Nonlinear Models of Reinforced Concrete Beam Elements with the Actual Reinforcement

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Abstract. The problem of modeling reinforced concrete structures with bar finite elements using a nonlinear material that allows to consider the direct reinforcement is studied. An approach to the creation of a computational model of a reinforced concrete column is proposed, the peculiarity of which is to specify reinforcing bars at the appropriate integration points of the cross-section. As a material of reinforced concrete bar elements, a nonlinear material based on Eurocode-2 is used, which can model the nonlinear behavior of both concrete and reinforcement for different integration points. Numerical experiments were carried out using the LS-DYNA software package. The results of the calculation of the bar reinforced concrete column are compared with the data for the column modeled using solid finite elements with direct reinforcement. In addition, a comparative analysis of the studied column with the results of full-scale tests is performed. Studies have shown good convergence of stresses, strains, and displacements, as well as the coincidence of the value of the ultimate breaking load and the similar nature of the destruction of the reinforced concrete column.

1. Introduction
The design of buildings and structures should be supported by a feasibility study. Approaches to such calculations and their complexity depend on the type and criticality of the structure. For civil engineering in seismically safe areas it is not always advisable to complicate the method of calculations (use nonlinear methods). However, if we are talking about unique buildings, as well as some industrial sector facilities, carrying out calculations in a nonlinear formulation considering the geometric, physical, and structural nonlinearities is necessary. In addition to the use of nonlinear methods in the calculations, the accuracy of modeling of structural elements, especially reinforced concrete ones, remains an important issue. State-of-the-art software packages, in particular LS-DYNA, enable to model behavior of concrete by means of solid finite elements, and reinforcing bars by means of bar elements. Thus, the design diagram considers the direct reinforcement of reinforced concrete elements. However, this approach requires significant computing power and much computer time. Currently, approaches to modeling of reinforced concrete structures by bar finite elements are beginning to develop, in which the distribution of concrete and reinforcing bars across the cross section is regulated by integration points. The studies described in this article were carried out based on one of these approaches.
2. Relevance
In domestic and foreign literature, there are similar methods of modeling of load-bearing elements of building structures using bar finite elements [1,2,3,4]. However, in [1, 2], direct reinforcement of reinforced concrete elements is not considered; instead, the assumption of "optimal" reinforcement is introduced. This approach is generally acceptable in the calculation of structural elements for operating loads close to breaking ones. It is worth noting that the use of this assumption for the calculation of buildings and structures for special types of effects is no longer correct.

State-of-the-art calculation software packages provide extensive databases of material models, in particular for the behavior of concrete and reinforced concrete. Based on the material described in [5], it can be concluded that from many concrete models implemented in the LS-DYNA software package, only a few materials can be applied to bar elements. One of these materials is the MAT_172 Concrete EC2 model based on the provisions of Eurocode-2 [6, 7]. The obvious advantage of this model is the ability to account for direct reinforcement.

Studies of the behavior of shell finite elements modeled with the use MAT_172 Concrete EC2 have been carried out abroad for a long time already [8, 9, 10], and the ability to set bar elements in a correct formulation using this material is relatively recent. Therefore, studies on this topic, comparison of the obtained numerical results with the data of field experiments is an important task aimed at optimizing the methods of calculating the elements of building structures for various types of effects [11].

3. Problem statement
The object of the study is an eccentric-compressed reinforced concrete column of square section of 150×150 mm, 1150 mm in height, with longitudinal reinforcement with a diameter of 12 mm and transverse reinforcement with a diameter of 6 mm. The longitudinal compressive force acts with an eccentricity of 15 mm (Figure 1) [12].

![Figure 1. Calculation scheme of reinforced concrete columns.](image)

The column was modeled by bar finite elements in the LS-DYNA software package. MAT_172 Concrete EC2 was used as a material model for reinforced concrete.

The aim of the study was to compare the results of a similar column but modeled with solid (concrete) and bar (reinforcing bars) finite elements (reference column) [13, 14] with the behavior of the column modeled only with the help of bars. In addition, a comparison with the results of the real experiment described in [12] was assumed.

4. Theoretical part
Numerical studies were carried out using nonlinear methods. Physical nonlinearity of materials was considered using the Continuous Surface Cap Model (MAT_159 CSCM) [15, 16, 17, 18] for solid concrete elements and using the Concrete EC2 model (MAT_172) for a column modeled with bar elements only.
In [19, 20], the features of the MAT_159 CSCM model are described in detail, and the results of the verification of the work of this material are also presented.

The peculiarity of the MAT_172 Concrete EC2 model is that with its help either only concrete, or only steel of reinforcing bars, or at the same time parameters of both concrete and reinforcing bars (reinforced concrete) can be specified using it. In Figure 2 and 3, identifiers of parameters that are specified in this model are highlighted.

![Figure 2. Parameters for specifying concrete.](image)

![Figure 3. Parameters for specifying reinforcement.](image)

This model enables to consider the concrete cracking under tension, its compression fracture, as well as the appearance of fluidity in reinforcing bars. Concrete cracking under tension occurs when the maximum primary stresses reach the ultimate tensile strength. After cracking begins, tensile stresses decrease with increasing strain. In addition, another feature of this model is that the average value of tensile strength, the value of the modulus of elasticity and strain are calculated automatically using the provisions of Eurocode-2 from the known value of cylindrical compression strength [6]. The diagram of concrete behavior is shown in Figure 4.

![Figure 4. Concrete deformation diagram.](image)

The ability to specify both concrete and reinforcing bars with a single material enables to use another relevant approach implemented in the LS-DYNA software package: adjust the distribution of concrete and reinforcing bars across the cross-section with the use of integration points.

Integration points enable to specify the bar elements of the cross-section of arbitrary shape. Each integration point is a rectangle with a relative area of $A_i/A$. Where $A_i$ is the actual area of the integration point and $A$ is the actual cross-sectional area. In addition to the relative area for each integration point, the coordinate of its center of gravity in relative coordinates $t - s$ is specified (Fig. 5). Where $-1 \leq t \leq 1$ and $-1 \leq s \leq 1$. 

Another feature of the arbitrary setting of integration points is that different characteristics of the same material can be specified for each point. Thus, it is MAT_172 that allows to specify both reinforcement and concrete for one cross-section. Figure 5 shows the distribution of integration points across the element cross-section. Moreover, for the concrete points located along the contour and for the reinforcing bar points, a criterion for the removal of the element in the form of ultimate strains is introduced.

5. Practical relevance
The approach described above for bar elements enables to simulate most accurately the behavior of a structural element, which is not the case when implementing other techniques. Below are the results of numerical studies and a comparison of these results with experimental data. The good convergence of many dependencies, the coincidence of the values of the breaking load, as well as the same fracture pattern enables to note the accuracy of modeling the bar elements using the above technique.

Figures 6–7 show stress-strain diagrams for concrete and reinforcing bars, respectively.
Figure 8 shows a comparison of diagrams of horizontal displacements of the center of the column.

![Graph of horizontal displacement of the column center](image)

**Figure 8.** Graph of horizontal displacement of the column center.

Figure 9 shows the column fracture pattern, presents the results of a full-scale experiment, the results of a numerical calculation of a column modeled with solid elements considering the direct reinforcement, as well as numerical results of calculating a column modeled with bar elements with the distribution of reinforcing bars over integration points.

![Column fracture patterns](image)

**Figure 9.** The nature of the column destruction a) full-scale experiment [12]; b) reference column [13]; c) column modeled by beam elements with direct reinforcement.

Table 1 presents the values of breaking loads for each case.

| Type of experiment | Ultimate breaking load value P, kN | Discrepancy, % |
|-------------------|------------------------------------|----------------|
| Full-scale experiment | 607.8                             | -              |
| Reference model   | 587.5                             | 3.33           |
| Beam model        | 597.5                             | 1.69           |

6. Conclusions

Analysis of the results of numerical studies and comparison with the results of the field experiment allow to conclude that it is permissible and expedient to model columns with the use of bar finite elements using MAT_172 Concrete EC2. Acceptable convergence of stress-strain and displacement diagrams, similar fracture pattern, and good coincidence of the fracture load value suggests that the considered technique works correctly for the investigated type of structure. For carrying out similar
calculations of other load-bearing elements of building structures for various types of effects, it is necessary to conduct additional studies of the accuracy of the MAT_172 Concrete EC2 operation in the LS-DYNA software package.

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