NUMERICAL SIMULATION OF LATCONX - A NOVEL SELF-HEALING CEMENTITIOUS-SHAPE MEMORY POLYMER MATERIAL

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ABSTRACT

This paper describes the development of a new non-linear layered beam model for simulating cracking in cementitious material combined with a previously presented polymer numerical model[1] to simulate an innovative shape memory polymer (SMP) – cementitious composite material system with active crack-closing and self-healing capability, called LatConX[2]. The model utilises a new "Beam-Hinge" element developed by the author that introduces cracking behaviour into a two-noded element. The hinge which simulates a crack can be located at any position within the element although for simplicity the derivation presented considers a central crack.

The new composite material system that is proposed makes use of shape memory polymers (SMPs), which, when activated (e.g. under heat), shrink and induce a compressive force in the concrete, enhancing the natural autogenous healing of cementitious materials. Further details of healing and curing regimes are presented elsewhere[3] and Figure 1 presents the main findings of an experimental investigation of this concept compared to the numerical simulation presented in this paper.

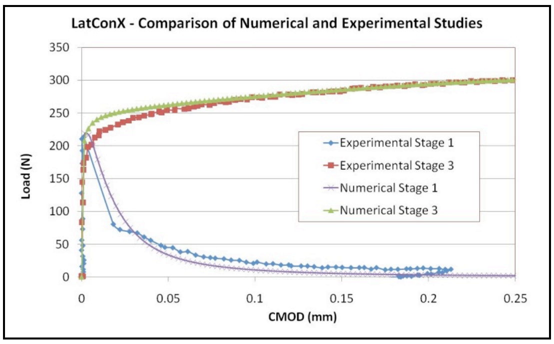
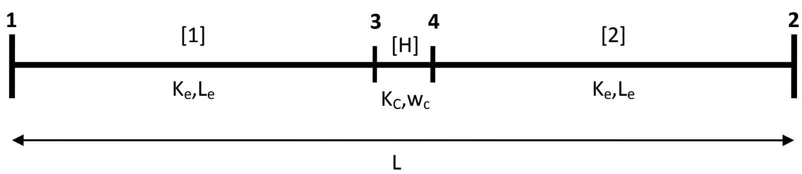


Figure 1: Proof of Concept Results.



$$K_C = \begin{bmatrix} k_{shr} & 0 & -k_{shr} & 0 \\ 0 & \Omega_c & 0 & -\Omega_c \\ -k_{shr} & 0 & k_{shr} & 0 \\ 0 & -\Omega_c & 0 & \Omega_c \end{bmatrix} \quad K_e = \frac{EI}{L_e}\begin{bmatrix} 12/L_e^2 & 6/L_e & -12/L_e^2 & 6/L_e \\ 6/L_e & 4 & -6/L_e & 2 \\ -12/L_e^2 & -6/L_e & 12/L_e^2 & -6/L_e \\ 6/L_e & 2 & -6/L_e & 4 \end{bmatrix}$$

Figure 2: Beam-Hinge Element

In order to develop a two-noded element with an in-built crack, a 4 noded element was initially considered which consisted of a central hinge element simulating a crack. The central nodes were then condensed out using a process of static condensation. A schematic of the beam-hinge is seen in Figure 2, in which E is the Young's Modulus and I is the 2nd moment of area.

The crack terms Ω_c and β in their non-linear form are defined in Equations 1 and 2 below, in which E_i is the Young's Modulus determined using the polymer model presented previously[1], b_i is the width, z_i is the depth and i denotes the layer number:

$$\beta = \int_{i=1}^{nlay} \frac{E_i . b_i . z_i . dz}{\int_{i=1}^{nlay} E_i . b_i . dz} \tag{1}$$

$$\Omega_c = \int_{i=1}^{nlay} \frac{\frac{2}{w_c} \int_{i=1}^{nlay} E_i . b_i . z_i . dz}{\int_{i=1}^{nlay} E_i . b_i . dz} E_i . b_i . z_i . dz - \int_{i=1}^{nlay} \frac{2 . E_i . b_i . z_i{}^2 .}{w_c} dz \tag{2}$$

The process of static condensation yields the following reduced stiffness matrix for a beam hinge element:

$$K_{cra} = (K_{eC} - K_{eH} . K_H^{-1} . K_{eH}^T) \tag{3}$$

In which;

$$K_{eC} = \begin{bmatrix} \frac{12EI}{L_e^3} & \frac{6EI}{L_e^2} & 0 & 0 \\ \frac{6EI}{L_e^2} & \frac{4EI}{L_e} & 0 & 0 \\ 0 & 0 & \frac{12EI}{L_e^3} & -\frac{6EI}{L_e^2} \\ 0 & 0 & -\frac{6EI}{L_e^2} & \frac{4EI}{L_e} \end{bmatrix} K_{eH} = \begin{bmatrix} -\frac{12EI}{L_e^3} & \frac{6EI}{L_e^2} & 0 & 0 \\ -\frac{6EI}{L_e^2} & \frac{4EI}{L_e} & 0 & 0 \\ 0 & 0 & -\frac{12EI}{L_e^3} & -\frac{6EI}{L_e^2} \\ 0 & 0 & \frac{6EI}{L_e^2} & \frac{4EI}{L_e} \end{bmatrix} K_H = \begin{bmatrix} \frac{12EI}{L_e^3} + k_{shr} & -\frac{6EI}{L_e^2} & -k_{shr} & 0 \\ -\frac{6EI}{L_e^2} & \frac{4EI}{L_e} + \Omega_c & 0 & -\Omega_c \\ -k_{shr} & 0 & \frac{12EI}{L_e^3} + k_{shr} & \frac{6EI}{L_e^2} \\ 0 & -\Omega_c & \frac{6EI}{L_e^2} & \frac{4EI}{L_e} + \Omega_c \end{bmatrix}$$

A series of validation examples were undertaken prior to the simulation of the LatConX system seen in Figure 1. The model can be seen to accurately simulate the experimental behaviour of both first cracking and cracking of the system following polymer activation and healing. The model does though assume that complete stiffness is regained when the crack is closed by polymer activation, whereas in reality there will be some reduction[4] due to misalignment of crack surfaces at micro and sub-micro scales, this is seen by the 85% stiffness recovery in Figure 1. The Stage 1 fracture softening curve is considered to be within the bounds of experimental variation and is therefore adjudged to be acceptable.

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