



# Different Approaches for FEM Modelling of Strain-Hardening Cementitious Composites

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**Abstract.** Strain-hardening cementitious composites (SHCCs) are a special class of fibre-reinforced concretes which develop multiple, fine cracks when subjected to an increasing tensile load. This ensures remarkably high strain capacities of up to several percent, making SHCC an advantageous material both for new structures subjected to high mechanical loading or in severe environmental conditions and for the retrofitting/strengthening of existing structures by application of thin SHCC layers.

Finite element modelling (FEM) can be an efficient tool to predict the behaviour of SHCC under different loading types. This paper lists some recent advances in finite element modelling of strain hardening fibre reinforced cementitious composites. Based on a comprehensive literature review two main approaches are highlighted, the continuum model approach and the advanced lattice modelling approach. This paper provides an overview of both approaches and their functionalities with respect to each other, based on results from literature. The work reported in this paper is part of a larger study into the use of SHCC for shear strengthening of existing concrete structures.

**Keywords:** Fibres · Strain-hardening cementitious composites · Finite element modelling

## 1 Introduction

Strain-hardening cementitious composites (SHCCs) are a special class of high-performance fibre-reinforced cementitious composites which under tensile stress show multiple cracking and a very high ductility, [1]. This material, also commonly referred to in literature as engineering cementitious composites (ECC), are typically reinforced with high strength short plastic fibres such as poly-vinyl alcohol (PVA) or high-density polyethylene (HDPE). Through well considered fibre types and tailored matrix design, SHCC can show strain hardening behaviour having tensile strain capacities of up to 8% [2–4]. This remarkable deformation is caused by the fine distribution of cracks in the material, which are bridged by short fibres. These properties make SHCC an interesting choice not only in construction but also as a repair material to strengthen existing structures.

In order to successfully implement SHCCs in the construction industry, there is a need for reliable modelling techniques, both at the level of material performance and

structural behaviour. During the last two decades, researchers have tried to develop an accurate model representation of the complex SHCC material behaviour. Traditionally, micromechanics-based analytical methods are used to tailor the mix composition of SHCC and to ensure multiple cracking. According to this methodology, a fibre bridging law is applied by satisfying both energy and strength criteria which eventually leads to steady-state crack propagation. These criteria are explained in detail in the literature [5, 6].

The modelling of SHCC members is characterised by a few differences when compared to conventional concrete. The additional complexity arises with the continuous formation of multiple cracks. In order to simplify the process, continuum-based finite element models have been developed in which the composite is modelled as a single continuum instead of analysing the interaction between fibres and the matrix. Continuum models can follow various constitutive laws which are found in literature and can be broadly classified as homogenization-based constitutive laws [7, 8] and improved individual-based constitutive models [9–11]. Continuum models, however, come with limitations as they are usually not able to predict the sequential formation of cracks and the crack spacing. Considering these limitations, few advanced models are also studied which consider the effect of each fibre in the matrix and attempts to model the post multiple cracking behaviour. Most frequently studied are rigid body spring models [13, 14] and lattice models [15, 16]. In contrast to the technical work done in this field, an overview of FEM modelling approaches for SHCC materials is lacking.

In this paper, an overview of FEM models for SHCC members is presented. Firstly, different variants of continuum-based models are highlighted. After that, some recent advanced approaches are discussed including lattice and rigid based models. As this paper deals with FEM modelling of SHCC, specifically, experimental works and other types of fibre reinforced composites are excluded.

## 2 Continuum-Based Modelling

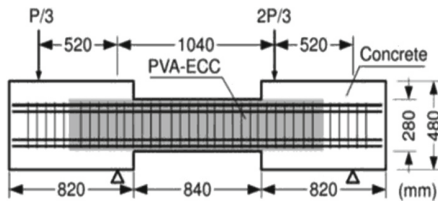
SHCC comprises of a cementitious matrix and embedded short fibres. Associated to this combination, the fibre-matrix interface is of governing importance. While complex micro-models can accurately depict the response by incorporating different heterogeneities in SHCC, it can require higher computational power. In this respect, continuum macro-models can provide a practical solution to simulate the structural behaviour of SHCC elements [18]. These models are easy to use and are often already incorporated in proprietary non-linear FEM packages (such as Diana, Abaqus, Atena, etc.). Various constitutive models are used by researchers in the continuum-based approach which can be broadly classified as homogenization-based constitutive models [7] and individual-based continuum models [9].

### 2.1 Homogenization-Based Approach

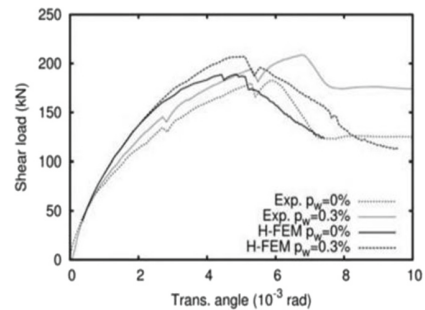
Kable [19] proposed in 2002 a homogenization-based constitutive law for SHCC materials (Fig. 2 which is derived as a relation between total stress and total strain of a representative volume element. This volume element comprises of up to two mutually

perpendicular sets of parallel distributed cracks. These cracks are assumed to form when the maximum principal stress reaches the value of first cracking strength. The overall response of the continuum is then governed by a linear hardening relationship obtained from the uniaxial tensile test. Once formed, the crack direction is assumed to remain fixed. However, the crack can slide in case of a change in direction of principal stresses. Crack sliding is assumed to be resisted by bridging fibres.

This constitutive law is used in [20] to simulate the experiments on SHCC beams which were designed to fail in shear, also referred as Ohno beams (Fig. 1a) [18]. The authors studied the effect of bond-slip behaviour, the influence of tensile properties and fibre stiffness. The authors found that only a fraction of SHCC’s uniaxial capacity was utilized, possibly because of fibre damage due to relative crack slipping. To match experimental results, the authors recommended using lower fibre shear modulus values. The results in Fig. 1b shows that although the analysis predicted peak loads fairly reasonable, the peak load was higher and the post-peak response was stiffer in the simulations and the cracks were not correctly represented. The model predicted cracks at  $45^\circ$  which was a higher angle than that in the experimental results.



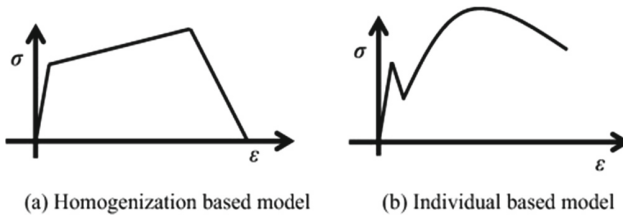
**Fig. 1a.** Ohno Shear beam configuration [18]



**Fig. 1b.** Analytical (H-FEM) and experimental results of beams with stirrup reinforcement ratios  $p_w = 0$  and  $p_w = 0.3\%$  [18]

## 2.2 Individual-Based Approach

Considering the limitations of homogenization-based models, Kabele [10, 21] and Yang and Fischer [9] proposed the individual-crack-based approach shown in Fig. 2b. In this modelling technique the crack opening vs bridging stress relationship is first derived by experimental testing of notched tensile specimens. For a particular element, the post-peak response is then calculated by dividing the crack opening by the element dimension perpendicular to the crack. As shown in Fig. 2b there is a drop in stress with crack opening and then a further increase in stress as the load is transferred to the fibres. According to Kabele [21] this approach can improve the results under non-proportional stresses as compared with homogenized-based models. However, in the earlier model of Kabele [21] one crack will form in each element as soon as the tensile strength is



**Fig. 2.** Continuum-based models for SHCC

reached, so the mesh size becomes an important factor to determine crack spacing. For an accurate analysis of crack spacing, a priori information on the crack pattern is required to select the mesh size. Yang and Fischer [9] and Kabele [10] used an alternative approach where they considered variation of crack bridging behaviour among different sections based on experimental results and they imposed a minimum crack spacing criteria so that cracks are formed sequentially under increasing stresses.

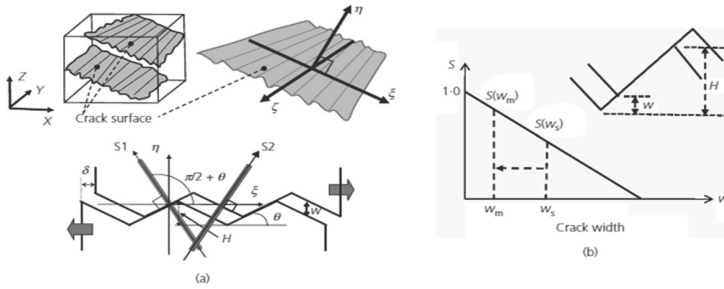
### 3 Lattice Models

Initially lattice models found their application in the concrete industry to simulate chloride diffusion and moisture transport [22]. However, recently there is an increasing interest in their usage for structural analysis especially for high-performance cementitious composites [23, 24]. In the following section, different types of lattice models developed to model SHCC are reviewed.

#### 3.1 Lattice Equivalent Continuum Model (LECM)

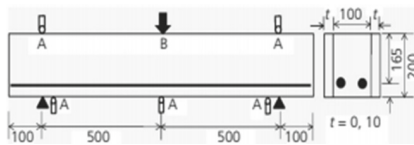
Zhang et al. [25] developed a shear lattice system for analysing the crack surface of SHCC based on a lattice equivalent continuum model (LECM) [26], which consists of a combination of compression, tension and shear lattices. LECM involves the use of discrete lattice modelling of the cement matrix. Even though the continuum model retains its uniaxiality of stress-bearing materials, a combination of these approaches leads to a change of characteristics from an orthotropic model to a more anisotropic model. Conceptually, this model starts with a lattice approach but ultimately governing equations represent the equivalent continuum element of that lattice system.

The stress-strain relationship of SHCC under tension is modelled by experimental data from uniaxial tests while the compression behaviour can be modelled by a suitable compression softening model. In LECM, the shear transfer model is formulated considering the shear stress transfer mechanism such as aggregate interlocking and shear deformation at the crack surface. The crack surface is simulated as a geometry comprising a series of triangles. In this, shear lattice contact stress in the contact area is compressive stress ( $S_1$  in Fig. 3) perpendicular to the inclined crack surface while for the crack area having no contact there is a fibre bridging stress ( $S_2$  in Fig. 3). Furthermore, an additional coefficient  $S$  is also added that takes into account the contact rate related to crack width.

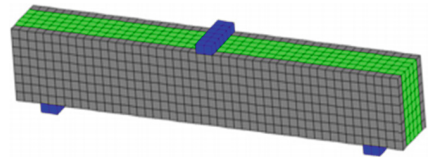


**Fig. 3.** Shear lattice expressing crack surface of SHCC (a) assumed crack surface, (b) contact area [27]

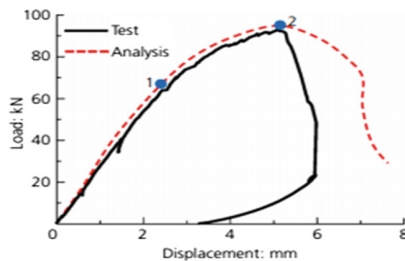
In literature, this particular model has been successfully applied to predict both the shear behaviour of SHCC beams [25] and also to simulate SHCC as a shear repair material [27]. Figure 4 shows the geometry of a SHCC repaired RC beam and corresponding LECM model. As demonstrated in Fig. 3, this model takes into account of contributions from both fibre bridging effect on the crack surface and the contact effect of the matrix. Figure 5 shows the experimental and numerical load-displacement curves of the repaired RC beams. The results show good agreement and validate the proposed shear transfer model, for the configurations used in that study. Numerical evaluation of the SHCC strengthening layer also revealed fine multiple cracking and final failure due to crack localization which shows the contribution of fibre bridging effect [27] (Fig. 4b).



**Fig. 4a.** SHCC layer geometry for RC shear strengthening [18, 27]



**Fig. 4b.** Model of SHCC repaired RC beam [27]



**Fig. 5.** Load displacement curves (experiment and simulation) of SHCC repaired RC beams [27]

### 3.2 Discrete Lattice Model

Recently, Lukovic et al. [23] simulated the behaviour of normal concrete and SHCC beams using a 3D lattice mesh model. Contrary to the previously discussed models, no continuum concept was applied in this model. Instead, it considers different phases of the composite and models them as truss or beam elements (Fig. 6). These elements form a lattice mesh and show usually linear elastic behaviour. Loading is then applied in steps and after each step elements that exceed the defined limit are removed till failure is reached. A 20 mm cubical grid was made with each cube having a lattice node at a random location. Four of the closest nodes were connected with concrete beams using Delaunay triangulation. These concrete beams were assumed to have linear elastic behaviour before failure and ascribed material properties such as tensile and compressive strength determined by experiments.

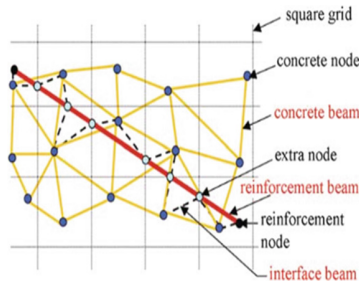


Fig. 6. SHCC layer geometry for RC shear strengthening [18]

Lukovic et al. [23] performed simulations on beams reinforced with 0.69% longitudinal reinforcement and  $a/d = 3.3$ . SHCC elements were simulated using ideally plastic material law with 5% strain capacity instead of linear elastic law which was used to simulate concrete. The tensile strength of both concrete and SHCC was assumed to be the same. Figure 7 shows the results of normal concrete and SHCC beams. The capacity of the SHCC beam was found to be almost twice the value of the normal concrete while the failure mechanism shifted from shear to bending in the SHCC beams. It was also noted that SHCC failed in a brittle manner and under smaller deflection compared to normal concrete beams.

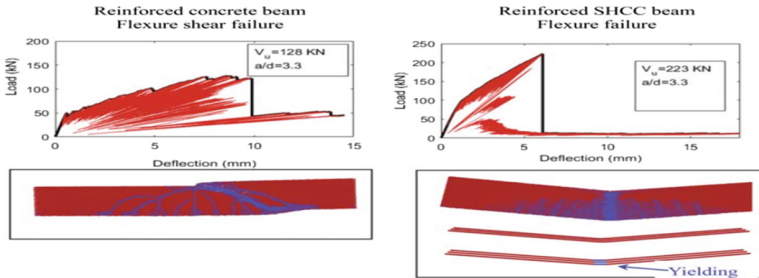
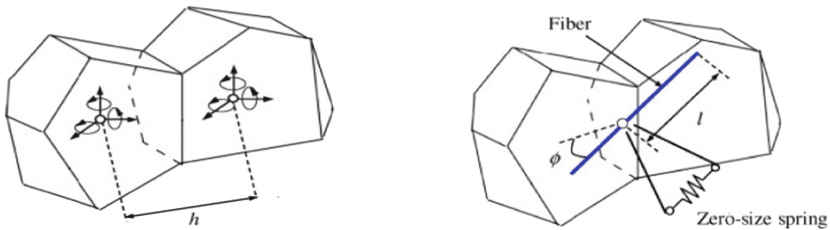


Fig. 7. Behaviour of reinforced SHCC and reinforced concrete beams [27]

### 3.3 Rigid-Body Lattice Model

RBSM is a discrete modelling approach based on the bond stress-slip behaviour of single fibres, as outlined for SHCC materials by Kunieda et al. [28]. Similar to other lattice models, matrix and fibres are modelled separately in RBSM with the location of each fibre identified usually by conducting a parametric analysis. Bolander and Saito [29] performed 2D parametric analysis in which fibres were modelled as beam elements to predict tensile fracture of fibre reinforced concrete [28].

Figure 8 shows a typical example of 3D polyhedral (Voronoi) cells which are assumed to be rigid bodies and assumed to have 6 degrees of freedom [30]. Neighbouring cells are connected with six springs across their common facet. Each facet comprises two tangential, one normal and three rotational springs representing 6 degrees of freedom. The mechanical properties of normal and tangential springs are determined by the properties of the matrix (tensile strength, fracture energy, elastic modulus), while the properties of rotational springs are defined by facet geometry [30]. Short fibres are placed at a random location as shown in Fig. 8b. A zero sized spring is placed at each point where a fibre crosses a facet between two cells. The bridging force provided by the spring is determined by integration of the bond stress-slip relationship. Embedment length and orientation angle are also calculated for every single fibre.



**Fig. 8a.** Rigid cells and defined DOF [14]    **Fig. 8b.** Fibre model and zero-size spring [14]

RBSM is shown to be applicable to predict the behavior of SHCC [9, 14] but studies are scarce, and the size of the assessed members is of small scale. Kunieda et al. [14] performed tests on rectangular beams  $30 \times 13 \text{ mm}^2$  having 100 mm span length. In order to simplify the model and to make the computation more efficient, the authors used cells of rectangular ( $30 \times 13 \text{ mm}^2$ ) cross-sections at 1mm spacing. Fibres were randomly distributed in the matrix as shown in Fig. 9.

Figure 10 compares the experimental stress-strain relationship with that of the model. The value of tensile strength used in the analysis was 7.5 MPa which was determined through flexural testing of the plain matrix. Flexural and tensile strengths were assumed to be equal. The model predicts a softening behaviour in 1.0% fibre volume whereas experimental results show a strain-hardening up to 1.0% strain. For the 1.5% fibre volume case, the analysis predicted repeated gain and losses in stresses after the first crack. The model exhibits strain-hardening of about 5.2% while the experimental results showed an ultimate tensile strain capacity ranging from 2.0% to 2.5%. More work is needed to achieve more accurate modelling.

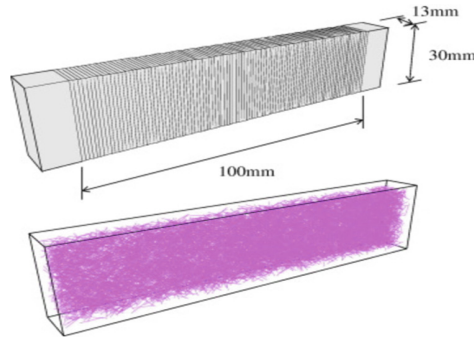


Fig. 9. Discretized RBSM SHCC beam model [27]

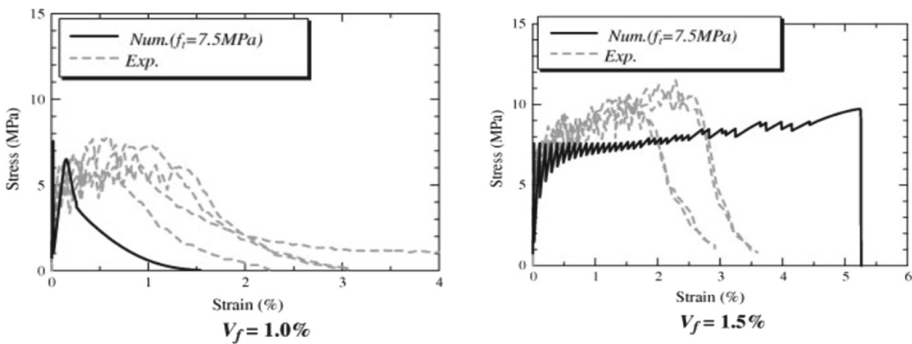


Fig. 10. Experimental and numerical load displacement curves [27]

### 4 Concluding Remarks

This paper gives an overview of FEM modelling techniques for simulating fracture in SHCC members. The complex fracture process in a heterogeneous material such as SHCC is not easy to predict, especially due to fibre-matrix interaction and potential multiple cracking. The physical and chemical properties of the applied fibres, and the matrix composition play a significant role in the nucleation and propagation of cracks. Most common used SHCC modelling approaches in the literature include analytical micromechanical models for micro or meso scale material modelling. For macro scale FEM modelling, different types of continuum models and lattice models have been applied. In basic FEM models, SHCC is assumed as a continuum element, whereas more advanced FEM models consider the interaction between SHCC phases more explicitly, to predict its macroscopic behavior. It is difficult to conclude which technique is the most suitable since each approach has its merits and demerits.

Conventional continuum models can provide a practical solution by idealizing the cracking state as an equivalent homogenization continuum. However, there are studied



cases when this approach leads to an overestimation of load capacity of SHCC members especially when the member is loaded in non-proportional stresses such as shear [21]. The application of lattice models has proved to have potential of being more reliable and effective to simulate the shear behavior. The lattice equivalent continuum model is one of the models which has shown promising results in modelling SHCC as a shear repair material.

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