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Some remarks on the retrofitting of masonry structures with composite materials

M. Angelillo [a], E. Babilio [b], L. Cardamone [c], A. Fortunato [a,*], M. Lippiello [b]

[a] Department of Civil Engineering, University of Salerno, Via Ponte Don Melillo, 84084 Fisciano, SA, Italy
[b] Department of Structures for Engineering and Architecture, University of Naples "Federico II", Via Forno Vecchio 36, 80134 Napoli, Italy
[c] Progetti Europa & Global, Piazza Stia 8, 00138 Roma, Italy

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ABSTRACT

This paper presents some numerical simulations, aimed to the assessment of the structural performance of masonry walls, reinforced with FRP composite materials. The problem is modeled in two dimensions, and the effects of seismic loads and of foundation settlements are studied numerically. The tool we use to perform the numerical analysis, is a new minimization software developed by the authors to analyze masonry constructions, modeled as unilateral structures. The material model we adopt, no-tension with elastic–plastic (associated) behavior in compression, is path-dependent and rate-independent. The trajectory of the system, under a given loading history, is approximated as a sequence of minimizers of a path dependent form of energy, updated at each stage of the step-by-step, time-discretized procedure. The results we obtain confirm that the application of fiber reinforced composites must be done carefully, since the increase of strength in some structural elements, due to the retrofitting, may prevent the structure from developing its natural, stress relieving, kinematics.

1. Introduction

In this paper we present some numerical simulations that allow us to evaluate the effect of the application of composite material reinforcements on the structural performance of masonry walls, subjected to seismic loads and foundation settlements. A similar issue is also considered in the recent paper by Paroni et al. [19]. The tool through which this numerical experiments are performed is a new software, developed by the authors in recent years (see [3,8]), for the analysis of masonry structures composed of unilateral materials such as the NENT (Normal Elastic No-Tension) and the ML (Masonry-Like) materials.

Indeed the most basic assumption that can be made (especially for old masonry), in view of the small and often aleatory value of the tensile strength of masonry materials, is that the material behaves unilaterally, that is, only compressive stresses can be transmitted (NT assumption). It is generally recognized that such an assumption is the first clue for the interpretation of fracture patterns (see Huerta [26] and references therein), that is the masonry most peculiar manifestation, representing the way in which the masonry buildings relieve and can survive also to radical and, sometimes, dramatic changes of the environment. Based on the unilateral model, the safety of the structure is a matter of geometry rather than of strength of materials, in keeping with the spirit of the "rules of proportion" used by the ancient architects for masonry design. The origins of the unilateral masonry-like model can be traced to the pioneering work of Heyman [25] but a more complete description of the load compatibility conditions and of the motion, due to the unilateral assumptions, is contained in the papers by Di Pasquale [21], Giaquinta and Giusti [23], Del Piero [20], Angelillo [2], Angelillo and Rosso [10], Lucchesi et al. [28]. A detailed account on boundary value problems for ML materials, both from the analytical and numerical point of view, and a comprehensive list of useful references on the NT model can be found in the recent papers by Fortunato [22], Angelillo et al. [8,7] and on the forthcoming book [11].

The NENT model describes a unilateral NT material that, with suitable hypotheses on the fracture strain, behaves as a non-linear hyperelastic material. An elastic energy density function, depending only on the total strain, exists such that the stress can be obtained as the derivative of this function with respect to the total strain. The material can be described in the non-smooth mechanics framework, since the strain energy φ is of class C^1, but the gradient of φ with respect to the total strain (that is the stress) is only continuous and its Hessian (the elastic tensor) is only piecewise

* Corresponding author. Tel.: +39 089964073.
E-mail addresses: mangelillo@unisa.it (M. Angelillo), enrico.babilio@unina.it (E. Babilio), cardamone.l@pegitaly.it (L. Cardamone), a.fortunato@unisa.it (A. Fortunato), maria.lippiello@unina.it (M. Lippiello).

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continuous. This is a feature common to Tension Field Theory (TFT) and wrinkling ([29,30,9]) for which the material is unilateral and the wrinkling field (as the fracture field for NENT materials) can be seen as a singular perturbation of the tension field solution (see [12,15]).

The main feature that distinguish the behavior of the NENT material from other non-smooth materials is its unilaterality: the NENT material is non-smooth in the neighborhood of the origin which often implies the absence of any linear elastic behavior even for very small strains and loads. The linear elastic behavior can be recovered only with the application of a sufficiently high external pressure (a small external pressure is not sufficient). The difficulties in dealing numerically with unilateral materials are well known, and there is no doubt that researches following the introduction of the NENT model, have not produced, so far, computational tools sufficiently reliable and simple to be used in commercial codes; this despite the extreme simplicity of the NENT model which appears as rather crude in the description of the real mechanical behavior of masonry. The description of these numerical difficulties, essentially due to the presence of non-trivial zero-energy modes, are first described in the paper by Alfano et al. [1] where a new, specifically tailored, return mapping algorithm is proposed.

The infinite compressive strength of NENT materials heavily restricts the capability of the model to describe the most elementary responses in many situations of common technical interest such as the progressive cracking and the final shear collapse of a wall subjected to constant vertical loads and increasing horizontal forces (shear behavior). The main feature that, in many cases of technical interest, the NENT model is not able to capture is perhaps one of the most significant: the capability to relax high stress levels, associated to the variation of boundary conditions, with a combined pattern of fractures and slips, that allows the structure to settle into a new equilibrium configuration. A proper strength criterion in compression must be added to the model. Since at the structural level, under compression and shear, masonry walls generally display a sensible (though limited) ductility, an elastoplastic criterion can be adopted. Here, and in paper [8], we consider a material model for masonry, called ML model, obtained by adding to the NENT restrictions a Drucker–Prager type yield criterion in compression and considering a flow rule for the corresponding inelastic strain rates of the associated type.

The main contribution given by authors in the paper [8] (with respect to other existing numerical models for ML materials, such as those proposed in [27]) consist in the development of an alternative numerical procedure providing a simple and efficient tool for dealing with NT materials. The numerical method we adopt uses a descent minimization algorithm (based on a code, developed by the authors for the minimization of complex energy forms in problems concerning folding [5] and fracture [4,6], which is insensitive to zero-energy modes) to solve the equilibrium problem at each loading step. The algorithm involves a direct and simple computation of the plastic strain increment.

The possibility for the structure of developing a controlled collapse mechanism often preserves the overall integrity of masonry. This is the way in which the structure accommodates, through rigid block displacements and a limited amount of crushing, non-uniform ground settlements. Therefore, as the examples presented in the body of the present paper show, composite reinforcements should be applied with caution to masonry structures. A check on the behavior of the structure under non-uniform ground consolidation is always necessary, since the retrofitting with composite reinforcements could have the negative effect of preventing the natural, stress relieving, rigid block kinematics, forcing the structure in such a way to induce extensive uniaxial material crushing, a failure mode that, compared to biaxial and combined crushing and sliding, appears as much less ductile. The type of reinforcement we consider is the gluing of FRP plates on the surface of the shear resistant members of the wall. A thorough description of this kind of technology for concrete and masonry applications can be found in the paper by Feo et al. [13,18], Grande et al. [24], and, in Italy, is the object of a specific Regulation [14].

As a final remark we may say that the philosophy behind correct masonry repair can be summarized as follows: “prevent large scale displacement and damage, limiting crushing rather than hairline cracking” and, by looking at some of the recent examples of old masonry retrofitting with the new FRP technologies, it appears that the aim of the designer is different, namely: “providing the masonry structural elements with the otherwise missing strength to tensile stress”.

We must say explicitly that wrong retrofitting is not the fault of FRP, and that FRP repairing, done in a proper way, has many advantages compared to traditional techniques (for instance, it is lightweight, easy to apply and to remove, shows no corrosion); but the point is that many applications of FRP to old masonry that we see lately (such as vault packaging with FRP plating, often coupled with the filling removal) tell a completely different story.

2. Initial and boundary value problem

2.1. Masonry-like material model

The model adopted to characterize the masonry material represents a natural extension of the NENT model introduced by Di Pasquale [21] and analyzed by Giaquinta and Giusti in [23] and by Del Piero in [20]. The formulation is restricted to small deformations and generalized plane stress. The small deformation assumption allows us to adopt the following additive decomposition of the symmetric part $\mathbf{e}$ of the displacement gradient (that can be considered as a proper strain measure)

$$\mathbf{e} = \frac{1}{2}(\nabla \mathbf{u} + \nabla \mathbf{u}^T) = \boldsymbol{\varepsilon}^e + \boldsymbol{\varepsilon}^p = \boldsymbol{\varepsilon} + \boldsymbol{\lambda} + \boldsymbol{\varepsilon}^p, \tag{1}$$

where $\boldsymbol{\varepsilon}^p$ is the plastic part of the strain and $\boldsymbol{\varepsilon}^e$ is the elastic one, which is decomposed into the fracture part $\boldsymbol{\lambda}$ and the part $\boldsymbol{\varepsilon}$ related to the stress tensor $\mathbf{T}$ through the linear isotropic elastic relation for generalized plane stress

$$\mathbf{T} = \mathbb{C}[\boldsymbol{\varepsilon}] = \frac{E}{1+\nu}\boldsymbol{\varepsilon} + \frac{\nu E}{1+\nu^2}\,\mathrm{tr}\;\boldsymbol{\varepsilon}\;\mathbf{I}. \tag{2}$$

Here E and ν represent the Young modulus and the Poisson ratio of the material.

By denoting $\mathbb{N}$ a compact convex subset of *Sym* (the space of symmetric tensors), containing the null tensor, we restrict the stress to belong to a feasible region $\mathbb{T}$:

$$\mathbf{T} \in \mathbb{T} \equiv \mathbb{N} \cap \mathbb{N}Sym, \tag{3}$$

$\mathbb{N}Sym$ being the cone of negative semidefinite symmetric tensors. The choice of the shape of $\mathbb{N}$ depends on the adoption of a specific crushing strength criterion based on the yield surface

$$\mathbb{J} = \partial\mathbb{N} \cap \mathbb{N}Sym. \tag{4}$$

It is assumed that the fracture strain tensor $\boldsymbol{\lambda}$ belongs to the cone $\mathbb{P}Sym$ of positive semidefinite symmetric tensors and does zero work for the corresponding stress $\mathbf{T}$

$$\boldsymbol{\lambda} \in \mathbb{P}Sym \Longleftrightarrow \mathrm{tr}\;\boldsymbol{\lambda} \geqslant 0 \text{ and } \det\boldsymbol{\lambda} \geqslant 0, \qquad \mathbf{T}\cdot\boldsymbol{\lambda} = 0. \tag{5}$$

For the plastic strain $\boldsymbol{\varepsilon}^p$ an associated flow rule is assumed. To any $\mathbf{T} \in \mathbb{T}$ the corresponding plastic strain rate obeys to the following rule

$$(\mathbf{T} - \mathbf{T}^*)\cdot\dot{\boldsymbol{\varepsilon}}^p \geqslant 0, \qquad \forall \mathbf{T}^* \in \mathbb{T}. \tag{6}$$