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Uses and limits of the Equivalent Frame Model on existing unreinforced masonry buildings for assessing their seismic risk: A review

E. Quagliarini, G. Maracchini, F. Clementi*

Department of Civil and Building Engineering, and Architecture (DICEA), Polytechnic University of Marche, Ancona, Italy

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ABSTRACT

Since the late 1970s, nonlinear static analysis have had an increasing use in the seismic assessment of existing unreinforced masonry (URM) buildings. Different modelling strategies can be used to evaluate the global seismic response of these buildings, such as the Continuous Constitutive Laws Model (CCLM) and the Equivalent Frame Model (EFM). Despite the CCLM modelling approach seems to be the most suitable at this aim, it needs many input data, which are often quite difficult to be known, and requires a high computational effort. For this reason, the EFM, which is based on strongly simplified hypotheses, is preferred in professional practice, where a small computational burden and a time- and cost-saving structural analysis by using few mechanical parameters is needed. In this paper, a review of its uses and limits is proposed, in order to identify the most critical issues and define its proper use in professional practice when applied to existing URM buildings. As a result, it is highlighted that the EFM can be reasonably used as a first conservative approach for the seismic assessment of existing URM buildings with box behaviour and quite regular opening patterns. Thus, up to now, from this review its use is encouraged in seismic analysis of existing URM buildings after providing them a reduction of their floors and roofs deformability, an adequate wall-to-floor and wall-to-roof connections and a regularization of the opening patterns.

1. Introduction

The structural safety and conservation of existing unreinforced masonry (URM) buildings is a prominent concern in our society due to their high seismic vulnerability, showed during recent and past earthquakes [1–5], and, in case of historic and monumental buildings, due to the importance of their cultural value and of the functions that they still maintain nowadays, too. Up to now, people living in existing URM buildings still die after an earthquake [6,7], as recent Italian events sadly testify. Thus, having good representative structural models for modelling existing URM buildings makes possible to rightly assess their seismic risk as well as design proper strengthening interventions on them.

Generally, existing URM buildings show a non-linear behaviour even at early stages of seismic loading due to the low tensile strength of masonry, thus nonlinear analyses should be adopted [8]. Among nonlinear analyses, dynamic ones could be certainly the most accurate for predicting the structural seismic behaviour. However, several drawbacks make this tool scarcely diffused in practice, such as:

(i) a considerable calculation effort;
(ii) a strongly dependence of the results on additional input data not easy to obtain in practice (such as the seismic input in terms of appropriate acceleration time histories, see e.g. [9–11]);
(iii) the difficulty on the individuation of performance limits [12,13];
(iv) the need of specialized practitioners for performing the analysis [14,15].

Thence, with the aim of approximating the real nonlinear dynamic behaviour with more practice-oriented tools, simplified Nonlinear Static Analyses (NSAs) are usually adopted since from the late 1970s [16,17]. The NSA is to date the most diffused tool for the seismic assessment of the global response of existing URM buildings in the engineering practice. It allows describing the displacement capacity of the structures by subjecting them to an increasing pattern of horizontal static forces (load pattern) under a displacement control. The assessment is made by comparing the displacement capacity obtained from the force-displacement ("pushover") curve with the displacement demand of the predicted earthquake [8]. Several Performance Based Assessment (PBA) procedures have been developed based on NSA (e.g. Coefficient Method [18,19], Capacity Spectrum Method [20,21], N2 method [22–24] and Displacement-Based Method [25,26]).

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* Corresponding author.
E-mail address: francesco.clementi@univpm.it (F. Clementi).

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At the same time, several methods have been developed for the modelling strategies of existing URM buildings during last years [27]. Masonry is to date both the oldest and the most complex and least understood construction material in terms of both strength and deformation characteristics [28]. Moreover, the *morphological variations* that often occur during the life-span of these buildings increase the already existing difficulty, common for most of existing buildings, on the identification of *actions* (mechanical, physical, chemical, etc.), *structural details* and *material properties* [27,29–33]. Several uncertainties may also arise on the correct representation of *loading history* (including construction stages, past earthquakes and long-term damage processes), *existing damage or alterations* (such as cracks, disconnections, crushing, deformations and out-of-plumbs) and *possible interventions* (stabilization, repair or strengthening measures). Concerning Soil-Foundation-Structure Interactions, they may be significant for both slender building typologies [34], due to rocking effects and associated damping in the system, and for massive high frequency structures, since, due to their stiffness, the support to the ground cannot be considered as rigid. However, they can be judged as irrelevant in some cases, see e.g. [35,36], or potential dangerous, as for example, when existing URM buildings are built on soils characterized by many surface cavities, natural or man-made, that may affect the effective ground surface acceleration due to earthquake [37].

Generally, in case of existing URM buildings, the modelling strategy is chosen based on the type of the building seismic response [38]. In fact, damage survey after past earthquakes showed that in presence of walls with good masonry quality (namely where chaotic failures of the walls can be neglected), two different types of seismic response can occur usually related to out-of-plane mechanisms and in-plane response, respectively. The latter prevalently characterizes the global response, when local out-of-plane mechanisms are prevented [39–41].

Focusing on the analysis of the global response of existing URM structures, towards which this work is oriented, *Continuous Constitutive Laws Models (CCLM)* [38], usually regarded as Finite Elements *Macro-models* [31], constitute today the most natural approach, as evidenced in [27,31]. Within this framework, where a large amount of different formulations have been developed, the masonry is usually considered as a fictitious homogeneous material while the structure is described by means of a continuous mesh of 2D or 3D Finite Elements. This method has the pros of being quite general, allowing the evaluation of the combined in-plane and out-of-plane contribution to the global seismic response in terms of both stiffness and strength, without making any simplification on the localization of the masonry damage pattern and the structure's geometry. Moreover, it represents today the best compromise between accuracy, generality and computational effort [42]. For this reason, its use prevails in research or academic literature and for each kind of existing URM structure, such as churches and mosques (e.g. [43–49]), palaces (e.g. [50,51]), towers (e.g. [52,53]) and bridges (e.g. [54]).

However, from a practice-oriented point of view, this approach still requires a high computational burden (especially for particularly complex and large structures [55]). Moreover, it requires the definition of many mechanical parameters that are not easily evaluable in practice, which may also strongly affect the analyses results, compromising the gain in accuracy provided by this approach towards more simplified methods [31], and an ex-post identification of the limit states of the structure [56]. In fact, since in the CCLM the structure is modelled as a continuum, the elements on which the drift parameters generally related to the limit states are monitored should be identified after the analyses. This identification may be ambiguous and may imply repeated average operations performed ex post [56].

Discrete and/or rigid element approaches [57–61] could be considered as a valid alternative to CCLM models. However, even in this case a relevant size of buildings leads to a huge computational demand that can be reduced only with a coarser or unrealistic discretization [59].

Thence, in order to perform global analyses with a reasonable computational efforts and a small amount of mechanical parameters, in the last decades several *Structural Element Models* have been developed, in which structures are described as an assembly of macroscopic structural elements [15,62–64]. Among the others, the *Equivalent Frame Model* (EFM) (e.g. [65–74]) is today the most widely diffused in the engineering practice, generally used in combination with the NSA [17,75,76]. This approach is in fact suggested by several international Standards (see e.g. [22,77–79]). Clearly, the reliability of this method depends on the consistency between the strongly simplified hypothesis on which it is based and the real structural behaviour, both at the structural element scale and at the wall/building scale.

Then, in this paper, a review of this modelling approach is proposed with particular regard to its application to existing URM buildings. The ability of the EFM approach to give a good prediction of the global seismic response of existing URM buildings through NSA is investigated, highlighting the most critical issues, limits of applicability and criteria for its correct use in this field in the engineering practice. Finally, some critical points that should be investigated and developed in future researches are evidenced.

2. The Equivalent Frame Model and existing URM buildings

The Equivalent Frame Model (EFM) is today the most widely diffused analysis tool for the seismic assessment of the global seismic response of existing URM building in engineering practice. However, its application to them is not so trivial due to the possible presence of specific features that differentiate these buildings from new ones and, in particular, from other buildings typologies (steel or RC frames) for which the frame idealization has been initially developed.

In this way, the next sections will be focused on these specific features that can be summarized as follow: the wall's discretization criteria (Section 2.1), the element's constitutive laws developed for each structural element for the in-plane and out-of-plane response (Sections 2.2 and 2.3 respectively), the modelling of diaphragms and the other structural elements (Section 2.4), the 3D assembling criteria (Section 2.5) and the modelling of the seismic masses (Section 2.6).

Finally, some considerations on the possible use of the EFM for the assessment of artistic assets' damage, if present, is reported in Section 2.7.

2.1. Wall's discretization

The core of the EFM strategy is certainly the discretization of the load bearing walls. In case of existing URM buildings, a regularization of the real building's geometry is firstly performed. In this way, slight misalignments between the different levels, small curvatures of the walls and walls' out-of-plumbs are usually neglected. Then, the structure is meshed by referring to piers, which are the principal vertical resistant elements to both dead and seismic forces, and spandrels, which are secondary elements that couple piers in case of seismic loads. Rigid cross panels (or rigid zone), whose dimensions directly come out from the identification of spandrels and piers, represent masonry portions in which, as evidenced by observations from after earthquake scenario (e.g. [1–5]), damage does not usually occur.

Piers and spandrels are usually schematized by means of two-node elements (geometric centerlines), which are connected to each other through infinitely rigid beams [66,80,81] or rigid offsets [67], which intend to represent the coupling between the deformable elements provided by the rigid zones. This is a quite rough approximation of the complex stress transfer mechanism between horizontal and vertical elements that takes place over the nodes [59,67,82]. Fig. 1 reports the main steps of the wall's discretization along with two possible EFM idealizations, which mainly differ in the rigid zone schematization.

Systematic parametrical analyses (numerical and experimental)

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