FE-MODELLING OF CONCRETE BEHAVIOUR UNDER MIXED MODE CONDITIONS WITH NON-LOCAL AND COHESIVE CONSTITUTIVE MODELS

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1. Introduction

The behaviour of concrete is very complex due to its heterogeneity, anisotropy, non-linearity and localisation of deformation in the form of cracks (failure mode I) and shear zones (failure mode II). An understanding of the mechanism of the formation of strain localisation is very important, since it acts as a precursor to the ultimate fracture and failure. Classical FE-simulations with material with softening are not able to model localisation properly. The obtained results suffer from the mesh sensitivity. The reason is that differential equations of motion change their type and the boundary value problem is ill-posed. To capture properly strain localisation within continuum mechanics, a characteristic length of the microstructure has to be included. It restores a well-posedness of a boundary value problem and enables one to obtain an objective numerical solution. In addition, a deterministic size effect can be captured.

The aim of the paper is to show results of realistic FE-simulations of concrete elements under mixed mode conditions (simultaneous occurrence of the failure mode I and II) [1]. To describe strain localization in concrete, three constitutive models defined within continuum mechanics were enriched by a characteristic length of micro-structure using a non-local theory. Alternatively, FE-simulations of strain localiztaion were also performed using cohesive elements.

2. Constitutive models

First, an elasto-plastic model with isotropic hardening and softening was assumed. In a compression regime, a linear Drucker-Prager criterion with a non-associated flow rule was used. In a tensile regime, a Rankine criterion wit an associated flow rule was adopted. Second, a strain formulation of the damage model was used with a single scalar damage parameter. Different definitions of the equivalent strain measure were tested. Alternatively, a multi-fixed orthogonal smeared crack model was assumed. In this approach the crack was created, when the maximum tensile stress exceeded the material tensile strength. The orientation of the crack was described by its primary inclination at the formation time, i.e. the crack did not rotate during loading. To define softening of the material in a normal direction under tension, a Hordijk curve was assumed. After cracking, the shear modulus was reduced by a shear retention factor. All constitutive laws were enriched in a softening regime by a characteristic length of micro-structure by means of a non-local theory to capture properly strain localisation [2].

As an alternative, a discrete approach using cohesive elements was adopted [3]. These elements were defined at the interface between standard elements to nucleate cracks and propagate them following the deformation process. They governed the separation of crack flanks in accordance with irreversible cohesive laws. A simple class of mixed-mode cohesive laws was used accounting for tension-shear coupling obtained by introduction of an effective opening displacement (including both the normal opening displacement and sliding displacement).

3. Benchmark problems for concrete elements

Two benchmark problems with curved cracks under mixed mode conditions were carefully analysed. First, a double-edge notched concrete specimen under various different loading paths of combined shear and tension was analysed [4]. The dimensions of the largest specimen and boundary conditions are presented in Fig.1. The loading was prescribed by rigid steel frames glued to concrete. In one of the loading paths [4], first a shear force P_s was applied until it reached a specified value, while the horizontal edges were free. At the second stage, the shear force remained constant and the vertical tensile displacement was prescribed. Two curved cracks with an inclination depending of the value of the shear force (for small value of P_s – almost horizontal, for large value of P_s – highly curved) were obtained.

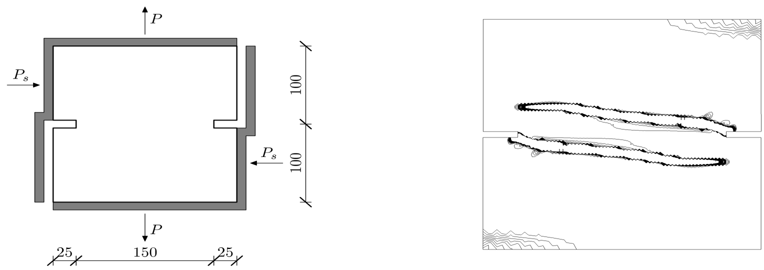

Fig. 1. Test [4]: geometry and FE-results within elasto-plasticity with non-local softening

Next, the single-edge notched (SEN) concrete beam under four-point shear loading (anti-symmetric loading) was analysed [5]. The dimensions and boundary conditions are shown in Fig. 2. A curved crack starting from the lower-right part of the notch towards a point to the right of the lower right support was obtained both in the experiment and FE-calculations.

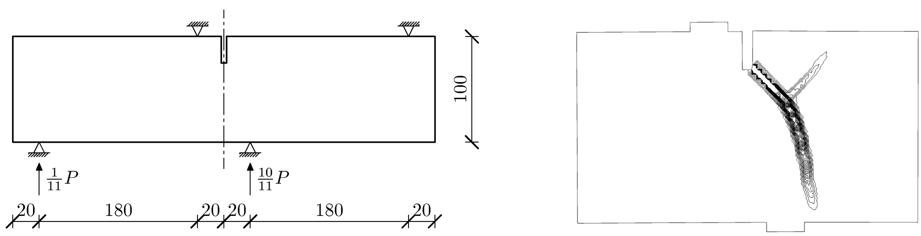

Fig. 2. Test [5]: geometry and FE-results within elasto-plasticity with non-local softening

4. References

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