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CIVIL INFRASTRUCTURE

Biomimetic Materials in Construction Industry: the Necessity of Simulation

Biomimetic materials are a possible solution to tackle the environmental and sustainability concerns of the construction industry. Automation in repairing and self-healing features can increase the durability of brittle materials which are susceptible to cracking. A number of different self-healing technologies have been introduced over the past two decades; however, further research is needed to simulate their behaviour and study their performance. Mathematical models are needed for design and assessment purposes. In this paper the formulation as well as the application of a micromechanical model is presented. This model can capture simultaneous fracture and healing processes. The results from this constitutive formulation can be implemented in finite element framework for simulating the boundary value, and multiscale problems. The model is tested for an encapsulated self-healing cementitious mortar and the results show that it can capture the stiffness recovery with an acceptable accuracy

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INTRODUCTION

The materials used for construction are required to be produced in a large volume. Despite their low environmental impact per unit, the overall impact on environment is enormous [1], due to the high-volumes of these materials used by the construction industry. In addition to the impact of producing new materials for buildings, the economical and environmental cost because of repair and maintenance are other concerns that motivate researchers to look for much more sustainable solutions [2]. Cementitious materials, lime mortar and geomaterials are the most frequent materials used in buildings [3]. These materials are brittle which means they are prone to cracking under tensile loading. Structural durability is significantly affected by cracking. Inspired by nature, researchers have introduced some new biomimetic techniques to enhance the performance of conventional materials employed in construction industry [4]. In particular, self-healing and crack closure systems have been developed for enhancing durability. The behaviour of these materials is governed by a set of coupled chemo-physical processes. Employing autonomous self-healing techniques such as micro and microencapsulation, embedding vascular network and using bacteria can provide the self-healing features for these materials in case of damage [5]. Using microfibres or shape memory tendons can control and close the crack which aids autogenous healing (i.e., inherent self-healing that naturally occurs in cementitious materials, e.g., hydration of unhydrated particles) [6]. Fig. 1 shows schematically the different methods employed for developing biomimetic materials.

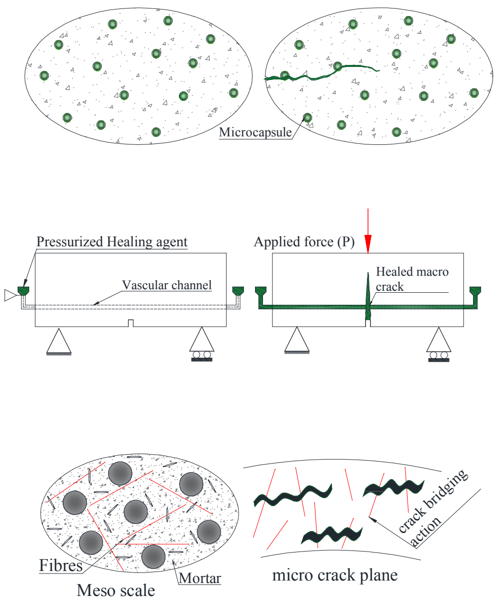

Fig. 1. Different self-healing practice, a) encapsulation (top), b) vascular network (middle) and c) fibre-reinforcing (bottom).

Some experimental research has been undertaken to evaluate the performance of these materials [5-6]. However, a little research has been devoted to determining the mechanisms observed in these experiments [7]. Finding a reliable model which can capture the essential behaviour of self-healing materials is essential for assessment and design.

In the reminder of this paper the newly developed methodology for simulating mechanical properties of biomimetic material is explained. The numerical results for encapsulated system briefly presented in the Results section.

MATERIALS AND METHODS

The biomimetic materials used in construction industry are composite multiphase systems. The chemo-mechanical actions within these materials occur at different length scales. To capture the behaviour of these materials, a multiscale method is required that can bridge between the different length scales. For these purposes, the micromechanical formulation is adopted to simulate the complex behaviour of this materials. The overall mechanical properties are obtained through homogenization techniques. A hierarchical multiscale averaging method is employed to upscale each phase properties to the higher scale. Fig.2 Shows schematic procedure for projecting each scale properties to the desired length scale.

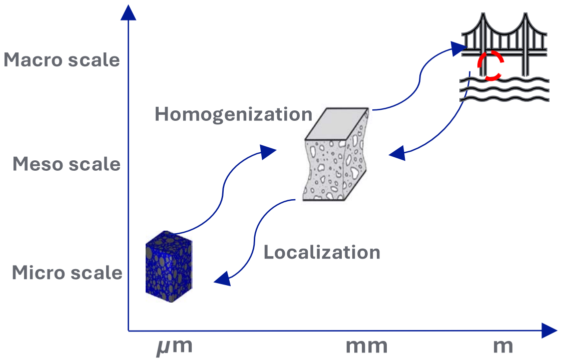

Fig. 2. Schematic procedure for hierarchy homogenization and multiscale analysis

The microcracking effect on the mechanical response is considered by assuming the formation of randomly distributed penny shaped microcracks inside the considered medium. Equation (1) shows how the effect of cracks is represented mathematically:

$$\mathbf{s}_{\mathrm{L}}(\theta,\phi) = \big(1-\omega(\theta,\phi)\big)\mathbf{D}_{\mathrm{L}}\boldsymbol{\varepsilon}_{\mathrm{L}}(\theta, phi) \tag{1}$$

where $\mathbf{s}_{\mathbf{L}}$ and $\boldsymbol{\varepsilon}_{\mathbf{L}}$ are the stress and strain local vector on a crack plane respectively. ω is the matrix damage parameter and $\mathbf{D}_{\mathbf{L}}$ is the local crack plane stiffness matrix. The healing contribution is added to the above equation as follows:

$$\mathbf{s}_{\mathrm{Lh}} = (1-\omega)\mathbf{D}_{\mathrm{L}}\boldsymbol{\varepsilon}_{\mathrm{L}} + h_v\mathbf{D}_{\mathrm{Lh}}(1-\omega_h)(\boldsymbol{\varepsilon}_{\mathrm{L}}-\boldsymbol{\varepsilon}_{\mathrm{h}}) \tag{2}$$

where the subscript h is for declaring the healing materials. h_v is the amount of the cracks that healed and $\boldsymbol{\varepsilon}_{\mathbf{h}}$ is healing offset strain for thermodynamic consistency condition. These equations represent 1D crack-healing constitutive behaviour. The overall 3D response is derived through the micromechanical integration proposed by Budiansky & O'Connell's method [8]. The full formulation derivation is explained in detail in forthcoming paper.

The performance of the proposed model is tested for a distributed crack-healing scenario. A concrete cylinder with embedded encapsulated healing agent was tested under compressive loading [9]. the degree of healing was measured by the stiffness recovery. The experimental sample details are presented in Table.1

Material/Properties	v_f %	E(GPa)	f_t(MPa)
Concrete	99.0	32	2
Microcapsules	1	0.3	0.24
Healing agent	-	16	4.5

Table.1. material properties

RESULTS

The stress-strain response under compression load is depicted in Fig.3. The stiffness recovery and its comparison with the experimental data is plotted in Fig.3. Figure 3a shows how the stiffness is derived before and after healing for the sample with 0.5% microcapsules.

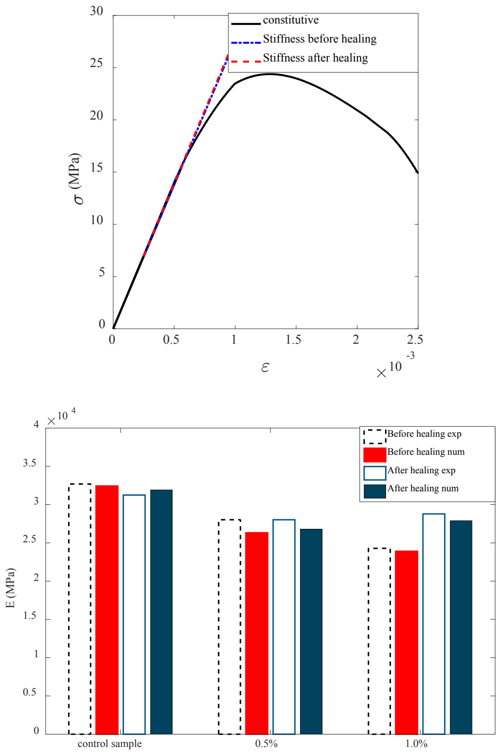

Fig. 3. Numerical results; a) compressive stress-strain relation (top), and b) stiffness recovery comparison (bottom).

DISCUSSION

The results show that the overall main mechanical characteristics of the composite system can be captured through the proposed closed form formulation. Furthermore, the comparison between elastic moduli of the encapsulated systems with the different volume fractions indicates that microcapsules can reduce the initial mechanical properties of cementitious composite systems. Using a high-volume fraction of microcapsules can increase the probability of triggering and following that the healing. This shows the importance of simulation in finding the optimum dosage of microcapsules in design applications.

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Conflicts of interest

The authors declare no conflict of interest.

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