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MODELING OF SMART CONCRETE BEAMS WITH SHAPE MEMORY ALLOY ACTUATORS WCCM – ECCM – ECFD 2014 CONGRESS

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Abstract. In the present work, a computational strategy for the modeling of reinforced concrete beams with shape memory alloy (SMA) actuators for flexural cracks repair is developed. In particular, for the concrete, a nonlocal damage and plasticity model is adopted; the model is able to consider peculiar macroscopic behaviors which characterize the quasi-brittle materials, such as the tensile and compressive damaging, accumulation of irreversible strains and the unilateral phenomena. The development of the flexural cracks in concrete are modeled using the cohesive zone interface formulation, which accounts for the mode I, mode II and mixed mode of damage, the unilateral contact and the friction effects. The interface model considers even the coupling between the body damage and the interface damage ensuring that body damage and interface damage cannot evolve independently one from the other. A uniaxial SMA model able to reproduce both the pseudo-elastic behavior and the shape memory effect is adopted for the reinforcing SMA wires.
Finally, finite element simulations are developed in order to reproduce the experimental behavior of smart concrete beams subjected to three-point bending tests.

1 INTRODUCTION

In recent years smart materials technology has become an area of increasing interest also in civil engineering. Smart materials are multifunctional materials thought to execute other functions in addition to the structural one. In civil engineering, smart materials applications concern mainly smart concrete obtained adding special materials or devices to the traditional concrete. A particular type of smart concrete, widely studied and experimentally investigated, is the smart concrete obtained adding Shape Memory Alloy (SMA) bars. This kind of smart concrete can be used to allow the repairing or the self-repairing of concrete structural elements. Particular attention is paid to this kind of applications because they improve the durability of structural elements.

Concrete is a widely used structural material characterized by a low tensile strength. Reinforced concrete combines the good compressive response of the concrete with the tensile capacity of reinforcing steel bars. In this way the structural element is able to carry compression, bending and shearing forces. However, in these types of structural elements cracks are unavoidable. Diffuse and deep cracks are very dangerous for the durability and mechanical capacity of the element. In fact, because of the development of cracks, the steel reinforcing bars are subjected to the oxidation process which leads to reduce the steel net area. The damage and cracks repairing, the improvement of the mechanical proprieties and the water tightness regaining can ensure the safety and reliability of the structural system, which are essential for large scale structures when they are still in service.
Hence, the development of smart concrete technologies, assuring the repairing of the damage and cracks in real time, has become a very important research topic. Experimental campaigns [1,2,3] and theoretical and numerical researches have been rapidly performed in recent years. In particular, the special composite structural system, constituted by reinforced concrete with SMA wires embedded, exhibits a behavior highly nonlinear and, as consequence, complex to simulate.
In the present work, a new computational strategy for the modeling of reinforced concrete beams with SMA actuators for flexural cracks repair is proposed. In particular, the nonlocal damage and plasticity model proposed in [4] is adopted for the concrete; the model is able to consider the specific macroscopic behaviors which characterize the quasi-brittle materials, such as the tensile and compressive damaging, accumulation of irreversible strains and the unilateral phenomena. The development of the flexural cracks in concrete are modeled using the cohesive zone interface formulation, which accounts for the mode I, mode II and mixed mode of damage, the unilateral contact and the friction effects. The interface model also considers the coupling between the body damage and the interface damage ensuring that body damage and interface damage cannot evolve independently one from the other [4,5]. Both the pseudo-elastic behavior and the shape memory effect of SMA wires are reproduced using the model presented in [6].
Finite element simulations are developed in order to reproduce the experimental behavior of smart concrete beams subjected to three-point bending tests [1].

2 CASE OF STUDY

The experimental campaign carried out by Kuang et al. [1] concerning the study of the behavior of small scale smart concrete beams subjected to three-point bending test is considered.
The geometry of the tested beam is schematically reported in Figure 1. The beam has 100x100 mm^2 square cross section and a length of 400 mm. The upper reinforcement is characterized by two steel bars of 4 mm of diameter, the lower reinforcement by five SMA bars of 2 mm of diameter.
The reinforced beam is built in two phases:

- the beam is manufactured using mortar having the maximum size of the aggregates less than 6 mm, which is suitable for a small scale beam;
- steel blocks are attached on both the ends of the beam and the SMA wires are fixed in holes of the steel blocks.

The experimental three-point bending test is performed using a testing machine characterized by a distance between the supports of 350 mm.

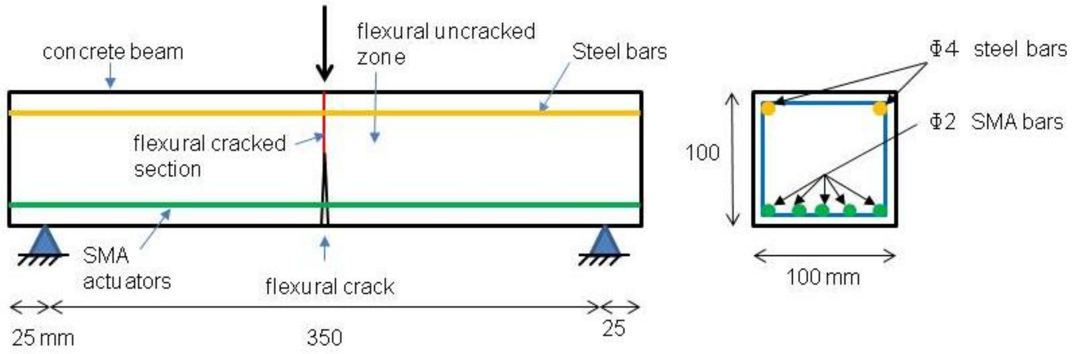

Figure 1: Schematic representation of reinforced concrete beam with SMA actuators.

The experimental test consists of two phases. In the first phase, the beam is loaded up to obtain the formation of cracks and the increasing of their width; in the second phase, the beam is unloaded, during the unloading the SMA elements are self-actuated thanks to the pseudo-elastic behavior. In this way, during this unloading phase the crack closure and the reduction of the residual beam deflection are observed.

3 MODELING

In this section the modeling of reinforced concrete beam with SMA actuators for flexural cracks repair is presented.

For the structural scheme investigated during the experimental campaign [1], the two-dimensional modeling reported in Figure 1, is considered. In particular, the structural modeling consists in considering:

- the damaging and plastic model for the concrete;
- the cohesive interface model for considering the potentially cracked concrete cross-sections, i.e. areas where the tensile damaging tends to localize and the flexural cracks to open. The propagation of the flexural cracks is assumed to be influenced by the damaging of the concrete;
- uniaxial SMA model for the wires, which takes into account both pseudo-elastic effect and the shape memory behavior;
- Mises plasticity model for the reinforcing steel bars.

Perfect adhesion hypothesis is assumed both between the concrete and the SMA wires interface and between the concrete and the steel bar interface.

The main aspects characterizing the adopted models are briefly described in the following.

The nonlinear behavior of the concrete is simulated considering the cohesive model recently proposed by Toti et al. [4]. The model is able to reproduce two important characteristic behaviors observed at the macroscale under cyclic loadings: degradation of the mechanical properties (damage) and accumulation of irreversible strains (plasticity). The model considers even the stiffness recovery and loss due to crack closing and reopening by introducing two scalar damage variables: a tensile and a compressive damage parameter. Moreover, it is assumed that the damage occurring in compression directly induces damage in tension; in other word the damage in tension results always not lower than the damage in compression. In particular, the evolution of the compressive damage depends on the nonlocal measure of the accumulation of the plastic strain, while the growth of the tensile damage is governed by the nonlocal value of the equivalent elastic strain or by the nonlocal measure of the accumulation of the plastic strain. The plastic flow is controlled by the effective stress through the introduction of a hyperbolic yield function, representing a branch of a modified hyperbola. The plastic-nonlocal model is able to capture the size effects and avoid spurious localization which gives rise to pathological mesh sensitivity in numerical computations. For the flexural crack concrete cross-sections, an interface model based on a cohesive zone formulation and on a coupling law, combining body and interface damage, is introduced [4,5]. In particular, the cohesive zone model is able to consider the unilateral contact behavior, interface damaging and friction phenomenon. The loss of cohesion at the interface is described by introducing a scalar damage variable, which is controlled by the relative interface displacement in reproducing the Mode I, Mode II and by the mixed mode. The coupling law is developed on the basis of a micromechanical idea introducing a Representative Elementary Area (REA) of interface. The SMA behavior is reproduced using the model proposed by Marfia et al. [6]. The model reproduces the pseudo-elastic behavior as well as the shape memory effect; in particular, the analysis is restricted to the case in which the temperature is greater than martensite start temperature. Thus, only austenite – single variant martensite and single variant martensite - austenite transformations are considered. In the formulation of the model the single variant martensite volume fraction is chosen as independent internal variable governing the phase transformations. The model takes into account the different behavior in tension and in compression of the SMA.

The described models are implemented in a research version of the finite element code FEAP [7]. The finite element discretization of the beam is reported in Figure 2. Because of the symmetry of the problem only half part of the beam is modeled by using suitable boundary conditions. In particular, four nodes quadrilateral elements are adopted to model the concrete, four nodes macrocrack interface elements are used to model potentially flexural cracked cross-section, SMA beam elements are joined in series with elasto-plastic spring elements in order to reproduce the behavior of the equivalent SMA bar, taking into account the limited stress level occurring in SMA elements because of the plastic effect in the alloy.

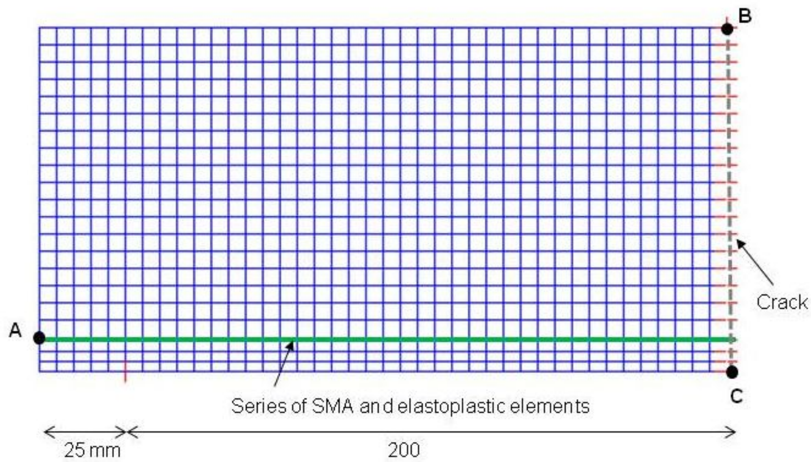

Figure 2: Mesh of the numerical simulation.

In Table 1, Table 2, Table 3 and Table 4 the mechanical proprieties assumed, for the concrete elements, for the interface elements, for beam SMA elements and for the elasto-plastic spring elements in series with SMA, are reported, respectively. The steel reinforcement in compression is not considered in the numerical simulations because the overall response of the reinforced beam is not strongly influenced by the presence of the steel bars in compression. All the four node nonlocal damage and plasticity quadrilateral elements used to model the concrete behavior are square elements of size 5 mm, except for the elements used to simulate the behavior of support concrete which are rectangular elements of 5×3 mm^2. The total length of SMA bar and elastoplastic spring elements is of 5 mm. The spring element is modeled by a short bar with the same area of the SMA bar. To define SMA elements new nodes are generated, which have the same coordinates of the nodes of concrete elements. In Table 5, the loading history adopted to simulate the building phase and the experimental test is illustrated. In particular the loading history phases are reported below.

- **Phase 0**: the prestrain of the SMA equivalent bar, at the room temperature, is reproduced (time step 0-1). This phase simulates the effect of the initial tension of the SMA wires which are introduced and locked in the holes of predisposed steel blocks positioned at both the ends of the beam. In fact, in time step 0-1 the SMA equivalent bar is prestrained imposing an axial displacement w_A of the node A of the SMA bar (see Figure 2). During phase 0, the SMA elements are independent from the concrete elements, only at the end of phase 0 the nodes of SMA elements are linked to nodes of concrete elements in order to simulate the adherence between the two materials. The nodes of SMA elements near the cracked section are not linked to the correspondent concrete ones in order to reproduce the not perfect adhesion between SMA bars and concrete.
- **Phase 1**: the flexural loading of the beam at room temperature is applied. In this phase (time step 3-4), the displacement v_B of the node B of the beam is gradually incremented.
- **Phase 2**: the unloading of the beam at environmental temperature is reproduced. In this phase (time step 4-5) the displacement v_B of the node B of the beam is gradually

reduced. During this phase the S → A phase transformation occurs in the material and SMA elements explicate the pseudo-elastic behavior.

Table 1: Mechanical proprieties of the concrete.

$E\ [N/mm^2]$	ν	$\sigma_Y\ [N/mm^2]$	k_u	$R_c\ [mm]$	ε_0	$R_t\ [mm]$
25000	0.2	54.3	0.007	25	8e-05	25

Table 2: Mechanical proprieties of the interface (crack).

$\tau_T^0\ [N/mm^2]$	$G_{cN}\ [N/mm]$	$K_N\ [N/mm^3]$	$\tau_T^0\ [N/mm^2]$	$G_{cT}\ [N/mm]$	$K_T\ [N/mm^3]$	μ
2	0.09	20000	2	0.09	20000	0.5

Table 3: Mechanical proprieties of the SMA elements.

$E_A\ [N/mm^2]$	50000	$\sigma_s^{AS,+}\ [N/mm^2]$	119.5
$E_S\ [N/mm^2]$	50000	$\sigma_f^{AS,+}\ [N/mm^2]$	139.5
ξ_L^t	0.05	$\sigma_s^{AS,-}\ [N/mm^2]$	119.5
ξ_L^c	0.05	$\sigma_f^{AS,-}\ [N/mm^2]$	139.5
$M_s\ [°C]$	-56.1	$C^{AS,+}\ [MPa/°C]$	5
$M_f\ [°C]$	-84.6	$C^{SA,+}\ [MPa/°C]$	6
$A_s\ [°C]$	-15.5	$C^{AS,-}\ [MPa/°C]$	5
$A_f\ [°C]$	12.1	$C^{SA,-}\ [MPa/°C]$	6

Table 4: Mechanical proprieties of the elasto-plastic elements (spring).

$E\ [N/mm^2]$	ν	$f_y\ [N/mm^2]$
50000	0.3	550

Table 5: Phases of the loading history.

	Time	Displacement $[mm]$		Temperature $[°C]$
		w_A	v_B	
Phase 0	**0**	0	-	20
	1	0.8	-	20
Phase 1	**2**	-	0	20
	3	-	0.8	20
Phase 2	**4**	-	0	20

4 RESULTS

Three numerical simulations are performed on the basis of different choices of the material model adopted for the concrete and the damage interface law. In particular, it is considered:

- a linear elastic model;
- a model with plastic nonlocal damaging behavior, adopting for the contact zone the uncoupled interface model (i.e the evolution of the interface and the body damage are not coupled);
- a model with plastic nonlocal damaging behavior, adopting for the contact zone the coupled interface model (i.e. the interface damage is influenced by the body damage).

In the graph of Figure 3, the results of the numerical simulations, plotted in terms of reaction of the node B versus vertical displacement v_C, are compared with experimental dates provided in [1].

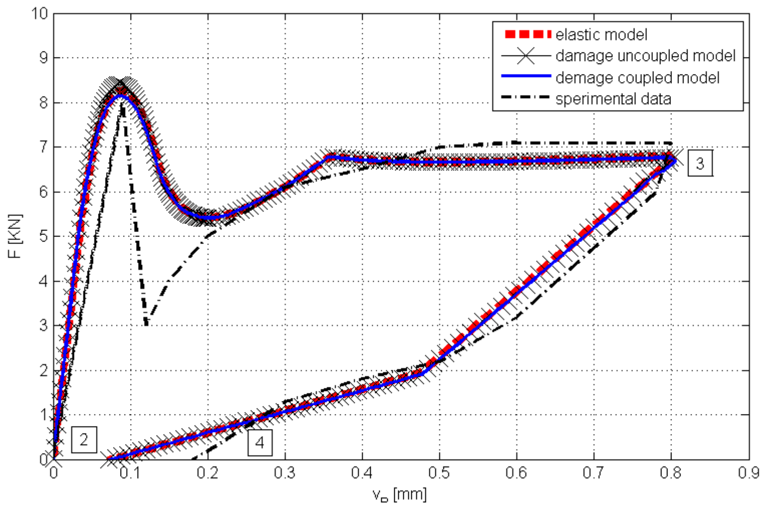

Figure 3: Experimental and numerical mid-span displacement versus load graph. (specimen L1 [1]).

It can be remarked that:

- the numerical analyses are stable;
- the numerical results obtained adopting the three considered modeling approaches (elastic, uncoupled, coupled) are very similar; this means that a reduced damage evolution occurs before the macrocrack development.

5 CONCLUSIONS

A computational strategy for the modeling of reinforced concrete beams with SMA actuators for flexural cracks repair has been developed in the present work. The strategy consists in modeling concrete using the nonlocal damage and plasticity model proposed in [4], flexural cracks in concrete using the interface model proposed in [4,5], SMA wires using the model presented in [6]. This computational strategy has been used for finite element simulations of the experimental behavior of a smart concrete beam subjected to three-point bending test.

Numerical results have been compared with experimental data carried out experimentally by Kuang et al. [1] to validate the model. The comparison shows the effectiveness of the proposed computational strategy to capture the experimental behavior of a smart concrete beam, both in the damaging phase and in the repairing one.
Finally, it can be emphasized that this computational strategy is an efficient tool for designing smart structural elements.

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