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Numerical investigation of non-linear equivalent-frame models for regular masonry walls

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ABSTRACT

The accuracy of the Equivalent Frame Method (EFM) in modelling the seismic non-linear behaviour of unreinforced masonry (URM) buildings is investigated for regular walls (i.e. walls with regular openings’ distribution) with different pier-to-spandrel geometrical relations. The developed EFM is composed of pier and spandrel elements with spread plasticity to simulate the flexural behaviour and lumped plasticity to simulate the shear behaviour. The investigation focuses on checking, by means of comparison with Finite Element Model (FEM) assumed as reference, the applicability of EFM to existing buildings. These structures are often characterized by geometrical schemes difficult to be represented by ideal frames. To point out the role of the geometrical configuration, the numerical results provided by the two modelling approaches are compared for different representative cases of regular walls characterized by pier-spandrel configurations rather typical in existing URM buildings. In addition to the innovative EFM approach, based on a fiber discretized beam element, also a more traditional approach, based on beam elements with lumped plasticity, is included in the comparative study. The two different EFM approaches were implemented in the software *Midas GEN* © [44], while an open source software was used to implement the FEM (Kratos Multiphysics [59–60]). All the models were used to perform static non-linear analyses under equivalent loading and boundary conditions.

The evaluation of EFM and FEM is derived from a comparative simulation of a two-storey URM wall experimentally tested by other researchers. Two alternative approaches are assumed for the definition of piers’ effective heights in the EFM, i.e. the models proposed by Dolce [1] and Augenti [2]. The results demonstrate that remarkable differences may be detected in EFM and FEM predictions of the shear capacity and damage mechanisms as a function of pier-spandrel geometrical configurations. This result highlights the need for a cautious application of EFM to existing URM structures.

1. Introduction

The study of the structural behaviour of new buildings is usually based on the quantitative evaluation of stress and deformation fields by means of numerical models. This approach is not easily applicable to the heterogeneous portfolio of existing masonry buildings. The mechanical inhomogeneity of the material and the huge variety of materials and constructive techniques, in fact, make the study of unreinforced masonry (URM) structures very challenging. The problem is further complicated by the complexity of the possible walls’ geometrical configurations. In most cases, existing masonry buildings were non-engineered at the time of their construction and may have undergone many changes over time.

The classical approach to the structural modelling of masonry constructions focused on simplified models aimed at evaluating the safety conditions of singular structural elements, e.g. columns, arches, vaults, etc. [3]. Only at the end of the seventies, the attention moved to global models by extending to masonry structures the methods initially developed in different fields of structural engineering, such as the Discrete Element Method (DEM) [4,5] or the Finite Element Method (FEM) [6–8]. The difficulty in characterizing the mechanical parameters of the material and the high computational cost of detailed models prevented their application to ordinary buildings and therefore their wide diffusion. For this kind of structures, the research focused mainly the formulation of simplified modelling approaches derived from the study of more engineered structures, like reinforced concrete

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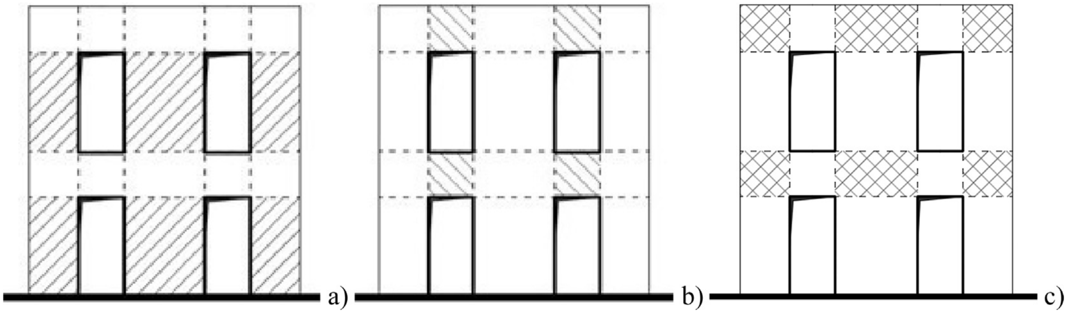

Fig. 1. Discretization of a masonry wall into macro-elements: piers (a), spandrels (b) and node panels (c).

(RC) and steel structures. The Equivalent Frame Method (EFM) [9–10] is one of the most known approaches derived from the analogy of the actual structure with a simple structural scheme, like a frame.

The widespread use of the EFM for non-linear analysis of URM structures stems from the large reduction of computational cost that it allows. As known, the EFM is based on the assumption that a masonry load-bearing wall can be modelled as a plane frame. The shear wall in-plane behaviour is then studied by discretizing it into discrete components (piers and spandrels) connected through rigid links (node panels), as shown in Fig. 1.

In this approach, a crucial role is played by the definition of the macro-elements geometry, particularly in the case of piers which represent the main resisting elements of the equivalent frame scheme. Two approaches are commonly used for the definition of the piers effective height. The first criterion, proposed by Dolce [1], allows the identification of the effective deformable length of piers by applying a simple geometrical rule accounting for both the equivalent stiffness of the pier and the deformability of the surrounding spandrels. By updating the criterion provided by FEMA 356 [11], Augenti [2] proposed an alternative criterion in which the effective height of piers is defined as the height of consecutive opening from the side of the earthquake loading. Recent studies [12,13] have investigated the influence of the mentioned criteria on the reliability of EFM results demonstrating their strong sensitivity to the geometry of the equivalent frame schemes.

Numerical tests and validation studies based on the comparison with experimental tests [14–17] have shown that the EFM can be successfully applied to the structural analysis of new URM buildings. At the same time, some uncertainties still hamper its application to the structural modelling of existing URM buildings. In this case, in fact, the simplified interpretation of the structural behaviour proposed by EFM is more uncertain. In particular, the application of EFM may be limited [18] by the presence of irregular geometries [19]. In case of regular walls, i.e. walls with openings aligned along both vertical and horizontal directions, the use of EFM may be critical in presence of pier-to-spandrel geometrical relations that do not comply with a classical frame configuration. Specifically, the EFM does not provide satisfactory results in the case of walls including squat piers or spandrels. In specific, Siano et al. [18] have demonstrated the limitations of EFM in modelling the response of façades with cross sections' inertia of spandrels 10 times greater than those of the piers.

Further uncertainties can also arise in the identification of structural details, loading history, occurred damage and eventual refurbishment interventions. The correct inclusion of these details in the equivalent frame scheme is still troublesome in case of existing constructions because of the morphological variations that usually affect these structures over their lifecycle [20–22].

An accurate and systematic validation of EFM is therefore necessary to define clear limits for its applicability to URM existing constructions. In line with this purpose, Siano et al. [18,23,24] presented a wide parametric investigation to study the limits and potential application of the EFM approach to regular and irregular 2D walls. The investigation involved a wide sample of URM walls characterized by different geometrical configurations and tested in the linear and non-linear ranges. The shear capacity and damage mechanisms predicted by equivalent-frame models (EFM) were compared with Finite Element Models (FEM), assumed as reference. The EFM and FEM results were also compared with experimental results available in the scientific literature [25].

Linear analyses both on regular and irregular façade configurations, reported in [18], showed the role of the geometrical configuration of the wall with respect to its ideal EFM representation. It was shown that differences between EFM and FEM results cannot be neglected in case of significantly irregular distribution of openings. The same is found for regular walls with pier-to-spandrel geometrical relations not compatible with a classical frame configuration, although representative of many old buildings. This fact leads to the distinction, measured by appropriate non-dimensional parameters, between *frame-like* walls - for which EFM can provide acceptable results - and *non-frame-like* walls.

However, given the strong non-linearity of masonry structures, the validation of a numerical approach cannot be limited to the linear field. In this paper, the results obtained in the linear analyses [18] are extended to the non-linear field. Namely, non-linear static analyses are used for the assessment of the seismic response of 2D walls representative of existing URM buildings, as they represent a widespread tool in the engineering practice [26,27]. The non-linear validation reported here focuses only on regular geometries, selected among those showing a problematic behaviour in the linear analyses described in [18].

2. Non-linear models for masonry walls

The main cause of non-linearity in the behaviour of masonry is its small or almost negligible tensile strength. This low tensile strength causes cracking of the resisting cross-sections and the reduction of the effective resisting area to the portions working in compression. The mechanical response becomes non-linear even under low stress levels.

Given the relative ease of application of linear elastic analysis, many studies initially derived failure models from the elastic study of masonry components [28] and applied those linear models to complex monumental constructions [29,30]. However, the linear elastic approach cannot be considered adequate to describe the structural behaviour of masonry constructions, especially when simulating their seismic response. The interest towards the seismic performance of masonry constructions has motivated the development of non-linear structural models during the last decades. In this context, the application to masonry structures of non-linear Finite Elements models [6–8] provided a wide range of solutions characterized by different modelling scales. The level of detail of FEM models ranges, in fact, from a macro-scale approach to more refined micro-models.

In case of macro-models [8,21,31–33], masonry is modelled as a homogenous ideal continuum by neglecting the interaction between the single components (e.g. bricks and mortar). These models require a careful mechanical calibration that can be carried out directly by deriving homogenised continuum parameters by experimental tests on