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The relative dynamic resilience of masonry collapse mechanisms

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ABSTRACT

Masonry structures have exhibited recurrent collapse mechanisms during past earthquakes, and building codes now require that the seismic capacities of typical mechanisms are assessed. In this paper, a new framework is proposed for predicting out-of-plane seismic collapse of masonry walls. The method remains relatively simple by utilizing linearized equations of motion, while improving upon previous methods by considering the dynamic rocking response. The equations of motion for the rocking response of masonry walls with three fundamental scenarios of loading are first presented. Both applied external forces and external inertial forces are considered, in addition to the possible formation of a two-body (three-hinge) mechanism if the wall is restrained at its top and bottom. After linearization, these fundamental loading scenarios are all described by a single equation of motion, allowing them to be combined to consider a much wider variety of loading scenarios. The proposed framework is then used to investigate the dynamic resilience of different collapse mechanisms by considering the response to pulse-type ground motions. For this purpose, an analytical solution which describes the collapse envelope for pulse-type ground motions and one-sided rocking is derived. The comparison between collapse envelopes makes it possible to describe the relative resilience of each mechanism compared to the others. Eventually, the proposed framework is used to investigate the relative resilience of the mechanisms observed in a church damaged in the 2009 L'Aquila earthquake.

1. Introduction

Historical masonry constructions under seismic action may exhibit a global failure mechanism, but more frequently display local out-of-plane failure of individual structural elements [1–3], particularly where connections are not designed to transmit seismic loads (Fig. 1). The damage induced by earthquakes has shown that failure mechanisms develop in a recurrent way, independent of the age of construction, the mechanical characteristics of masonry, or the geographical location, although all these aspects can influence the specific mechanism that takes place [4]. Indeed, masonry structures are made by recurrent architectural elements (façade, wall, gable, vault, bell tower, etc.), making it possible to catalogue the damage and identify, for each macro element, the most likely failure mechanisms. Such recurring collapse mechanisms have been the object of several studies (*e.g.* [5]), and are currently used for civil protection surveys and vulnerability assessment.

A statistical analysis carried out on the basis of the data collected after the L'Aquila 2009 earthquake revealed that overturning of perimeter walls was the most frequent mechanism activated by the seismic action [6,7]. Because collapse is primarily governed by stability against overturning, rather than by the local compressive or tensile failure of the material, the capacity of the wall to survive an earthquake primarily depends on its geometry and on the capacity of connections to surrounding structural elements. These principles were reported in historical essays (*e.g.* [8]), and were well-known through the beginning of the twentieth century, when the design of load bearing masonry walls was driven by geometrical aspect ratios, codified over the centuries, to ensure stability under gravity loads.

During an earthquake, the dynamic response of any formed mechanism within a masonry structure naturally involves rocking motion, during which the free rocking period is amplitude dependent, and the response is therefore time dependent [9,10]. While rocking theory is now well-developed, it is rarely adopted in codes of practice, where simple assessment procedures are required. For example, the Italian building code [11] suggests two equivalent static assessment procedures, one strength-based procedure, and one displacement-based procedure. The strength-based procedure simply specifies the capacity of the structure to resist ground

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acceleration as a multiple (typically two) of the ground acceleration needed to initiate the mechanism. While this procedure is simple, it completely neglects the dynamics of the response, and therefore the scale effect which might cause the top of a slender structure to be more vulnerable to overturning than the entire structure about its base [12].

Meanwhile, the displacement-based procedure [11] essentially specifies an average secant rocking stiffness for an acceptable range of rocking motion (up to 40% of the collapse displacement), and then uses the linear elastic spectral displacement at the averaged secant period to determine expected rocking demand. Similarly, ASCE 43-05 [13] proposes an 'approximate method' which is also based on the linear elastic spectral response. These procedures follow the direction of Priestley et al. [14] and often provide an improved prediction of collapse compared to strength-based methods because they do include dynamic effects, albeit in a simplified manner. However, rocking and elastic oscillation are dynamically very different, and the accuracy of predictions using linear elastic spectra will therefore always be inherently limited [15]. For example, this is evident when comparing predicted and experimental data, where the scatter in results for the displacement-based method described above is considerably larger than for predictions that utilize appropriate equations of motion to predict the rocking response [16]. However, despite its limitations, the displacement-based procedure remains conservative in many cases through specification of a displacement safety factor of 2.5, which is implemented by defining the capacity as 40% of the collapse displacement.

In this context, the objective of this work is to develop a framework in which rocking theory is directly used to predict the capacity of expected collapse mechanisms, in a simplified manner that could be implemented in codes of practice. The first requirement of such a framework is the ability to define all collapse mechanisms with the same set of fundamental parameters that define the response of a single rocking block. The second requirement is to then develop a codified method of specifying the seismic rocking capacity of the single block in a simplified manner, which would then be applicable to any structure if the first requirement is achieved. Notably, ASCE 43-05 [13] outlines an option to conduct full time-history analysis using the rocking equations of motion and multiple earthquake records. However, alternative simplified procedures which do not require full time-history analysis, but which could be informed by the wealth of previous studies on the rocking block, are still required.

The primary objective of this paper is to achieve the first requirement above with particular focus on out-of-plane collapse of masonry walls. The secondary objective is to achieve the second requirement above for a specific type of ground motion: ideal trigonometric pulses. The scope is limited to trigonometric pulses for two reasons. First, a deterministic solution is accessible although not yet completely defined, and second, the response to pulse-type motions directly illuminates the relative dynamic resilience of possible collapse mechanisms, which could then be used to prioritize retrofit efforts.

In the following section, the derivation of the fundamental rocking parameters necessary to describe a variety of out-of-plane masonry collapse mechanisms is presented. Subsequently, the response of these mechanisms to pulse-type ground motions is considered, for which new analytical solutions which predict collapse for one-sided rocking mechanisms are introduced. Finally, the relative capacities of possible collapse mechanisms are exemplified for a case-study structure.

2. General formulation

Starting with Giuffrè [1], increasing attention has been paid to the development of a methodology for seismic analysis of masonry based on the use of collapse mechanisms. In this context, limit analysis based on kinematics became increasingly popular [17], and has been recently included in the Italian building code [11]. Thanks to the limited influence of the deformability and the strength of the material, the approach consists in defining, for each macro element, according to the expected collapse mechanism, a kinematic chain, *i.e.* a system of rigid and infinitely resistant blocks undergoing a motion governed by a single degree of freedom, as depicted in Fig. 2.

The use of limit analysis makes it possible to estimate the static load that activates the mechanism and the load–displacement response curve which governs stability during motion. By neglecting the contribution of internal forces at the crack regions (friction and cohesion) and assuming that the external forces are constant during the evolution of motion, the following terms have to be taken into account in the analysis of the kinematic chain:

- The masses of the blocks pertaining to the macro element, M_b.
- The additional masses M_i, such as floors, roof, beams, which are sustained by the macroelement and can be considered as concentrated at the support regions.
- The non-bearing inertial masses M_j, which are supported by other structural elements but are expected to transmit the inertial forces induced by ground motions.
- The external static forces F_k such as vault and roof thrusts, soil pressure, and tie bar reactions.

Fig. 1. Seismic failure mechanisms in masonry churches: Overturning of the façade (left), overturning of the gable (right).