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Experimental and numerical investigation of concrete structures with metal and non-metal reinforcement at impulse loadings

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Abstract. Manufacturing durable and high-strength concrete structures has always been a relevant objective. Therefore special attention has been paid to non-metallic composite reinforcement. This paper considers experimental and numerical studies of nature of fracture and crack formation in concrete beams with rod composite reinforcement. Fiber glass rods, 6 mm in diameter, have been used as composite reinforcement. Concrete elements have been tested under dynamic load using special pile driver. The obtained results include patterns of fracture and crack formation, maximum load value and maximum element deflection. Comparative analysis of numerical and experimental studies has been held.

1. Introduction

Current scientific and technological development establish new special requirements to building materials: along with strength and deformation properties attention has also been paid to corrosion resistance, electrical, magnetic and radio resistance. At the same time the basic structural material currently is reinforced concrete that does not meet the mentioned requirements in most cases. Increasing seismic activity in many regions of the Russian Federation has lead to strengthening the requirements on providing seismic resistance of buildings and structures. Along with that it requires novel design and engineering solutions with the use of modern building materials [1].

Reinforcement of concrete structures with non-metallic composite polymer rods can become a possible option to solve this problem. Composite reinforcing rods are characterized by low relative density, corrosion resistance, dielectric properties, as well as magnet inertia and radio transparency. However these materials also have disadvantages significantly restricting their application fields: relatively low values of deformation properties, low fire resistance, lack of stable pre-stressing technology. Thus the issues of design, calculation and application of concrete structures reinforced with non-metallic composite polymer materials are of great relevance [2–4].

2. Research program

In order to define crack formation patterns and study deformability of concrete beams reinforced with fiber glass rods experimental study program has been elaborated, including: manufacturing

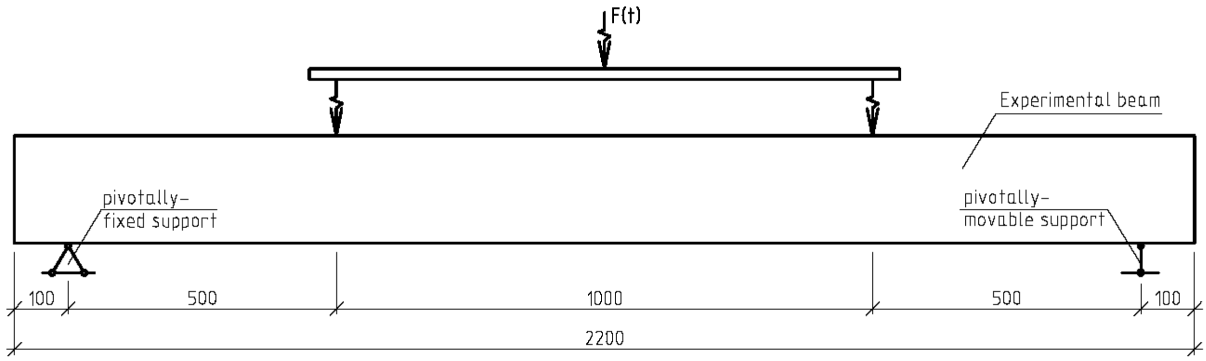

Figure 1. Scheme of load application.

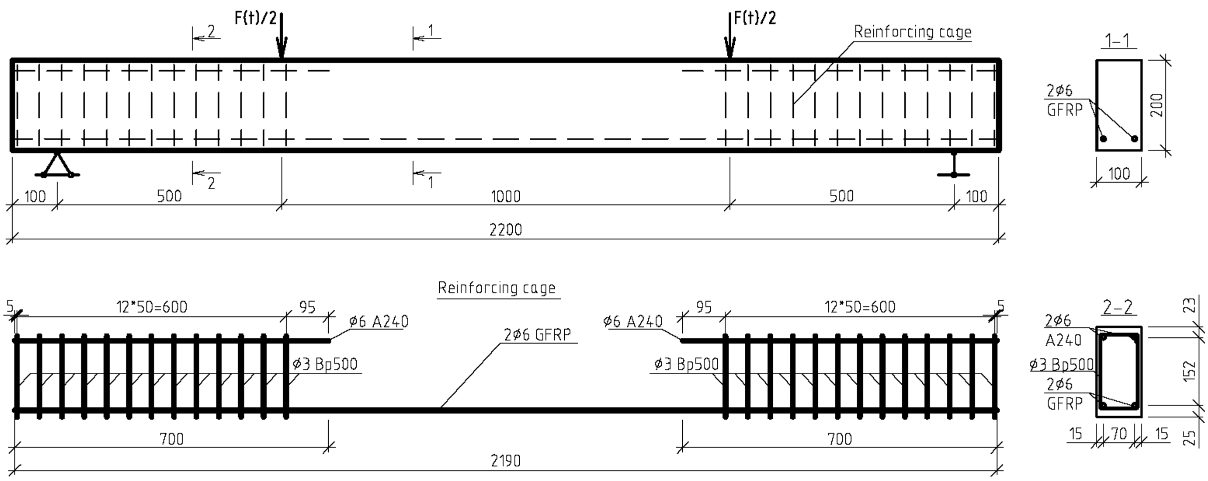

Figure 2. Design of concrete beam with glass fiber reinforcement.

of concrete beams reinforced with composite rods and their further testing under short-term dynamic loading. Tests have been carried out using special pile driver, inducing short-term dynamic loading. The experimental load was measured by dynamometer. The received load had an appearance: maximum value of impulse 94 kN has been observed at the time period of 4 ms, total duration of loading is 110 ms (figure 1).

3. Material properties

Heavy concrete composition with class of compressive strength B30 has been used for sample production. Portland cement of M500 class has been used as a hydraulic binder. Water–cement ratio equals to 0.65. Composite fiberglass rods with an external diameter of 6 mm have been used as longitudinal bar reinforcement (GFRP). Fiber glass rods have ribbed surface for bonding with concrete. Reinforcing steel rods of class A240 have also been used. As the transverse reinforcement reinforcing wire of Bp500 class has been used (figure 2). The materials used in experiment conform to requirements of construction norms in Russia.

Preliminary experimental testing of tensile strength and deformability of fiber glass rods has shown (table 1) that the reinforcement has high tensile strength (up to 1280 MPa), while the longitudinal deformation of the rods are in the range from 2 to 3%, and Young's modulus is 40–60 GPa. Specific weight of reinforcement is 1.95 g/cm^3, that allows reduction of the total weight of structures up to 1.9% 112.7 kg when replacing steel reinforcement with composite rebar. Other

Table 1. Properties of the materials used.

Material	Strength of samples under tension (MPa)	Strength of samples under compression (MPa)	Shear strength (MPa)	Young's modulus under tension (GPa)	Young's modulus under compression (GPa)	Specific weight (g/cm^3)
Glass composite	1280	790	553	60	40	1.95
Concrete	2.09	26.12	4.07	32.4	32.4	2.45

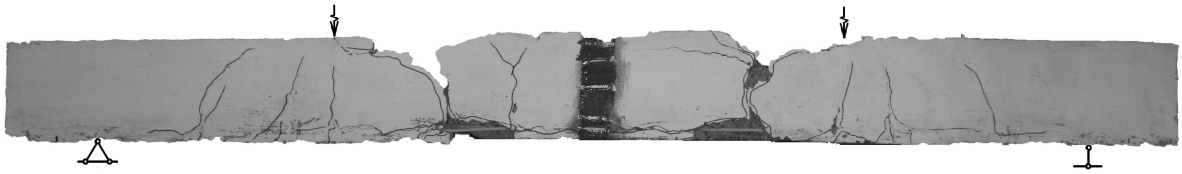

Figure 3. Peculiar patterns of crack formation and fracture of sample concrete beams under short-term dynamic loading.

studies have been conducted to check resistance of composite rods to the influence of alkaline environment using advanced methodology as stated by Russian National State Standard [5]. The studies have shown insignificant change of physical-mechanical parameters for glass composite reinforcement, thus corresponding to high level of alkali resistance. At the short-term dynamic loading influence of many factors on strength of concrete and reinforcement is considered integrally, by multiplication of the corresponding coefficients of dynamic strengthening by static strength. For concrete, estimated coefficient of dynamic strengthening for tension and compression changes in a range 1.2–1.3; for composite reinforcement, that is accepted equal 1.15 [6, 7].

4. Experimental results

The obtained results showed the peculiar patterns of crack formation and fracture of concrete beams, reinforced with fiber glass rods ø 6 mm (figure 3). Analysis of patterns of fracture and crack formation demonstrated that elements fracture occurred along the section normal to longitudinal axis of beams with formation of the main crack within the zone of pure bending. During tests slipping of fiber glass rods in concrete has not been observed.

The nature of work of elements reinforced with composite reinforcement differs from that of reinforced concrete. Concrete beams reinforced with composite rods have been characterized by strongly marked damped oscillations under short-term dynamic loading, while after unloading the initial geometrical form of the element recovered. The results of an experimental studies showed that the beams reinforced with fiber glass rods with an external diameter 6 mm, in comparison with the beams reinforced by steel rods (A500) with an external diameter 10 mm had the same load-bearing capacity, while deformability increased by 30%. The replacement of steel rods by fiber glass rods with reduction of an external diameter allows to keep load-bearing capacity of concrete samples under short-term dynamic loading and to increase their deformability.

5. Mathematical model

Numerical calculations of deformation under short-term dynamic loading have been conducted for experimental studies of strength and deformability of concrete beams reinforced with composite rods. Program software developed by the authors [8] is used in numerical studies. It enables to calculate the values of longitudinal and lateral deformations, patterns of crack formation and fracture at different periods of time. Finite element analysis is applied in these calculations using mesh scheme by Johnson, enabling to calculate the studied structures in 3D dynamic wave mode. The quantity of finite elements is 15 million.

During numerical experiment dynamic load acting on concrete element has been taken as equal to load obtained during the experiment, using dynamometer. Direction, value and location of load application correspond completely to the experimental data.

While numerical studies concrete, fiber glass and steel had the following model: stress tensor components in materials up to fracture are presented as a sum of deviator S^{ij} and P spherical part:

$$\sigma^{ij} = -Pg^{ij} + S^{ij}, \tag{1}$$

where g^{ij}—metric tensor.

Supposing that the principle of minimum work of true stresses on the increments of plastic deformations is true, we register the connection of tensor component of deformation velocity and stress deviator as:

$$2G\left(g^{im}g^{jk}e_{mk} - \frac{1}{3}g^{mk}e_{mk}g^{ij}\right) = \frac{DS^{ij}}{Dt} + \lambda S^{ij}, \quad (\lambda \geq 0), \tag{2}$$

where time derivatives of the stress tensor components are accepted according to Jaumann:

$$\frac{DS^{ij}}{Dt} = \frac{\mathrm{d}S^{ij}}{\mathrm{d}t} - g^{im}\omega_{mk}S^{kj} - g^{jm}\omega_{mk}S^{ik},$$

where $\omega_{ij} = \frac{1}{2}(\nabla_i v_j - \nabla_j v_i)$, G—shear modulus.

Parameter $\lambda = 0$ at elastic deformation, and at plastic deformation ($\lambda > 0$), as defined using von Mises criterion:

$$S^{ij}S_{ij} = \frac{2}{3}\sigma_{\mathrm{d}}^2. \tag{3}$$

Here σ_{d}—dynamic yield stress. In concrete yield stress depends on the pressure and is expressed by the following dependence:

$$\sigma_{\mathrm{d}} = \sigma_{\min} + \frac{(\sigma_{\max} - \sigma_{\min})kP}{(\sigma_{\max} - \sigma_{\min}) + kP}, \tag{4}$$

where $k = 0.82$, $\sigma_{\min} = 0.0077$ GPa, $\sigma_{\max} = 0.0216$ GPa [9].

Pressure in the material was calculated using the Mie–Gruneisen equation as a function of specific internal energy E and ρ density:

$$P = \sum_{n=1}^{3} K_n \left(\frac{V_0}{V} - 1\right)^n + K_0\rho E, \tag{5}$$

where K_0, K_1, K_2, K_3—constants of materials (table 2).

Hoffman criterion is used as a criterion of fracture of concrete and fiber glass. This criterion allows using different strength properties of materials under compression and tension and stress tensor component expressed through scalar function is as follows:

$$\begin{aligned} f(\sigma) = {} & C_1(\sigma_2 - \sigma_3)^2 + C_2(\sigma_3 - \sigma_1)^2 \\ & + C_3(\sigma_1 - \sigma_2)^2 + C_4\sigma_1 + C_5\sigma_2 + C_6\sigma_3 + C_7\sigma_4^2 + C_8\sigma_5^2 + C_9\sigma_6^2 \geq 1, \end{aligned} \tag{6}$$

Table 2. Constants of materials.

Material	K_0	K_1 (GPa)	K_2 (GPa)	K_3 (GPa)
Steel	1.91	61.5	176	53.1
Glass composite	0	52.6	0	0
Concrete	0	11.4	0	0

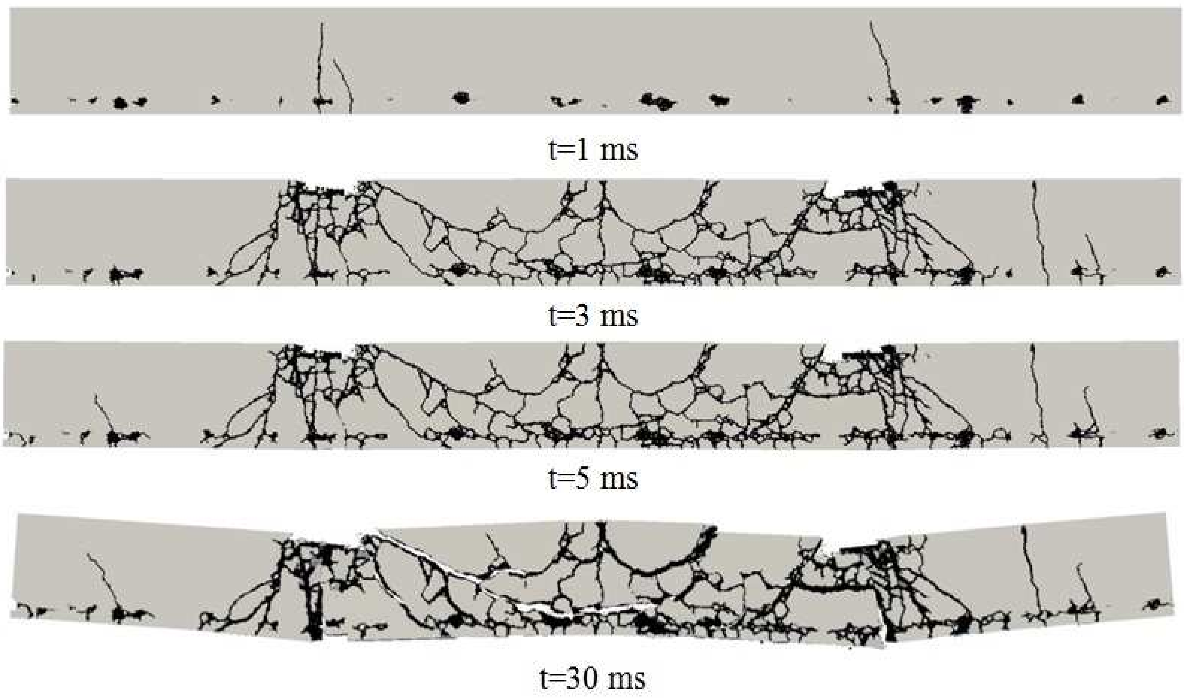

Figure 4. General view of reinforced concrete beam at various timepoints.

where the coefficients $C_{1\text{–}9}$ are determined from ultimate tension, compression and shear strength (see table 1). Formulas for calculation $C_{1\text{–}9}$ are given in [10].

Suppose that material fracture in the conditions of intensive dynamic loads occurs as follows [11, 12]: if strength criterion (5) is broken under compression ($e_{kk} \le 0$), then further material behavior is described by hydrodynamic model, in this case the material keeps only its compressive strength, while stress tensor becomes spherical ($\sigma_{ij} = -P\delta_{ij}$); if criterion (5) undergoes under tension ($e_{kk} > 0$), then the material is considered to be completely fractured and stress tensor components are supposed to be equal to zero ($\sigma_{ij} = 0$).

Also concrete damaged under compression can fracture completely ($\sigma_{ij} = 0$) when realizing the criterion considering ultimate value of plastic deformations intensity:

$$e_u < \frac{\sqrt{2}}{3}\sqrt{3T_2 - T_1^2}, \tag{7}$$

where T_1, T_2—the first and the second invariants of deformation tensor, $e_u = 0.15$.

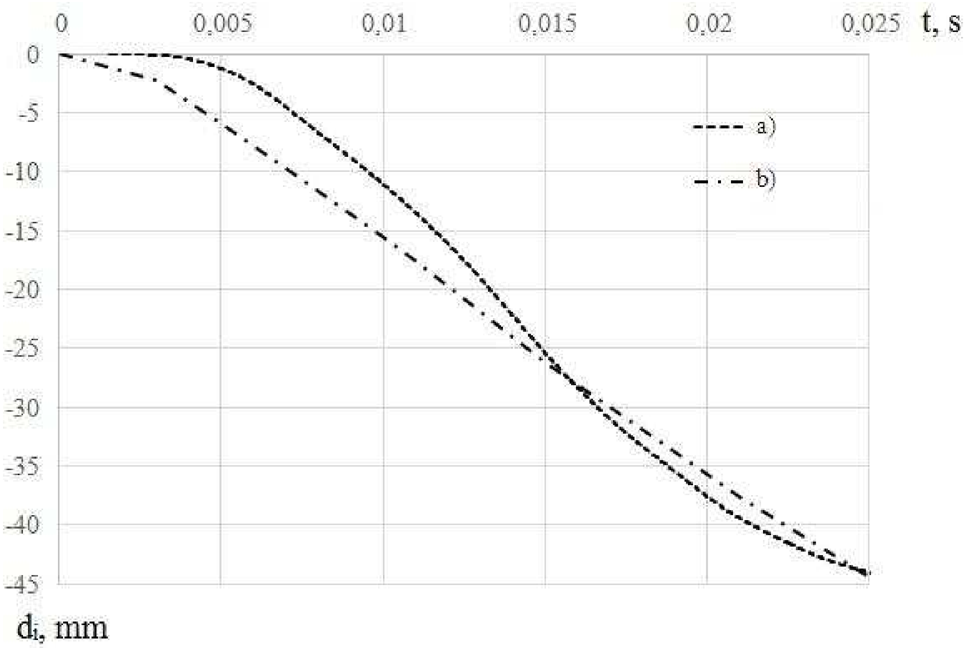

Figure 5. Maximum beam deflection: a) experimental; b) numerical.

6. Results discussion

Numerical calculations resulted in obtaining peculiar patterns of crack formation and fracture of concrete beam under short-term dynamic loading. In figure 4 at various timepoints beam with fiber glass and steel rods under short-term dynamic loading is presented. It allows tracking dynamics of fracture. Fracture zones in a beam are formed on a back surface and in the areas close to reinforcing rods. Fracture occurs as a result of the tensile stress. In process of time the cracks spread upwards in a beam, causing concrete fragmentation. In general, numerical calculations have good correspondence with the experimental studies.

Numerical and experimental beam deflection maximum value has been compared in the course of time (figure 5).

Values of maximum deflection in numerical and experimental samples coincide. Maximum disagreement makes not more than 10%.

7. Conclusions

Analysis of experimental and numerical testing of samples under dynamic loading showed that application of fiber glass rods in concrete beams enables to increase the load-bearing capacity of structural element, at the same time increasing its deformability.

Increased deformability of concrete beams reinforced with composite rods influences positively the load-bearing capacity and durability of concrete beams undergoing dynamic loading.

The suggested mathematical model of concrete behavior and fiber glass reinforcement demonstrated qualitative and quantitative correspondence with the experimental data.

Numerical presentation of concrete plastic properties enables to consider appropriately the development of defects and microcracks in concrete structures under study.

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