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Modeling of smart concrete beams with shape memory alloy actuators

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A B S T R A C T

In the present work, a computational strategy for the modeling of reinforced concrete beams with SMA actuators for cracks repair is developed. In particular, for the concrete, an original transition damage–fracture technique is proposed in order to simulate the microcrack arising, their coalescence and, finally, the macrocrack development. Microcracks are modeled adopting a nonlocal damage and plasticity approach, which is able to consider the tensile and compressive damaging, accumulation of irreversible strains and the unilateral phenomenon. Macrocracks are modeled using a cohesive zone interface which accounts for the mode I, mode II and mixed mode of damage, the unilateral contact and the friction effects. The interface models the transition from the continuum damage (simulating the presence of microcracks) to fracture. A uniaxial SMA model able to reproduce both the pseudo-elastic behavior and the shape memory effect is adopted for the reinforcing SMA bars.

Finite element simulations are developed in order to reproduce the behavior of smart concrete beams subjected to three-point bending experimental tests available in literature (Kuang and Ou, 2008, Daghia et al., 2011). The construction phases of the beam are simulated and the loading history, consisting in three-point bending tests, are reproduced; in particular, the repairing phase due to pseudo-elastic behavior and shape memory effect is reproduced. Numerical results are compared with experimental data to validate the computational strategy.

1. Introduction

Smart materials technology has become an area of increasing interest in recent years also in civil engineering. Smart materials are multifunctional materials thought to execute other functions in addition to the structural one. Usually the main features required to smart materials are: sensing or self-sensing, actuating, self-healing [1]. In civil engineering, smart material applications concern especially smart concrete, obtained adding special materials or devices to the traditional concrete. A class of materials with very special features that can be used to obtain smart concrete is constituted by the Shape Memory Alloys (SMA). Because of the austenite–martensite and martensite–austenite transformations governed by the temperature and the stress state, SMA can undergo large deformations, exhibiting the so-called pseudo-elastic behavior and the shape memory effect [2]. In particular, because of the pseudo-elastic effect SMA can be successfully used as alternative to conventional actuators such as hydraulic, pneumatic, and motor-based systems. In recent years, thanks to the researches on SMA and, in particular, to the development of Polycrystalline Ferrous Alloys [3], cheaper than the traditional NiTi alloys, the use of SMA bars, wires or fibers as reinforcement of traditional concrete has been increased providing the development of smart concrete elements. This kind of smart concrete can be used to control the mechanical features of prestressed structural elements [4], to obtain active confinement of columns [5,6], to control the dynamic features of a structure [7], to repair or to allow the self-repairing of concrete structural elements [8–10]. Particular attention is paid to the last kind of application, as the improvement of the durability of structural elements is an important issue in civil engineering.

While a certain number of experimental investigations of concrete beams reinforced with SMA bars have been developed, a lack of studies concerning the numerical simulation of these kind of smart structures can be remarked. This can be due to the complexity of the numerical simulations of the response of concrete beams with SMA bars, because of the several nonlinearities governing the overall behavior of the structure. In fact, concrete is a cohesive material subjected to damage and fracture, SMA presents a very special nonlinear response. The few works, available in literature, concerning the modeling of SMA concrete elements, adopt simplified approaches both for reproducing the SMA and the concrete response [11,12].

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Different models have been proposed in literature over the years to simulate the response of concrete and SMA materials which can be used to reproduce the mechanical behavior of this special composite structural system.

Concrete is a quasi-brittle material exhibiting a mechanical response characterized by damage with softening due to the development of microcracks and by the presence of irreversible strain in compression. The mechanical behavior of quasi-brittle materials has been largely investigated and different constitutive models have been proposed even in the framework of nonlocal approaches [13–18]. The nonlocal approach is used to avoid spurious mesh sensitivity, typical of the local approach when softening constitutive laws are considered.

To simulate the presence and development of cracks, interface models can be adopted; in fact, cracks are zones of very small thickness in which the material nonlinear effects are localized. In literature several interface models have been proposed because of the variety of mechanical and numerical issues and of the range of possible applications [19–24]. In particular, models mainly based on damage and/or plasticity theories have been proposed in order to reproduce the fracture phenomenon; the proposed models are able to consider the damage and plastic evolution and often even the unilateral effect.

Indeed, the concrete behavior should be modeled considering both damage and crack development; in fact, during a loading test, the initial formation and evolution of microcracks can be properly modeled by damage mechanics, while the coalescence of microcracks leads to a macrocrack, which is suitably simulated adopting the fracture mechanics approach. Some models combining damage and fracture have been proposed in the literature [25,26].

To reproduce the SMA behavior several mathematical models based on micromechanical or macromechanical approaches can be adopted [2]. Macromechanical models are useful for engineering applications because of the relative simplicity of implementation in computational procedures. In order to simulate the response of concrete element reinforced with SMA bars, a one-dimensional SMA model can be successfully adopted. Many one-dimensional SMA models have been proposed in literature, e.g. [27–31].

In the present work, a computational strategy for the modeling of reinforced concrete beams with SMA actuators for cracks repair is developed with the aim to model the experimental tests concerning smart concrete beams subjected to three-point bending loading presented in [9,10].

The main novelty of the paper is the development of an overall nonlinear model for the analysis of the considered structural complex system, taking into account the nonlinear behavior of all the constituents adopting accurate models for concrete, SMA and steel bars.

In particular, a new approach for the transition from damage to fracture is proposed to model the response of the concrete. It is based on the coupling of the concrete damage with the damage of a cohesive interface. In fact, continuum nonlocal damage and plasticity model is adopted to simulate the development of microcracks in the concrete beam. The model is able to consider the tensile and compressive damage, the accumulation of irreversible strains and the unilateral phenomenon. The development of the macrocracks in concrete, due to the coalescence of the microcracks, is modeled coupling the concrete damage model with a cohesive zone formulation which accounts for the mode I, mode II and mixed damage mode, the unilateral contact and the friction effects. In particular, the model considers the coupling between the continuum damage and the interface damage ensuring that the interface damage cannot evolve independently from the continuum damage [32,33].

For what concerns the SMA behavior, both the pseudo-elastic and the shape memory effects of SMA bars are reproduced using the model presented in [34].

A robust numerical procedure able to solve the highly nonlinear problem is implemented in the framework of the finite element code FEAP [35]. Finite element simulations are developed in order to reproduce the experimental behavior of smart concrete beams subjected to three-point bending loading [9,10].

The remainder of the paper is organized as follows. In Section 2, the models adopted for reproducing the concrete and SMA response are discussed; in Section 3, the experimental campaigns concerning reinforced concrete beams with SMA actuators [9,10] are described; Section 4 deals with the finite element modeling of experimental campaigns, numerical simulation results and comparisons with experimental data. Finally, Section 5 draws some conclusions of the present study.

2. Modeling of reinforced smart concrete elements

In this section, the modeling of reinforced smart concrete elements with SMA actuators for cracks repair is presented. The structural modeling herein proposed consists in considering:

- a nonlinear continuum damage model with transition to fracture for the concrete, which includes:
  - a nonlocal damage and plasticity model in order to simulate the microcrack development;
  - a cohesive interface model for the potentially concrete cracks, i.e. areas where the tensile damage tends to localize and the cracks to open. The propagation of the macrocracks is assumed to be influenced by the microcracks, i.e. by the damaging of the concrete;
- an uniaxial SMA model for the bars, which takes into account both the pseudo-elastic effect and the shape memory behavior;
- the Mises perfect-plasticity model for the reinforcing steel bars, which is not detailed in the following, as it is a classical model available in literature.

The constitutive laws characterizing the proposed models for the concrete and SMA bars are briefly described in the below subsections, reporting the fundamental equations governing the cohesive and SMA constitutive laws for making the paper self-contained.

2.1. Damage–fracture concrete model

2.1.1. Nonlocal damage and plasticity continuum model

The development of microcracks in the concrete body Ω is described adopting the cohesive damage–plastic continuum model recently proposed by Toti et al. [33]. The model is able to account for the tensile and compressive damage, the accumulation of irreversible strains and the unilateral phenomenon, i.e. the stiffness recovery and loss due to crack closure and reopening.

The stress–strain constitutive relationship assumes the form:

$$\boldsymbol{\sigma} = \bar{\boldsymbol{\sigma}}\left[\left(1 - D_t^{\Omega}\right)H(J_1^e) + \left(1 - D_c^{\Omega}\right)\left(1 - H(J_1^e)\right)\right] \tag{1}$$

where $\bar{\boldsymbol{\sigma}} = \mathbf{C}(\boldsymbol{\varepsilon} - \boldsymbol{\pi})$ is the effective stress tensor, with $\boldsymbol{\pi}$ the plastic strain and $\mathbf{C}$ the constitutive tensor; D_t^{Ω} and D_c^{Ω} are two damage variables which describe the stiffness degradation of the concrete in tension and compression, respectively; $J_1^e = tr(\mathbf{e})$ is the first invariant of the elastic strain $\mathbf{e}$; $H(x)$ denotes the Heaviside function, with $H(x) = 1$ if $x \geqslant 0$ and $H(x) = 0$ otherwise.