EXTENSION OF DISCRETE MODEL FOR SIMULATIONS OF BALLISTIC EXPERIMENTS

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Abstract
During the ballistic experiments, fiber-reinforced concrete panels are loaded by a high-velocity projectile. The meso-scale discrete model built in programming language C++ is used to simulate these tests. The mechanical behavior of short fibers crossing a single crack is derived and implemented. The explicit time integration scheme is under development to replace the current implicit solver utilizing the generalized-alpha method. The paper presents some partial results.

Keywords
Meso-scale discrete model, transient regime, explicit time integration scheme, fiber-reinforced concrete, ballistic experiments

1 INTRODUCTION

Fiber-reinforced concrete panels are loaded by a high-velocity projectile during the ballistic tests. Analysis of the projectile impact is of interest to a number of scientists all over the world [1], [2], [3]. The projectile impact causes significant fracture processes and damage to the material, which result in discontinuities in the displacement field. When the cracks occur in heterogeneous material with strain softening response, discrete material representation seems to be a good option for modelling. A number of discrete models have been developed and improved by different scientists all over the world [4], [5].

One of the advantages of the discrete approach is that it allows straightforward description of the discontinuity in the displacement field caused by fracture processes. The heterogeneities of the material are represented by an assembly of interconnected discrete units. The meso-scale models directly provide material length scale and fluctuation of stresses due to inhomogeneities. Unfortunately, they are computationally expensive, but reducing kinematics by discrete representation helps to substantially decrease the computational burden.

Concrete is a natural brittle material and performs well in compression. However, its efficiency in tension is significantly lower. Reinforcement is required to improve mechanical behavior of the concrete, specifically its tensile strength and ductility. Concrete used for a ballistic protection are usually reinforced with short synthetic fibers with a small diameter. Nowadays, mechanical behavior of the fibers are broadly reported by many scientists [6], [7], [8]. Although each work has its own contribution to this scientific field, most of them refer to the work of Naaman et al. [9].

Extension of the model to transient (dynamic) regime is required to simulate ballistic experiments. A time discretization utilizing both explicit and implicit integration schemes is usually used [10], [11]. Unconditional stability is one of the advantages of the implicit methods. Time step length controls accuracy of the solution. Implicit time integration schemes are more convenient for longer time period but require solution of a large system of linear equations. On the other hand, the explicit methods are suitable for short time periods with high loading rates. A disadvantage of these schemes is that they require very small time steps to keep the solution stable, which increases the number of time steps and computational time. Despite this, the explicit time integration scheme is considered more suitable for simulations of the ballistic experiments.

The presented discrete meso-scale model similar to the LDPM [5] is built in programming language C++. The model simulating the ballistic tests is under development, and some partial results will be shown. The future tasks and unsolved problems will be discussed.

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2 METHODOLOGY

Discrete meso-scale model of concrete

The presented discrete meso-scale model is under development. The concrete is modeled as a two-phase material, which represent aggregates and mortar. Larger aggregates and surrounding matrix are represented by individual rigid particles. The particles are created by placing spheres randomly into domain with a minimal mutual distance corresponding to the diameter of the real mineral grains.

Rigid particles are connected via bonds with contact faces. The basic particle of the discrete model has convex polygonal (2D) or polyhedral (3D) geometry. The proper geometry and perpendicularity between bond normals and contact vectors are ensured by the Voronoi tesselation. The mechanical elements are defined by the edges of Delaunay simplices and represent aggregates as well as cement matrix behavior.

Transient (dynamic) regime

The authors extend the model with an implicit time integration scheme, specifically the generalized-α method [12]. The method allows control the numerical damping by user-specified parameter, spectral radius ρ_∞. The algorithm was verified using a simple example of an elastic cantilever beam loaded by a single force at its free end (Fig. 1). The geometry of the model, material parameters, and obtained results are shown by the authors in Ref. [13].

The extension of the model to include the explicit time integration method is required since the projectile impact represents high-rate loading with short time period. This extension is currently under development. The same example of the cantilever beam from Ref. [13] is being solved. The obtained results will be compared with the dynamic response of the beam using the implicit time integration scheme.

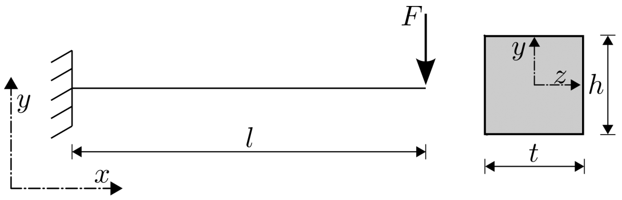

Fig. 1 Scheme of the numerical example of the cantilever beam.

Fiber-reinforced concrete

The mechanical behavior of the fiber crossing a single crack is currently implemented in the model. The typical evolution of the bridging force is governed by two main equations. First equation represents the debonding stage of the fiber, where the bond between the fiber and surrounding material is partially damaged. Second equation represents the pulling-out stage, where the bond is fully damaged and the fiber is pulling out of the material. The governing equations were primarily taken from Ref. [6] and the typical evolutions of the bridging force in dependence on the pullout, shown in Fig. 2, correspond to the theory.

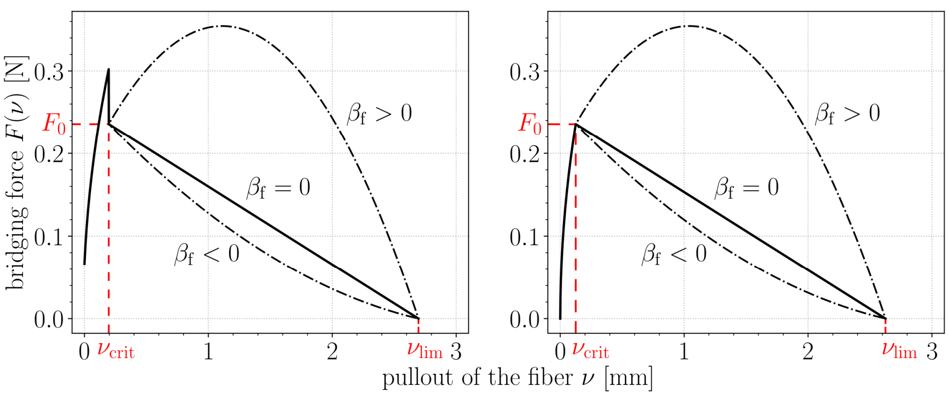

Fig. 2 Governing equations of the fiber mechanical.

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When the fiber crosses the crack, the bridging forces from the right and the left-hand side of the fiber must be equal. The equilibrium between the forces must be maintained during the whole simulation, for which the Newton iterative method is used. The contribution of the fibers in the elastic regime is neglected. The bridging force remains zero for the rest of the computation once the fiber is fully pulled out of the matrix or ruptured.

During the general computation, the cracks can grow, close and grow again. The governing equations have to be modified to capture every possible behavior of the crack and ensure equilibrium between the forces. For this purpose, the linear unloading-reloading functions towards the origin are used. The evolution of the bridging force respects the governing equations again when the crack reaches the last maximum opening.

Proper implementation of the unloading-reloading functions was tested on the simple example of a single fiber crossing a single contact.

Fiber-reinforced concrete panels loaded by prescribed displacement at one point are tested. The geometry and the boundary conditions of the models correspond to the real ballistic experiments. The model of the panels, including the mechanical elements and fibers, is shown in Fig. 3. Damage to the concrete is highly localized during the ballistic tests. The elements are finer only around the impact of the projectile to decrease the computational burden of the calculations.

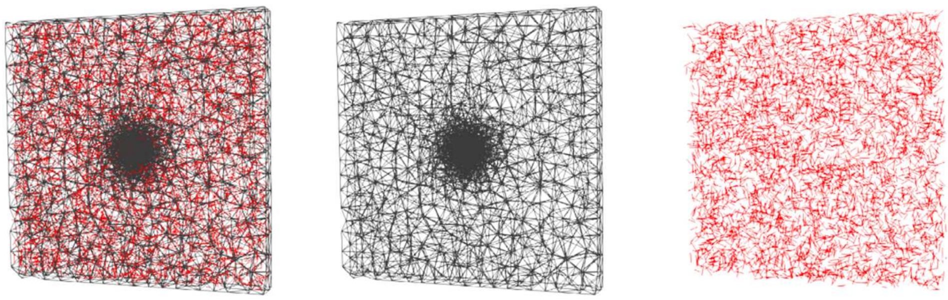

Fig. 3 (a) Model of fiber-reinforced concrete panel, (b) mechanical elements, (c) fibers.

3 RESULTS

Transient (dynamic) regime

The dynamic response of the cantilever beam using the explicit time integration scheme was analyzed. The obtained results were compared with results computed utilizing the implicit algorithm. Only the 2D model of the cantilever beam is presented. The evolution of the deflection as well as evolution of the reaction in time is shown in Fig. 4.

The orange curves represent the dynamic response of the model using newly implemented explicit time integration scheme. The black curves, belonging to implicit solver, are obtained and verified from the previous research [13].

Fiber-reinforced concrete

Fig. 5 shows the evolution of the bridging force in dependence on the pullout of the fiber. racks close and open repeatedly during the general simulation. The black curves represent governing equations with respect to the linear unloading-reloading functions.

The red curves represent the rupture condition of the fiber. The fiber simply breaks when its tensile strength is reached. The bridging force of the fiber immediately decreas to zero and remains zero for the rest of the computation. The same applies when the shorter side of the fiber is fully pulled out of the material.

4 DISCUSSION

Dynamic response computed with the explicit time integration scheme corresponds to the earlier obtained and verified results. Unfortunately, satisfactory results were obtained only for 2D beam. For 3D model, the time step length was extremely small, and the computation was too expensive for now.

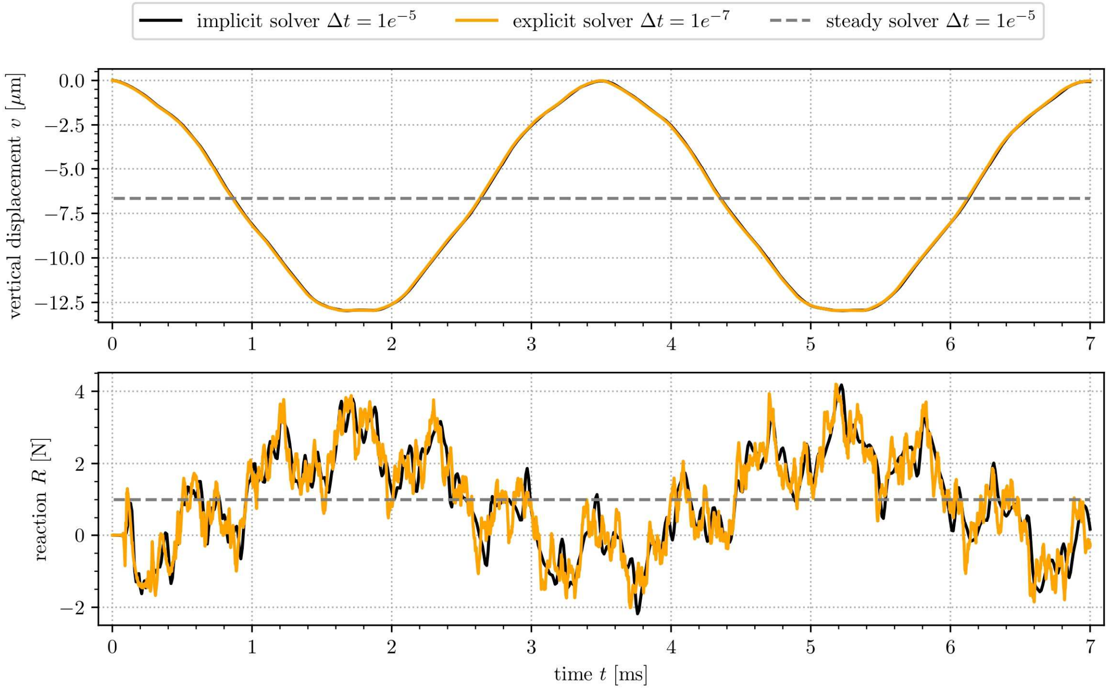

Fig. 4 Dynamic response of 2D model of the cantilever beam.

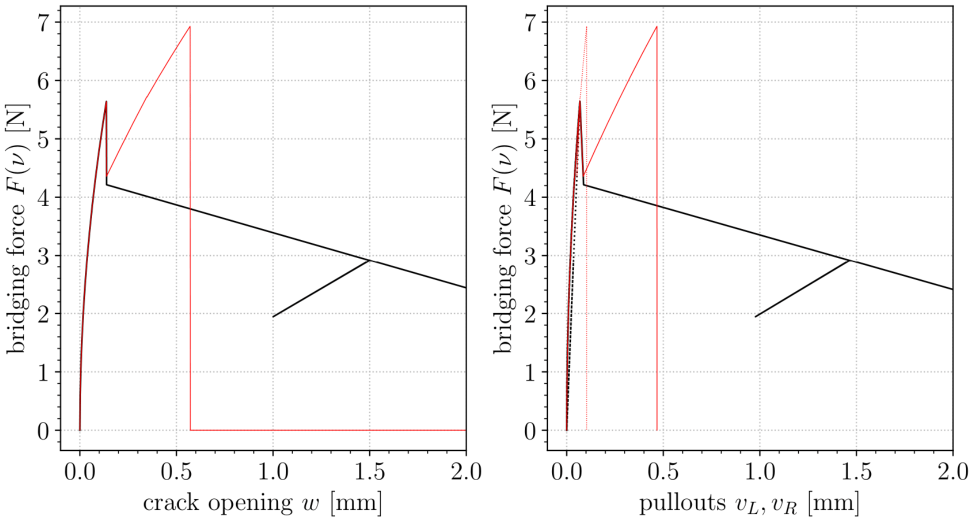

Fig. 5 Modified governing equations of the fiber behavior using unloading-reloading linear functions towards the origin.

The explicit methods are commonly used and several ways to make the calculations more efficient have been developed. The critical time step length for the each model can be calculated [14]. The stability of the solution is ensured by using a smaller time step length than the critical one. The critical time step length depends on the highest natural frequency of the system. Therefore, the weight of the smallest rigid particle of the discrete system is decisive.

So-called Coarse Graining (CG) methods can be used to reduce the computational cost of discrete models. The methods are based on the particles enlargement. Mathematical and computational structure of the model must remain the same. In addition to the lower number of the degrees of freedom, the CG method also increases the critical time step length [15].

The mechanical behavior of the fiber fully corresponds to the expectations. The linear functions towards the origin were implemented to simulate unloading and reloading response of the fiber. Implementing of the fiber stiffness is necessary to compute the mechanical response of the whole reinforced model with the implicit solver. Current interpretation is insufficient as the models converge poorly.

5 CONCLUSION

The presented work achieved some partial goals.

- Both implicit and explicit time integration schemes are implemented in the current model.
- Mechanical behavior of a fiber crossing a single crack is derived and implemented.
- Models of fiber-reinforced concrete panels are prepared to be used in transient regime.
- The results will be compared to experiments.

The obtained results meet the expectations and correspond with the already published works. The unsolved problems pointed out in the article will be the subject of the interest for the near future. After the fiber-reinforced concrete panels in transient regime will be validated, the projectile impact on these models will be implemented.

Hopefully, the developed model will be able to simulate the real ballistic experiments to save time and mainly financial costs of the tests. In addition, the simulations can significantly speed up the development of concretes for ballistic protection.

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