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FRAGILITY FUNCTIONS FOR SEISMIC RISK IN REGIONS WITH MODERATE SEISMICITY

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ABSTRACT

Current seismic risk evaluations are mostly based on approximate vulnerability curves. Damage prediction is improved by considering structural characteristics of building. Such improved fragility functions do not exist for many structures, especially in countries with moderate seismicity. Typical structures of these regions, such as unreinforced masonry buildings URM, differ notably from structures usually considered in seismic risk. Due to low perceived seismic hazard, these types of structures have not been adequately investigated. Moreover, experimental investigations have shown that their deformation capacity is often underestimated. As a consequence, advanced methodologies have not yet been developed. This paper describes the results obtained with an analytical displacement-based methodology to assess the seismic risk in existing buildings through fragility functions. The study is based on URM existing buildings, common in North Western Europe. These low or mid-rise buildings with basements generally do not have significant structural plan irregularities. The impact and the accuracy of several parameters (such as the damage grade definition, the prediction of the ultimate drift, and the strength of the walls) are addressed. The fragility curves obtained are compared to those obtained using empirical methods in a typical existing URM building.

Introduction

Existing unreinforced masonry (URM) buildings present a complex seismic behaviour. In regions with moderate seismicity, such as North Western Europe, the low perceived seismic risk led to an inadequate investigation of these existing buildings. The latter are often low and mid-rise and they represent an important percentage of the total building stock, e.g. two third in the city of Visp, Valais (Switzerland). One of the most common methodologies used to study this issue is the fragility analysis. However, when European typologies are considered as in regions with moderate seismicity, there is a lack of knowledge on their seismic behaviour. Therefore, fragility functions (also called fragility curves) determined to other parts of the world and for different building classes are often extrapolated.

In order to avoid this extrapolation and to better estimate the seismic risk, it is essential to

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define a well-adapted fragility framework. Hence, it is crucial to determine the impact and the accuracy of certain parameters of seismic assessment, such as the damage grade (DG) definition, the ultimate drift (δ_u) and the strength estimation of the masonry walls (V_{Rd}). Moreover, a probabilistic framework is also needed to integrate all the computations.

Several authors proposed simplified approaches to assess the vulnerability of existing buildings. One of the first displacement-based seismic assessment (Calvi 1999), considers both reinforced concrete (RC) and unreinforced masonry buildings (URM). Moreover, it proposes failure mechanisms and a study of the variability of structural properties. Thus, this seismic assessment is one of the most important advance in this topic and it constitutes the basis of the Direct Displacement-Based Design methodology (Priestley 2003; Priestley et al. 2007). Some improvements were first introduced to reinforced concrete (Borzi et al. 2008; Crowley et al. 2004), and then for masonry structures, such as MeBaSe methodology (Restrepo Vélez 2003). The later tackled the structural and non-structural damages and both in-plane and out-of-plane behaviour. It also treated the variability of certain parameters, such as structural configuration and strength values.

Another simplified approach exists, based on non-linear static principles and replacing the empirical formulations for damage grades and fundamental periods by analytical ones (Lang 2002). This approach proposes a methodology for seismic vulnerability assessment of RC and URM buildings. Thanks to its simplicity, earthquake scenarios can be assessed (Lang and Bachmann 2004). This methodology is adapted and improved in this paper, in order to provide an analytical fragility approach, based on simplified assumptions and considering the in-plane behaviour of masonry walls. Then, an existing building is analyzed and its results in terms of fragility curves are compared to empirical data from HAZUS.

Methodology

In this section, both main principles of the Lang's methodology and the proposed enhancements are treated. Based on a simplified non-linear static approach, the original approach (Lang 2002) details the missing elements.

Capacity curve

The total capacity curve of a building is obtained by stacking the capacity curves of each URM wall. This elementary capacity curve presents a simplified bi-linear behaviour and it is determined by three parameters: the strength of the wall (V_{Rd}), the elastic displacement at yield (Δ_y) and the ultimate drift (δ_u) at the first level (Figure 1). These curves are computed at the top of the building. The elastic deformation is determined assuming a constant drift over the height of the building. During the plastic behaviour, it is assumed that these deformations occur at the first storey.

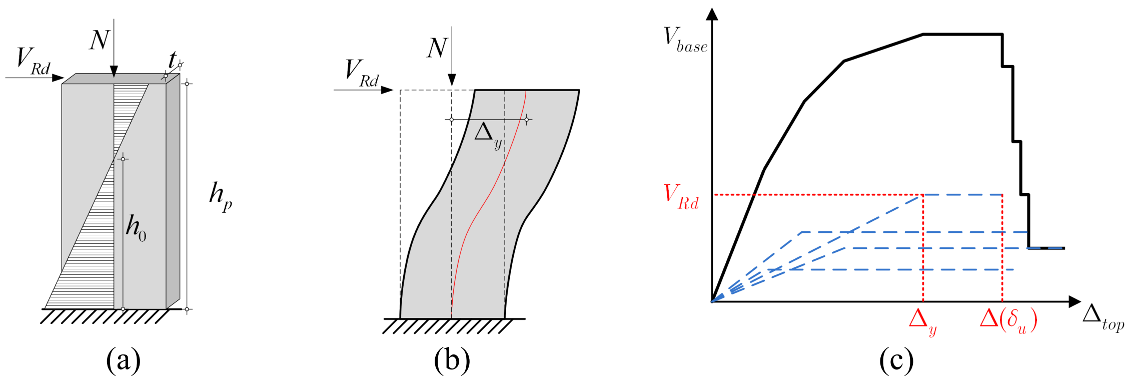


Figure 1. Procedure for determining the total capacity curve. (a) A wall in the bottom level under normal and lateral forces with the diagram of moments. (b) In-plane deformation of the wall. (c) Parameters of capacity curve for the walls (dashed) and the building (solid), where V_{base} is the base shear of the building.

Strength of masonry walls (V_{Rd})

The original methodology (Lang 2002) proposes to estimate the strength of a wall following the stress field theory, as shown in Eq. 1, depending on the design strength of the masonry orthogonal (f_{xd}) and parallel to the mortar bed (f_{yd}), the wall length (l_w), the thickness of the wall (t), the normal force (N) and the height of zero moment (h_0) defined on Figure 1, the angle of inclination (α) and the angle of internal friction (ϕ).

$$V_{Rd} = \min\left(\frac{f_{yd} \cdot l_w \cdot t \cdot N \cdot \tan(\alpha)}{N + N \cdot \tan^2(\alpha) + 2 \cdot f_{yd} \cdot t \cdot h_0 \tan(\alpha)}, \frac{(f_{xd} - f_{yd}) \cdot \tan(\alpha) \cdot t \cdot l_w \cdot N - N^2 \tan(\alpha)}{(f_{xd} - f_{yd}) \cdot \tan(\alpha) \cdot t \cdot 2 h_0 - N}, N \tan(\phi) \right) \quad (1)$$

Despite the theoretical basis of Eq. 1, a scatter in the prediction of V_{Rd} remains (Fehling et al. 2007; Magenes et al. 2008), thus the Eurocode 6 (CEN 1995) formulation is also considered (Eq. 2). An additional parameter is introduced: the shear strength under zero compressive stress f_{vk0}.

$$V_{Rd} = \min\left(\frac{N \cdot l_w}{2 \cdot h_0}\left(1 - 1.15 \cdot \frac{N}{l_w \cdot t \cdot f_{xd}}\right), \frac{1.5 \cdot N \cdot f_{vk0}}{0.85 \cdot f_{xd}} + 0.4 \cdot N \right) \quad (2)$$

Elastic displacement at yield (Δ_y)

The yielding displacement at the top of the studied wall is computed using the principle of virtual work (Lang 2002), thus

$$\Delta_y = V_{Rd} \cdot H_{tot} \cdot \left(\frac{h_p \cdot (3 \cdot h_0 - h_p)}{6 \cdot EI_{eff}} + \frac{\kappa}{GA_{eff}} \right) \quad (3)$$

where H_{tot} is the total height of the wall, h_p is the height of the pier (see Figure 1(a)), $\kappa = \frac{6}{5}$ is the factor form for wall with a rectangular cross section and EI_{eff} and GA_{eff} represent the effective bending and shear stiffness respectively. Note that a constant drift over the height of the building is assumed. In order to improve this assumption, one can compute the top displacement considering the displacement and the rotation of each wall at each storey over the height.

Ultimate drift (δ_u)

Using a linear interpolation of few experimental tests, the original formulation (Lang 2002) for estimating ultimate drift (Eq. 4) as a function the normal stress $\sigma_n = \frac{N}{l_w \cdot t}$, and geometrical parameters h_p and l_w (Figure 1) is:

$$\delta_u = \begin{cases} 0.8 \cdot (0.8 - 0.25\sigma_n) & \frac{h_p}{l_w} < 0.5 \\ 0.8 - 0.25\sigma_n & 0.5 < \frac{h_p}{l_w} < 1.5 \\ 1.2 \cdot (0.8 - 0.25\sigma_n) & \frac{h_p}{l_w} > 1.5 \end{cases} \quad (4)$$

However, when the experimental database of URM walls is extended, one finds a significant scatter. Therefore, another simple formulation (Eq. 5) based in a more extensive study of experimental test is proposed. In addition to consider the same parameters as Eq. 4, it accounts for the strength of masonry f_{xd} and the boundary conditions h_0.

$$\delta_u = \begin{cases} a & \frac{h_p}{l_w} \geq 1 \text{ et } \frac{\sigma_n}{f_{xd}} \leq 0.05 \\ b & \frac{h_p}{l_w} < 1 \text{ et } \frac{\sigma_n}{f_{xd}} > 0.05 \\ \frac{2 \cdot a}{1.85 + 3 \cdot \frac{\sigma_n}{f_{xd}}} & \frac{h_p}{l_w} \geq 1 \text{ et } \frac{\sigma_n}{f_{xd}} \leq 0.05 \\ \frac{2 \cdot b}{1.85 + 3 \cdot \frac{\sigma_n}{f_{xd}}} & \frac{h_p}{l_w} < 1 \text{ et } \frac{\sigma_n}{f_{xd}} > 0.05 \end{cases} \quad (5)$$

Where $a = 0.6 \cdot \frac{\min(h_0, h_p)}{l_w} + 0.3$ and $b = 0.9 \cdot \frac{\min(h_0, h_p)}{l_w} + 0.3 \cdot \frac{h_p}{l_w}$.

A simplified estimation is introduced by the Eurocode 8 (CEN 2003). It proposes two ultimate drift values

$$\delta_u = \begin{cases} 0.8\% \text{ (rocking)} \\ 0.4\% \text{ (shear)} \end{cases} \quad (6)$$

Limitations

Case studies showed that Lang's method does not provide satisfactory results in some cases, especially in high-rise buildings (Bigler 2009) in spite of the precedent modifications. Further studies are currently performed, particularly in the estimation of the elastic deformation shape. However, using proposed modifications, this method is quite satisfactory for low and mid-rise buildings, such as those treated in this paper.

Damage grades

Qualitative and quantitative damage grade (DG) definitions can be significantly different (Hill and Rossetto 2008). The original methodology studied in this paper proposes analytical formulations for the visual criteria from EMS-98 (Grünthal 1998). On one hand experimental measurements based on ambient-vibration approach showed that first analytical DG from Lang are quite conservative (Michel et al. 2008). On the other hand, last DG are deeply related to δ_u estimation, thus some modifications are expected when Eq. 5 is used instead of Eq. 4.

Table 1. Comparison between DG definitions from Lang and the corresponding modifications proposed.

	Lang	**Proposed**
DG1	Displacement corresponding to the **first** wall that reaches the onset of cracking, **neglecting** the tensile strength	Displacement corresponding to the **mean** number of walls that reaches the onset of cracking, **considering** the tensile strength
DG2	Displacement corresponding to the **first** wall that yields	Displacement corresponding to the **mean** number of walls that yields
DG3	Displacement corresponding to the **last** wall that yields	The same as Lang's criterion
DG4	Displacement corresponding to the **first** walls that fails (reaches the δ_u)	The same as Lang's criterion, but using Eq.5 instead Eq. 4
DG5	Displacement corresponding to a $\frac{1}{3}$ drop of the V_{base}	The same as Lang's criterion, but using Eq.5 instead Eq. 4

Probabilistic framework

When determining fragility curves, log-normal median (μ) and standard deviation (β) are needed (Federal Emergency Management Agency 2003). The methodology described before provides only deterministic DG values. However, a simple probabilistic framework can be defined. One knows that there are several sources of uncertainty in this methodology. Hence, the masonry compressive strength f_{xd} can be defined as a random value following a log-normal distribution. Therefore, all the parameters related to this value follow the same random distribution, such as f_{yd}, the elastic modulus E_m, the shear modulus G_m. Similarly, the tensile strength f_t, the shear strength under zero compressive stress f_{vk0}, the effective stiffness $r = \frac{EI_{eff}}{EI} = \frac{GA_{eff}}{GA}$, and the ultimate drift δ_u also follow a log-normal distribution.

Finally, a significant amount of computations needs to be performed (500) and one obtains log-normal median and standard deviation for the DG. The number of computations depends on the convergence of obtained results.

Application to an existing building

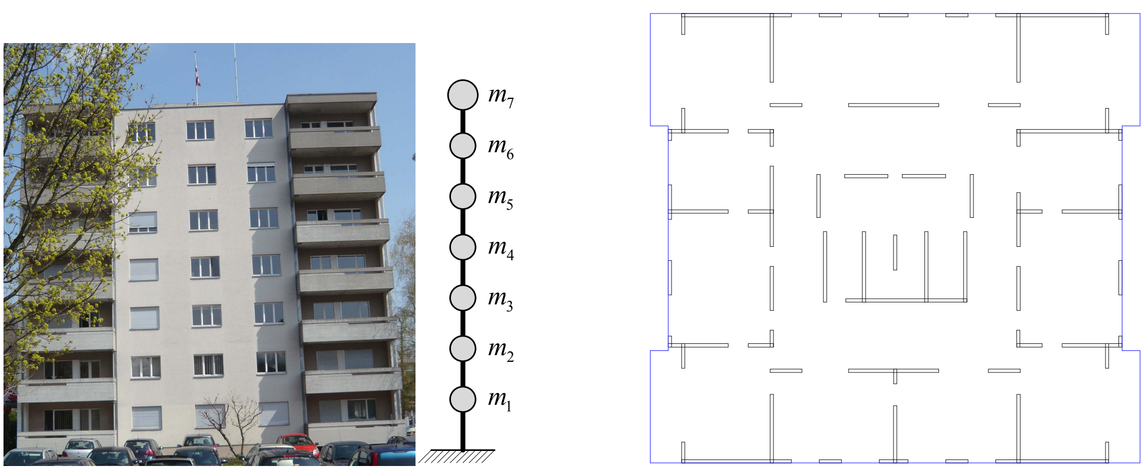
A 7-storey URM building in Delémont (Northern Switzerland) is studied (Figure 2). Table 2 shows the detailed values of μ and β of the studied building, described in Fragility curves section. In this Table f_{xd}, f_{yd}, E_m, G_m, f_t and f_{vk0} are expressed in $[MPa]$; r [-]; and δ_u in [%]. The height of a storey $h_p = 2.5[m]$ is constant. The beam model is considered fully constrained at the base, because the basement of the building.

An elastic finite element model (FEM) was defined in order to determine the height of zero moment h_0. Thus, the elastic displacement can be computed. The elastic displacement following X and Y directions and using an FEM analysis, the proposed methodology and Lang's approach (Figure 3). The proposed estimation provides less conservatives results than Lang's method. However, more research is needed in order to improve it.

Table 2. Detail of the log-normal median and standard deviation values of the different random variables considered in this methodology.

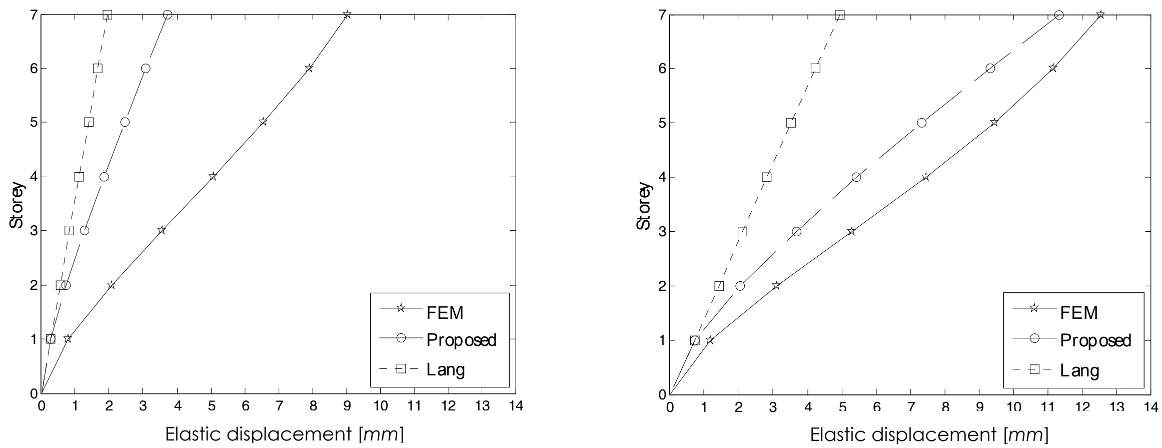
	f_{xd}	f_{yd}	E_m	G_m	f_t	f_{vk0}	r	$\delta_{u\,Lang}$	$\delta_{u\,proposed}$	$\delta_{u\,EC}$
μ	3.5	1.05	3500	1400	0.25	0.2	0.5	Eq. 4	Eq. 5	Eq. 6
β	0.3	0.3*	0.3*	0.3*	0.3	0.3	0.2	0.74**	0.46**	0.55**

* A random value is also added
** Obtained from an experimental database



(a) (b)

Figure 2. The 7-storey URM building in Delémont. (a) Picture of the structure and the corresponding beam model. (b) Plan $(20[m] \times 20[m])$ showing the different URM walls.

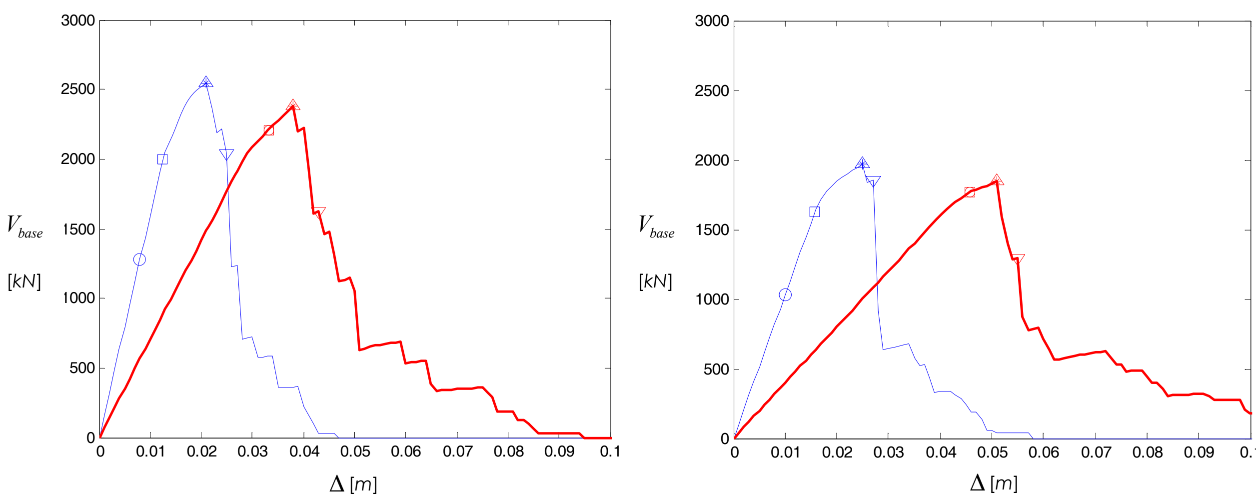


(a) (b)

Figure 3. Elastic displacement following the X and Y directions of the studied building (Delémont). (a) Elastic displacement for the X-direction. (b) Elastic displacement for the Y-direction.

Capacity Curves

In order to compare capacity curves computed with different methods, Figure 4 shows the computed curves using Lang method (blue) and the proposed approach (red). Moreover, the displacements at the damage grades are also represented. Note that proposed methodology provides less conservative results than Lang.

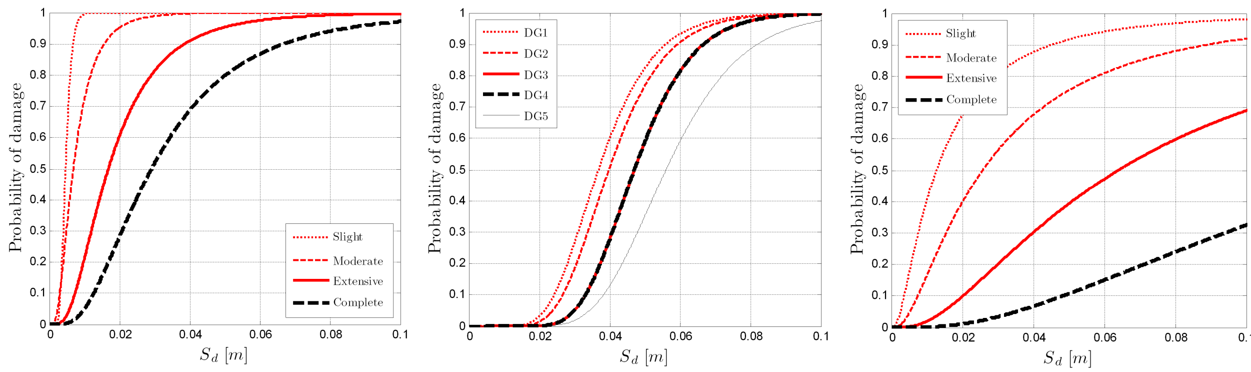


(a) (b)

Figure 4. Capacity curves considering Lang method (blue) and proposed approach (red) over the X and Y directions. The damage grades are also showed: DG1 ○, DG2 ☐, DG3 *, DG4 Δ, DG5 ∇. (a) X direction (b) Y direction.

Fragility Curves

Fragility curves are computed using the probabilistic framework. Figure 5(b) shows the probability of damage as a function of spectral displacement ($S_d[m]$). The latter is defined as the ratio of the top displacement over the modal participation factor.



(a) (b) (c)

Figure 5. Fragility curves. (a) Using data from Risk-UE (class M3.3H). (b) Computed with proposed methodology. (c) Using data from HAZUS (class URMM).

Fragility Curves from HAZUS and Risk-UE

In order to use the data from HAZUS (FEDERAL EMERGENCY MANAGEMENT AGENCY 2003) and Risk-UE guidelines (Milutinovic and Trendafiloski 2003), the studied building should belong to a pre-defined building class. Hence, fragility curves can be estimated using M3.3H (URM building with composite slabs having more than six storeys) from Risk-UE and URMM (URM for building having more than three storeys) from HAZUS (Figure 5(a) and Figure 5(c) respectively). Note that HAZUS is based on US building stock, thus significant differences are expected. Even if it is based on European building classes, differences are also expected, because the proposed methodology studies a particular building instead of a building class. The data provided by Risk-UE consider the topology of Barcelona.

Results, obtained using the proposed methodology, are more conservative than HAZUS and less than Risk-UE. Then, the computed order of magnitude is coherent.

Conclusions

The simplified displacement-based methodology presented in this paper, considering geometrical and mechanical characteristics of buildings, leads to fragility curves. Probabilistic framework is introduced considering the variability of material characteristics and the uncertainty of shear strength estimation and the ultimate drift prediction. Moreover, more realistic DG definitions were used. The proposed methodology can improve fragility functions, especially in regions with moderate seismicity, where URM buildings were not correctly investigated.

In order to show the enhancement obtained with this methodology and the differences observed when it is compared to other methods, an existing 7-storey URM building in Delémont (Switzerland). This application shows that, on one hand URMM (HAZUS) building class does not provide realistic empirical parameters for the current building. On the other hand, one observes that DG's in M3.3H Risk-UE class building remains quite conservative. Indeed, the proposed methodology studies specifically Delémont building, instead of a class such as Risk-UE.

Note that torsional behaviour is negligible in the studied structure. For building with significant asymmetries, further research is needed in order to estimate the impact of torsion in fragility curves.

In this paper, a single building was studied. Studying a set of similar buildings will permit to obtain fragility curves corresponding to a building class without any modification of the proposed methodology.

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