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Numerical simulation of the long-term behaviour of a self-healing concrete beam vs standard reinforced concrete

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ABSTRACT

Research on the self-healing cementitious composite material system named LatConX is presented, with predictions made as to the effectiveness of the system in limiting crack widths in concrete beams subjected to sustained loads. A layered beam numerical model for the transient thermo-mechanical behaviour of reinforced concrete has been developed and coupled to a previously published numerical model for transient thermo-mechanical behaviour of a shape memory polymer. The combined model has been validated by comparison with experimental data. Finally, the model is used to predict ten-year crack widths in standard reinforced concrete beams, and in beams employing the LatConX system. These results indicate that the LatConX system has the potential to reduce crack widths by up to 65% when compared with an identical beam without the LatConX system.

1. Introduction

This paper compares the predicted long-term behaviour of a new self-healing concrete material system with that of standard reinforced concrete. The new material system is named LatConX (LCX), it consists of both reinforcing steel and shape memory polymer (SMP) tendons included within a cementitious matrix. Once a beam has been cast, cured and loaded, the tendons' shrinkage process is triggered, applying a compressive force to the cementitious matrix. This compressive force has been shown to be beneficial to the cementitious matrix in three ways: it closes any cracks that have developed; it applies a compressive stress to the cracked faces, leading to improved healing of the cracks; and it improves the structural performance of the composite system by acting in the same manner as a prestressing system. This system has been described in more detail by Jefferson et al. [1]. The SMP tendons are formed from the widely available polymeric material polyethylene terephthalate (PET).

A numerical model has been developed to facilitate the comparison between LCX and standard RC beams. The model is composed of a set of sub-models, which are combined in order to simulate the transient thermo-mechanical behaviour of reinforced concrete beams. The model accounts for all relevant material behaviour and their interactions. These include: mechanical damage, creep, shrinkage, thermal expansion/contraction, and self-healing of the cementitious matrix; mechanical behaviour of reinforcement; and transient thermo-mechanical behaviour of SMP tendons.

The model presented herein was developed with simplicity, ease of use, and robustness in mind; in particular, speed of convergence was a vital factor in the design of the model due to the large time scales under investigation.

1.1. Material modelling of concrete

Most material models for concrete use either plasticity theory, damage mechanics or a combination of the two theories. Plasticity models require a yield surface, which is generally derived from a biaxial [2] or triaxial failure envelope, [3,4], as well as a hardening/softening and flow rule. A number of effective plasticity models have been developed to simulate the nonlinear behaviour of concrete [5–7] although the natural weakness of plasticity theory, in this context, lies in its inability to simulate the stiffness degradation that accompanies physical micro-cracking in tension.

Damage mechanics provides a natural means of simulating the loss of stiffness due to micro-cracking [8] and a number of effective isotropic damage models have been developed for the simulation of damage in both tension and compression [9–12]. Anisotropic damage models have also been investigated extensively over the last thirty years, which include those developed by Simo and Ju [13], Carol et al. [14], Borst and Gutierrez [15], and Desmorat et al. [16].

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Many investigators have combined plasticity and damage theories to produce models that simulate both stiffness degradation and frictional behaviour, the latter of which is characterised by the development of permanent or plastic strains [17–22].

For the present work, a one dimensional damage approach has been adopted to simulate tensile cracking and a plasticity model has been used to simulate the behaviour of concrete in compression. This cementitious material model has been applied in a nonlinear layered beam model.

1.1.1. Healing

The self-healing behaviour of cementitious materials has received considerable attention in recent years. Comprehensive reviews have been published by several authors including those of Joseph et al. [23], Wu et al. [24], and Van Tittelboom and De Belie [25].

There has also been significant work, over the past two decades, on the development of material models for self-healing materials. Some of these models have been developed in relation to specific materials; for example, Miao and coworkers [26] presented a model for rock salt, while Mergheim and Stein [27] considered the behaviour of self-healing polymers. In addition, a number of generic self-healing models have been developed which are applicable to a range of materials [28–30]. The behaviour simulated by these models results from the healing of any microcracks (or macro-cracks) and microvoids present, a process which has been considered to be the opposite of damage, with healing sometimes being described as 'negative damage' [26,28,29]. This approach is often termed continuum damage healing mechanics (CDHM), a term originally coined by Barbero et al. [28]. Furthering this concept, Voyiadjis and coworkers [30] developed a combined plasticity and CDHM model, including kinematic and isotropic hardening functions for plasticity, damage, and healing. Mergheim and Steinmann [27] developed a phenomenological model for self-healing polymers based on the assumption that healing is identical to negative damage. Their model is capable of simulating damage and healing processes simultaneously, and accounting for healing at non-zero strain.

A simple one-dimensional form of a healing model was presented by Schimmel and Remmers [29]. Their model is described in relation to discrete damage models however it can also be conveniently applied to the healing of continuum damage. The model allows a proportion of any damage present to be recovered due to healing at one time only; the progress of healing at this time is governed by a healing function, the form of which is chosen depending on the precise healing agent or process under consideration.

1.1.2. Modelling of creep and shrinkage in concrete

According to Bažant [31] there are two main model types for predicting the creep and shrinkage behaviour of concrete. There are true constitutive equations that simulate the real creep and shrinkage mechanisms and there are phenomenological models that approximate the mean behaviour of larger concrete elements.

The design models that appear in concrete codes of practice are generally of the latter type, of which examples include the ACI-209R-82 model [32], the B3 [33] and B4 [34] models, the CEB-FIP 1990 [35] models, GL2000 model [36], and Eurocode 2 [37]. Goel et al. [38] presented a comparative study of five of these creep and shrinkage models in which they summarised the merits, and shortcomings of the models reviewed.

Bažant and coworkers [39,40] developed a method for predicting concrete creep taking into account long-term aging and drying which has been termed solidification theory. A simplified version of a recently presented model [41], that uses some aspects of this solidification theory, has been developed for the present work. In this model, creep strains are predicted by a rheological model comprising multiple Maxwell elements in parallel. Creep strain predictions from Eurocode 2 [37] are also used to assess the accuracy of the computational creep model.

2. LatConX system model

The nonlinear numerical model developed to simulate the long-term behaviour of the LCX material system is illustrated in Fig. 1. The model is composed of a number of elements; the exact configuration of which depends on the details of the LCX structure being considered. There are three different element types; continuum beam elements, fracture process zone (FPZ) elements and SMP bar elements. In all cases presented in this article, the model consists of two continuum beam elements either side of a central FPZ element, with the SMP element being incorporated as required. In this configuration, the model is applicable to situations in which either there is distributed time-dependent cracking along the beam, and/or there is a localised (dominant) crack at the centre of the beam. The latter, in particular, occurs in experimental beams that contain a central notch. The model in this form is considered adequate for all of the beam configurations considered in this paper; however, if required, the model could be applied with multiple FPZ elements and used to simulate a range of concrete beams types.

The model setup considered for all applications presented in this article is shown in Fig. 1. This is a simply supported beam of length L, with a significant central notch, subjected to a centrally applied point load, P. The overall model comprises two continuum beam elements, each of length L_e, and a central FPZ of length w_c. The element that represents the PET tendon and the reinforcement layer are also shown in Fig. 1.

The fracture process zone width represents the physical zone over which micro-cracking occurs adjacent to a macro-crack and is normally assumed to be approximately three to five times the size of the coarse aggregate particles [42]. However, since the post-peak stress–strain relationship used in the FPZ element is

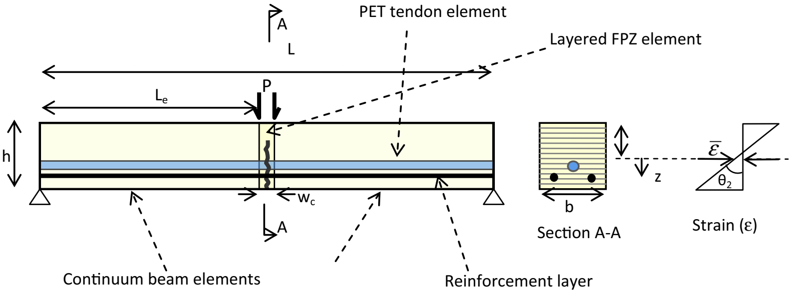

Fig. 1. Schematic diagram of numerical model.