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A simplified procedure for Nonlinear Static analysis of masonry infilled RC frames

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ABSTRACT

Masonry walls are widely used in existing Reinforced Concrete (RC) structures, either as external infill or as internal partitions. Although their mechanical contribution is usually neglected in structural analysis and design, they significantly affect the seismic response of RC frames. This paper proposes a simplified procedure based on NonLinear Static (NLS) analysis for evaluating the seismic response of masonry infilled RC frames. NonLinear Time History (NLTH) analyses are firstly carried out for understanding the actual seismic response of such frames. To this end, an "equivalent-strut" model available in the scientific literature is considered for simulating the nonlinear response of masonry walls under the cyclic actions induced by seismic shakings. Then, based on the results of such NLTH analyses, the aforementioned simplified NLS procedure is formulated by unveiling a stable correlation between the observed dynamic response and a simple scalar parameter that can be easily determined through two NLS analyses carried out on the infilled frame and the corresponding bare one. A statistical description of the accuracy and reliability of the proposed method is finally proposed.

1. Introduction

Masonry walls are widely employed in existing Reinforced Concrete (RC) structures, both as external infill and internal partitions. Although they clearly interact with the main structural members and, hence, they influence the seismic response of RC frames, the mechanical contribution of masonry infill walls are generally neglected in practice-oriented structural analyses [1]. Actually, simulating the actual dynamic behaviour of these components and evaluating their influence on the global seismic response of RC structures received a great attention by the scientific community [2–4]: nevertheless, no procedure was established so far for taking into account the contribution of masonry infills in practice-oriented seismic analyses of RC frames.

As a matter of fact, NonLinear Static (NLS) analysis is nowadays a common tool for evaluating the seismic response of both new and existing structures [5]. Although it is generally carried out on bare frame models, a recent contribution was proposed in the scientific literature for determining the seismic response of masonry infilled RC frames by means of NLS analyses [6]. In fact, it is based on formulating a specific R–μ–T relationship, developed from the results of an extensive parametric study employing a SDOF, aimed at determining the inelastic demand spectra of structures whose capacity curve is characterised by a significant softening branch [7], induced by the progressive damage affecting the masonry walls during the seismic excitation [8]. In principle, such a relationship was intended at replacing the simpler one that, within the framework of the N2 Method, can be applied to structures characterised by the substantially bilinear capacity curves generally obtained from NLS analysis of bare RC frames [9]. Although this method generally results in accurate predictions of the actual seismic response of infilled RC frames (at least in the case of regularly distributed walls), its analytical definition of the aforementioned relationship R–μ–T is formally complicated and based on several parameters whose determination is not generally straightforward. Moreover, in the case of "weak" infills, the aforementioned procedure [6] does not clearly reduce (as it should be expected in principle) to the one defined in the N2 Method [9] based on well-established principles (i.e., the so called "equal displacement rule", for medium-to-long period structures) and adopted in the most up-to-date seismic codes [10].

Significant improvements were recently proposed about assessing the seismic capacity of infilled frames using the Capacity Spectrum Method (CSM) and the Coefficient Method [11]. Moreover, a systematic parametric comparison between the predictions of ductility demand obtained by applying the

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aforementioned CSM and the N2 Method was also presented [12]. However, the effort towards formulating a simpler, accurate and reliable procedure for determining the seismic response of masonry infilled RC structures by means of NLS analysis is still a relevant challenge: it would be desirable that this procedure could be clearly based on an extension of the currently adopted (and validated) relationships employed in NLS analyses of bare frames, such as those assumed as part of the aforementioned N2 Method [9,10].

Therefore, this paper presents a possible extension of the N2 Method to structures with masonry infill walls. Particularly, it explains the conceptual genesis of the proposed procedure and describes the "inductive process" followed by the Authors in formulating the present proposal based on the results of a parametric study. The monotonic and cyclic response of infill walls is simulated through the attractive and computationally convenient approach based on the "equivalent strut" concept [13], widely accepted and validated in the scientific community. Particularly, a recent proposal is considered herein for determining the equivalent strut parameters depending on the actual geometric and mechanical properties of masonry walls, and taking into account the effect of openings within masonry walls. Various relevant parameters, such as the number of storeys, the distribution of walls within the frame, the wall properties and the level of the seismic excitation are taken into account in this analysis. The actual seismic response of the frames under consideration was determined through NonLinear Time-History (NLTH) analyses intended as "numerical experiments" and aimed at unveiling the role of infill walls on the global structural response: the ratio between the displacement demand obtained for the infilled frame and the one determined for the corresponding bare one is particularly scrutinised. Then, the results of NLTH analyses are considered for calibrating a simplified procedure based on the results of NonLinear Static (NLS) analyses carried out on both the infilled and the bare frames. These analyses were carried out for two levels of seismic intensity (PGA = 0.10g and PGA = 0.35g): on the one hand, it should be noted that the validation of the proposed method is bounded within the aforementioned seismic intensity levels, albeit, on the other hand, they are certainly representative of the actions to be considered for serviceability and ultimate limit state checks in medium-to-high seismic hazard regions of Europe.

The paper is organised as follows. Section 2 outlines the State-of-the-Art on "equivalent-strut" models available in the literature and provides the details about the one adopted in Section 3 for performing NLTH analyses of both bare and infilled frames. Then, Section 4 reports the formulation of the proposed method based on NLS analyses and Section 5 outlines a statistical assessment of its accuracy. The key findings of this study are finally summarised in Section 6.

2. Modelling masonry infill walls in RC frames

Several modelling options are available in the scientific literature and can be nowadays considered for simulating the mechanical behaviour of masonry infill walls: they range between the simplest "equivalent strut" models (macro-models), whose first conceptual definition dates back to the 1960s [13], to more recent and refined 2D/3D continuum models (Fig. 1), often formulated within the framework of the Finite Element Method (FEM). While the latter are not considered herein, the former are more often employed in global analyses, as they are less computationally demanding. However, defining their geometric parameters (i.e. the width and depth of the diagonal strut and the equivalent nonlinear behaviour of the masonry infill) is not straightforward, especially when openings, such as doors or windows, are present in the wall. Therefore, recent studies are available in the literature for describing the influence of relevant parameters, such as the vertical loads acting on the frame [14], the elastic modulus and Poisson's ratio of infill masonry walls [15].

A thorough discussion about the aforementioned models is beyond the scopes of this paper and can be found in another article recently published by the same Authors [8]. Although alternative solutions based on adopting a variable number of struts for simulating the mechanical response of walls are actually available in the literature [16], the analyses presented in this paper are based on employing just two diagonal equivalent struts, which can carry loads only in compression as defined in a recent study [17].

Hence, the infill walls are macro-modelled herein by means of a tri-linear relationship representing the horizontal force–displacement behaviour of masonry infill walls. The initial stiffness R_1 of the curve represented in Fig. 2 is defined as follows [17]:

$$R_1 = \frac{G_w t_w l_w}{h_w} \tag{1}$$

in which G_w is the shear modulus of the masonry infill, while t_w, l_w and h_w are the thickness, the length and the height of the masonry wall, respectively. The maximum strength F_m is defined according to a proposal available in the literature [17]:

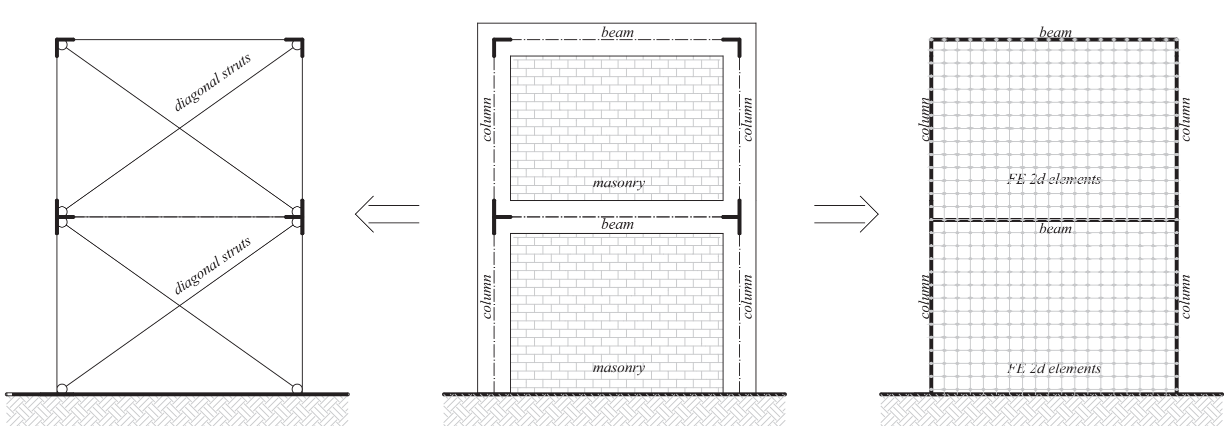

Fig. 1. Modelling masonry infill with equivalent diagonal struts (on the left) and 2D continuum model (on the right).