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IN-PLANE FRAGILITY ASSESSMENT OF MASONRY INFILL PANELS

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ABSTRACT

Recent seismic events have provided clear evidence that damage on masonry infills can lead not only to large economic losses and downtime but also to significant injuries and even fatalities. Reliable fragility curves are required for the estimation of damage of such elements and the corresponding consequences within the Performance-Based Earthquake Engineering (PBEE) framework. Despite an important number of previous studies on in-plane testing of masonry infills, very limited work on development of fragility functions has been published. This paper 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 masonry infilled RC or steel frames tested under in-plane lateral cyclic loading, with different types of masonry blocks. Three damage states associated with the structural performance and reparability of infill walls have been defined. Moreover, two sources of uncertainty are carefully evaluated: specimen-to-specimen and finite-sample. Additionally, the effects of measured mortar compression strength and prism compression strength, as well as the presence of openings are evaluated. The fragility curves developed in the present study can be 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.

Keywords: Fragility Functions, Masonry Infills, Drift Demands, Damage States

1. INTRODUCTION

Surveys and reconnaissance missions after recent major earthquakes such as the L'Aquila, Italy, 2009 (Braga, Manfredi, Masi, Salvatori, and Vona, 2011), the Maule, Chile, 2010 (Fierro, Miranda, and Perry, 2011; Miranda, Mosqueda, Retamales, and Pekcan, 2012), and the Muisne, Ecuador, 2016 earthquakes showed that damage to non-structural components often produces 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 but also in the fact that damage to non-structural components is typically triggered at lateral displacement levels much lower than those required to produce structural damage (Taghavi and Miranda, 2003).

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. (Como, 2013)). 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 that have tested masonry infill walls, most of them have focused on determining their lateral strength and evaluating their seismic response 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.

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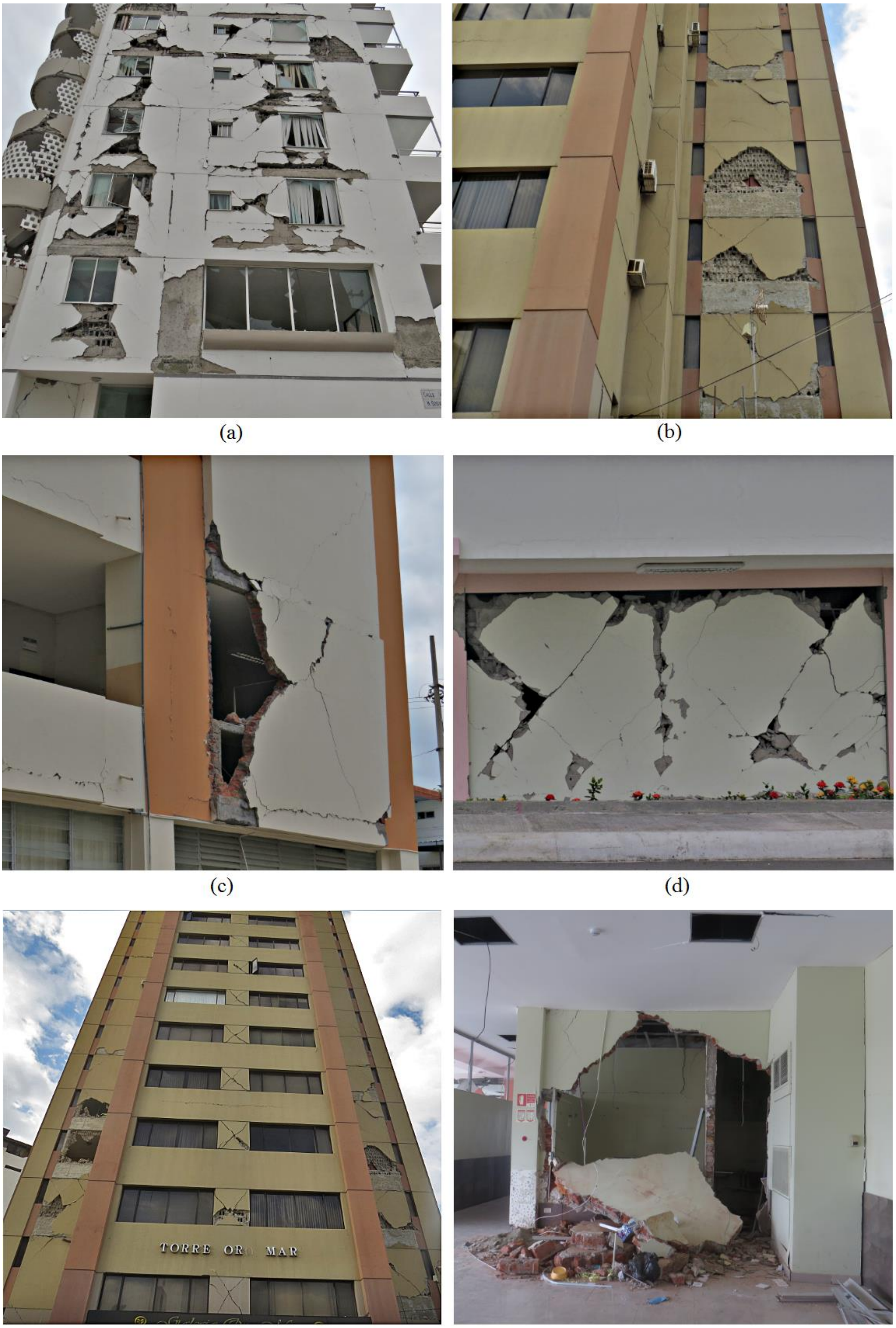

Figure 1: Masonry infills damaged after the Ecuador 2016 earthquake (photos by E. Miranda).

Figure 1 depicts several 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 (Colangelo, 2013). As a consequence, 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 conducted to estimate the damage evolution based on imposed lateral deformations (see e.g. (Ricci, De Risi, Verderame, and Manfredi, 2012)).

Recently, there has been an increasing interest on performance-based seismic assessment procedures (Deierlein, 2004; Krawinkler and Miranda, 2004), which are aimed at assessing the seismic risk of man-made facilities while considering most of potential sources of uncertainty. In particular, the Performance-Based Earthquake Engineering (PBEE) methodology 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 (Aslani and Miranda, 2003) 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:

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

with (1)

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

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 as a function of increasing levels of building response, for example as a function of 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 (Aslani and Miranda, 2005) developed drift-based fragility curves for slab-column connections in non-ductile RC structures. Similarly, Ruiz-Garcia and Negrete (Ruiz-García and Negrete, 2009) 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 (Cardone and Perrone, 2015) and the work by Sassun et al. (Sassun, Sullivan, Morandi, and Cardone, 2016) 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 different fragilities.
The aim of the present contribution is to summarize drift-based fragility functions developed in (Chiozzi and Miranda, 2017) 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. DAMAGE STATES DEFINITION

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, 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, and therefore demolition and reconstruction are advised.

3. EXPERIMENTAL DATABASE

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 interstory drift ratio (IDR) for which each specimen 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 downscaled 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 Chiozzi and Miranda (2017) 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 developing 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 various factors such as block type, mortar and masonry compressive strengths and presence of openings were carefully analyzed. For each damage state, a cumulative frequency distribution was obtained by plotting interstory drift ratios IDR_i at which the damage state was observed, sorted in ascending order, against a plotting probability F_i. A lognormal distribution was 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 were estimated according to the method of moments. Table 1 contains the statistical parameters for the fitted lognormal probability distribution for each damage state. A Lilliefors goodness-of-fit test at 5% significance level was conducted for each fragility function (see (Lilliefors, 1967)). Figure 2(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., (Crow, Davis, and Maxfield, 1960)) for each of the statistical parameters defining the assigned fragility function (see Figure 2(b-d-f)).
Fragility curves portrayed in Figure 2(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 were conducted to establish if the logarithmic means of the three samples differs significantly from each other. As shown in (Chiozzi and Miranda, 2017), brick type, per se, seems to have a clear influence only for some damage states. For example, a significant difference is found for the IDR corresponding to damage state DS3 between solid clay bricks and hollow clay bricks, in agreement with the findings contained in (Sassun et al., 2016). However, it is expected that a more consistent and statistically significant influence on fragility is provided by quantitative 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 was 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 were computed through lognormal fitting for each dataset and for each damage state. Figure 3(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 for this 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.

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.

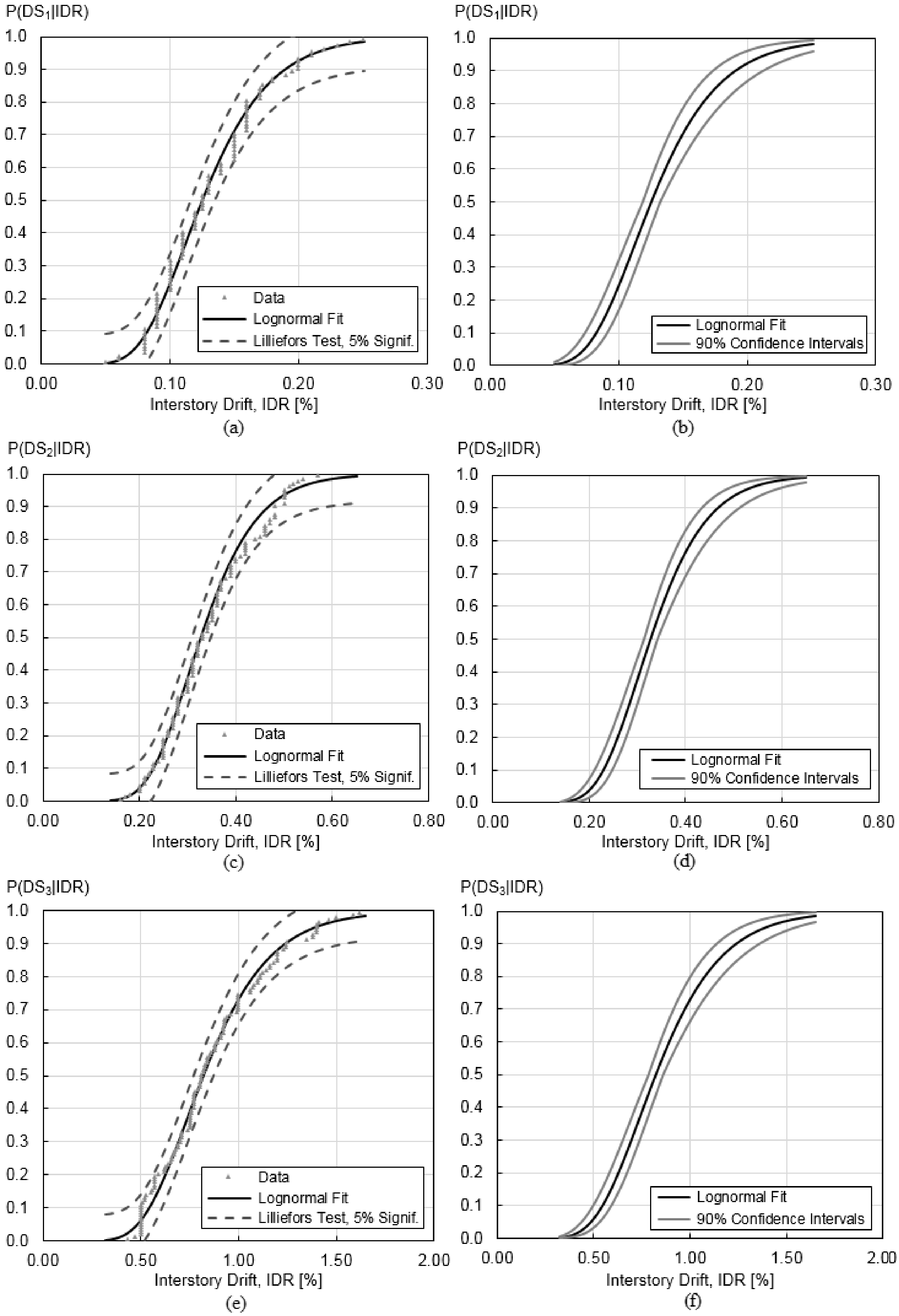

Figure 2: Fragility functions for damage states DS_1 (a-b), DS_2 (c-d), DS_3 (e-f).

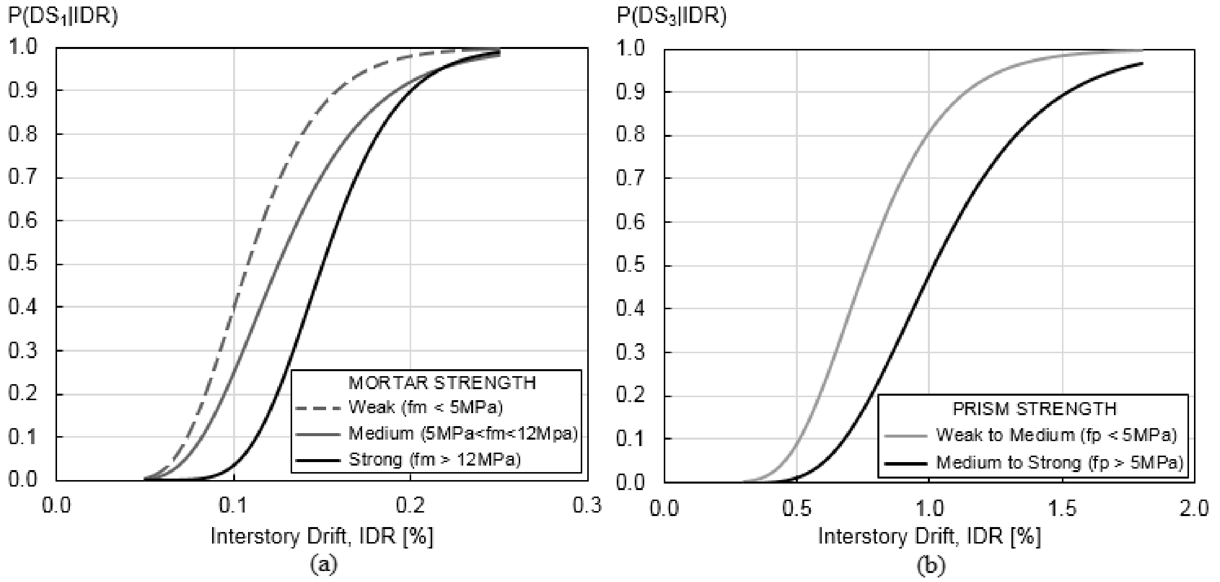

Figure 3: (a) Fragility functions for damage state DS1 and three different levels of mortar strength and (b) fragility functions for damage state DS3 with two different levels of masonry prism strength.

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 was further 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 were 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 3(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 (Aslani and Miranda, 2003)), like the one shown in Figure 4 for mortar compressive strength. For more details the reader is referred to (Chiozzi and Miranda, 2017).

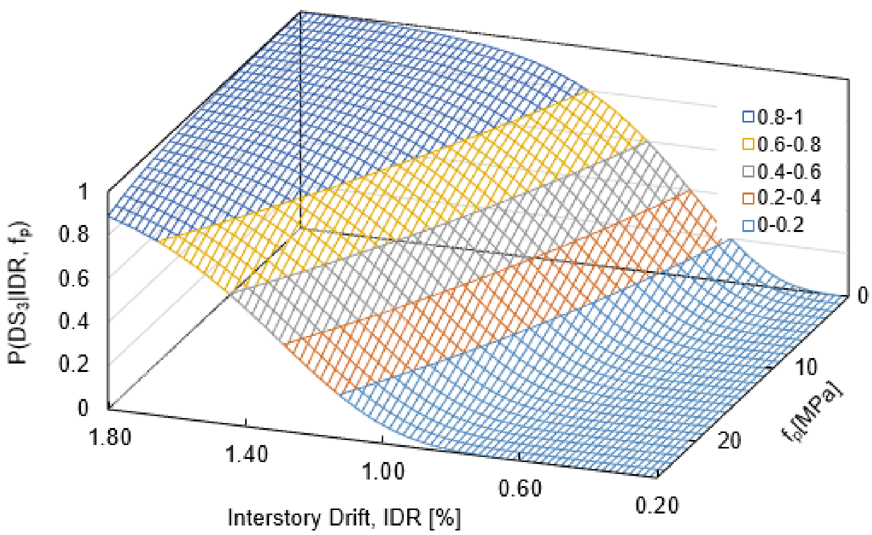

Figure 4: Fragility surface to estimate damage state DS3 as a function of IDR and compressive mortar strength.

Finally, the presence of openings can also 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, it 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.

5. SUMMARY AND CONCLUSIONS

Drift-based fragility functions providing a probabilistic estimation of the level of damage experienced in masonry infill walls in reinforced concrete and steel frame buildings have been developed. The new fragility functions were developed for three damage states which were defined based on damage patterns observed both in laboratory tests as well as on damaged buildings after earthquakes and on the associated required repair actions. A large experimental dataset based on 33 different investigations comprising a total of 152 specimens was gathered and used as the basis for the development of drift-based fragility curves. Experimental results are limited to in-plane loading only, so the fragility functions are aimed at estimating only in-plane damage. Out-of-plane response or interaction of in-plane and out-of-plane loading are not accounted for. The hypothesis that lognormal distribution suitably describes collected data was confirmed through Lilliefors goodness-of-fit tests.
From the analysis of the various parameters controlling the seismic performance of masonry infills and of the variability which introduces uncertainty in determining the damage state in a given masonry infill for a given level of drift demand, it has been found that brick type does not seem to introduce a clear statistically significant influence on fragility functions. On the contrary, compressive strength of mortar was shown to significantly influence the attainment of lower damage states DS_1 and DS_2, whereas masonry prism compressive strength has a significant influence on all three damage states. For these reasons, bivariate fragility functions (fragility surfaces) were also developed taking into account both *IDR* and materials compressive strength for cases in which such information is available or can be estimated. Even if the sample size of specimens with openings was not large enough to allow an analysis of the influence of opening combined with other sources of variability, results indicate that presence of openings significantly decreases the average *IDR* required to reach damage states DS_1 and DS_2, whereas no clear influence of openings was observed for damage state DS_3.
The drift-based fragility functions developed in this study provide a powerful tool for estimating damage in masonry infills and can be used in a probabilistic performance-based assessment framework. For cases in which no information of the mortar strength and/or prism masonry strength is available, fragility functions that are only a function of *IDR* can be used. However, for cases in which the mortar strength and/or prism masonry strength are known or can be estimated, fragility surfaces are proposed, which provide an improved estimate of the probability of reaching or exceeding various damage states.

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