Behavior of reinforced concrete structures with metal and non-metal reinforcement at impulse loadings

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Abstract. Results of the study on the operation of the reinforced concrete columns joints without reinforcement and reinforced by metal casing under short-term dynamic loading are presented in the paper. Program of experimental and numerical studies was developed. As a result of experimental studies schemes of deformation, cracking and fracture, as well as values of fracture loads of experimental samples were obtained. Present results are compared with data of the numerical calculations performed using the computational program based on finite elements method. Results of experimental and numerical calculations showed good convergence and reliability of columns joints strengthening by metal casing.

1. Introduction
The study of reinforced concrete columns joints operation is of a significant demand nowadays, as while constructing reinforced concrete frames of multistoried residential and civil buildings defects and failures occur reducing bearing capacity of the columns and their joints. This may lead to fracture of separate structures of the building or building as a whole [1]. Besides, dynamic impacts can be experienced by structures, which were not earlier calculated for dynamic loadings, as seismic activity is now increased in many regions of Russia and, especially in cities of Western Siberia [2, 3].

2. The results of experimental studies
The program of experimental and numerical studies which included three series of samples was developed for observation of operation of the concrete columns joints strengthened by metal casing, for identification of maximum load rate and nature of fracture under short-term dynamic loadings. Each series had five samples in scale 1:4 to real columns with different variations of joints and reinforcement in the joint area and external strengthening by means of metal elements. The following labels were used for experimental samples: K_d – a sample without joint; SK_d – a sample with a joint, with grids in joint area; SKD_d – a sample with a joint without grids in joint area; SKM_d – a sample with a joint with grids in joint area and reinforced by a metal casing; SKMD_d – a sample with a joint without grids in the joint area and reinforced by a metal casing. All experimental samples were...
reinforced by spatial knitted frameworks. Principle reinforcement was made of 8 rods with 8 mm diameter of the class A-III (A-400). Confinement reinforcement (collars and grids) was made of a wire of Bp-I (B500) with a diameter of 3 mm. For prevention of local fracture in the adjacent areas confinement reinforcement is placed in the form of 5 grids with a gap of 20 mm. In case of reinforced concrete columns joints without defect (SKd, SKDd) five grids with a gap of 20 mm were placed in the joint area. In case of reinforced concrete columns joints with defect (SKDd, SKMDd) grids in a joint area were absent. All prototypes were made of concrete which corresponds to the class B20.

In order to obtain information of the behavior of the elements, patented pile driver with the measuring system devices of the Department of Reinforced Concrete and Masonry Structures of Tomsk State University of Architecture and Building was used [4] (Figure 1). It allows testing concrete element under short-term dynamic loading of the type presented in Figure 1a.

![Figure 1. General view of the stand for testing of experimental samples under short-term dynamic load (a) and the nature of the load is applied to the experimental samples and its dependence on the duration (b).](image)

The conducted experimental studies allowed to reveal nature of deformation and fracture of reinforced concrete columns and their joints (Figure 2) at dynamic loadings, and also to determine values of ultimate loads (Figure 1b) for experimental samples: for a sample Kd – 305.0 kN; sample SKd – 253.0 kN; sample SKDd – 104.4 kN; sample SKMd – 371.6 kN; sample SKMDd – 326.5 kN.

3. Numerical simulation

Numerical calculations of the dynamic deformation under loadings of the type illustrated on Figure 1b were carried out in addition to experimental studies of reinforced concrete columns joints. Samples of numerical simulation fully conformed to the ones of experimental studies. In these studies method of finite elements applying finite-difference scheme of Johnson was used [5]. This approach allows us to study the fracture mechanism of the samples under dynamic loading.

In the numerical finite element model on the free surfaces boundary conditions with absence of shear stresses at the contact surfaces – the sliding conditions without friction were applied. The initial velocity of the load was 4.43 m/s and it fully coincided with experimental studies. The total number of finite elements in the sample was $1 \cdot 10^6$.

For the description of metal load behavior elastoplastic model was used and for the description of experimental concrete sample behavior brittle-plastic model was used. The medium was represented as quasi-homogeneous.
The complex of equations describing non-stationary adiabatic movements of the compressible media in the Cartesian coordinate system of XYZ includes the following equations [5, 6]:

– continuity equation

\[
\frac{\partial \rho}{\partial t} + \nabla \rho \vec{u} = 0,
\]

– equation of motion

\[
\rho a^k = \nabla^L \sigma^{k} + F^k,
\]

where

\[
a^k = \frac{\partial \vec{u}}{\partial t} + \vec{u} \times \nabla^L \vec{u} ; \nabla^L \sigma^{k} = \sigma_{j}^{k} + \sigma^{m}_{j} \Gamma^{k}_{m} + \sigma^{k}_{j} \Gamma^{m}_{j},
\]

– energy equation

\[
\frac{dE}{dt} = \frac{1}{\rho} \sigma^{ij} e_{ij}.
\]

Here \( \rho \) – density of the media; \( \vec{u} \) – velocity vector; \( a^k \) – acceleration; \( F^k \) – components of mass forces vector; \( \Gamma^{k}_{j} \) – Christoffel symbols; \( \sigma^{ij} \) – symmetric components of the stress tensor; \( E \) – specific internal energy; \( e_{ij} \) – components of the symmetric strain rate tensor: superimposed dots mean a derivative on time; separation of symbol by comma – a derivative on the corresponding coordinate.

Components of a stress tensor in the sample before fracture correlate with coefficients of generalized Hooke's law which was expressed through strain rates:

\[
\hat{\sigma}_{ij} = C_{ijkl} e_{kl}.
\]

For failure criterion of the sample Hoffman's criterion [7] is used. This criterion allows using
various strength characteristics of material under compression and tension. The component of a stress tensor expressed through scalar functions, looks as follows:

$$
C_1(\sigma_2 - \sigma_3)^2 + C_2(\sigma_3 - \sigma_1)^2 + C_3(\sigma_1 - \sigma_2)^2 + 
C_4\sigma_1 + C_5\sigma_2 + C_6\sigma_3 + C_7\sigma_4^2 + C_8\sigma_5^2 + C_9\sigma_6^2 \geq 1,
$$

(5)

where $C_i$ – material constants.

It is supposed, that fracture of anisotropic materials in the conditions of intensive dynamic loadings happens as follows: in areas where the strength criterion is violated under compression ($e_{ik} \leq 0$), it is considered that material loses properties of anisotropy, and its behavior is described by hydrodynamic model, and the material keeps strength only under compression; stress tensor becomes in this case spherical ($\sigma_{ij} = -P$); in areas, where the strength criterion is violated at tension ($e_{ik} > 0$), the material is considered completely fractured, and components of a stress tensor are set equal to zero ($\sigma_{ij} = 0$).

Pressure in the material of samples fractured under compression is calculated by means of the equation of a state [9]:

$$
P = \left[ \exp\left(4\beta\frac{V_0-V}{V_0}\right)-1 \right] \frac{\rho_0\alpha^2}{4\beta}.
$$

(6)

Here $\rho_0$ – the initial density; $V_0$, $V$ – initial and current specific volumes. Coefficients of this equation are calculated from the shock adiabatic curve: $D = \alpha + \beta U_m$, where $\alpha = 1400m/s$, and $U_m$ – the mass velocity.

For the numerical studies calculation software developed by Radchenko A.V. and Radchenko P. A. was used.

Values of relative fracture volume $V_c/V_i$ are shown on Figure 3 in gray gradations. Values $V_c$ and $V_i$ are given in the grid points: $V_c$ – number of elements in node which satisfy fracture criteria; $V_i$ – the total amount of the elements forming this node. Value $V_c/V_i = 1$ corresponds to final fracture of a material in the node of the computational grid. Nodes, in which the material is completely fractured, are excluded from calculation for clearness.

4. Conclusion

Numerical calculations allowed revealing fracture schemes of experimental samples in different time periods (Figure 3) with good convergence with experimental studies.

The analysis of results of experimental and numerical studies of samples under dynamic loading showed reliability of strengthening of reinforced concrete columns and their joints. Increased load bearing capacity due to the metal casing was 40% in the test sample SKM$\delta$ compared with sample SKD$\delta$ and more, than three times at test of sample SKMD$\delta$ in comparison with SKD$\delta$ sample. The strengthening by a metal casing allowed increasing the bearing ability of a sample with joint SKMD$\delta$, having a defect, in comparison with SK$\delta$ sample by 29%.
Figure 3. General view of destruction of an experimental sample in time at numerical experiment: a) without joint; b) with a joint of columns without reinforcing.

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