A damage-plasticity approach for modeling the failure of engineered cementitious composites

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Abstract

Engineered Cementitious Composite (ECC) materials are known to exhibit ductile strain hardening during tensile failure. This ductile response makes these materials popular for application in which structural members are subjected to severe cyclic loading. However, there is limited understanding how ECC interacts with ordinary steel reinforcement. Detailed finite element (FE) modelling of structural concrete members with ECC has the potential to provide this understanding. This requires constitutive models for ECC which are suitable for FE analyses.

The aim of this research is to develop a constitutive model, which can predict the ductile tensile behaviour of ECC based on input parameters related to fibre and matrix properties, and is suitable for the finite element approach applied to concrete members with steel reinforcement.

Key words: *ECC; ductility; reinforced concrete; damage-plasticity*

1 Introduction

The ductility of ECC is achieved by the formation of multiple cracks due to fibre bridging. Because of the slip-hardening bond relation between cementitious matrix and typical PVA fibers in tension, fibre bridging stress of ECC will increase until the bridging capacity is reached [1]. After reaching the bridging capacity, strain localisation and tensile softening happens. A numerical approach to predict the tensile behavior and strain capacity of ECC is important, because it will assist with designing structural members made of ECC material.

Typical constitutive models used for modeling ECC at the structural level with the FE method is by phenomenological desctiption of different stages of the ECC tensile response (elastic stage, tensile hardening stage and tensile softening stage) [2]. However, the process of the formation of multiple cracks and the evolution of fiber debonding and pullout are often neglected. In this research, a new modelling approach, which includes the overall stress acting on a single crack surface, the multiple cracks forming process and evolution of fibers debonding and pullout is combined. The present modelling approach is based on the single fibre pullout model by Lin and Li [3] and a damage-plasticity model for the cementitious matrix material developed by Grassl and co-workers [4]. A new modelling technique for the cracking process during the hardening stage of the ECC material is proposed to convert crack openings of single cracks into continuum strains. The model is implemented in the finite element program OOFEM [5] and compared to experimental results of direct tensile tests made of ECC. Then, the model is applied to analyses of steel reinforced tensile ECC specimens reported in [6]. The effect of ECC on the overall ductility of the specimens is well predicted by the modelling approach.

2 Methodology

The constitutive model proposed in this study is based on multiple cracking process and interaction between fibers and matrix for one single crack surface. When the composite tensile strength is reached, the fiber stress is initiated and increases, multiple cracks form until the maximum number of cracks reached. The fiber stress increases until the bridging capacity of fiber pullout is reached. After both the maximum number of cracks and the bridging capacity are reached, strain localisation and softening happens at one of the cracks. In this model, the multiple cracks are considered smeared cracks within the ECC specimen. Within each crack, the Lin and Li constitutive model [3], which predicts fiber stress as a function of the crack opening, is adapted.

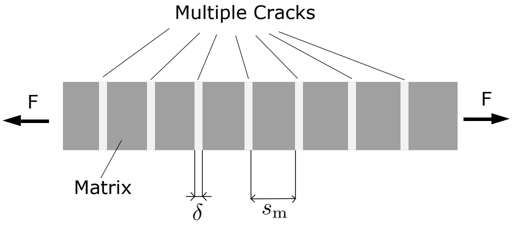


Figure 1: Schematic illustration of crack pattern assumed in ECC model.

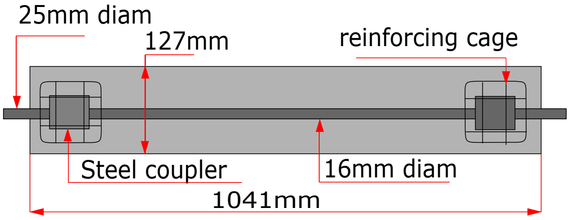


Figure 2: Geometry and setup of R-ECC and RC specimen according to experiments reported in [6].

This model links the micro-scale fibre stress and crack opening relation to the macro scale overall strain and stress relation based on the following assumptions:

1. Crack surface are perpendicular to the first principle strain direction and distributed uniformly among the ECC specimen.
2. The ECC material is homogeneous, which at each cracks volume fractions of fibers are at same value.

Due to force equilibrium, the overall stress is equal to the sum of fibre stress and matrix stress at each crack surface:

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}_{\mathrm{m}} + \boldsymbol{\sigma}_{\mathrm{f}} \tag{1}$$

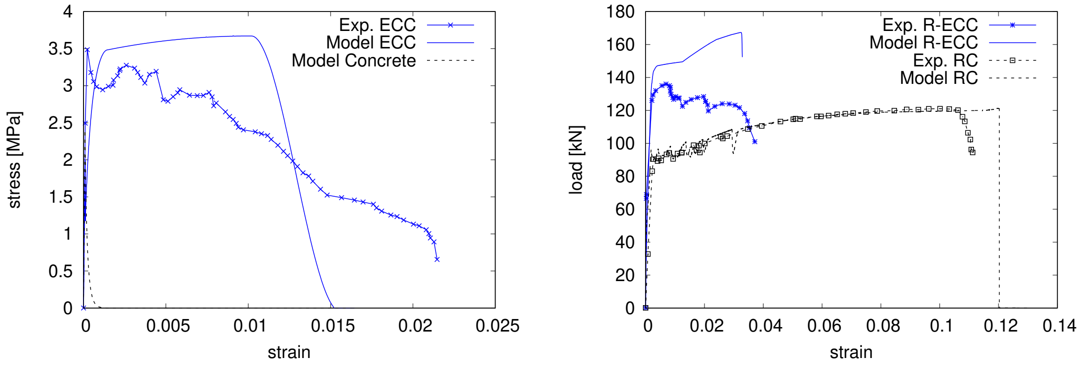
The crack opening at each crack is the same for all cracks during the tensile hardening process. The cracking strain can then be calculated from the crack opening at each crack and the crack spacing as

$$\boldsymbol{\varepsilon}_{\mathrm{cr}} = \frac{\boldsymbol{\delta}}{s_{\mathrm{m}}} \tag{2}$$

where $\boldsymbol{\varepsilon}_{\mathrm{cr}}$ is the cracking strain of ECC, $\boldsymbol{\delta}_{\mathrm{cu}}$ is the crack opening at each crack, s_{m} is the crack spacing between two cracks. A constant number of cracks is assumed during the cracking process, i.e. it is assumed that when cracking is initiated, the number of cracks increases to the maximum number immediately and remains like this until localised cracking occurs. The fibre model is connected to the damage-plasticity model CDPM2 in [4] by adjusting the damage part of CDPM2 so that the nominal stress is equal to the stress calculated from the fibre model.

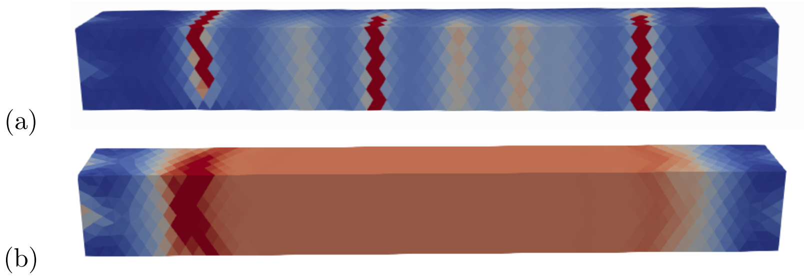
3 Analysis and Results

The new model is implemented in the open source finite element program OOFEM [5] and applied to the simulation of a steel reinforced concrete prism. The matrix of the prism is made of both plain concrete and ECC as described in the experiments reported in [6]. The setup and geometry of the analysis is shown in Figure 2.



(a) (b)

Figure 3: Analysis results: a) Matrix response in uniaxial tension for ECC and concrete, b) Reinforced member response for R-ECC and R-C. All the experimental results are from [6].



(a)

(b)

Figure 4: Principal maximum strain: a) RC and b) R-ECC. Red stands for high strain values.

The length of specimen is 1.04 m. The edge length of the square section is 0.126 m. The diameter of reinforcement for specimens is 16 mm. The material property of concrete and ECC are chosen according to the information provided from the experiments. For ECC, Young's modulus of matrix is $E = 30$ GPa, tensile strength of matrix $f_\mathrm{t} = 2.9$ MPa, length of fibres $l_\mathrm{f} = 12$ mm, diameter of fibre $d_\mathrm{f} = 40$ μm, volume fraction of fibres $V_\mathrm{f} = 0.02$. For concrete, $E = 30$ GPa, $f_\mathrm{t} = 1.4$ MPa, compressive strength $f_\mathrm{c} = 31$ MPa. These material properties result in uniaxial tension stress-strain curves for the matrix material as shown in Figure 3. From the experiments, only the tensile stress-strain response of the ECC material is available. The ductility predicted in the model is greater than in the experiment, which is due to the assumption of strain hardening in the model. The minimum crack spacing is selected to 30mm, which results in strain localisation and maximum fibres stress being close to the experimental results.

The material parameters are used in the structural model to study interaction of ECC and steel reinforcement. The structural response is shown in the form of load versus strain in Figure 3a and maximum principal strain contour plots in Figure 4. For reinforced concrete (R-C), multiple cracks occur. This is seen by the red colour in Figure 4a, which indicates high strain values. The load-strain curve in Figure 3b shows a ductile response which is similar to the bare steel response used as an input in the modelling. These analysis results are in good agreement with the experimental observations in [6]. For reinforced ECC (R-ECC), the strain is initially distributed, which represents strain hardening in the material model. When the strain localises, it is only in one crack, which is again similar to the experimental results. The load capacity of R-ECC in Figure 3b is higher than for R-C, because the cracks are bridging stresses due to the presence of the fibres. The fracture of the reinforcement bar happens at a lower strain than for the R-C model.

4 Conclusion

The proposed plastic-damage approach can predict well the mechanical behavior of ECC in tension. The multiple cracks at the lower scale are considered as plastic strain in the model. Damage occurs when the strain localisation is initiated. The model is implemented in the open source finite element software OOFEM. The comparison of numerical result and experimental result shows that this approach can predict well the interaction between reinforcement and ECC.

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