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FE homogenized limit analysis model for masonry strengthened by near surface bed joint FRP bars

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ABSTRACT

A homogenized limit analysis model for the prediction of collapse loads and failure mechanisms of masonry walls reinforced with near surface bed joint GFRP bars is presented. Reinforced masonry homogenized failure surfaces are obtained by means of a compatible identification procedure, where each brick is supposed interacting with its six neighbors by means of finite thickness mortar joints, filler epoxy resin and FRP rods.

In the framework of the kinematic theorem of limit analysis, a simple constrained minimization problem is obtained on the unit cell, suitable to estimate – with a very limited computational effort – reinforced masonry homogenized failure surfaces.

A FE strategy is adopted to solve the homogenization problem at a cell level, modeling joints, bricks, filler and FRP rods by means of eight-noded infinitely resistant parallelepiped elements. A possible jump of velocities is assumed at the interfaces between contiguous elements, where plastic dissipation occurs. For mortar and bricks interfaces, a frictional behavior with possible limited tensile and compressive strength is assumed, whereas for epoxy resin and FRP bars some formulas available in the literature are adopted in order to take into account in an approximate but effective way, the delamination of the bar from the epoxy and the failure of the filler at the interface with the joint.

In order to validate the model proposed, two meaningful examples are critically analyzed. The first relies on a reinforced masonry beam in four-point bending, whereas the second is a full scale wall constrained at three edges and loaded until failure with a distributed out-of-plane pressure. While the first example is useful to test the model at a cell level, since only horizontal ultimate bending moment is involved in the failure mechanism, the second provides a full assessment of the procedure proposed at a structural level. In both cases, very good agreement is found with literature data, meaning that the model proposed may provide useful information for all practitioners interested in the design of masonry walls reinforced with bed joint FRP bars.

1. Introduction

The recent devastating earthquake occurred in Abruzzo (Italy) in 2009 demonstrated that historical buildings – largely constituted by masonry structures – are scarcely resistant to horizontal loads and highly vulnerable to seismic actions [1]. Such inadequacy under earthquakes is rather common and is due to several concurring factors, among the others the most important being the low strength of mortar joints, which represent preferential planes of weakness where cracks propagate.

With the aim of increasing resistance or restoring the original strength of already damaged masonry elements, upgrading and rehabilitation interventions are required [2,3].

Conventional retrofitting techniques, such as external reinforcement with steel plates, surface concrete coating and welded mesh, are impractical, time expensive and add considerable mass to the structure (which may increase earthquake-induced inertia forces). In this context, the utilization of FRP as reinforcement instead of conventional methods seems the most suitable solution [4], for its limited invasiveness and good performance at failure.

In all the situations where the utilization of FRP strips is not possible, the so called FRP-repointing may represent an interesting alternative. Traditionally, repointing is a technology which consists in the application of short steel rods – anchored by cement injections – across cracks [5].

More recently, steel bars have been substituted by FRP materials, which exhibit several suitable properties for their utilization as structural reinforcement, such as high tensile strength, corrosion insensitivity, etc. [6–8].

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As well known from consolidated literature, in case of out-of-plane loaded brickwork panels reinforced with both FRP strips and pultruded laminates, it is expected that failure occurs for delamination near the supports, due to the reduced strength of the bond near the anchoring zone. In addition, external strips can not be externally applied on fair faced bricks, due to aesthetic reasons.

On the contrary, as shown by a number of experimental works available in the literature concerning brickwork strengthening with bed joints FRP bars (e.g. [9–14]), composite rebars demonstrate a good performance at failure, with a promising bond strength between bar and mortar joints, also offering rapid and aesthetic application suitable for masonry veneers and façades.

However, while several design procedures have been specifically established for the use of FRP bars in concrete reinforcement [15,16], the research about masonry strengthening with bed joint repointing is still under investigation.

In particular, no numerical models for the collapse analysis of entire masonry walls reinforced with bed joints bars are available in the literature. Heterogeneous approaches (i.e. separate modeling of joints, bricks and FRP bars, also known as micro-modeling) are hardily applicable in this case, because prohibitive full 3D analyses should be performed at a structural level. On the other hand, macro-modeling (i.e. substitution of the heterogeneous material with a fictitious homogeneous orthotropic one) needs a very difficult mechanical characterization of the interaction between constituent materials, which is somewhat complex in this case.

In this framework, homogenization (e.g. [17–21]) may represent an acceptable compromise between micro- and macro-modeling, since macroscopic masonry behavior is obtained solving suitable boundary values problems on the unit cell, thus taking into account constituent material mechanical properties and geometry only at the micro-scale. When dealing with the inelastic brickwork behavior, limit analysis is a valuable alternative to expensive non-linear FE simulations. Indeed, it has been widely used for the analysis at failure of masonry structures [22,23], because it requires only a reduced number of material parameters, providing limit multipliers of loads, failure mechanisms and, at least on critical sections, the stress distribution at collapse. Therefore, with the aim of reproducing masonry panels reinforced with bed joint FRP bars behavior when loaded out-of-plane, a kinematic limit analysis homogenization model is here adopted. A compatible kinematic approach similar to [19,21] is presented, where masonry skeleton is represented by a three-dimensional (3D) discrete system of blocks interacting through finite thickness mortar joints. A full description of the model can be given considering a representative volume constituted by a generic brick with its six neighbors. A sub-class of possible elementary deformation modes acting in the unit cell is a priori chosen in order to describe joints cracking under normal and tangential actions. Finally, power dissipated in the discrete model is equated to that dissipated in a continuum macroscopic 2D equivalent plate (identification). The assemblage of a central brick with its six neighbors, finite thickness joints and FRP bars is the so-called representative element of volume (REV or elementary cell), which is modeled in the framework of FE limit analysis by means of eight-noded rigid infinitely resistant brick elements with possible dissipation at the interface between adjoining elements. Since internal dissipation can take place only at the interface between eight-noded parallelepipeds, a simple constrained minimization problem in few variables is obtained. In this way, macroscopic FRP reinforced masonry failure surfaces are numerically evaluated as a function of the macroscopic moments (bending and torsion) and out-of-plane shear.

Homogenized masonry strength domains so obtained are then implemented in a upper bound FE limit analysis code for the analysis at collapse of entire FRP reinforced walls out-of-plane loaded. Rigid infinitely resistant three-noded plate elements are used to model masonry at structural level.

In order to test the capabilities of the numerical approach proposed, a meaningful comparison at a cell level with some experimental results on a masonry beam tested in horizontal bending [11] is presented. After the validation at a cell level, an entire wall supported at three edges, reinforced with bed joint FRP bars and loaded out-of-plane until failure (some experimental data are available from [24,25]) is finally analyzed. Results in terms of collapse load and failure mechanism are compared with literature data available. In both cases, accurate results are obtained, indicating that the simple approach proposed may be used by practitioners for design purposes and safety assessments, at a fraction of the computational effort required by standard FEM non-linear heterogeneous approaches.

2. FRP bars repointing: technology

FRP bars repointing technology consists in the insertion of continuous FRP rods in the horizontal joints of a wall previously grooved, reproducing the original bricks pattern. Colour of mortar and workmanship of the joints can be accurately reproduced.

The masonry texture has to present continuous horizontal joints, with either running courses or stack bond. Obviously, in the latter case, continuous embedded rods can be applied also vertically.

Before the application of the rods, constituent materials characterization tests are needed in order to determine the basic mechanical properties to use in limit analysis numerical simulations.

Except for special cases, functional collaboration between masonry and strengthening is based on the bond properties of the groove filler, which is the medium for the stress transfer between the FRP bar and masonry. FRP-filler interface most relevant mechanical properties are tensile and shear strength. Tensile strength is especially important when the embedded bars have a deformed surface, which produces high circumferential tensile stresses in the cover formed by the groove filler as a result of the bond action. In addition, the shear strength is important when the bond capacity of the reinforcement is controlled by cohesive shear failure of the groove filler.

Indeed, the paste has several important roles, including bonding, anchoring and stress transferring, but also workability, surface appearance and easiness of installation. Typically, this "epoxy mortar" is perfectly compatible with FRP materials and presents a very low ratio of void inclusions.

Preparation of the walls for strengthening is a procedure consisting in removing the outer part of the mortar joints to obtain grooves, whose depth has to be related to the rod diameter in order to optimize bond strength [15,16] and in the installation of the paste through guns, with the subsequent insertion of the rods.

Especially for rehabilitation application or post-damage repair, some injection or reconstitution of the substrate may be necessary. Also, a preliminary primer application can be considered when interface bonding needs to be improved. The FRP bars are usually deformed by a helical wrap with a sand coating to improve the bond between the bar and the embedding paste. The bars are produced using a variation of the pultrusion process using 100% vinylester resin and e-glass fibers (GFRP). Typical fiber content is 75% by weight. FRP structural repointing has the advantage of providing remarkable structural benefits maintaining the original appearance of the masonry wall and completely complying with durability and maintenance issues. Due to the lightness of the materials involved, site equipment and handling requirements are reduced and simplified.