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Dissipative Homogenised Reinforced Concrete (DHRC) constitutive model dedicated to reinforced concrete plates under seismic loading

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ABSTRACT

A new stress resultant nonlinear dissipative constitutive model for reinforced concrete (RC) plates under cyclic solicitations is presented. This constitutive model, named DHRC for Dissipative Homogenised Reinforced Concrete, is expressed within the usual thin plate kinematics framework. It is built by a periodic homogenisation approach using the averaging method and it couples concrete damage and periodic debonding between steel rebar and surrounding concrete. The generality of the proposed method leads to a generic closed-form for the Helmholtz strain energy density function and the two dissipation pseudo-potentials that can be adapted to any material with an internal structure similar to the RC structural element one. A restricted number of geometric and material characteristics are needed from which the whole set of model parameters are identified through an automatic numeric procedure performed on a Representative Volume Elements (RVEs) of the RC plate. Finally, comparisons of finite element simulations with experimental results concerning the seismic behaviour of reinforced concrete wall made structures are proposed and discussed.

1. Introduction

1.1. Context

Many industrial facilities, in particular power generation plants, are composed with large and complex reinforced concrete (RC) buildings. Severe structural strength requirements (for instance under several external aggression such as seismic loading or severe wind) have often to be considered. Both conceptual design and periodic re-examination during life-duration require practitioners to perform best-estimate numerical analyses, accounting for the nonlinear behaviour of materials. However, only a few numbers of realistic nonlinear constitutive models dedicated to RC slabs and walls exist, ensuring rational computational costs, numerical efficiency and robustness for whole finite element analysis, in particular for cyclic and dynamic loadings. Stress resultant plate and shell models are frequently used in civil engineering due to their efficiency in modelling strategy. As far as the nonlinear cyclic behaviour of RC structural elements is considered, we are interested in the nonlinear stiffness reduction and the dissipated energy modelling, both items being key-factors in the dynamic response. They require a proper micromechanical approach, to justify the constitutive parameters chosen to describe the structural response.

The present paper is a direct continuation of the previous work by Combescure et al. (2013), where one could find a detailed overview of the state of the art, and in particular, the overall framework used to formulate a homogenised resultant nonlinear constitutive model for RC members, based on the averaging method applied to plates, see for instance (Caillerie and Nedelec, 1984; Ciarlet, 1979) and the main assumptions done to formulate the overall potentials of the constitutive model, based on the Generalised Standard Materials theory (Halphen and Nguyen, 1975; Sanchez-Palencia et al., 1987; Suquet, 1993). That first paper proposed a one dimensional closed-form model for RC members under cyclic solicitations, used to assess the ability of the homogenisation theoretical framework and the chosen assumptions to produce a nonlinear constitutive model addressing in a suitable manner the initial engineering needs. Then, we presented a one-dimensional stress resultant nonlinear constitutive model for members under cyclic solicitations. That formulation is hereafter extended to the so-called DHRC (Dissipative Homogenised Reinforced Concrete) stress resultant RC plate model, which includes membrane-bending coupling, needed by general modelling situations.

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1.2. Selected phenomena to model overview

The following section gathers the selected phenomena to model.

We assume an isothermal linear elastic, isotropic initial state of each material in the RVE. The assumptions related to local microscopic constitutive relations are gathered hereafter. First, steel reinforcement is assumed to be linear elastic.

In the following, we do not represent strain rate effect on the RC properties (e.g. concrete and steel strengths) even if this effect becomes relevant from strain rates about $10^{-2}\ s^{-1}$ (Asprone et al., 2012). Indeed, neglecting this effect can be seen as conservative and this study focuses on stiffness reduction and dissipative processes affecting the structural behaviour or RC elements and available safety margins in order to reproduce the experimentally observed highly pinched hysteresis load–displacement curves for low span RC shear walls under seismic loading, or for alternate axial loading on RC members (cf Fig. 1-1).

Microscopic crack distribution in concrete is modelled by means of damage mechanics, without defining a separate damage variable for concrete in tension and compression, according to the Continuum damage mechanics (Kachanov, 1958). For the sake of simplicity, we assume a scalar measure of damage since we can nevertheless represent anisotropic effects on stiffness by means of appropriate Helmholtz free energy and dissipation potential. As described by Feenstra and De Borst (1996), micro and macro-cracking phenomena in the concrete phase are considered separately: first the onset and development of a homogeneous diffuse micro-cracking resulting in concrete stiffness reduction (or damage), second the apparition of macro-cracks leading to displacement discontinuities on specific surfaces, ensuring a partial stress transfer (aggregate interlock, bridging and expanding effects), (Li et al., 1989). We decided not to account for the latter explicitly, but will represent it by an inhomogeneous distribution of damage within the RVE.

We do not represent the plastic strain in concrete, contrary to more sophisticated models, for instance (Krätzig and Pölling, 2004), considering, for now, that this phenomenon is of minor importance for the desired applications. Similarly, shear force transfer across concrete macro-cracks by aggregate interlock and so-called "bridging effect" is neglected. Indeed, according to Feenstra and De Borst (1996), the effect of aggregate interlock decreases with increasing crack width. Moreover, we neglect the dowel action effect (in shear mode), see Pimentel et al. (2010). The failure of the concrete domain within the RVE arises when diagonal cracks separating diagonal tensile zones (orthogonal to concrete ties – or struts – in compression) have opened enough to cancel the aggregate interlock.

In order to involve both independent processes that are irreversible strains stemming from bond-slip mechanism and concrete damage, we decided to use two dissipation potential functions. This process is inspired from the work of Einav et al. (2007) for plastic strain and damage coupling constitutive models with decoupled dissipation using two "yield surfaces". This may be justified from the experimental observation that damage can happen without equivalent plastic strain associated to bond-slip mechanism.

Bond-slip mechanism is recognised as a major effect controlling the response of reinforced concrete structures under cyclic loading, including damage evolution of concrete, for both plain or ribbed bars (Fernandes et al., 2013; Melo et al., 2011; Murcia-Delso et al., 2011). This mechanism is responsible for the "tension stiffening effect", i.e. the stress transfer from steel rebar to concrete domain located between two cracks, resulting in a contribution of cracked concrete to the RC panel overall stiffness. Bond-slip mechanism can be idealised as a specific interface mechanism at steel–concrete boundary, though it involves localised micro cracking and crushing of concrete. Moreover, this mechanism is able to produce irreversible strains and displacements in the RC panel, associated to larger hysteretic energy dissipation than the contribution from the concrete damage alone. In practice a simple stepped rigid-perfectly plastic bond stress-slip relationship for ordinary plain or ribbed rebar seems to be sufficient to catch the main features of this mechanism (Marti et al., 1998; Pimentel et al., 2010). Indeed, according to the analysis for instance quoted by Anyfantis (2014), for the range of usual steel–concrete relationship modulus $E_{sc} \approx 50000\ \text{MPa/m}$, usual cohesive strength $\tau_b \approx 10\ \text{MPa}$, and usual Griffith's fracture toughness $G_{fb} \approx 100\ \text{kJ/m}$ (Eligehausen et al., 1983), we are funded to assume a ductile failure rather than a brittle one for debonding, because the cohesive length scale – which is a parameter aiming at distinguishing the contribution of physical phenomena between fracture mechanics and strength criterion (Bazant and Oh, 1983) – here defined by $l_c = E_{sc} \frac{G_{fb}}{\tau_b^2} \approx 50\ \text{m}$ is much larger than the RC

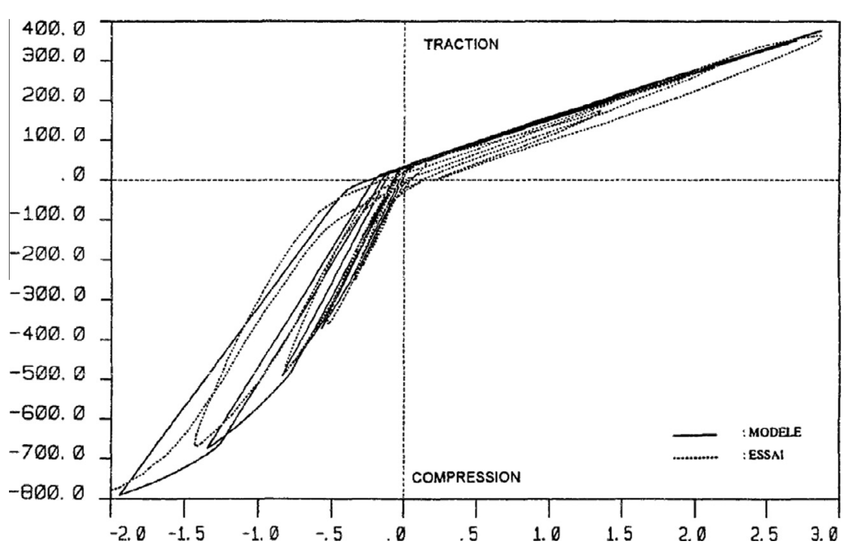

Fig. 1-1. Experimental results of a RC column under alternated tension–compression loadings (from Benmansour, 1997): axial stress resultant (in kN) versus axial strain.