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FRAGILITY ASSESSMENT OF UNREINFORCED MASONRY WALLS UNDERGOING EARTHQUAKE-INDUCED LOCAL FAILURE MECHANISMS

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Abstract. *Damage observations from strong earthquakes show that unreinforced masonry buildings have exhibited recurrent local failure mechanisms and constitute a serious life-safety hazard. This contribution is aimed at evaluating the fragility functions for unreinforced masonry walls in the presence of local failure mechanisms induced by out-of-plane loading. The out-of-plane response consists of the overturning of the entire or a part of the wall insufficiently connected to the rest of the structure. The wall can be idealized as a number of rigid bodies undergoing rocking motion. They are assumed to undergo one-sided rocking or vertical spanning strip wall displacing as an assembly of a coupled rigid body. In this study, we use a set of 44 ground motions from earthquake events that occurred in Italy from 1972 to 2017. For any given wall undergoing a specific collapse mechanism, the probability of collapse is evaluated through a Multiple Stripe Analysis (MSA). Then, a fragility curve is fitted to the MSA data points. The procedure outlined may be extended to obtain typological fragility functions as a combination of the fragility curves corresponding to the various mechanisms analyzed. A preliminary application of the procedure to the historical centre of Ferrara, Italy, is described.*

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1 INTRODUCTION

The out-of-plane behavior of UnReinforced Masonry (in the following, URM) structures subjected to ground motion excitations has been widely investigated. Recent seismic events have shown that overturning of entire or parts of walls represents one of the most serious life hazards [1]. Ancient buildings not conceived with specific design criteria against earthquake actions are generally more vulnerable than new buildings, because of the inadequacy of connections of walls to transverse stabilizing walls and floor structures.

In Italy, the seismic analysis of masonry structures based on the study of local collapse mechanisms starts with Giuffrè [2] and a design method based on kinematic analysis is currently reported by the Italian building code [3]. Another approach, often more accurate, makes use of the motion equations of rocking rigid blocks subjected to a given acceleration time history. In this context, the study of rocking oscillators starts with the seminal paper by Housner [4], which derives the out-of-plane response of a parapet wall considered as a single degree of freedom (SDOF) system. Following Housner, the research focuses on the dynamic response of rigid blocks subjected to pulse or earthquakes excitations [5]. In particular, it is shown that this response is characterized by strong nonlinearity and dynamic instability.

Later, other models are developed to approximate the rocking response of complex multi-block systems with an equivalent SDOF system [6]. In particular, a useful SDOF idealization for the displacement-based analysis of the out-of-plane bending of URM walls is proposed in [7].

The increasing interest in a probabilistic approach that allows taking account of uncertainties, vulnerabilities and risk in earthquake engineering provides a description of the structural response by means of dynamic analyses. In PEER-PBEE framework [8], the fragility curve represents one of the main key tools. Several studies provide fragility curves for rocking blocks as a function of various intensity measures [9, 10].

The aim of the present study is to propose a dynamic approach using rigid block modeling to derive fragility curves for two types of very frequent local failure mechanisms. In particular, we analyze one-sided rocking and one-way vertical spanning strip walls (VSSW) displacing as an assembly of two rigid bodies. Section 2 reviews the mechanical models used to reproduce the out-of-plane behavior. Section 3 presents the procedure for evaluating the fragility curves and reports some results. As a case study, a preliminary application to the historical centre of Ferrara (Figure 1), Italy, is presented.

a) b)

Figure 1: Typical URM buildings in the historical centre of Ferrara

2 MECHANICAL MODELS REVIEWS

This section presents the equations of motion for the one-sided rocking and two-block rocking mechanisms. The dynamic response of the rigid blocks to prescribed acceleration time histories is obtained from a specifically suited MATLAB code that numerically solves the nonlinear equations with a 4th-5th order Runge-Kutta integration technique.

2.1 One-sided rocking

A rectangular block resting on a horizontal plane and presenting a vertical one-sided restraint is considered (Figure 2). The friction coefficient is assumed large enough to avoid sliding between the block and the plane.

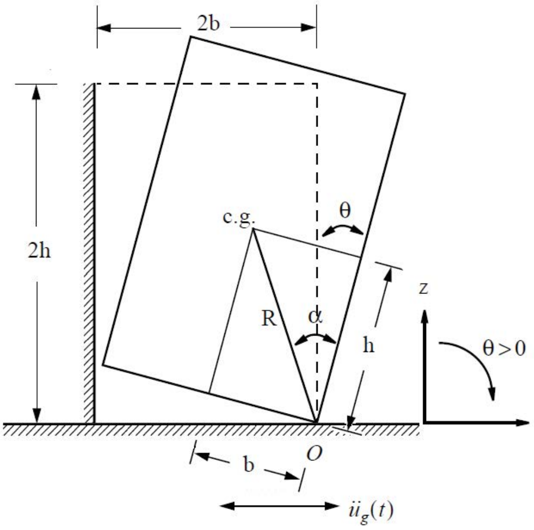


Figure 2: One-sided rocking under ground motion.

The equation of motion that governs the one-sided rocking response can be written as follows:

$$I_0\ddot{\theta} + gM_bR\sin(\alpha-\theta) = -M_bR\ddot{u}_g\cos(\alpha-\theta) \tag{1}$$

with R being the distance between block centroid and rotation centre O, θ the angular rotation, I_0 the polar second moment of area, α the angle between R and the vertical edge of the block, M_b the block mass of the block and g the gravity. The presence of a vertical restraint makes rotation θ remain positive.

In this paper, a coefficient of restitution is accounted for to estimate the energy dissipation. This coefficient, defined as the ratio between angular velocities after ($\dot{\theta}^+$) and before ($\dot{\theta}^-$) the generic impact, takes the following form [11]:

$$\eta_{1s} = \left(1-\frac{3}{2}\sin^2\alpha\right)^2\left(1-\frac{3}{2}\cos^2\alpha\right) \tag{2}$$

2.2 Two-block mechanism

A wall with a deformed shape corresponding to the formation of pivot interfaces at the top, the bottom, and an intermediate height is now considered (Figure 3). The main parameters that describe the mechanism are angles α_1 and α_2, defining the slenderness of the two blocks; M_{b1} and M_{b2} represent the masses of the blocks and I_{01} and I_{02} their polar second moments of area.

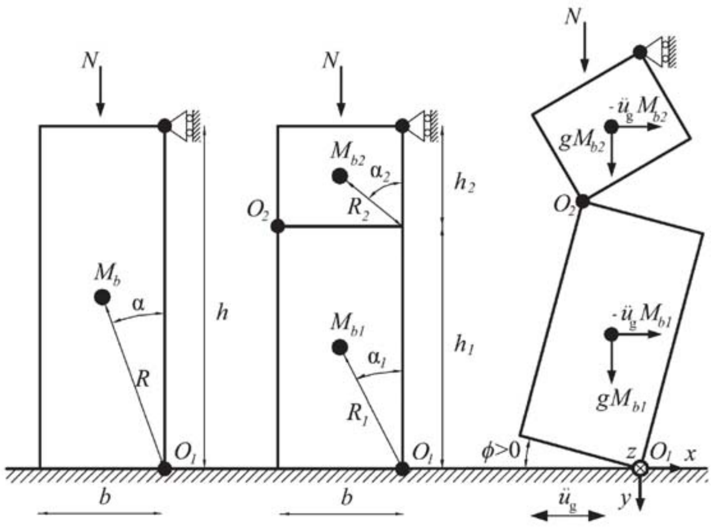


Figure 3: two block mechanism under ground motion

The equation of motion can now be written in the following form (the interested reader is referred to [12] for more details):

$$\begin{gathered}\left(I_{01}+B_1 I_{02}+B_2 M_{b2} R_2^2\right)\ddot{\phi}+\left(C_1 I_{02}+C_2 M_{b2} R_2^2\right)\dot{\phi}^2+gAR_2\left[M_{b1}+M_{b2}\left(1+\frac{B_2}{4A^2}\right)\right]= \\ -A\left(M_{b1}+M_{b2}\right)R_2\cot\left(\alpha_1-\phi\right)\ddot{u}_g+Q\end{gathered} \tag{3}$$

The coefficient of restitution for this mechanism, depending of the block slendernesses, is defined as [12]:

$$\eta_{tb}=\frac{M_{b1}R_1^2+I_{01}\dfrac{\tan\alpha_2}{\tan\alpha_1}-2M_{b1}R_1^2\sin^2\alpha_1+M_{b2}R_1^2\left[2+\dfrac{\sin\alpha_1\cos\alpha_1}{\tan\alpha_2}-\sin^2\alpha_1\left(4+\dfrac{\tan\alpha_2}{\tan\alpha_1}\right)\right]}{M_{b1}R_1^2+I_{01}-I_{02}\dfrac{\tan\alpha_2}{\tan\alpha_1}+M_{b2}R_1^2\left[2+\sin\alpha_1\cos\alpha_{11}\left(\dfrac{1}{\tan\alpha_2}+\tan\alpha_2\right)\right]} \tag{4}$$

This coefficient decreases with wall slenderness and elevation of the intermediate hinge. The experimental evidence shows that the coefficient of restitution ranges between 0.84 and 0.90 of the predicted value [13].

3 FRAGILITY ANALYSIS

The fragility curve is defined as a conditional probability of failure.

$$P\left(C\middle|IM=x\right)=\Phi\left(\frac{\ln\left(x/\theta\right)}{\beta}\right) \tag{5}$$

where x is the median value of the selected Engineering Demand Parameter (EDP), while θ is the capacity related with the collapse damage state. Coefficient β is the logarithmic standard deviation of the demand conditioned on the Intensity Measure (*IM*). Fragility parameters may be estimated from an Incremental Dynamic Analysis (IDA) or a Multiple Stripe Analysis (MSA). In this contribution, the second approach is chosen.

3.1 Ground motion selection

A set of 44 natural ground motions from the ITACA [14] is used. The ground motion set collects the horizontal components of acceleration time histories recorded in Italy during 23 earthquake events occurred from 1972 to 2016. The ground motions are selected with a large range of peak ground acceleration (PGA) and peak ground velocity (PGV). The intensity measure used for the fragility curves is the PGA, which is the key strong motion parameter for seismic design in Italy [3].

3.2 Engineering Demand Parameter

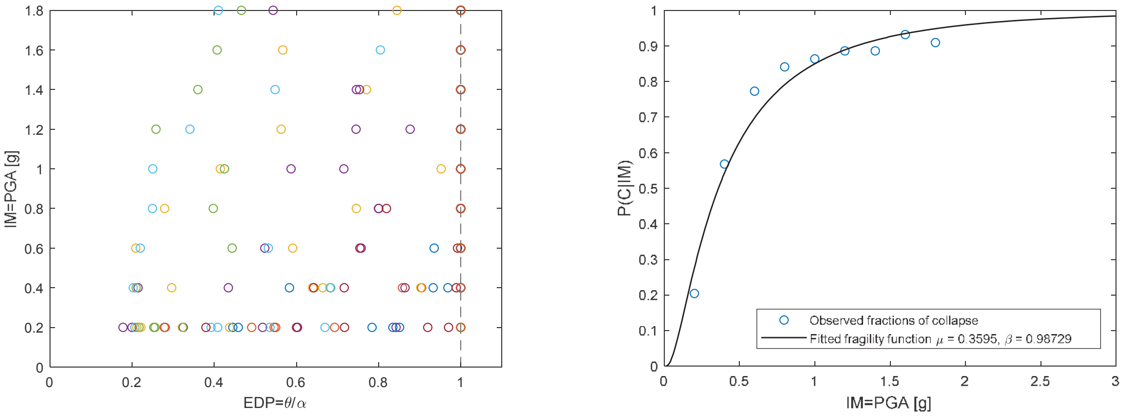
An appropriate choice of the EDPs is necessary for the fragility analysis. The EDP for an overturning block may be chosen as the ratio between block rotation θ and slenderness angle α (see Figure 1):

$$\mathrm{EDP} = \theta/\alpha \tag{6}$$

Values of the EDP larger than zero imply that the structure starts to rock. When the EDP exceeds 1, the overturning occurs. This definition of the overturning condition is a simplification on the safe side. In fact, a rocking block might exhibit a higher EDP without overturning [15].

3.3 Multiple Stripe Analysis (MSA)

This type of analysis consists of a series of time history analyses for a specified set of *IM* levels [16]. Compared with the IDA, the MSA offers the advantage of a reduced computational effort. The maximum likelihood criterion is then used to fit the computed fragilities with suitable analytical functions (Figure 4).

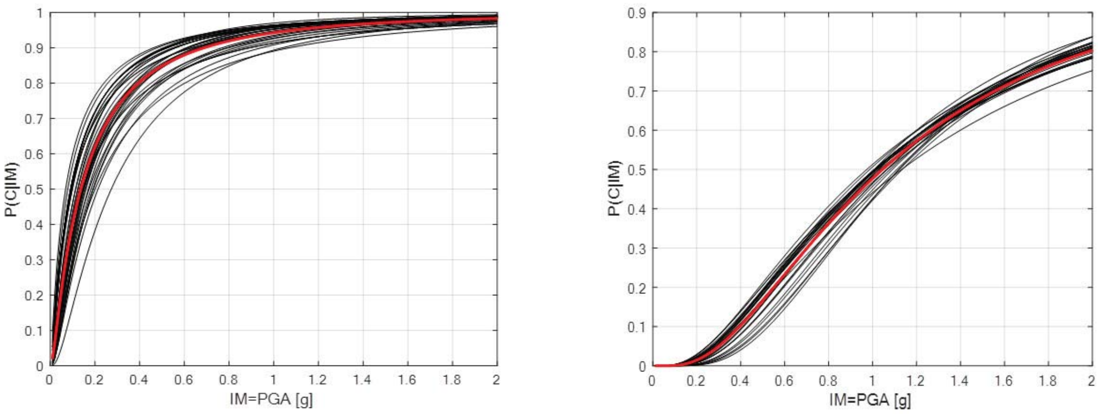


a) b)

Figure 4: a) example of MSA results. b) collapse probability as a function of IM and estimated fragility curve.

3.4 Fragility curves

A survey of an aggregate of buildings in the historic centre of Ferrara, Italy, has been preliminary carried out to form a “population” of masonry walls. The probability of occurrence of the one-sided rocking and two-block mechanism is estimated based on peculiar characteristics of the the surveyed buildings. The corresponding fragility curves are evaluated (Figure 5). These curves describe the vulnerability of the aggregate according with the analyzed mechanisms. It is worth noting that the rocking mechanism is more vulnerable than the two-block mechanism. This greater vulnerability relies upon the nature of the rocking mechanism, which has a trigger acceleration lower than that of the two-blocks mechanism.



a) b)

Figure 5: a) one-sided rocking fragility curves; b) two block mechanism fragility curves. (the red line represents the average curve)

4 CONCLUSIONS

The paper presents a procedure for evaluating the analytical fragility curves of out-of-plane loaded URM walls with a non-linear dynamic approach.

In a future research, a suitable combination of the obtained fragility curves taking account of the probability of occurrence of the various collapse mechanisms could allow to define typological fragility curves for classes of URM buildings.

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