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DRIFT-BASED FRAGILITY ASSESSMENT OF MASONRY INFILLS

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Abstract. *Masonry infills represent one of the prevailing types of non-structural elements in buildings of both Western and Eastern modern architecture. Recent seismic events have provided evidence that damage on masonry infills can lead not only to large economic losses but also to significant injuries and even fatalities. The estimation of damage of such elements and the corresponding consequences within the Performance-Based Earthquake Engineering (PBEE) framework, requires reliable fragility curves. Although there is an important body of work on testing masonry infills, there is very limited work that has led to the definition of fragility functions. This contribution presents drift-based fragility functions developed for in-plane loaded masonry infills, derived from a comprehensive experimental dataset gathered from current literature, comprising 152 specimens of infilled RC or steel frames tested under lateral cyclic loading, with different types of masonry blocks. Three key damage states associated with the structural performance and reparability of infill walls have been defined. In particular, four sources of uncertainty are evaluated: specimen-to-specimen, finite-sample, measured mortar compression strength and prism compression strength, presence of openings. The fragility curves developed in the present study are very useful for estimating damage and expected earthquake-induced economic losses for infilled buildings, by employing recently proposed methodologies based on aggregating the estimated damage at the component level for a specific structure.*

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1 INTRODUCTION

Surveys and reconnaissance missions after recent major earthquakes (L'Aquila, Italy, 2009 [1], Maule, Chile, 2010 [2,3], Muisne, Ecuador, 2016) witnessed that damage to non-structural components often produce most of the earthquake induced economic losses. The reason lies in the fact that non-structural components usually account for a large part of the total cost of buildings and also in the fact that damage to non-structural components is typically induced at much lower levels of lateral displacement than those required to produce structural damage [4].

Masonry represents a widespread structural typology in both Eastern and Western architecture and the mechanics of masonry structures has been studied in-depth since decades (see e.g. [5–17]). In particular, masonry has been widely employed for the construction of infill walls, which are among the commonest non-structural elements, used for exterior closures as well as interior partitions within both reinforced concrete (RC) and steel frame constructions. Masonry infills are usually made of clay bricks (solid or hollow), or concrete units joined with cement or lime mortar. Despite a good number of studies have been proposed on masonry infill walls, most of them have focused on inferring their lateral strength and seismic response essentially by measuring their hysteretic behavior. However, there is quite a limited number of works that have tried to estimate the level of damage as a function of the level of lateral deformations.

Figure 1 depicts a number of pictures taken from buildings hit by the Ecuador 2016 earthquake, illustrating examples of both in-plane and out-of-plane failure of exterior and interior masonry infill walls, pointing out the how the failure of these elements may pose a serious threat to life safety, in addition to widespread economic losses.

Most of current seismic codes are force-based and therefore primarily rely on checking on the strength of structural elements giving a secondary importance to lateral deformations [18]. As a consequence, that there is an important body of work addressing the assessment of the strength of masonry infill walls and their influence on building response, whereas very few studies have been finalized to estimating damage evolution based on imposed lateral deformations (see e.g. [19]).

Recently, an increasing interest is drawn by performance-based seismic assessment procedures [20,21], which are aimed at assessing the seismic risk of man-made facilities while considering most of potential sources of uncertainty. In particular, Performance-Based Earthquake Engineering (PBEE) developed by the Pacific Earthquake Engineering Research Center (PEER) is a fully probabilistic framework which explicitly and rationally accounts for uncertainties propagating from the seismic hazard, seismic response, damage estimation and loss estimation. For instance, based on the PBEE framework, Aslani and Miranda [22] developed a building-specific loss estimation methodology in which the expected annual loss EAL is computed as the sum of expected losses in each component at a given level of ground motion intensity and then integrating over the mean annual frequencies of exceeding of all possible intensities as follows:

$$EAL = \int_0^\infty \sum_{j=i}^{n} E\left[L_j \mid IM = im\right] \left| \frac{d\nu(IM)}{d(IM)}\bigg|_{im} \right| d(IM)$$

with (1)

$$E\left[L_j \mid IM = im\right] = \int_0^\infty \sum_{i=1}^{m} E\left[L_j \mid DS = ds_i\right] P\left[DS = ds_i \mid EDP_j = edp\right] dP\left[EDP_j > edp \mid IM = im\right]$$

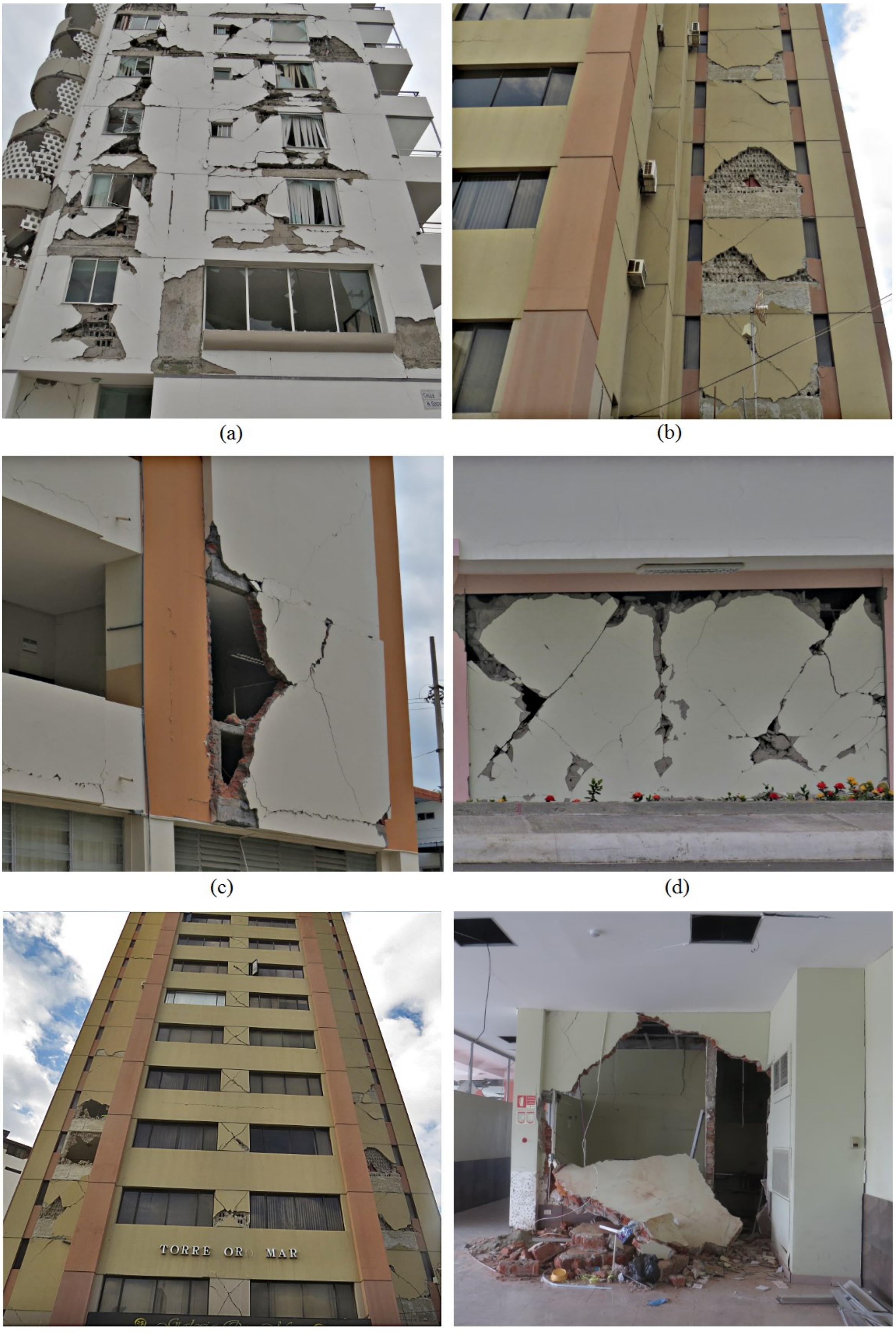

Figure 1: Masonry infills damaged after the Ecuador 2016 earthquake (photos by E. Miranda).

where $E[L_j \mid DS = ds_i]$ is the expected loss in the j-th component given that it has reached damage state ds_i whereas $P[DS = ds_i \mid EDP_j = edp]$ is the probability that the j-th component will reach or exceed damage state ds_i conditioned on undergoing an engineering demand parameter (*EDP)* equal to *edp*; *n* is the total number of components whereas *m* is the total number of damage states considered. Furthermore, $P[EDP_j > edp \mid IM = im]$ is the exceedance probability of the engineering demand parameter *edp* conditioned on the intensity measure *IM* reaching the value *im* and $\nu(IM = im)$ is mean annual frequency of exceedance of $IM = im$, that is, the ordinate of the site-specific seismic hazard curve at $IM = im$. In Eq. (1), $P[DS = ds_i \mid EDP_j = edp]$ is what is commonly referred to as the fragility function, providing information on the probability of reaching or exceeding various damage states at increasing levels of building response, for example at increasing levels of peak interstory drift.

In modern performance-based seismic assessment ‘procedures, damage estimation to most structural and nonstructural components is done as a function of interstory drift demands. It is clear from Eq. (1) that those performance assessment methodologies rely on the availability of fragility functions. For example, Aslani and Miranda [23] developed drift-based fragility curves for slab-column connections in non-ductile RC structures. Similarly, Ruiz-Garcia and Negrete [24] proposed drift-based fragility curves for confined masonry walls.

However, there is very little research specifically addressing the development of drift-based fragility functions for masonry infills. Two notable exceptions are the recent work by Cardone and Perrone [25] and the work by Sassun et al. [26] who, to the best or our knowledge, proposed the first drift-based fragility functions for masonry infill walls. Although both of these studies are extremely valuable, they are based on a relatively small sample and limited statistical analyses were conducted to determine which are the main variables that lead to statistically significant fragilities.

The aim of the present contribution is to summarize drift based fragility functions obtained in [27] based on a wide and up-to-date survey of experimental results contained in literature on in-plane loaded infilled frames, suitably defining three damage states strictly related to the repair/replacement actions required as a result of the damage state. Main sources of uncertainty have been accounted for in a sound probabilistic treatment of collected data.

2 DEFINITION OF THE DAMAGE STATES

Three discrete damage states are defined, which describe the evolution of damage in masonry infills undergoing earthquake-type in-plane loading. The damage states have been defined based on the damage patterns observed both experimentally and on reconnaissance missions in buildings hit by strong seismic events.

- **Damage State 1 (DS_1).** Initiation of small hairline cracks in masonry, up to 2mm wide, mainly concentrated in bed and head joints, in plaster or along the interfaces with the columns and/or the top beam of the frame. No significant joint sliding and crushing of the units is observed. DS_1 requires only very light and simple repair interventions.
- **Damage State 2 (DS_2).** Beginning of significant cracks, even diagonal, more than 2mm wide, propagating through both mortar joints and masonry blocks with possible but very limited sliding between joints and localized crushing of units (for example at the corners). Heavier interventions are required to repair an infill in this damage state.
- **Damage State 3 (DS_3).** Development of wide diagonal cracks (larger than 4mm) with significant sliding between joints and widespread crushing and spalling of masonry units. Repairing is not economically convenient, demolition and reconstruction are advised.

Figure 2: Example of damage states: DS_1 (a-b), DS_2 (c-d), DS_3 (e-f) (photos by E. Miranda).

3 EXPERIMENTAL DATASET

Experimental results from 152 specimens of masonry infilled RC or steel frames, tested under lateral cyclic loading were collected from literature, in order to infer the required statistical information about the lateral displacement capacity of masonry infills. A careful interpretation of the collected data allowed to determine the *IDR* for which each specimens experienced the onset of one or more of the damage states defined in the previous Section. More precisely, data from 33 experimental research programs conducted over the last 32 years were considered, in which specimens were not excessively scaled in size and a description of the damage was provided with sufficient detail at various stages of testing. Three different kind of masonry units, corresponding to the most prevailing types actually employed in the construction practice, were used for the specimens analyzed: solid clay bricks, hollow clay bricks and concrete masonry units. Infill specimens with the presence of openings were also included. In addition to the drift levels at which one or more of the defined damage states occurred, information about the measured compressive strength for both mortar and the masonry prism, the dimensions of the panel and presence of openings were also compiled. We refer the interested reader to [27] for further details on the dataset used.

4 FRAGILITY FUNCTIONS

The *IDR* at which each damage state was observed in the masonry infilled specimens exhibits relatively large specimen-to-specimen variability. This variability can be explicitly taken into account by building drift-based fragility functions describing the likelihood for a given infill panel of exceeding a certain damage state conditioned to an assigned *IDR*. The experimental dataset described is used for deriving fragility functions for each damage state. Furthermore, the influence of factors such as block type, mortar and masonry compressive strengths and presence of openings were analyzed. For each damage state, a cumulative frequency distribution is obtained by plotting interstory drift ratios IDR_i at which the damage state was observed, sorted in ascending order, against an plotting probability F_i. A lognormal distribution have been chosen for fitting this experimental cumulative frequency distribution:

$$P(DS \geq ds_i \mid IDR = \delta) = 1 - \Phi\left(\frac{\ln(\delta) - \mu_{\ln(\delta)}}{\beta}\right) \tag{2}$$

where $P(DS \geq ds_i \mid IDR = \delta)$ is the conditional probability of reaching or exceeding a certain damage state ds_i in the masonry infill at a specific *IDR* value equal to δ. $\mu_{\ln(\delta)}$ and β represent the central tendency and the dispersion parameters of the cumulative standard log-normal distribution Φ. The two parameters characterizing the log-normal distribution are estimated according to the method of moments. Table 1 contains the statistical parameters for the fitted lognormal probability distribution for each damage state.

Damage State	$\overline{IDR}$ [%]	$\mu_{\ln(\delta)}$	β	Number of Specimens
DS_1: light cracking	0.125	-2.078	0.325	100
DS_2: moderate cracking	0.327	-1.118	0.278	118
DS_3: heavy cracking	0.820	-0.198	0.320	132

Table 1: Statistical parameters estimated for IDRs corresponding to the three damage states.

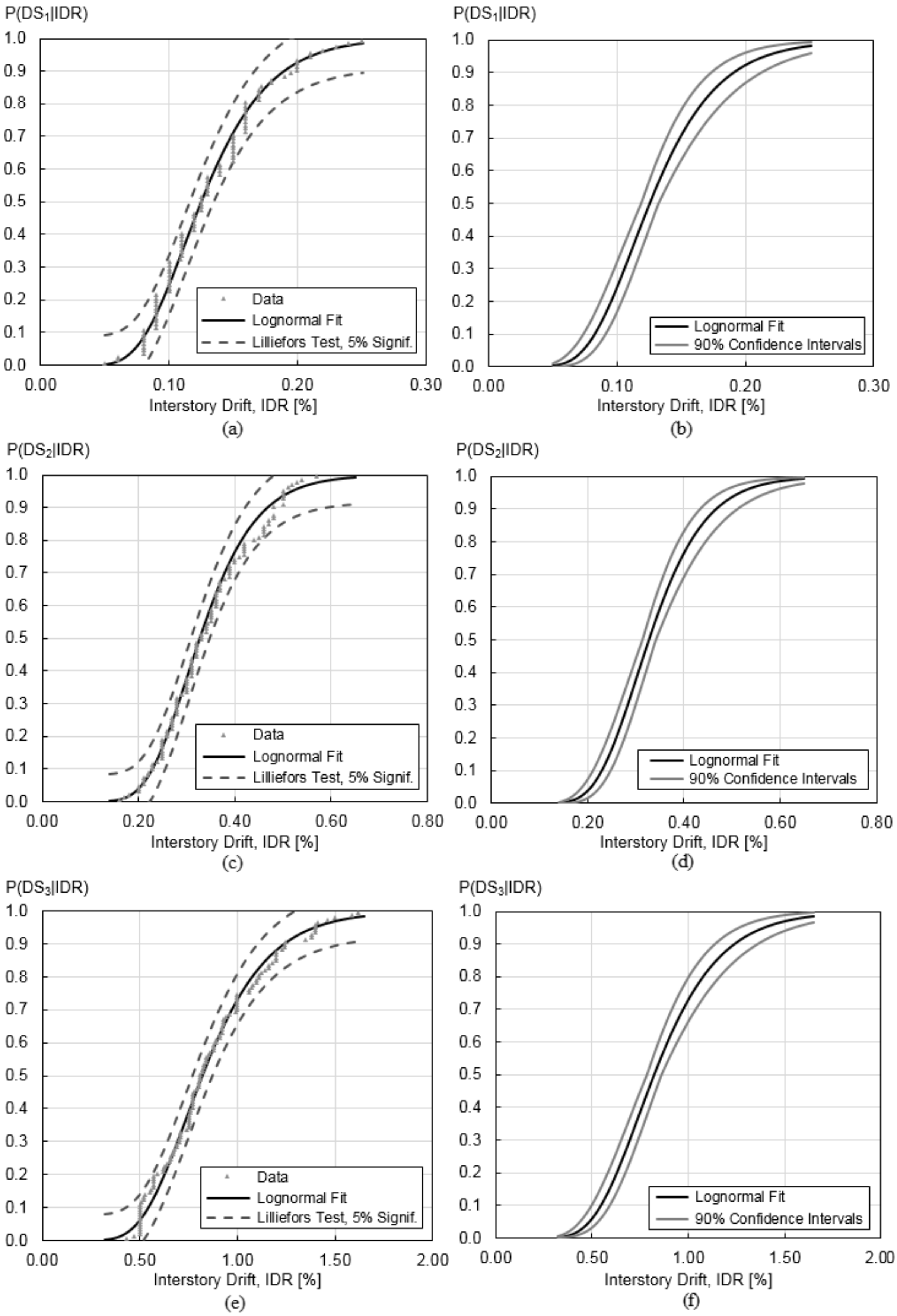

Figure 3: Fragility functions for damage states DS_1 (a-b), DS_2 (c-d), DS_3 (e-f).

A Lilliefors goodness-of-fit test at 5% significance level was conducted for each fragility function (see [28]). Figure 3(a-c-e) depict, for each damage state, the empirical cumulative distributions of observed data, the proposed fragility functions obtained through log-normal fit, and a graphical representation of the Lilliefors test.
The additional uncertainty due to the fact that the parameters defining the proposed fragility functions have been estimated from a limited number of specimens (finite-sample uncertainty) has been evaluated by computing the confidence intervals (see, e.g., [29]) for each of the statistical parameters defining the assigned fragility function (see Figure 3(b-d-f)).
Fragility curves portrayed in Figure 3(a-c-e) were obtained by considering all 152 specimens without taking into account the possible effects of brick type, material properties or geometry. To assess if brick type has any significant influence on the likelihood of attaining a certain damage state, two-sample t-tests have been conducted to establish if the logarithmic means of the three samples significantly differs from each other. As shown in [27], brick type, per se, turns out not to have a clear impact on the fragility function of a masonry infill. However, it is expected that a more consistent and statistically significant influence on fragility is provided by measures of mortar or masonry prism compressive strengths.
In order to study whether the level of compressive strength for mortar f_m has some influence on the probability of exceeding a given damage state, the initial dataset has been subdivided into three subgroups according to mortar strength: infills with weak mortar, for which $f_m \leq 5\,\text{MPa}$, infills with medium mortar strength, for which $5\,\text{MPa} < f_m \leq 12\,\text{MPa}$, and infills with strong mortar, for which $f_m > 12\,\text{MPa}$. Fragility functions are computed through lognormal fitting for each dataset and for each damage state. Figure 4(a) depicts fragility curves for damage state DS_1 and the three levels of mortar strength. From an analysis of the results, a significant dependence on mortar strength for damage states DS_1 and, to a less extent, DS_2 is observed. On the other hand, damage state DS_3 seems not to be significantly influenced by mortar strength. A possible explanation is that, while at low damage levels the damage pattern involve significant cracking in the mortar, at higher levels of damage cracks and damage primarily involve also masonry units.

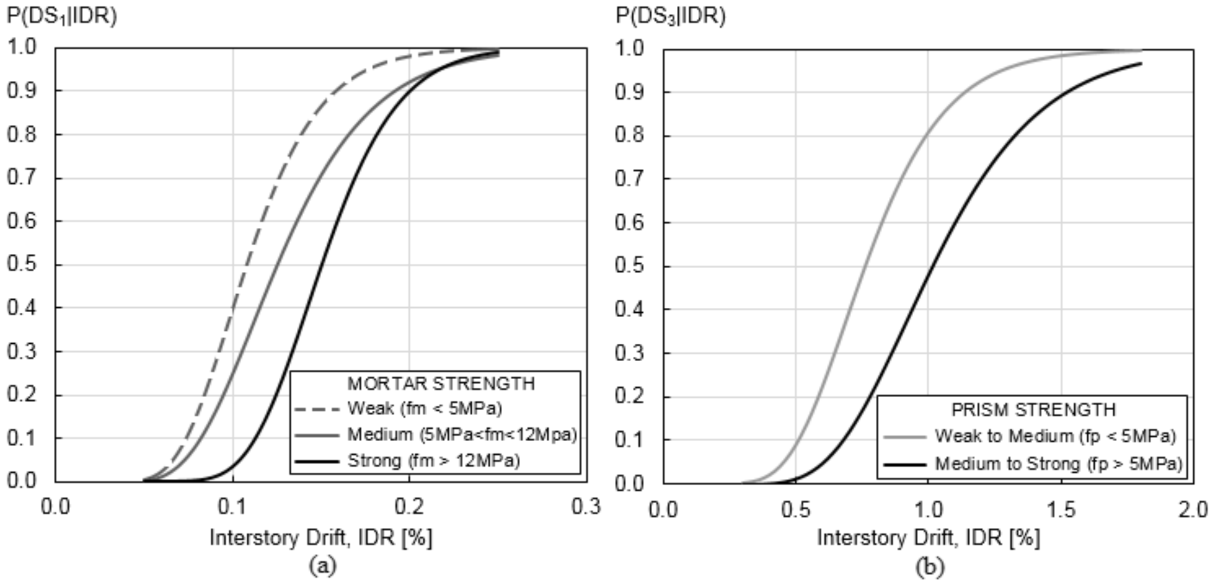

Figure 4: (a) Fragility functions for damage state DS_1 and three different levels of mortar strength and (b) fragility functions for damage state DS_3 with two different levels of masonry prism strength.

For this reason, it is also interesting to investigate whether masonry prism compressive strength f_p, which accounts for the strength of both mortar and bricks, influences significantly the *IDR* for which all three damage states are attained by a given masonry infill. To this aim, the initial dataset has been subdivided according to prism compressive strength into two subgroups: infills with weak to medium prism strength, for which $f_p \leq 5\,\text{MPa}$, and infills with medium to strong prism strength, for which $f_p > 5\,\text{MPa}$. Again, fragility functions are computed through lognormal fitting for the two dataset and for each damage state. It turns out that compressive prism strength, as expected, influences significantly all three damage states. In particular, Figure 4(b) depicts fragility curves obtained for damage state DS_3 and the three levels of prism compressive strength. Further statistical analyses are possible, which allow to incorporate uncertainties from mortar and masonry strength into fragility functions leading to bi-variate fragility functions (i.e. fragility surfaces, see [22]), like the one shown in **Figure 5** for mortar compressive strength. More details are contained in [27].

Finally, the presence of openings can, as well, influence the *IDR* level at which infills experience a given damage state. Unfortunately, the number of specimens with openings in the initial dataset (i.e. 38) is rather limited compared to the number of specimens without openings (i.e. 114), thus preventing a combined analysis of the influence of openings and material compressive strength. However, is still possible to assess whether the presence of openings in the specimens is significantly influential when comparing *IDR* values at the onset of a given damage state with the same values observed for specimens without openings. From an analysis of the results, it can be seen that the probability of reaching or exceeding damage states DS_1 and DS_2 is statistically different for infill masonry walls with or without openings. On the contrary, no statistically significant influence is observed for damage state DS_3.

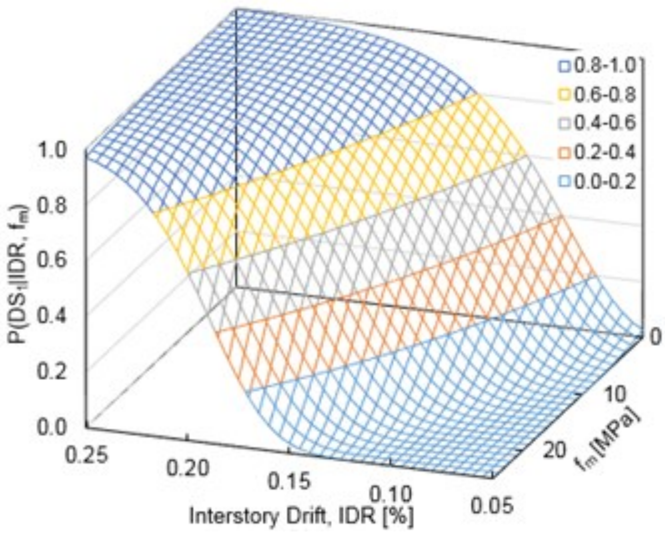

Figure 5: Fragility surface to estimate damage state DS_1 as a function of IDR and compressive mortar strength.

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