Computers and Structures 152 (2015) 215–227

Contents lists available at ScienceDirect

Computers and Structures

journal homepage: www.elsevier.com/locate/compstruc

Nonlocal damage propagation in the dynamics of masonry elements

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ARTICLE INFO

Article history:
Received 24 February 2014
Accepted 10 January 2015
Available online 14 March 2015

Keywords:
Dynamic analysis
Masonry
Nonlocal damage
Finite element method

ABSTRACT

In this work, a nonlocal damage-plasticity model for dynamic finite element analyses of cohesive structural elements is presented. The proposed cohesive model is able to reproduce the main relevant behaviors of quasi-brittle materials despite being quite simple, i.e. governed by only a few parameters which can be determined by standard laboratory tests. In particular, the model is able to reproduce the mechanisms of cohesive materials under static or dynamic loads: degradation of the mechanical properties (damage) and accumulation of irreversible strains (plasticity). Moreover, the model also simulates the cyclic macroscopic behavior of quasi-brittle materials, taking into account the loss and recovery of stiffness due to crack closure and reopening. The latter effect represents a particularly important characteristic in the case of dynamic loads. The proposed formulation is implemented as a constitutive model for two-dimensional plane stress four-node quadrilateral elements. The second order equations of motion are solved adopting the implicit Newmark time integration scheme. The proposed model is validated and its dynamic performance is numerically demonstrated through the analysis of a large-scale structural element.

1. Introduction

Earthquakes represent one of the major threats to the world's architectural heritage, which consists mostly of structures made of cohesive materials, such as concrete or masonry. Thus, the inelastic dynamic analysis has become an important task for evaluating the safety of existing structures subject to seismic actions. One of the most crucial point in the modeling process is the adoption of appropriate material constitutive laws. Many mathematical models and computational tools have been proposed to date for nonlinear analysis of structures made of cohesive material. Common models able to satisfactory reproduce the cyclic behavior, which is a quite complex phenomenon of cohesive materials, are based on damage mechanics, plasticity theory or a combination of both.

The failure of cohesive material is modeled by constitutive laws characterized by strain softening; indeed, numerical approaches based on standard local constitutive models are widely deemed inappropriate for studying this class of materials. Applications of these models in finite element programs to perform structural analyses run into severe difficulties. In fact, in a finite element approach, the strain may localize into narrow bands whose width depends on the finite element size and tends to zero when the mesh is refined; consequently, the bulk energy dissipated in the process zone tends to zero. Therefore, the numerical solution becomes ineffective as strongly depending on the choice of mesh made by the analyst. A general and effective way to avoid strain localization into a zero volume and to overcome spurious mesh sensitivity is the use of regularized models based on nonlocal continuum approaches [1–4].

The presence of damage or of other inelastic phenomena modifies the overall structural dynamic response, and the damage propagation potentially interacts dynamically with the element vibrations; in other words, the degradation of the mechanical properties of a system are associated with changes in its structural behavior. Based on these considerations, research efforts have sought to use variations in the dynamic behavior to detect structural damage. Particular attention has been focused on the use of frequencies only, on account of the ease of measuring them and, therefore, their experimental reliability. Within this framework, dynamic analyses of damaged structures have been performed in [5,6] with the aim of detecting damage and evaluating the condition of the structure.

The study of the evolution of damage under dynamic loading has been approached in [7], where a local one-dimensional

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http://dx.doi.org/10.1016/j.compstruc.2015.01.011
0045-7949/

constitutive law implemented into a fiber model is proposed for a beam finite element.

In the field of nonlocal constitutive laws, an integral nonlocal damage model is presented in [8], where an explicit time step algorithm is implemented in a parallel finite element code. A gradient nonlocal model for nonlinear dynamic analysis of heterogeneous media is presented in [9], where the coupling between rate-dependent plasticity and rate-independent damage is considered. A nonlinear elasticity approach has been adopted for investigating the transverse vibration of bilayer graphene sheets [10]. Numerical simulations developed adopting both local and nonlocal constitutive laws of high velocity impact problem of a rigid projectile within softening material are presented in [11]; it is shown that the nonlocal model allows to alleviate numerical instabilities, spurious post-bifurcation and mesh dependency solutions.

A further aspect of the dynamics of structures in which evolving damage occurs is the opening and closure of microcracks, which define the damage state. Indeed, when the material is subjected to compressive strain, the microcracks reclose, inducing a stiffening recovery of the damaged material. The unilateral behavior of damaged materials has been studied mainly in the framework of quasi-static cyclic analyses, as for instance in [12–14]. It can be remarked that the unilateral phenomenon can induce peculiar features in the dynamics of damaged elements [5].

It can be remarked that, while there is a great interest in the response of damaging and damaged structures subjected to seismic actions, there is a quite reduced research activity concerning the dynamic structural response in the framework of nonlocal formulations for damage evolution, allowing softening effect. The main purpose of this paper is to give a contribution in this direction, developing a suitable numerical procedure to study the mechanical behavior of structures made of cohesive materials.

On the base of the above considerations, this work explores the dynamic response of two-dimensional cohesive structural elements taking into account the damage evolution, the presence of inelastic strains, and the unilateral effect due to crack closure within a nonlocal constitutive law. To this end, a nonlocal model [15] is formulated in a dynamic framework for investigating the damaging evolution of vibrating structures. Specifically, a slightly modified version of the model is presented and the validation of the formulated methodology in reproducing the degradation of structures under dynamic cyclic loadings is provided. Moreover, the present work presents a set of applications with the aim to validate the model for the dynamic analyses, by emphasizing the importance of the adoption of a nonlocal constitutive law, able to satisfactorily simulate the hysteretic behavior of a cohesive material. Therefore, the presented model reproduces the typical behavior of quasi-brittle materials, while remaining quite simple; indeed, the model is governed by only a few parameters which can be determined by standard laboratory tests. In particular, through the introduction of only five parameters, the model is able to reproduce the main features characterizing the macroscopic response of the quasi-brittle material under static or dynamic loads: degradation of the mechanical properties in tension and in compression, different strengths and softening responses in tension and in compression, evolution of irreversible strains, and unilateral phenomena due to microcrack reclosure and nonlocal stress-strain relationships. The proposed formulation is implemented as a constitutive model for two-dimensional, four-node quadrilateral elements in a research version of the finite element code FEAP [16,17]. The second-order equations of motion are solved adopting the implicit Newmark time integration scheme.

The dynamic performance of the proposed model is assessed through the numerical analysis of a large-scale structural element. Specifically, a vertical structural member belonging to the Basilica of S. Maria di Collemaggio, an important medieval church located in L'Aquila town and heavily damaged during the 2009 earthquake, is considered as a case study. The damage propagation induced in the examined mechanical system by two types of imposed base motion, i.e. by a simple harmonic motion and by the motion produced during 2009 L'Aquila earthquake, is investigated. The variations in the dynamic behavior (i.e. displacement amplitudes, frequency contents, hysteretic dissipation energy) due to harmonic motions are analyzed for the structural member with respect to undamaged condition. The performance of the cohesive model in reproducing the degradation state observed after 2009 L'Aquila earthquake are tested. Furthermore, some advantages provided by the nonlocal approach, compared to the local formulation, are verified for both applied loading functions.

The paper is organized as follows. First, the governing equations of the cohesive model are provided. Then, the numerical procedure is briefly presented and the results of some numerical applications are illustrated. Finally, concluding remarks are made.

2. Cohesive constitutive model

2.1. Constitutive law

The following isotropic damage model is introduced:

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

where $\boldsymbol{\sigma}$ and $\bar{\boldsymbol{\sigma}}$ are the stress tensor and effective stress tensor, respectively; D_t and D_c are two damage variables which capture the stiffness degradations of the concrete in tension and compression; $J_1^e = tr(\mathbf{e})$ is the first invariant of the elastic strain; $H(x)$ denotes the Heaviside function (i.e. $H(x) = 1$ if $x \geqslant 0$, otherwise $H(x) = 0$). In formula (1), as the damage variables affect the whole effective stress $\bar{\boldsymbol{\sigma}}$, an isotropic damage state is implicitly considered.

The effective stress tensor is computed as:

$$\bar{\boldsymbol{\sigma}} = \mathbf{C} : (\boldsymbol{\varepsilon} - \boldsymbol{\pi}) = \mathbf{C} : \mathbf{e} \tag{2}$$

where $\boldsymbol{\varepsilon}, \boldsymbol{\pi}$ and $\mathbf{e}$ are the total strain, the plastic strain and the elastic strain, respectively; $\mathbf{C}$ is the fourth-order elastic stiffness tensor; the colon symbol indicates the double contraction.

It can be remarked that the constitutive law defined by Eqs. (1) and (2) leads to discontinuities in the stress-strain relationship. Indeed, considering an isotropic cohesive material subjected to a shear strain γ_{12} accompanied with $\varepsilon_{11} = \varepsilon_{22} = \alpha$, the shear stress is $\tau_{12} = G\gamma_{12}[(1 - D_t)H(\alpha) + (1 - D_c)(1 - H(\alpha))]$, with G the shear modulus. Setting $D_t > D_c$ and taking γ_{12} as a constant, τ_{12} suddenly modifies when the value of α changes from negative to positive. It can be considered realistic to have a stiffer shear response when the material point is subjected to volumetric contraction ($\alpha < 0$) with respect to the case of volumetric expansion ($\alpha > 0$), because of the positive effect of the friction in compression. However, this strong discontinuity of the response in the material point is undesirable from both a physical and a mathematical point of view. For this reason, in order to avoid the strong discontinuity in the stress value, a regularized form of the Heaviside function is adopted in the present model; in particular, it is posed:

$$H(x) = \frac{1}{1 + e^{-x/h}} \tag{3}$$

where h is a small parameter governing the regularization effect (h = 0.001–0.0005).

The introduction of the regularization function (3) in the constitutive law (1) does not completely overcome the deficiency of the model but improves and confines the sudden jumps, which occur for infrequent cyclic strain paths.