Numerical analysis of plain and fiber reinforced concrete structures during cyclic loading: Influence of frictional sliding and crack roughness

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Concrete is a quasi-brittle material, characterized by a non-negligible, finite-sized fracture process zone (FPZ) in which various toughening mechanisms play a significant role on crack development and propagation. Concrete is often reinforced with fibers to improve the serviceability and longevity of concrete structures by controlling the maximal crack widths and providing residual carrying capacity to initiated cracks. In quasi-brittle materials such as concrete, toughening mechanisms such as crack deflection due to the presence of large heterogeneities, contact shielding, i.e., wedging and crack closure induced by debris and rough crack faces, crack bridging by tough aggregates, unbroken ligaments and fibers (in fiber-reinforced concretes), are mostly governing damage evolution under monotonic and especially under cyclic loadings. All these items contribute to a complex non-linear response in terms of load-displacement curves observed in experimental investigations. Many investigations have been performed on plain concrete, but not so many for high-performance fiber-reinforced concrete. The extension of this crack model to fiber-reinforced high-performance concrete, we model these mechanisms and their evolving influence on damage development using a discrete crack approach, and take into account the imperfect closure of cracks and friction between crack faces that come in contact during loading/unloading of the specimen. Within the scope of this contribution, we present the formulation of the model and illustrate its performance through selected numerical experiments under monotonic and cyclic loading of plain and fiber-reinforced high-performance concrete specimens. Model predictions are compared with laboratory measurements.

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1 Introduction

Concrete is one of the most frequently used building materials. In the recent decades, high-performance (HPC) and ultra-high-performance (UHPC) concretes have been specially designed to meet certain predefined performance and uniformity requirements, in particular with respect to durability and strength. Fibers are often added to improve the ductility of plain concrete. The design is, however, still largely based on experimental evidence and empirical rules rather than a well understood set of physical laws. This is even more true in regards to the behavior of fiber reinforced concrete (FRC) in case of cyclic loading. Recent investigations have made an attempt to better understand the mechanisms governing the damage evolution and durability of fiber-reinforced cementitious composites under cyclic loading (see, e.g., [3], [4]). In regards to computational analysis, a number of numerical models have been proposed to describe the behavior of plain and fiber-reinforced concrete under cyclic loading (e.g., [1], [5], [6]). This contribution presents an extension of a numerical model for structures made of plain and fiber reinforced concrete, previously proposed by the authors [7], which accounts for the formation of hysteresis loops during loading/unloading of concrete specimens due to internal frictional sliding mechanisms.

2 Finite Element Model

For the modeling of propagating cracks, a discrete crack finite element model (see, e.g. [8], [9], [10]) is adopted. It is characterized by zero-thickness interface elements, which are inserted between bulk material finite elements in regions where cracking is expected (see Figure 1) [2, 7]. The bulk material elements are modeled by a linear elastic material model, while the interface elements are equipped with non-linear traction-separation laws to characterize the fracture behavior of plain concrete and FRC. It is important to note that this method is computationally expensive, especially in 3D analyses, because the nodes of bulk material elements have to be duplicated in order to insert interface elements. For this reason, it is very important to use this model within a highly optimized finite element framework, such as in this case, Kratos Multiphysics [11], which enable large-scale parallel simulations to be performed. One advantage of the proposed methodology is the automatic enforcement of crack continuity, without need for crack-tracking techniques, and the possibility to model arbitrarily many cracks, including branching and coalescence, limited only by the computational power at hand. At the level of a single interface element, a traction-separation law for plain concrete with an exponential softening behavior, characterized by a tensile strength and fracture energy in mode I as well as, in an analogous manner, in shear, using two mixed mode parameters parameters $\beta$ and $\kappa$ introduced in [8], [10]. The extension of this crack model to fiber-reinforced concrete was formulated and validated in [12] and enhanced and re-validated on a different data set in [7]. In this contribution, an extension of the constitutive model to account for frictional sliding and crack closure/reopening mechanisms is presented. These additional effects occur only when

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In this subsection, a simple, but illustrative numerical experiment, characterized by a cube (100 mm × 100 mm × 100 mm) subjected to a nonproportional load history (Figure 3a) is presented. The cube is first subjected to uniaxial tension, leading to crack initiation, and then to uniaxial compression (-5 MPa), closing the initiated crack, and subsequently to shear to illustrate the capability of the proposed model to capture friction in the initiated cracks. Frictional sliding leads to the development of hysteretic loops as depicted in Figure 3b. Here, an interplay between damage evolution and plastic sliding can be observed as the shear stress decreases from around 4 MPa to 2.5 MPa, which is the residual frictional stress according to the prescribed boundary conditions and material properties ($\mu \cdot \sigma_{yy} = 0.5 \cdot 5$ MPa = 2.5 MPa). In this example, both displacement and load control have been utilized to drive different portions of the simulation. Therefore, the stresses in Figure 3 are the nominal stresses obtained by dividing the corresponding reaction force by the cross section area (100 mm × 100 mm). The material properties used in this example are listed in Table 1.

![Pre-Processing](image1.png)

**Fig. 1:** Illustration of the zero-thickness interface element insertion procedure applied during the pre-processing step to generate the discrete crack finite element model (left). Load-displacement diagrams from a monotonic three-point bending test for 3 different fiber orientations (right). The same configuration is also used in cyclic tests. Figure reproduced from [7].

3 Results & Discussion

3.1 Plain concrete cube under cyclic shear

In this subsection, a simple, but illustrative numerical experiment, characterized by a cube (100 mm × 100 mm × 100 mm) subjected to a nonproportional load history (Figure 3a) is presented. The cube is first subjected to uniaxial tension, leading to crack initiation, and then to uniaxial compression (-5 MPa), closing the initiated crack, and subsequently to shear to illustrate the capability of the proposed model to capture friction in the initiated cracks. Frictional sliding leads to the development of hysteretic loops as depicted in Figure 3b. Here, an interplay between damage evolution and plastic sliding can be observed as the shear stress decreases from around 4 MPa to 2.5 MPa, which is the residual frictional stress according to the prescribed boundary conditions and material properties ($\mu \cdot \sigma_{yy} = 0.5 \cdot 5$ MPa = 2.5 MPa). In this example, both displacement and load control have been utilized to drive different portions of the simulation. Therefore, the stresses in Figure 3 are the nominal stresses obtained by dividing the corresponding reaction force by the cross section area (100 mm × 100 mm). The material properties used in this example are listed in Table 1.
Fig. 2: Illustration of the constitutive model including crack bridging and the crack closure model. a) Rough crack surface and debris particles. The crack is not fully developed and there is some bridging that provides residual strength. Upon closure, rough crack lips come in contact with each other as well as debris particles. Contacts are indicated by stars in the illustration. b) Traction-separation law used for plain concrete at one material point. The crack closure model is illustrated in unloading. The initial stiffness parameter is denoted by $K_i$, and the damaged stiffness parameter by $K_d=(1-d)K_i$.

Fig. 3: A cube subjected to non-proportional load path. (a) Load history and deformed geometry of the cube (scale factor of 100). (b) Stress-displacement response.

3.2 Three-point cyclic bending tests on plain and fiber-reinforced concrete beams

To assess the performance of the proposed crack closure model, we perform numerical re-analyses of 3-point bending experiments performed at University of Wuppertal (see [7] for details). The material properties are listed in the Table 2. For fiber-reinforced concrete example, there are several additional parameters ($t_1=1.6487$, $t_2=1.4511$, $c_1=2.55$, $c_2=2.3$, $l_f=30.0$ mm) that account for the type, amount and orientation of fibers (see [7] and [12] for explanation). The overall shape of the hysteresis loops, even though at a single material point a very simple bi-linear loop is postulated (see Figure 2b) is surprisingly well captured. This is attributed to the fusion of closure contributions of many cracks. The size of the hysteresis loop.
loops are overestimated for larger crack-mouth-opening displacements (CMODs), while the residual openings are in general well reproduced. We assume here, that the "closure stress" is a material property and use the same value for both plain concrete and fiber-reinforced concrete. This assumption will be critically reflected in subsequent extensions of the model.

## 4 Conclusion

In this contribution, an improvement of a previously proposed crack model [7] for plain and fiber reinforced concrete was presented. It was shown, that consideration of a crack closure/reopening mechanism by means of a multi-surface plasticity model makes allows to reasonably match the complex load-displacement curve in case of cyclic bending plain concrete as well as fiber-reinforced concrete beams. Particularly attractive is the fact that the closure/reopening mechanism is characterized by a single parameter that can be related to the strength of debris particles inside the crack. This model, although a simplification of the real-life situation, provides insights into the mechanisms of crack closure under cyclic loading and particularly the physical mechanisms that cause hysteresis loops formation. The crack model has not yet adequately considered the additional contributions of the fibers to the hysteresis loops. This is the topic of ongoing research.

| Table 1: Material parameters for the plain concrete cube. | Table 2: Material parameters for the plain concrete beam. |
|--------------------------------------------------------|----------------------------------------------------------|
| E 35000.0 N/mm²                                      | E 39976.0 N/mm²                                      |
| ν 0.2                                                   | ν 0.2                                                   |
| Kᵣ 35000000.0 N/mm³                                   | Kᵣ 35976000.0 N/mm³                                   |
| fᵣ 3.0 N/mm²                                          | fᵣ 5.7 N/mm²                                          |
| β 1.0                                                  | β 5.0                                                  |
| G₅ 0.1 Nmm/mm²                                        | G₅ 0.11 Nmm/mm²                                       |
| κ 1.0                                                  | κ 10.0                                                 |
| μ 0.5                                                  | μ 0.5                                                  |
| σ_closure 0.0 N/mm²                                    | σ_closure -1.4 N/mm²                                   |

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