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A numerical model for the analysis of masonry walls in-plane loaded and strengthened with steel bars

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ABSTRACT

A novel macro-model for the analysis of masonry shear walls reinforced with steel bar grids is presented. The model is based on the so-called disturbed state concept (DSC), with a modified hierarchical single yield surface (HISS-CT) plasticity model accounting for a distinct behavior in tension and compression. The effect induced by the introduction of different reinforcement ratios is discussed, in terms of increase of both failure load and ductility. With reference to a quasi-square shear wall, an optimal reinforcement ratio is evaluated by means of the numerical model proposed and subsequently compared with recommendations provided by the Canadian masonry design standard. The comparison shows how minimum values proposed by Canadian standard are suboptimal and hence not totally suitable to obtain a proper increase of the seismic performance of shear walls in high seismicity region. A second example, relying into a shear panel with eccentric openings and subjected to horizontal loads, is analyzed in detail. It is assumed to strengthen the structure by means of a light and a heavy reinforcement, to deeply investigate the role played by steel bars in masonry seismic upgrading. A new explicit formula is finally presented, useful to provide a quick estimation of the load carrying capacity of reinforced masonry, to be eventually used in common design.

1. Introduction

Masonry is one of the oldest materials still used in modern building industry. Despite the great diffusion of masonry structures all over the world, essentially due to the practical simplicity and the flexibility to lay bricks one over the other, the numerical analysis of such kind of structures is at present a very challenging task.

As a matter of fact, the difficulties in masonry modeling depend on several concurring factors. Among the others, the most important are the following:

1) Masonry is a composite material obtained by the assemblage of units joined by thin mortar. The different mechanical properties of mortar and bricks result into a complex interaction, with non-negligible stress concentrations at the interfaces.
2) Typically, both mortar and bricks exhibit a marked softening behavior in tension. Tensile strength is usually one order of magnitude lower than compressive one. Due to the low tensile strength of mortar and the degradation of the mechanical properties after the peak, it is common practice to model masonry by means of a material incapable to withstand tensile stresses (no tension material NTM model [1]). NTM models, however, are unable to reproduce some typical properties shown by masonry near failure, as for instance the non-null shear resistance in the absence of vertical pre-compression (always zero in NTM models), the limited compressive strength (in NTM the compressive behavior is infinitely elastic) and the orthotropy both in the elastic and post-elastic range in tension [2,3].
3) Masonry compressive resistance lays, in agreement with both experimental evidences and codes of practice formulas (see for instance EC6 recommendations [4]), between brick and mortar strength and may be evaluated from constituent materials resistance by means of a well-established non-linear relationship. In addition, the post-elastic behavior in compression is typically brittle, with a small hardening range, where micro-cracks become to propagate, followed by softening. Crushing of both mortar and bricks is experienced in compression, with almost vertical macro-cracks on bricks surface. A complex 3D stress-state is therefore present in masonry pillars subjected to compressive loads, which is difficult to reproduce with simple numerical models, especially if bi-dimensional.
4) Orthotropy in tension of the masonry material has been demonstrated by some authors in the recent past, mainly from a numerical [3] point of view. Such a behavior is essentially

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connected to bricks staggering when masonry is built in running bond texture. Bricks misalignment is responsible for the uniform shear acting on the bed joint when a simple horizontal stretching is applied to a sufficiently large representative element of volume. In compression, orthotropy has very little effect for clay brick masonry, as shown by Page [5], since shear strength of the bed joint is usually one order of magnitude lower than constituent materials compressive strength. For these reasons, orthotropic behavior is important especially for out-of-plane loaded panels in two-way bending or for deep beams. In all other cases (e.g. shear walls, masonry with irregular texture, towers, multi-leaf masonry) it has been demonstrated to be less crucial. Hence smeared crack models, originally developed for concrete, may be adapted to reproduce macroscopically masonry behavior in both vertical tension and compression, even if they are intrinsically incapable to reproduce a different post-elastic behavior along material axes in tension.

At present, the most diffused numerical strategies to analyze masonry structures are micro-and macro-modeling. Both strategies are intrinsically conceived to be used in a finite element framework.

The so-called micro-modeling approach [6,7] relies in a distinct representation of bricks and mortar, usually modeled respectively by means of plate and shell elements and non-linear interfaces with zero thickness. Typically micro-modeling is well suited for small structures, namely when a detailed representation of crack patterns and the identification of stress concentration zones are needed in the post-processing phase.

While such approach is very suited for the analysis of laboratory specimens and small panels, it is computationally very expensive, especially in the non-linear range. For this reason, it is hardily applicable to large scale structures.

Macro-modeling [8] seems more powerful for the numerical analysis of large scale masonry structures. Essentially it relies in the substitution of the heterogeneous assemblage of blocks by means of a fictitious homogeneous material, which macroscopically should exhibit the same elastic and inelastic behavior of a small sample constituted by few bricks jointed by mortar.

As well known, masonry shows a different stress–strain behavior in tension and compression and along material axes, with marked softening, both in tension and compression.

Therefore, to be reliable, a macro-model should utilize a fictitious homogeneous material with softening and distinct inelastic properties (peak strength and fracture energy) for tension and compression.

Mechanical properties to be used should be derived either by means of experimental data on small specimens loaded in various ways or by means of homogenization procedures, i.e. solving a suitable boundary value problem in the inelastic range on a representative element of volume, which generates the whole structure by repetition.

While at present a number of different numerical models are available in the literature for the analysis of unreinforced masonry structures in the inelastic range (e.g. [3,6,8,9], etc.), the study of strengthened walls seems, at least from a numerical point of view, still at its initial stage. More specifically, while the scientific community focused recently on the experimental and numerical modeling of masonry strengthened with carbon fibers-FRP (e.g. [10,11,12,13], etc.), either through externally bonded strips or near surface mounted bars, little investigations have been conducted on the more traditional reinforcement with steel bars.

Steel bars strengthening is particularly suited either in seismic area to increase both the in-plane and the out-of-plane strength and ductility of masonry structural elements or to increase walls slenderness in non-seismic area.

From a practical point of view, a key issue to be investigated is the ratio percentage of vertical and horizontal bars to be used in different cases (e.g. shear walls, windowed panels, deep beams, out-of-plane loaded structural elements in simple and two-way bending), to guarantee an increase of both ductility and peak resistance.

Here it is worth noting that a few combined experimental and numerical studies in this field have been conducted in the recent past [14–17] to have a full insight into the problems connected with the reinforcement with steel bars and that national codes of practice design formulas (e.g. Canadian masonry design standard [18]), which are usually based on simplified analytical models that may be considered predictive only for simple cases. On the contrary, a comprehensive numerical model for the analysis of such kind of structures in the non-linear range seems still missing.

In this framework, in this paper, a novel simple numerical model for the analysis of masonry walls in-plane loaded reinforced with steel bars is presented. In the model masonry is substituted with a fictitious orthotropic material, within a macro-modeling strategy, whereas steel bars are modeled at a structural level by means of elasto-plastic truss elements.

When dealing with unreinforced masonry, a so-called modified disturbed state concept and hierarchical single surface model (hereafter called DSC/HISS-CT model, see Akhaveissy and Desai [19]) is utilized. In order to adapt the model to masonry actual behavior, different hierarchical single surfaces (HISS) are used to model the compressive and tensile (CT) behaviors of brickwork. The base model (HISS) was introduced a few decades ago by Desai et al. [20] and Desai and Salami [21], but is applied here for the first time to reinforced masonry.

DSC/HISS model is a unified and hierarchical model that can be used to characterize elastic, plastic and creep deformations, as well as micro-cracking that leads to fracture and failure, degradation or softening, and healing or strengthening. It has been used to model a wide range of materials, such as clays, sands, concrete, asphalt concrete, ceramic, metals, alloys and silicon, as well as interfaces and joints [22]. It has been implemented in nonlinear finite element procedures to solve a wide range of engineering problems, including two- and three-dimensional problems [22–24] and cyclic loading. DSC model has a number of advantages compared with other available models that often account for only specific behavioral aspect(s). The new feature utilized here is the use of distinct HISS yield functions in compression and tension and the application of external reinforcement by means of elasto-plastic truss elements.

After a brief description of the DSC/HISS-CT model proposed and the implementation of the reinforcement by means of 1D elements, two masonry shear walls are analyzed in detail. The first example is an unreinforced masonry shear wall experimentally tested by Vermeltfoort et al. [25] and already analyzed by many authors with micro- and macro-models (e.g. [3,19,26], etc.). The wall is here re-considered and reinforced with seven different sets of reinforcement, varying both vertical and horizontal reinforcement bars ratio, considering also the indications provided by the Canadian masonry design standard. From simulation results, it appears that the strengthening ratio influences considerably the percentage increase of both failure load and ductility of the wall. It is found (1) that an optimal reinforcement ratio exists, which allows to obtain a very good upgrading on the overall pushover curve of the structure and (2) that minimum values proposed by Canadian standard are suboptimal and hence not totally suitable to obtain a proper increase of the seismic performance of shear walls. A second example is finally discussed, consisting of a windowed panel subjected to horizontal loads. Two reinforcement