5 Modelling of Self-Healing Cementitious Materials

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5.1 Introduction

Self-healing, especially the autonomic one with engineered additions to promote self-healing, is still a young research topic. During the past decade the amount of research performed progressed very rapidly. However, the publications that can be found mainly focus on experimental work and modelling is still limited. In this chapter the state of the art on modelling is given. Most work is related to experimental work described in the previous chapters. The models described in section 5.2 deal with self-healing mechanisms that make use of embedded tubes containing healing agents and is based on the work of Joseph [5.1]. Section 5.3 describes modelling techniques to study autogenic self-healing of concrete on the macro-level, mainly due to on-going hydration and focusing on cracks in the early age of hydration. This work is based on the work of Schlangen et al. [5.2]. Section 5.4 describes models that can be used to study self-healing of fibre reinforced materials. Some analytical models to study the self-healing probability of cementitious materials containing encapsulated materials are presented. Here it is focused on the amount and size of capsules needed to obtain complete crack filling. Finally, section 5.6 deals with self-healing due to on-going hydration of cement paste and models to study this phenomenon on the micro-scale.

5.2 Lattice Modelling for Concrete with Tubular Encapsulation

For the modelling of cracks, a lattice type model is used by Joseph which is described in detail in [5.1]. Cracks are modelled discretely in the lattice approach, crack openings are therefore determined automatically. For a notched beam tested under three-point loading the CMOD may therefore be obtained directly from the model. The value of the CMOD can therefore be used as the criterion for governing the breakage of the glass capillary tubes, and hence the onset of healing. Once the capillary tubes have broken, it is assumed that the flow of the adhesive is controlled by the varying aperture of the crack at that location.

Glue setting may then be modelled in a staged manner whereby broken beams are replaced with ‘healed’ beams at predefined CMOD limits. The height of glue rise, and therefore, determination of which broken beams are to be healed, is
obtained from the non-uniform capillary flow theory described in the next sections. The healed beams are considered to be composite beams comprising part mortar and part glue. The axial stiffness of these composite beams is therefore determined from the axial stiffness of the mortar part and the glue part combined in series. The length of the glue part is determined by the width of the crack opening at the beam location just prior to healing. The same principle of modelling could also be adopted in other self-healing concepts using embedded long or short tubes described in the previous chapters.

### 5.2.1 Healing Algorithm in 1D

The numerical algorithm, as outlined above, is illustrated schematically in Fig. 5.1 for the simple case of a 1D parallel bar model comprising two elements supported between two rigid bar supports. The support bar on the left is fully fixed and the one on the right is only allowed to translate in the x-direction. The elements have identical stiffness \( k_1 = k_2 \), but the tensile strength of element 1 is less than that of element 2 \( f_{t1} < f_{t2} \).

The system is initially subjected to a prescribed displacement \( \delta_{hp} \), and resists this displacement with a stiffness \( k \) \( k = k_1 + k_2 \), as illustrated by line (i) in Fig. 5.1(b). When the stress in element 1 reaches its tensile strength \( f_{t1} \), element 1 breaks and its stiffness is removed from the system. The difference in the distance between the supports and the unstrained length of element 1 is defined as the crack mouth opening displacement (CMOD) for this simple 1D model.

As the prescribed displacement \( \delta_{hp} \) increases further, the CMOD increases by the same amount. The stiffness of the system at this point is \( k = k_2 \) as represented by the gradient of line (ii) in Fig. 5.1(b). When the value of the CMOD reaches the predefined level of healing (CMOD 1 in Fig. 5.1(b)), element 1 is considered healed. This involves replacement of the element with a new composite mortar/glue element. The new composite element is therefore considered as comprising two springs in series. The axial stiffness of this element \( k'_1 \) is given by Eq. (5.1).

\[
k'_1 = \left( k_m^{-1} + k_g^{-1} \right)^{-1}
\] (5.1)

where \( k_m \) is the axial stiffness of the mortar part, and \( k_g \) is the axial stiffness of the glue part, as given by:

\[
k_m = \frac{E_m A_m}{L_m}
\] (5.2)