Numerical simulation of mechanical behaviour of concrete under shock wave loading

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Abstract. In this paper results of numerical simulation of the mechanical behaviour of heavy concrete under preliminary compression and shock wave loading with intensity up to 1.2 GPa are submitted. The model specimen of concrete consisted of cement paste and granite filler with volumetric concentration above 65%. Mechanical behaviour of the representative volume of concrete was described by the model of the heterogeneous medium with stochastic distribution of filler particles. It was supposed that cement matrix can be considered as elastic-plastic material and granite of inclusions is a brittle material. The yield limit of cement paste was accepted to be 0.08 GPa, and the strength limit of granite equals 0.1 GPa. The absence of macroscopic and mesoscopic voids and cracks in the material was assumed. Ideal adhesion of filler material and matrix was supposed at the initial condition. Results of numerical simulation of the mechanical behaviour of concrete under shock loading have shown the formation of non-stationary and essentially non-uniform fields of deformations. The generation of a dissipative structure on the meso-scale level of the concrete under reshock wave loading was revealed in the simulation.

1. Introduction

The estimation of reliability of large scale concrete structures under natural and man-caused dynamic loadings remains to be one of urgent scientific and technical problems. The basic problem of the estimation of reliability of massive concrete constructions (dams, bearing elements of multi-storey buildings, concrete lining of tunnel and excavation) at intensive impacts is closely connected with prediction of the mechanical behaviour of concrete under combination of static and dynamic loads. Experimental data on properties of various grades of concretes in similar loading conditions practically are absent.

In the simulation of deformation of concrete constructions, concrete is often taken as homogeneous or quasi-homogeneous material. However, this material presents a complex of components (cement paste and filler) with different physical and mechanical properties. The components form the structure of concrete. The structure and its evolution during deformation can have a significant influence on the mechanical behaviour and the effective properties of concrete. However, the degree and nature of this influence is still incompletely understood.

In this connection, the present paper aims at the numerical simulation of the mechanical behaviour of concrete at macro-scale and meso-scale levels under preliminary compression and shock wave loading with intensity up to 1.2 GPa and study of effective mechanical properties of concrete with consideration for structural evolution during deformation of the material.
2. **Simulation of the mechanical behaviour of concrete**

The paper employs a plate of concrete consisting of a matrix (cement paste) and reinforcing inclusions (particles of granite filler) with volumetric concentration 65% to simulate loading by a plane shock wave. The simulation was performed on a rectangular fragment of the plane section of the plate along the direction of the shock wave front.

The concrete plate was loaded by a shock wave and an additional loading wave (reshock wave). The amplitude of particle velocity in shock wave equals 33 km/s, and the amplitude of particle velocity in additional loading wave equals 99 km/s. The additional wave was generated 23 micro seconds later than the loading by the first shock wave.

The mechanical behaviour of the concrete under the considered loading conditions was described using the physical and mathematical model of the two-phase condensed heterogeneous medium with an explicit description of its structure [1–3]. The used model assumes the heterogeneous medium as a set of interrelated structural elements, namely, a matrix and inclusions. Inclusions are arbitrary in shape and randomly distributed in the matrix. Mechanical interaction between structural elements occurs along internal contact surfaces, i.e., matrix - inclusion interfaces. Within interfaces of each structural element the medium is taken as homogeneous and isotropic while in transition through the interface physical and mechanical properties of the medium change abruptly.

It was supposed that cement matrix can be considered as an elastic-plastic material and granite of inclusions is a brittle material. The yield limit of cement paste was accepted to be 0.08 GPa and the strength limit of granite is equal to 0.1 GPa. The absence of macroscopic and mesoscopic voids and cracks in the material was assumed. Ideal adhesion of filler material and matrix was supposed at an initial condition.

Geometry of the simulated area and the number of structural elements was so chosen as to determine effective values of parameters of the mechanical state of the medium by averaging of calculated local values. The simulated area of the two-phase heterogeneous medium with the model structure is shown in Figure 1.

![Figure 1. Simulated area of the two-phase heterogeneous medium with the model structure of the concrete composed of the matrix (dark region) and arbitrary-shaped inclusions (light regions). The volume concentration of inclusions is 65%](image)

Effective parameters of the mechanical state of the heterogeneous medium loaded by a plane shock waves was determined by volume averaging of local values of the state parameters in thin flat layers perpendicular to the shock front direction. A method for determining effective parameters of the mechanical state was described in [4, 5].
3. Investigation of the mechanical behaviour of concrete

Results of numerical simulation of the mechanical behaviour of concrete under shock loading have shown a formation of non-stationary and essentially non-uniform fields of stress and deformation. Inelastic deformation of concrete under dynamic loading is a result of cement paste deformation and the movement of filler particles at the meso-scale level. Results are shown in Figure 2 and 3.

(a)  
(b)  
Figure 2. Calculated values of effective particle velocity \( \langle U_y \rangle \) (a) and effective stress \( \langle \sigma_y \rangle \) (b) under reshock wave loading of concrete

![Figure 2. Calculated values of effective particle velocity \( \langle U_y \rangle \) (a) and effective stress \( \langle \sigma_y \rangle \) (b) under reshock wave loading of concrete](image)

Figure 3. Calculated field of shear strength in the concrete plate under shock compression

![Figure 3. Calculated field of shear strength in the concrete plate under shock compression](image)

The simulation results have shown the formation of a dissipative structure at meso-scale level of the concrete under loading by the reshock wave with amplitude of 1.2 GPa, as one can see in Figure 4.

![Figure 4. Calculated field of particle velocity in the concrete and nucleation of a dissipative structure under reshock wave loading](image)
Nucleation of a dissipative structure leads to the change of distribution function of particle velocities at the meso-scale level in front of reshock wave. Results of numerical simulation have revealed the formation of bimodal distribution of velocities of material particles under loading of concrete by the reshock wave with amplitude of 1.2 GPa as seen in Figure 5.

![Figure 5. Distribution of particle velocity in shock wave.](image)

Formation of bimodal distribution in front of reshock wave

The simulation results have shown that distribution function of particle velocities behind the front of reshock wave is similar to logarithmically normal distribution function.

4. Conclusion

The effective Hugoniot elastic limit of concrete depends on the shear strength of a cement paste. Inelastic deformation of concrete under dynamic loading is a result of cement paste deformation and movement of filler particles at the meso-scale level.

Formation of the dissipative structure leads to the change of distribution function of particle velocities at the meso-scale level. The logarithmically normal distribution function takes place at shock waves with amplitudes less than 0.4 GPa.

Formation of a dissipative structure under loading of shock wave with amplitude of 1.2 GPa is accompanied by the formation of the bimodal distribution of velocities of material particles in the shock wave. Distribution function of particle velocities behind the front of reshock wave is similar to logarithmically normal distribution function.

References
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