COMPUTATIONAL MECHANICS 2023
38th conference with international participation
Srní
October 23 - 25, 2023

Development of meso-scale discrete model for simulations of ballistic experiments

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Fiber-reinforced concrete panels are used for ballistic protection. During their tests, the material is loaded by a high-velocity projectile. This dynamic loading causes significant damage and fracturing in concrete. The cracks results in discontinuity in the displacement field.

In case of heterogeneous material with strain softening constitutive response, the discrete meso-scale material representation can conveniently replace the most common finite element method. Discrete models allow straightforward description of the discontinuity in the displacement field and inhomogeneities of the material are represented by an assembly of interconnected discrete units. A number of discrete models were developed by many scientists all over the world [1, 3].

The meso-scale models directly represent material heterogeneity provide material length scale and fluctuation of stresses. They are computationally expensive, but reducing kinematics by discrete representation helps to substantially decrease their computational burden.

The presented meso-scale discrete model similar to the *Lattice Discrete Particle Model* [1] is built in programming language C^{++}. The concrete is described as a two-phase material (aggregates and mortar). Individual rigid particles represent larger aggregates and surrounding matrix and are created by placing spheres randomly into the domain with a minimal mutual distance corresponding to maximum diameter of the real mineral grains. Each two neighboring particles are connected via bonds, which define a contact face. The stiffness of the bonds are modified during the deformation according to the nonlinear constitutive functions defined in vectors.

The Voronoi tesselation is used to build the geometry of the rigid particles and ensure the perpendicularity between bonds and contact faces. The particles have polyhedral geometry and at least three vertices define contacts for 3D case. For 2D case, the particles are polygons and contacts are line segments prescribed by two vertices. Edges of Delaunay simplices define connections between the particles and therefore also the mechanical elements. The elements represents both aggregates and cement matrix behavior.

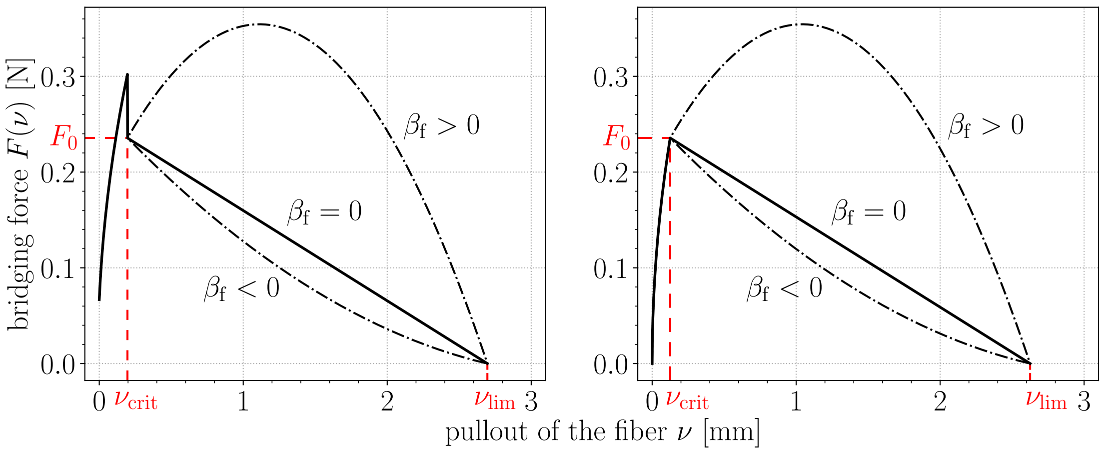
Transient (dynamic) regime is used to simulate the ballistic experiments. A time discretization based on the finite difference method is usually used. Implicit time integration scheme, specifically the generalized-α method, is currently utilized by the model [2]. Unconditionally stability and reduced numerical damping are the main advantages of this time integration algorithm. The numerical energy dissipation is controlled by user-specified parameter, spectral radius ρ_∞. The transient regime was verified on the simple example of the cantilever beam for both 2D as well as 3D case. The model was loaded by vertical force at the free end. The results are shown by the authors in [4].

The extension of the model to include also the explicit integration scheme is under development. Explicit methods are more suitable for short time periods with high-rate loading, but the stability of the calculation depends on the time step length.

Concrete, as a natural brittle material, performs well in compression. On the other hand, its efficiency in tension is significantly lower. Therefore, the reinforcement is usually required to improve poor performance in tension. In recent decades, short randomly distributed fibers of small diameter are very popular to use. Nowadays, fiber-matrix interaction is broadly reported by many works. Although each work has its own contribution to this scientific field, most of them refer to the work of Naaman et al. [5].

The model simulates behavior of a fiber crossing a single crack. Bridging forces from the left and the right side of the fiber has to be equal. The equilibrium is satisfied during the whole simulations. Newton iterative method is used to find the equilibrium between right and left bridging force. Contribution of the fibers in the elastic regime is neglected.

The mechanical behavior of the fiber can be divided into two main stages. First, there is the debonding stage, where the fiber is still bonded with the matrix at some length. The second is the pulling-out stage, where the fiber is fully debonded from the matrix. The stages and typical curves of pullout vs. bridging force diagram are shown in Fig. 1. Non-zero parameter β_f describe softening or hardening of the material. The border between the debonding and the pulling-out stage is represented by critical pullout of the fiber ν_{crit}. During the whole simulation, the rupture condition as well as the full pullout of the fiber ($\nu = \nu_{crit}$) have to be controlled. The bridging force immediately decrease to zero for the rest of the computation in both cases.



(a) Fracture energy $G_\mathrm{d} > 0$ (b) Fracture energy $G_\mathrm{d} = 0$

Fig. 1. Typical bridging force F(ν) versus pullout ν relationships

When the crack is closing, the linear unloading-reloading functions towards the origin ($F(\nu) = 0$, $\nu = 0$) are used to find the equilibrium between left and right side of the fiber. When the crack starts to open again, the same linear functions are used unless the crack width reaches the maximum from its previous opening.

The transient regime with fiber-reinforced concrete slabs are currently being tested. The model is loaded by prescribed displacement at one point. The convergence of the simulations as well as the obtained forces are analyzed. Boundary conditions of the model correspond to the real ballistic experiments. Also explicit integration scheme is being validated. Some partial results will be shown during the conference.

Acknowledgment

The authors gratefully acknowledge financial support provided by the Faculty of Civil Engineering, Brno University of Technology under project No. FAST-J-23-8329.

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