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Out-of-plane static and dynamic response of masonry panels

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ABSTRACT

Out-of-plane mechanisms induced by earthquakes are typical of many masonry structures such as standing out elements (spires, battlements of fortresses, *etc.*) or portions of façade badly connected to the building. The displacement-based assessment procedures in standards are based on the hypothesis of rigid block, which sometimes is unable to represent their actual behaviour; furthermore, very few information is available on dissipation, which is assumed as an equivalent viscous damping, usually kept constant to 5%. The paper illustrates the results of an experimental campaign on three mock-ups subjected to static and dynamic out-of-plane actions with the aim to verify the reliability of these assumptions for traditional irregular stone masonry panels under rocking.

1. Introduction

Out-of-plane mechanisms are very common in masonry structures, as it was observed after recent and past earthquakes [1–3]. These mechanisms include not only free-standing elements in ordinary or monumental buildings (such as parapets, battlements of fortresses, soaring portion of church façades), but also single artefacts, such as statues, pinnacles or balustrades. For this reason, the protection of cultural heritage assets represents a challenging issue, and seismic assessment procedures need to combine safety and conservation requirements.

Despite the wide variety of these elements (in terms of shape, size and materials), seismic damage has shown the formation of macro-blocks (Fig. 1). Models based on rigid-block assemblies provide a suitable framework for understanding the behaviour under seismic actions of free-standing existing masonry structures. They can be applied both in the dynamic and in the static fields.

In the dynamic field, the reference model is that of Housner [4], which describes the free and forced vibrations of a slender rigid block subjected to a rocking motion alternately around the base edges O and O′ (Fig. 2a), considered as an inverted pendulum.

According to Housner's model, the energy dissipation in rocking is obtained through the conservation of the angular momentum, which is quantified by the coefficient of restitution *c*, namely the ratio between the angular velocity after and before the impact, and directly related to the geometry of the rigid block (defined by the slenderness $\lambda = h/b = tan(\varphi)$ – see Fig. 2a):

$$c = \frac{\dot{\theta}_2}{\dot{\theta}_1} = 1 - \frac{3}{2}\cos^2\phi = \frac{2\lambda^2 - 1}{2(\lambda^2 + 1)} \cong 1 - \frac{3}{2\lambda^2} \quad (1)$$

The peculiar dynamic characteristics of this nonlinear system, in comparison with the classical elastic SDOF system, were described by Makris and Konstantinidis [5], who have also shown the limits of the Housner's linearized solution in the case of some typical forced vibrations. The dynamic response of a rigid block subjected to an accelerogram cannot be obtained analytically but only through numerical simulation; the maximum rotation of any rigid block under a given accelerogram is given by the rocking spectrum [6].

With the aim of adopting a displacement-based approach for the evaluation of the rocking response under seismic excitation, the possibility of adopting an equivalent nonlinear static SDOF system was firstly investigated by Priestley et al. [7] and, more recently, was taken up by different authors [8–10] and implemented in some codes [11–12]; FEMA 356-afterwards included in ASCE/SEI 41/06 [13]. According to the procedure proposed in Lagomarsino [10], the seismic out-of-plane behaviour of the examined free-standing structure is described by the curve α-d (Fig. 2b) obtained by applying incrementally (with geometric nonlinearities) the limit analysis [14], under the classical hypotheses of zero tensile strength, infinite compressive strength and absence of sliding. This curve actually represents the static multiplier α (defined as the ratio between the horizontal limit equilibrium force and the weight of the panel) for increasing finite values of the generalized horizontal displacement *d* (e.g. assumed as the one representative of the mechanism), up to the value for which $\alpha(d) = 0$.

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Fig. 1. Occurred damage to standing structures after L'Aquila earthquake, 2009 (a, b) and the Emilian earthquake, 2012 (c): (a) Santa Maria degli Angeli church (Civita di Bagno, AQ); (b) San Michele Arcangelo church (Villa Sant'Angelo, AQ); (c) San Francesco d'Assisi Church (Finale Emilia, MO).

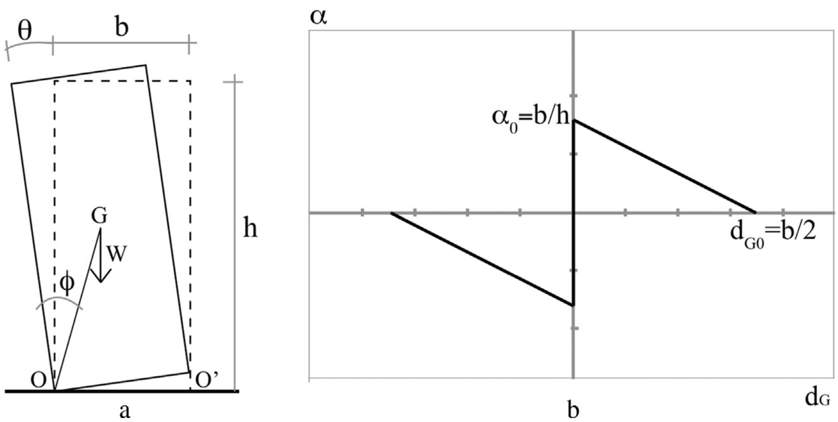

Fig. 2. Geometry of the rocking block (a); Curve of equilibrium condition (b).

In the case of a single block, this curve corresponds to the capacity curve of the system, where the value of the initial multiplier α_0, which starts the overturning, is equal to the inverse of the slenderness λ and the displacement d_G is that of the centre of gravity.

According to the hypothesis of rigid block, Housner's model and the Heyman's limit analysis consider that horizontal displacements occur only after the activation of rocking; however, laboratory [9] and in-situ [15] results on masonry panels show respectively a tri-linear and bi-linear behaviour with an initial pseudo-elastic period, due to small deformations that occur before rocking and which are given by the elastic deformability and the progressive formation of the hinge.

Both dynamic (Housner's model) and static (Heyman's limit analysis) approaches are affected by uncertainties and limitations in the capability of describing the actual behaviour of real masonry elements. These can be summarized in:

i. the reliability of the rigid block assumption to properly describe the actual behaviour of free-standing rocking structures, especially if they are characterized by a quite poor masonry quality, as sometimes the case of elements in historical buildings;
ii. the correct evaluation of dissipative phenomena, usually accounted for through an equivalent damping.

Regarding to the latter, despite the vast number of studies presented in the literature [16], damping still represents one of the more complex aspects, due to the lack of a mechanically-based description of the dissipative forces through a widely accepted model.

Referring to the particular case of the rocking mechanisms, traditionally the energy dissipation due to impacts of the element against the base foundation is interpreted in terms of:

i. Coefficient of restitution c (see Eq. (1)), according to the Housner's model. In this case, dissipation is related only to the aspect ratio, while both material properties (a rigid block is assumed) and block size are irrelevant on damping; experimental results [17,18] have shown that this approach is quite accurate if the block is slender and the masonry has good material properties.
ii. Equivalent viscous damping ξ [19,9], as commonly assumed in the dynamic analyses. The experimental evaluation is obtained through the logarithmic decrement method (originally proposed by Helmholtz [20] and later introduced by Lord Rayleigh [21]), starting from the results of free vibration tests. For slightly damped system ($\xi \ll 1$), as it is usually the case:

$$\xi = \frac{\delta}{2\pi} \tag{2}$$

where δ is the natural logarithm of the ratio between two consecutive peaks of displacement d of any point of the block (Fig. 3):

$$\delta = \ln \frac{d_{max,n}}{d_{max,n+1}} \tag{3}$$

The value of δ is constant in the case of a linear SDOF system with viscous damping, independently of the amplitude of vibrations, while it can be evaluated from the decay of free vibrations obtained