CYCLIC MODEL FOR CONCRETE IN DISCRETE LATTICE MODEL

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In this paper we will present discrete lattice model for simulating concrete subjected to cyclic loading. Finding a method of analysis of concrete structures subjected to earthquake is crucial for the safety and serviceability of buildings in seismic regions. For detailed analysis of structures under intensive seismic excitation we have to consider cyclic loading and unloading [1]. Many researchers investigated cyclic loading for concrete experimentally. Some experimental results for cyclic loading for concrete in compression and tension are presented in Figure 1 [2, 3]. As it is suggested from previous experimental results, there is significant difference between energy dissipation in compression and tension [2]. Energy dissipation in tension cycle can be neglected comparing to energy dissipation in compression cycle, therefore many researchers consider only energy dissipation in compression.
In computational analysis of concrete structures it is very important to have realistic stress-strain material models subjected to cyclic loading. Many scientists have been working on development of different computational methods for modelling of the behaviour of concrete and reinforced concrete structures subjected to cyclic loading [2]. During earthquakes, structures are exposed to cyclic loading, which cause cracks in concrete. Crack evolution leads to energy dissipation and crack tip influence the failure mechanisms [4]. So we have to model shape of unloading and reloading curve which enables us computing the energy dissipation of concrete exposed to cyclic loading.

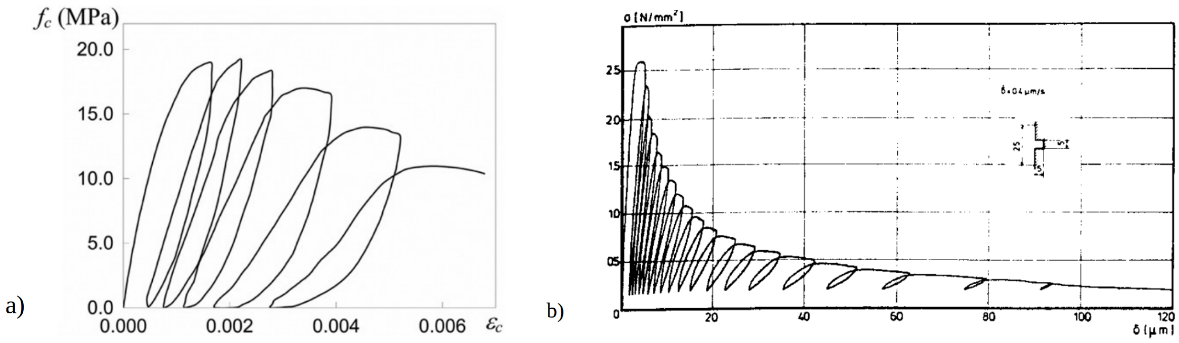

Figure 1: Cyclic compression test a) from Karsan and Jirsa (1969) and cyclic tension test b) from Reinhardt (1984)

Discrete lattice model with embedded strong discontinuities for propagating the cracks through concrete [5, 6] is used as a basis for developing cyclic loading model. Embedded strong discontinuities (ED-FEM) approach provide us mesh independence in terms of fracture energies in post-peak softening behaviour. The main reason for mesh independent presentation in ED-FEM is that discontinuity or displacement jump, always remains localized inside the element [5, 6]. This model is used to successfully represent failure mechanisms that happens in concrete. Our model is discretized with 2D Voronoi cells with Timoshenko beams as cohesive links between them with embedded strong discontinuity. Timoshenko beams are enhanced with additional kinematics to describe local failure mechanisms. Axial and shear strains in Timoshenko beams are enhanced to provide failure. Reasons why we have used this model are: linear elastic continuum and uniform straining of the topologically regular or irregular lattice with appropriate computation of lattice element parameters; localized failure by applying the breaking criterion on the lattice elements, which represents cohesive forces between the particles, the issue of singularity at the crack tip, presented in linear elastic fracture mechanics, is bypassed by the cohesive crack approach; complex and multiple crack propagations through the domain where one does not need to worry about the crack interactions; mesh-independent softening response, with introduction of embedded strong discontinuities by enhancing the kinematics of lattice cohesive link elements to represent displacement jumps [5]. Benefit of discrete lattice model is that we can use it for dynamic crack propagation, not only for quasi-static crack propagation [4].

Plasticity, damage and combination of both are often used to describe the non-linear response of concrete. In order to describe behavior of concrete under cyclic loading we choose the damage model. Following Ibrahimbegovic [8], this model describes change of elastic response in unloading which happens during cyclic loading of brittle materials. So with all benefits that we get from discrete lattice model and damage model, we can develop stress-strain model for computational analysis for concrete structures subjected to cyclic loading.

The model is used to simulate the behavior of specimen subjected to uniaxial tension and compression test. The computations are performed by a research version of the computer code FEAP [7]. Dimension of specimen is 10x10 cm (with unit thickness) and is meshed with triangles by Delaunay algorithm. Mesh generation is made my GMSH. The model has 427 nodes and 1210 elements. Elements in this discrete lattice model are Timoshenko beams, which are positioned at Delaunay edges from triangulation. In each test we show macroscopic reaction (sum of all reactions in Y direction) with respect to displacement.

Mechanical and geometric characteristics of specimen used in tension test are presented in Table 1. The specimen was subjected to imposed displacement of 0.05 cm, as is shown in Figure 2. The loading programme is completed through 400 steps which includes linear loading, unloading and reloading. Macroscopic response of specimen is shown in Figure 2.

$E = 10GPa, \nu = 0.2$
$\sigma_y = 1.8MPa, K_c = 1GPa, \tau_y = 0.1MPa, K_s = 1GPa$
$\sigma_{u,t} = 0.2MPa, G_{f,I} = 12N/m$
$\tau_u = 0.12MPa, G_{f,II} = 15N/m$
$\sigma_{u,c} = 2.2MPa, G_{f,c} = 350N/m$
Dimensions: 0.1x0.1x0.01 m

Table 1: Mechanical and geometric characteristics of specimen

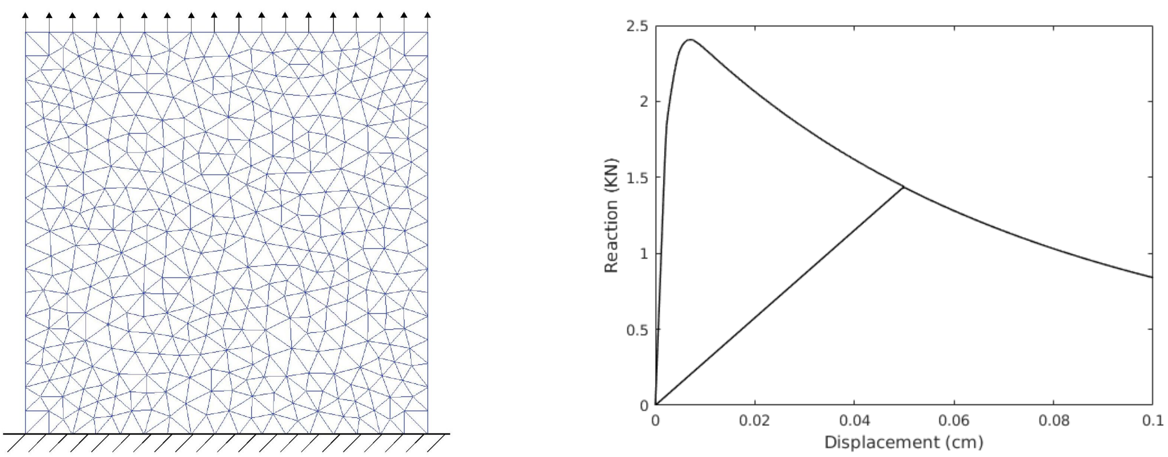

Figure 2: Uniaxial tension test: a) mesh and b) computed macroscopic response

From Figure 3 b) we can notice, that at the end of loading programme our specimen is broken. Micro cracks led to macro cracks and complete failure of specimen. From Figure 3 we can see final cracks that formed in the specimen after tension test. Most dominant crack is at the bottom of specimen, where specimen is connected to base.

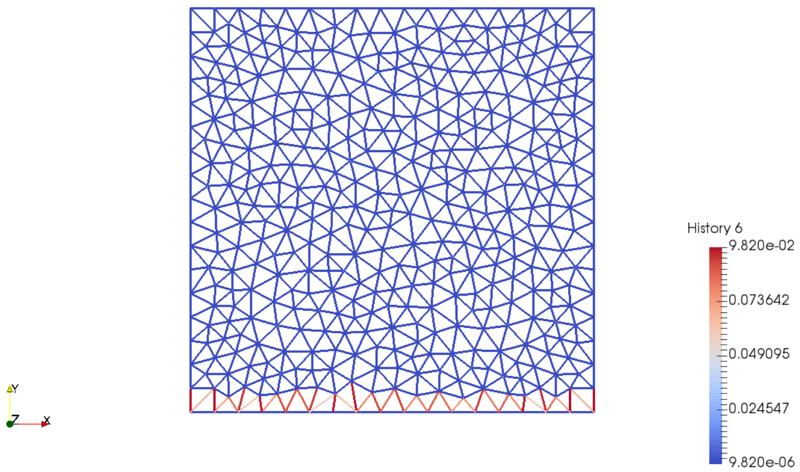

Figure 3: Final cracks formed after tension test

In compression test the geometric and mechanical characteristics of specimen are the same as in tension test (see Table 1). The specimen was subjected to imposed displacement of 0.05 cm as it is shown in Figure 4. We use the same loading programme as in tension.

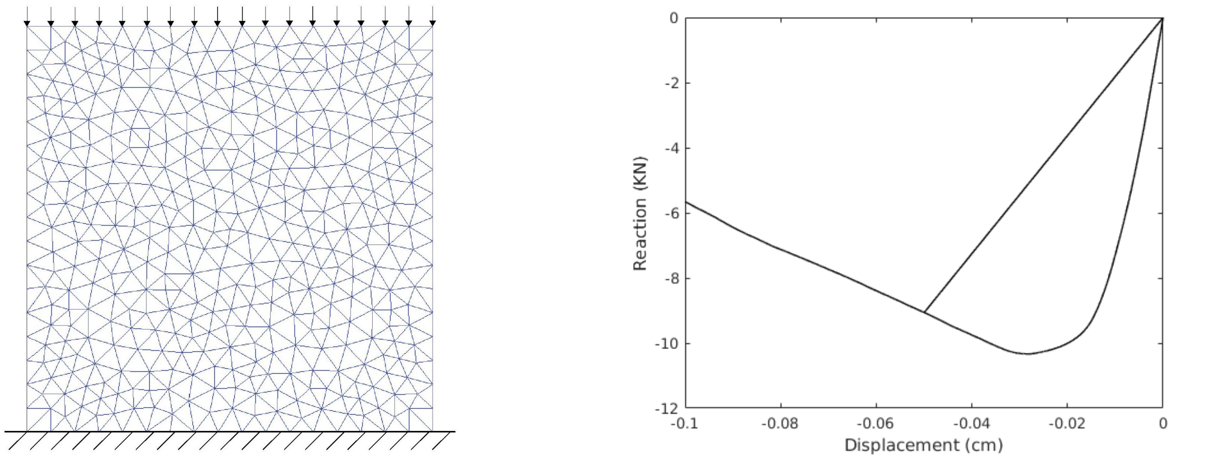

Figure 4: Uniaxial compression test: a) mesh and b) computed macroscopic response

From Figure 4 b) we can notice, that at the end of loading programme our specimen is broken. The final cracks that formed in the specimen after compression test is shown in Figure 5. Comparing the final cracks in Figure 3 with the Figure 5 we can see significant difference between forming macro cracks in tension and compression. In tension, main macro crack is formed at the bottom of specimen, and in compression, main macro crack is formed on diagonal of specimen. From macroscopic response of specimen, it is obvious that ductile phase of response during formation of the fracture zone is much more emphasized in compression then in tension.

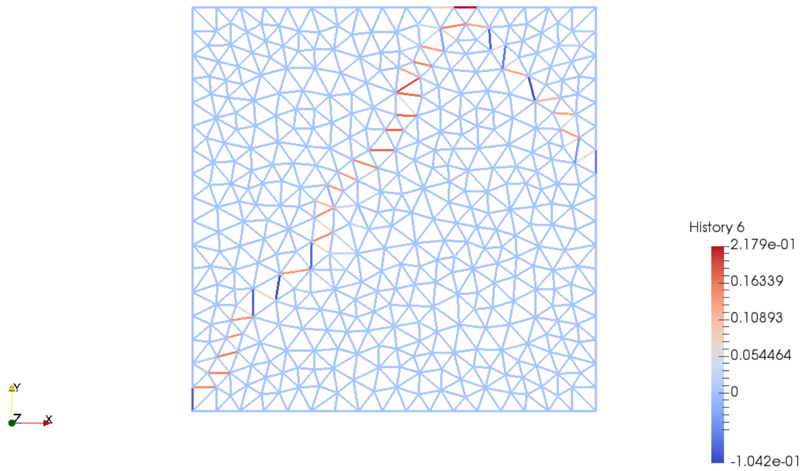

Figure 5: Final cracks formed after compression test

Proposed model is suitable for describing reduction of unloading stiffness, which is characteristic of brittle materials, when elastic response is affected by inelastic deformation. We showed the difference in propagation of macro cracks in tension and compression, which led to final failure of specimen. Developed damage model implemented in the framework of discrete lattice model, represents the first phase in simulation of the brittle materials subjected to cycle loading. Future development will include the coupling of the damage with the plasticity model.

Acknowledgments
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References

[1] Ž. Nikolić, N. Živaljić, H. Smoljanović, I. Balić *Numerical modelling of reinforced-concrete structures under seismic loading based on the finite element method with discrete inter-element cracks*, Earthquake Engineering & Structural Dynamics Eng 46(1), 159-178, 2017.

[2] J.F. Sima, P. Roca, C. Molins *Cyclic constitutive model for concrete*, Engineering Structures 30 (2008), 695-706, 2008.

[3] H.W. Reinhardt, H.A.W. Cornelissen *Post-peak cyclic behaviour of concrete in unaxial tensile and alternating tensile and compressive load*, Cement And Concrete Research. Vol. 14, 263-270, 1984.

[4] M. Nikolić, X. Nam Do, A. Ibrahimbegovic, Ž. Nikolić *Crack propagation in dynamics by embedded strong discontinuity approach: Enhanced solid versus discrete lattice model*, Comput. Methods Appl. Mech. Engrg. 340 (2018), 480-499, 2018.

[5] M. Nikolić, E. Karavelić, A. Ibrahimbegovic, P. Miscević *Lattice element models and their peculiarities*, Arch. Comput. Methods Eng. Vol.25, Issuse 3, 753-784, 2018.

[6] E. Karavelić, M. Nikolić, A. Ibrahimbegovic, A. Kurtović *Concrete meso-scale model with full set of 3D failure modes with random distribution of aggregate and cement phase. Part I: Formulation and numerical implementation*, Comput. Methods Appl. Mech. Engrg.344, 1051-1072, 2019.

[7] R.L. Taylor, *FEAP Finite element Analysis Program* University of California, Berkeley

[8] A. Ibrahimbegovic *Nonlinear Solid Mechanics: Theoretical Formulations and Finite Element Solution Methods*, Springer, 2009.