforced concrete.

### References

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