Destruction of concrete beams with metal and composite reinforcement under impulse action

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Abstract. This work presents results of integrated experimental and numerical study of destruction of reinforced concrete beam made of concrete and fiber concrete under short-term dynamic loading. Experimental studies were carried out using pile driver. Short-term dynamic loading acting on a beam was applied by falling weight, 450 kg, from the height 700 mm. The value of dynamic load in experiments was defined by means of force gauge, linear displacement transducers were used to define linear displacements. Numerical simulation was held three-dimensionally within phenomenological approach of continuum mechanics, the reinforcing elements were clearly defined. Finite element method was modified to solve dynamic tasks. Impact of load on a beam in calculations was replaced by impulse. The dependence of impulse on time was defined from the experiment. The influence of reinforcement on deformation and beam destruction was studied. Correlation of experimental and numerical data was performed.

1. Experimental studies
The goal of experimental studies on laminated beams is defining the peculiarities of their deformation, revealing crack formation and destruction patterns of reinforced concrete elements of laminated structure under short-term dynamic loading. Test beams comprise three different reinforcing layers throughout the height of section: fiber concrete–concrete–fiber concrete. Testing of laminated beams was carried out on single short-term dynamic loading on pile driver with destruction of experimental beam.

Test beams were 2200 mm in length with effective span of 2000 mm. The dimensions of cross-section of all wide beams were taken as 220 × 150 mm. Every beam consisted of three layers: the lower and upper levels, 20 mm thick, were made of and reinforced with carbon fiber concrete, and intermediate layer, 110 mm thick was made of reinforced concrete. Reinforcement ratio of fiber concrete layers with carbon fiber was accepted as 0.2% of the binders weight.

Reinforcement of beams with reinforcement bars was performed symmetrically looking as tied frame and meshes. Three-dimension mesh reinforcement consists of longitudinal principal reinforcement 8D10 400 connected by means of loops made from wire D4 500. In the middle of upper and lower fiber concrete layers of test beams, the tied mesh is placed comprising wire D4 500 with spacing 66 mm in both directions.

To obtain information on operation of test laminated beams while the process of their loading a package of primary transducers of measuring data has been used. The value of dynamic
load under short-term dynamic testing was defined by means of dynamometer gauge. Linear displacement transducers were applied to calculate linear displacements. Acceleration gauges were used to measure accelerations under short-term dynamic testing. Resistive strain gauges PKB-10 type with resistance $R = 201.6 \, \Omega$ were fixed in the middle of rods of mesh reinforcement to measure deformations of tensile and compressive reinforcement of test beams. To define concrete and fiber concrete deformations resistive strain gauges of PKB-20 and PKB-50 type were fixed on the surface of test beams.

The beam was placed on dynamometric supports enabling to record the number of support reactions under dynamic testing. Short-term dynamic loading acting on a beam was applied by falling weight 450 kg from the height 700 mm. The dynamic testing of beam resulted in beam destruction along the standard section with crack formation in the area of pure bending due to destruction of concrete compression area. Dynamic breaking load for beam comprised $F_{u,d} = 120 \, \text{kN}$.

Analysis of crack formation and destruction patterns of laminated beam (figure 1) showed that they fracture due to formation and further opening of cracks along the standard section with the destruction of concrete compressive area.

2. Numerical simulation results. Comparison with experimental part

Numerical simulation accepts the loading conditions, geometrical dimensions of the beam and reinforcement as held in the experiment described above. Numerical simulation is performed three-dimensionally within phenomenological approach of continuum mechanics with clear defining of reinforcing elements [1,2]. Finite element method modified for solving dynamic tasks was used for numerical calculation [3]. Authors software and algorithm enabling performing parallel calculations with high performance are used for calculations [4].

Behavior of concrete and fiber concrete is described within the model [1] using Hoffman strength criterion considering tensile and compressive strength of concrete and fiber concrete:

$$f(\sigma) = C_1(\sigma_2 - \sigma_3)^2 + C_2(\sigma_3 - \sigma_1)^2 + C_3(\sigma_1 - \sigma_2)^2 +$$
$$C_4\sigma_1 + C_5\sigma_2 + C_6\sigma_3 + C_7\sigma_1^2 + C_8\sigma_2^2 + C_9\sigma_3^2 \geq 0,$$

(1)
Table 1. Elastic and strength properties of materials.

| Material          | $\rho$, kg/m$^3$ | Sound velocity $C_s$, m/s | Poisson ratio | Tensile strength, MPa | Compressive strength, MPa | Shear strength, MPa | Young modulus $E$, GPa |
|-------------------|------------------|---------------------------|---------------|------------------------|--------------------------|---------------------|----------------------|
| Concrete          | 2450             | 4500                      | 0.2           | 1.75                   | 22                       | 3.4                 | 26                   |
| Fiberconcrete     | 2450             | 4500                      | 0.2           | 3.4                    | 41                       | 6.5                 | 41                   |
| Steel A400        | 7850             | 5930                      | 0.3           | 400                    | 400                      | 400                 | 204                  |

Figure 2. Problem statement.

Figure 3. Load dependency on time.

where coefficients $C_{1-9}$ are found from the following equations:

\[
C_1 = \frac{[(Y_t Y_c + Z_t Z_c)^{-1} - X_t X_c)^{-1}]}{2}, \\
C_2 = \frac{[(X_t X_c + Z_t Z_c)^{-1} - Y_t Y_c)^{-1}]}{2}, \\
C_3 = \frac{[(X_t X_c + Y_t Y_c)^{-1} - Z_t Z_c)^{-1}]}{2}, \\
C_4 = X_t^{-1} - X_c^{-1}, C_7 = S_{yz}^{-2}, \\
C_5 = Y_t^{-1} - Y_c^{-1}, C_8 = S_{zx}^{-2}, \\
C_6 = Z_t^{-1} - Z_c^{-1}, C_9 = S_{xy}^{-2}.
\]

(2)

where $X_t$, $X_c$ are the ultimate tensile and compressive strength along $X$ axis, $Y_t$, $Y_c$ are the ultimate tensile and compressive strength along $Y$ axis, $Z_t$, $Z_c$ are the ultimate tensile and compressive strength along $Z$ axis, $S_{xy}$, $S_{yz}$, $S_{zx}$ are the ultimate shear strength along the corresponding axes.

Behavior of steel reinforcement was described within elastic-plastic model [1]. Elastic and strength properties of materials are given in table 1.

Figure 2 shows the general view of the simulated beam. Fiberconcrete layers are placed above and below, the intermediate layer is concrete. The areas of impulse application on the front surface are marked; points of fixing on the back surface are marked in black. In the points of beam fixation displacements along $Z$ axis were restricted in negative direction.
Figure 4. Structural design of beam reinforcement.

Figure 5. Finite-element computation mesh.

Figure 3 demonstrates dependency of the applied load on time obtained from the experiment. Structural design of beam reinforcement similar to the experimental one is given in figure 4. Beam was divided into tetrahedral finite elements. The total number of finite elements in calculations comprised $1.8 \cdot 10^7$. Fragment of computation mesh is given in figure 5.

In order to work out the computational model and evaluate the influence of reinforcement on beam destruction the behavior of beam without reinforcement was studied at the same time. The load configuration of non-reinforced beam was similar to the load configuration of reinforced beam (figure 2). Figures 6 and 7 demonstrate computational distributions of destruction areas in beam without reinforcement (a) and in reinforced beam (b) at different periods. Fracture pattern in these beams differs significantly. In reinforced beam destruction areas (cracks) distribute almost over the whole beam and their destruction is less than the ones in beam without reinforcement. The main crack propagates in the beam without reinforcement.
Figure 6. Destruction of (a) beam without reinforcement and (b) reinforced beam, $t = 3$ ms.

Figure 7. Destruction of (a) beam without reinforcement and (b) reinforced beam, $t = 6$ ms.

Figure 8. Experimental and computational displacement in time of the central point of beam back surface, $x = 0$.

Figure 9. Experimental and computational displacement in time of the point on beam back surface, $x = 0.33$ m.

further leading to its fragmentation (figure 7a). Reinforcement provides stress distribution along the whole beam. In this case, the high level of ultimate breaking stress is located in the areas adjoining the reinforcing elements.
Table 2. The maximum values of stress.

| Time  | Material       | Stress component | $\sigma_{\text{min}}, \text{MPa}$ | $\sigma_{\text{max}}, \text{MPa}$ |
|-------|----------------|------------------|----------------------------------|----------------------------------|
|       | Steel          | $\sigma_{xx}$    | −92.4                            | 267                              |
|       |                | $\sigma_{zz}$    | −60.8                            | 52.1                             |
|       |                | $\sigma_{zx}$    | −35                              | 125                              |
|       |                | $\sigma_{xx}$    | −55                              | 7.18                             |
|       | Concrete       | $\sigma_{xx}$    | −13                              | 15.2                             |
| 3 ms  |                | $\sigma_{zz}$    | −55                              | 6.44                             |
|       |                | $\sigma_{zx}$    | −24.9                            | 5.94                             |
|       | Without reinforcement | $\sigma_{xx}$ | −7.33                            | 7.64                             |
|       |                | $\sigma_{zz}$    | −11.6                            | 6.19                             |
|       |                | $\sigma_{zx}$    | −455                             | 365                              |
|       | Steel          | $\sigma_{xx}$    | −131                             | 133                              |
|       |                | $\sigma_{zz}$    | −437                             | 402                              |
|       |                | $\sigma_{zx}$    | −281                             | 5.64                             |
| 6 ms  | Concrete       | $\sigma_{xx}$    | −19                              | 2.19                             |
|       |                | $\sigma_{zz}$    | −281                             | 6.24                             |
|       |                | $\sigma_{zx}$    | −4.59                            | 3.57                             |
|       | Without reinforcement | $\sigma_{xx}$ | −2                               | 2.8                              |
|       |                | $\sigma_{zz}$    | −3.43                            | 2.75                             |

![Figure 10. Experimental and computational displacement in time of the point on beam back surface, $x = 0.66$ m.](image)

Table 2 provides the maximum values of normal tensile and compressive strength (with “−” sign) $\sigma_{xx}$, $\sigma_{zz}$ and shear stress $\sigma_{zx}$ in axis ZX in steel reinforcement and concrete for reinforced beam as well as the value of these stresses in concrete layer in non-reinforced beam. Maximum values of stresses in reinforced beam are realized in steel reinforcement and the adjusting layer of concrete. As a result, destruction of concrete is observed in the area of its contact with reinforcing elements. Crack formation in this contact area leads to stress relaxation in the remaining concrete layers.

Figures 8–10 reflect comparison of timely changes of displacements points of the bottom surface of reinforced beam obtained in the experiment (solid curve) and in computation (dashed curve).
For the central point \((x = 0, \text{ figure 8})\) the divergence was 12\%, for point \(x = 0.33 \text{ m (figure 9)}\)—6\% and for point \(x = 0.66 \text{ m (figure 10)}\)—3\%. Considering the dimension of the solved task agreement with the experiment is satisfactory.

3. Conclusion

Resulting from the performed experiments the following conclusions can be made. The suggested model of concrete and fiber concrete behavior describes properly dynamics of stress-strain state and fracture pattern. The algorithm and calculation method enable to study the overall behavior of structure three-dimensionally. The obtained numerical results satisfy well with the experimental data.

References

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