Seismic Safety Evaluation of Turkish URM Buildings by Considering Both In-Plane and Out-Of-Plane Behavior

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SUMMARY:
This study focuses on the evaluation of seismic safety of unreinforced masonry (URM) buildings in Turkey by using fragility curves generated for two behaviour modes of load bearing walls: in-plane and out-of-plane. During generation of fragility curves, a force-based approach has been used. There exist two limit states in terms of base shear strength for in-plane behavior mode and flexural strength for out-of-plane behaviour mode. To assess the seismic vulnerability of Turkish URM buildings, fragility curves generated for in-plane behaviour, verified by observed damage during the 1995 Dinar earthquake, and for out-of-plane behaviour, verified by observed damage during the 2010 Elazığ earthquake, are combined. In the final phase, a single-valued parameter, called as "vulnerability score", is proposed to compare the seismic safety of URM buildings in Fatih subprovince of Istanbul and to assess the influence of out-of-plane behavior together with the in-plane behavior of these existing masonry buildings.

Keywords: unreinforced masonry, fragility, in-plane, out-of-plane, vulnerability score

1. INTRODUCTION

This study is focused on the assessment of in-plane and out-of-plane seismic vulnerabilities of unreinforced masonry (URM) buildings in Turkey through the use of fragility functions. By considering the previous research and site investigations, four major parameters are used in order to classify masonry buildings with in-plane behavior mode. These are number of stories, strength of load-bearing wall material, regularity in plan and the arrangement of walls (required length, openings in walls, etc.). In addition to these four parameters, floor type is also taken into account for the generation of fragility curves by considering out-of-plane behavior mode. During generation of fragility curves, a force-based approach has been used. In this study, there exist two limit states, or in other words, three damage states in terms of base shear strength for in-plane behavior mode and flexural strength for out-of-plane behavior mode. To assess the seismic vulnerability of URM buildings in Turkey, fragility curves generated for in-plane behavior, which is verified by damage statistics obtained during the 1995 Dinar earthquake, and for out-of-plane behavior, which is verified by damage statistics obtained during the 2010 Elazığ earthquake, are combined. Throughout the analysis, ground motion uncertainty, material variability and modeling uncertainty have also been considered.

Final part of the study is devoted to the development of a seismic vulnerability assessment procedure for populations of Turkish URM buildings. The procedure is mainly based on score assignment and it employs the generated fragility curves (for in-plane and out-of-plane responses) to rank masonry buildings in accordance with their existing vulnerabilities. The proposed methodology is then used in Fatih, Istanbul, which is the study region for Istanbul Masterplan Project, as the first (preliminary) stage of a two-stage seismic risk evaluation methodology.

2. IN-PLANE FRAGILITY OF TURKISH URM BUILDINGS

For the generation of fragility curves of Turkish URM buildings by considering in-plane behaviour only, a force-based approach was employed. The first phase is to develop generic models in accordance with the major structural parameters determined for Turkish masonry construction; namely number of stories, plan geometry, material type and quality, wall ratio and distribution of openings in masonry walls. Then the procedure is considered in two parts in order to generate demand and capacity statistics required for the generation of the fragility curves. For the determination of capacity, nonlinear static procedure is applied to the generated models. Then two limit states, which represent the serviceability (LS-1) and ultimate (LS-2) states respectively, are attained based on the capacity evaluation. The uncertainty in capacity is taken into consideration. For the determination of demand, a set of ground motion records are employed in order to simulate record-to-record variability. Seismic hazard parameter is selected as peak ground acceleration (PGA) in order to assess the fragility of rigid masonry structures. Then time-history analyses are employed in order to obtain seismic response of generic building models by applying the selected set of ground motion records. The final step is to compare the demand and capacity statistics (in terms of shear force) to determine the probabilities of exceeding the prescribed limit states given the intensity of seismic hazard in terms of PGA. The selected fragility function is the standard normal cumulative distribution. Overall, 120 different classes of fragility curve sets are generated for Turkish URM buildings, which have been classified according to the aforementioned major structural parameters. Typical fragility curves that represent the in-plane vulnerability of Turkish URM buildings of different number of stories, plan geometry, material type and quality are presented in Fig.2.1. The fragility curves indicate that for the selected classes of URM buildings, the probability of exceeding LS-2 increases with the increase in number of stories and plan irregularity, decrease in material quality and strength.

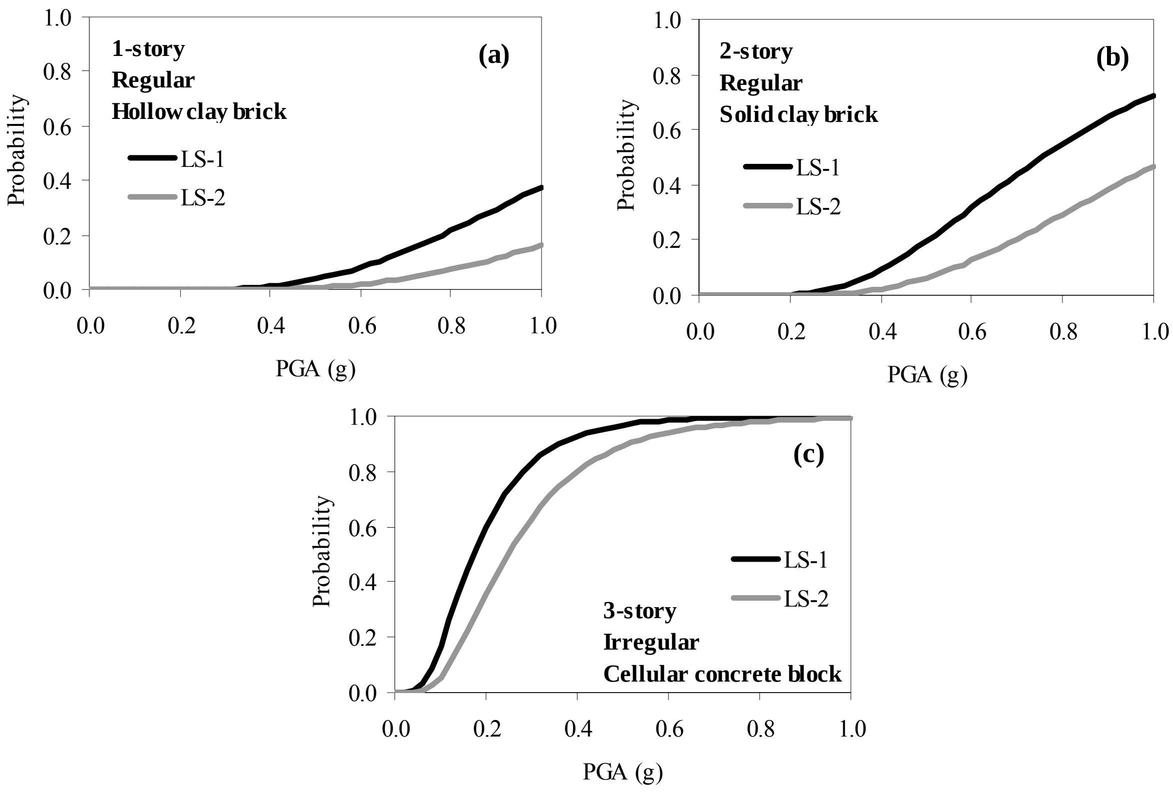

Figure 2.1. Typical fragility curve sets for in-plane behaviour of (a) a single story, regular masonry building with moderate quality hollow clay brick units; (b) a two story, regular masonry building with moderate quality solid clay brick units; (c) a three story, irregular masonry building with poor quality cellular concrete blocks.

The generated fragility curves are verified by comparing the estimated damage obtained from the fragility curves with the actual damage after the 1995 Dinar earthquake (M_w=6.1) as assessed from the Damage Evaluation Forms. More details about the fragility curve generation and the verification process can be found elsewhere (Erberik 2008).

3. OUT-OF-PLANE FRAGILITY OF TURKISH URM BUILDINGS

The recent moderate (M_w=6.0) earthquake in Elazığ, Turkey, by which 41 people were killed, reminded the importance of out-of-plane vulnerability of Turkish URM buildings, especially the rural ones (Akkar *et al*., 2011). After this earthquake, it was once more realized that out-of-plane wall failures impose a significant risk to the people living in these buildings, since they may be trapped in by this type of failure, which may lead to partial or complete collapse of the building. Hence it is misleading to evaluate the seismic vulnerability of masonry structures without considering the out-of-plane behavior.

The fragility curves for out-of-plane response are generated by using a force-based approach for some reasons. First, the method should be simple and practical since it is going to be applied to a population of buildings rather than an individual building in a short period of time. Furthermore, the selected method should be consistent with the one used for in-plane fragility of masonry buildings, in which a force-based approach was selected, so that they could be used together to yield the overall vulnerability of URM buildings. The fragility curve generation method is composed of four steps: determination of seismic demand, determination of capacity, determination of probabilities of exceedance by comparing demand and capacity, and finally the generation of continous fragility functions. In the first two steps, equivalent lateral static analysis (for demand) and out-of-plane moment versus curvature analyses (for capacity) are employed for the most critical face-loaded wall of the upper-most story of the masonry building. Uncertainty in demand, capacity and modeling are all taken into account and sampling is carried out by Latin Hypercube Method. Two limit states are considered, just like in the case on in-plane response. The hazard parameter is taken as PGA. Fig.3.1 and 3.2 present the fragility curves for out-of-plane response of a typical three-story URM building, which is made of hollow clay brick units. The fragility curves are generated for two different floor types: rigid RC floor slab (nearly fixed wall-to-floor connections) and flexible wooden slab (nearly hinged wall-to-floor connections) and for the most critical face-loaded masonry wall of each story. From the figures it is clear that the seismic vulnerability in the out-of-plane direction is critical for the upper-most stories of masonry buildings, which is a consistent observation with the damage surveys after major earthquakes. Furthermore, the out-of-plane vulnerability seems to increase further in the presence of flexible floors.

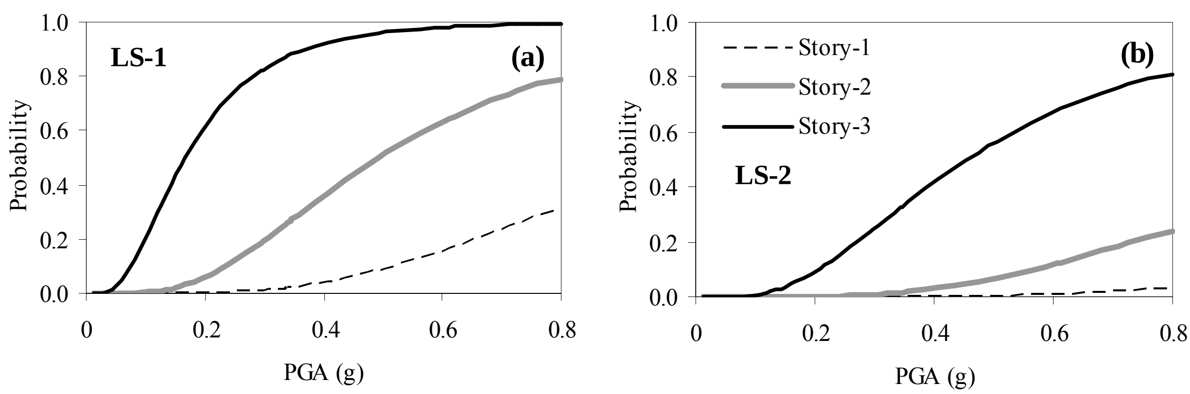

Figure 3.1. Fragility curves for a typical three story URM building with RC floor slab (nearly fixed boundary conditions) according to the story number where the critical face-loaded wall is located and for a) LS-1, b) LS-2

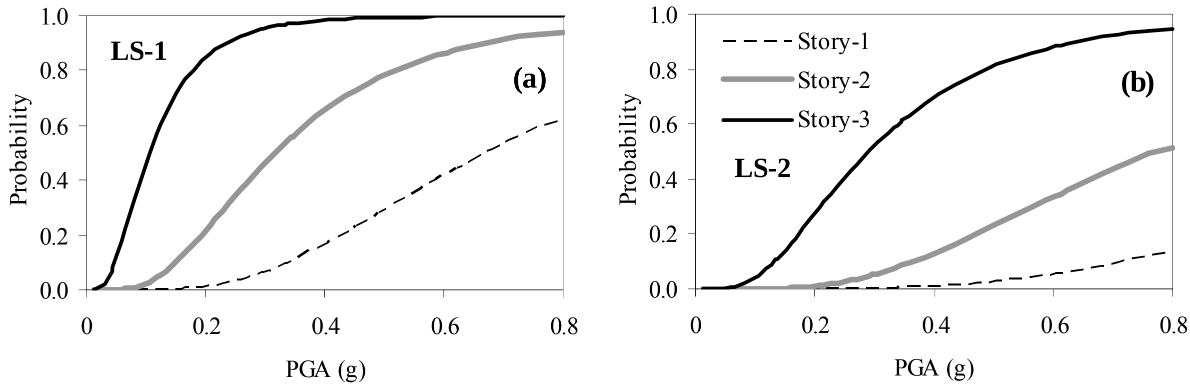

Figure 3.2. Fragility curves for a typical three story URM building with wooden floor slab (nearly hinged boundary conditions) according to the story number where the critical face-loaded wall is located and for a) LS-1, b) LS-2

Then the generated fragility curves for out-of-plane response are employed to estimate the damage of rural masonry buildings in Elazığ after the 2010 earthquake, together with the available curves generated for in-plane response. Since most of the damaged masonry buildings in the region suffered from out-of-plane vulnerability, this case study seems to be a good candidate in order to check the validity of out-of-plane fragility curves by comparing them with the observed damage. The verification study is focused on Okçular, since this is the most adversely affected village during the earthquake and the METU-EERC teams spent a considerable amount of time in this earthquake affected region, examining 70 damaged buildings. The comparison between the estimated and observed damage yields quite satisfactory results and encourage the use of out-of-plane fragility curves together with in-plane curves. More details about the fragility curve generation for out-of-plane response and the verification process can be found elsewhere (Ceran 2010).

4. SEISMIC SAFETY EVALUATION OF EXISTING URM BUILDINGS IN FATIH, ISTANBUL: A CASE STUDY

The efficiency of the mitigation efforts and post-disaster decision making process depend on the accuracy of the estimation of the expected damage and the associated loss in earthquake prone regions. Hence evaluation of seismic safety of existing masonry buildings is the most important part of this study. As stated by Erberik (2008), taking into consideration the estimated damage as a measure of seismic vulnerability is a reasonable way for the determination of the assessment of seismic performance of different masonry building types.

This section is devoted to the efforts for the embedment of the generated fragility information into seismic safety evaluation studies in Fatih sub-province, a highly populated earthquake–prone district in Istanbul. Fatih is one of the pilot study regions for "Earthquake Master Plan for Istanbul (EMPI)", which has been conducted by Istanbul Metropolitan Municipality (IMM) in order to find sustainable solutions for the complex problem of seismic risk mitigation and planning in Istanbul. In EMPI, multi-level strategies have been developed in order to prevent or mitigate seismic risk, prepare emergency rescue and restoration plans for the earthquake prone areas. These areas were identified in accordance with the risk priorities based on a previous earthquake loss estimation study for Istanbul, which had been conducted by Japan International Cooperation Agency (JICA and IMM, 2002).

In the context of EMPI project, a two-stage evaluation procedure has been developed for existing URM structures. In the first stage evaluation procedure, which is also referred as "sidewalk survey", the buildings under inspection are examined from the street by considering their major structural parameters that can be determined from outside the building. The buildings are classified according to these major structural parameters and then ranked with respect to their relative seismic performances, which are obtained through the generated fragility functions for the corresponding masonry building classes. The results of the first stage evaluation are used in order to distinguish the buildings with high damage risk, and examine them in detail in the second stage, which is out of the scope in this study.

The first-stage evaluation procedure starts with sidewalk survey of the masonry buildings in Fatih which means that, without entering inside the building, the masonry structures are examined by considering some major structural parameters. These major parameters that affect the seismic behavior have been determined from the lessons learned during the past earthquakes and statistical studies carried out using different existing masonry building databases. The ones that have been used in the classification of URM buildings during fragility curve generation can be listed as number of stories, plan geometry, load-bearing wall material and quality, wall length and openings in the walls, slenderness ratio, wall-to-wall and wall-to-floor connections and floor type.

After completing the sidewalk survey of 9,457 URM buildings in Fatih sub-province and collecting the building data, the next stage is the identification of seismic hazard in the region. Seismic hazard identification is carried out by using the probabilistic approach. The study region is divided into 250m×250m grids, for each of which ground motion parameters to be used in the risk analysis is obtained through hazard analysis. PGA values for each grid are calculated for events with exceedance probabilities of 2%, 10% and 50% in 50 years. Among these, the PGA values for the event with a return period of 475 years (10% exceedance probability in 50 years) is used in the assessment method since this also corresponds to the design level earthquake in the Turkish Earthquake Code (2007). The distribution of PGA values in Fatih sub-province is given for each grid in Fig. 4.1. The PGA values seem to vary between 0.4g and 0.54g.

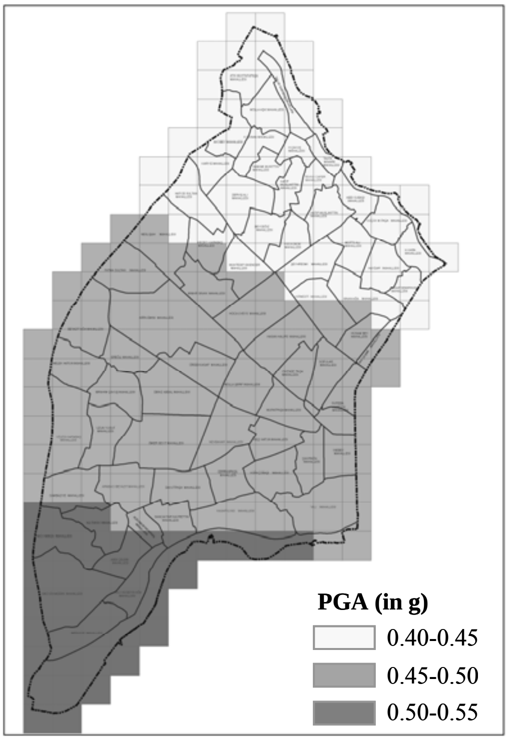

Figure 4.1. Grid by grid distribution of PGA values in terms of g for an event with a return period of 475 years in Fatih sub province.

The following stage of the first stage evaluation procedure is devoted to the assessment of building vulnerability. This part of the study is based on the employment of the generated fragility functions for specific classes of masonry buildings. A building class and the corresponding set of fragility curves are assigned to each building in the study region. Hence the seismic vulnerability of each building in Fatih is now defined in terms of a specific fragility curve set. The input for the fragility functions is the level of seismic hazard for each building in terms of PGA obtained from probabilistic seismic hazard analysis and the output is the damage state probabilities. However a single valued function is required in order to rank these buildings with respect to their seismic vulnerability. This is achieved by using the vulnerability score (VS). It can take values between 0 and 1. Higher the value of VS, the more vulnerable is the building under the given intensity of seismic action. If building data related to the out-of-plane response of URM buildings is missing or insufficient, or if out-of-plane response is assumed to have a minor effect on the global seismic performance of evaluated buildings, then the following VS formulation with three damage states (i.e. two limit states of in-plane response) can be used for calculating the score of each building.

$$\mathrm{VS}(\text{for IP}) = \sum_{i=1}^{3} w_i P_i \tag{4.1}$$

According to Eqn. 4.1, vulnerability score, VS, for in-plane (IP) response only is computed by the summation of the multiplication of the damage state constants w_i with the damage state probabilities P_i for the assigned PGA values. The damage state constants w_1, w_2 and w_3 are assumed as 0.0, 0.5 and 1.0, respectively. Considering the example in-plane fragility curves in Fig. 2.1.a-c, and for the arbitrarily selected hazard level of 0.6g, the following VS values can be obtained:

$$\mathrm{VS}\,(\text{for Fig.2.1.a}) = 0.0\times0.92 + 0.5\times0.06 + 1.0\times0.02 = 0.05 \tag{4.2.a}$$

$$\mathrm{VS}\,(\text{for Fig.2.1.b}) = 0.0\times0.68 + 0.5\times0.19 + 1.0\times0.13 = 0.22 \tag{4.2.b}$$

$$\mathrm{VS}\,(\text{for Fig.2.1.c}) = 0.0\times0.01 + 0.5\times0.05 + 1.0\times0.94 = 0.96 \tag{4.2.c}$$

The results imply that the class of masonry buildings represented by the fragility curve set of Fig.2.1.b (two story, regular masonry buildings with moderate quality solid clay brick units as the masonry wall material) are more vulnerable than the class of masonry buildings represented by the fragility curve set of Fig.2.1.a (single story, regular masonry building with moderate quality hollow clay brick units as the masonry wall material) but more safe than the class of masonry buildings represented by the fragility curve set of Fig.2.1.c (three story, irregular masonry building with poor quality cellular concrete blocks as the masonry wall material).

On the other hand, if out-of-plane response is also important in the evaluation and there exists sufficient data in order to classify evaluated buildings according to their out-of-plane (OP) vulnerabilities, then Eqn. 4.1. is slightly modified to include five damage states (because of two limit states for each of IP and OP response)

$$\mathrm{VS}(\text{for IP and OP}) = \sum_{i=1}^{5} w_i P_i \tag{4.3}$$

The sequence of limit states can change, which affects the calculation of VS. This means that the damage state constants w_i can take different values for different cases. But there exist a systematic way to assign the values for w_i. This is based on the following assumptions and rules:

- Out-of-plane limit states are attained for a wall or a number of walls. Therefore it may or may not endanger the overall safety of the building. However in-plane limit states are attained for the most critical story (i.e. generally the ground story) of the building. If a building experiences significant damage in terms of the in-plane behavior of its load bearing walls, the out-of-plane behavior for that building is assumed to be irrelevant. Briefly if in-plane behavior governs, out-of-plane mode is not considered for that limit state.
- If in-plane behavior governs, damage state constants are increased by 0.50.
- If out-of-plane behavior governs, damage state constants are increased by 0.25.

All possible combinations and sequences of IP and OP modes are listed in Table 4.1, together with their damage state constants w_i. As an illustrative example, corresponding fragility curves of a two story regular masonry building with poor quality solid clay brick units and a reinforced concrete floor are shown in Fig. 4.2. As it is seen from the figure, out-of-plane serviceability limit state (OP-LS1) is first exceeded for any seismic hazard level. Then, in-plane limit states, serviceability (IP-LS1) and ultimate (IP-LS2), governs the characteristics of the building fragility. Finally, out-of-plane ultimate limit state (OP-LS2) seems to take part. Since there are four limit states in two sets of fragility curves, five damage state constants should be applied in the calculation of VS.

Table 4.1. Damage state constants w_i for the corresponding sequence of limit states

Sequence	w_1	w_2	w_3	w_4	w_5
OP-LS1, IP-LS1, OP-LS2, IP-LS2	0.0	0.25	0.5	0.75	1.0
OP-LS1, OP-LS2, IP-LS1, IP-LS2	0.0	0.25	0.5	0.75	1.0
OP-LS1, IP-LS1, IP-LS2, OP-LS2	0.0	0.25	0.5	1.0	0.0
IP-LS1, OP-LS1, IP-LS2, OP-LS2	0.0	0.5	0.0	1.0	0.0
IP-LS1, IP-LS2, OP-LS1, OP-LS2	0.0	0.5	1.0	0.0	0.0
IP-LS1, OP-LS1, OP-LS2, IP-LS2	0.0	0.5	0.0	0.75	1.0

The damage state constants for DS-1, DS-2, DS-3, DS-4, DS-5 are taken from Table 4.1 as 0.0, 0.25, 0.5, 1.0, 0.0, respectively. Then VS for the considered masonry building type for a given hazard level of 0.4g is calculated according to Fig. 4.2 with the help of Eqn. 4.3:

$$\text{VS (for Fig.4.1)} = 0.0 \times 0.08 + 0.25 \times 0.14 + 0.5 \times 0.22 + 1.0 \times 0.33 + 0.0 \times 0.23 = 0.47 \qquad (4.4)$$

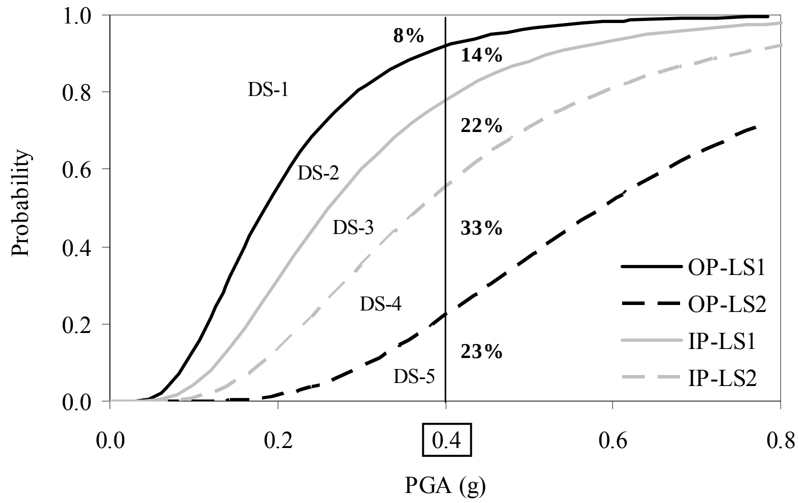

Figure 4.2. Demonstration of VS calculation by using the fragility curves (both for IP and OP response) of the selected masonry building type

For the sake of comparison, seismic safety evaluation procedure is applied to the existing URM buildings in Fatih in two different ways. First, only the in-plane vulnerability of the building stock is considered. Second, by conservatively assuming that all the buildings are vulnerable to out-of-plane action (i.e. poor wall-to-wall and wall-to-floor connections, presence of long and slender walls, etc.), the seismic safety of the same building stock is re-evaluated. Finally the results obtained in these two phases are compared.

4.1. Application of Seismic Safety Evaluation Procedure (only in-plane vulnerability)

The procedure explained above is applied to 9,457 buildings in Fatih subprovince of Istanbul by only considering the seismic vulnerability through in-plane response only. A fragility class is assigned to each building in the stock and VS is calculated by considering the on-site PGA value at the site of each building. Then the buildings are ranked in terms of their relative seismic vulnerabilities. The results are shown in Table 4.2 in terms of the relationship between VS and the number of stories for URM buildings in Fatih. It is observed that as the number of stories increases, the scores shift to values closer to unity (i.e. most vulnerable case). Sucuoğlu *et al.*(2006) stated that buildings which have VS greater than 0.7 can be accepted as possessing “high risk” in terms of seismic safety depending on the parametric studies and expert opinions. Nearly 38% of the URM buildings in Fatih study region fall into this category and it has been decided to examine these buildings in a more detailed manner in the second stage of evaluation in the context of EMPI. Examples of buildings from Fatih database with relatively high risk (VS > 0.7) and relatively low risk (VS < 0.7) are presented in Figs. 4.3 and 4.4.

Table 4.2. Relationship between VS and the number of stories by considering only the in-plane vulnerability

Vulnerability Score (VS)	Number of stories					Total
	1	2	3	4	5	
0.0 ≤ VS < 0.1	907	395	5	0	0	1,307
0.1 ≤ VS < 0.2	30	146	33	1	0	210
0.2 ≤ VS < 0.3	473	364	322	8	1	1,168
0.3 ≤ VS < 0.4	681	304	295	39	1	1,320
0.4 ≤ VS < 0.5	152	97	44	239	1	533
0.5 ≤ VS < 0.6	0	17	278	283	26	604
0.6 ≤ VS < 0.7	0	60	410	49	176	695
0.7 ≤ VS < 0.8	173	582	88	273	55	1,171
0.8 ≤ VS < 0.9	30	231	231	268	169	929
0.9 ≤ VS ≤ 1.0	0	136	485	516	380	1,517
Total	2,446	2,332	2,191	1,676	809	9,454

Figure 4. 3. Examples of URM buildings in Fatih sub-province with relatively high seismic risk (VS>0.7) after vulnerability score assignment

4.2. Application of Seismic Safety Evaluation Procedure (both in-plane and out-of-plane vulnerability)

For the sake of comparison and to examine the effect of out-of-plane vulnerability in the overall ranking of buildings according to their seismic safety, the buildings in the study region are further classified according to the parameters required for out-of-plane action (floor type, information about wall-to-floor and wall-to-wall connections, critical wall geometry, etc.). Hence two different sets of fragility curves for in-plane and out-of-plane response are assigned to each classified building and VS is calculated as explained above.

Figure 4. 4. Examples of URM buildings in Fatih sub-province with relatively low seismic risk (VS<0.7) after vulnerability score assignment

Table 4.3 presents the VS statistics of the URM buildings in Fatih in terms of number of stories when both in-plane and out-of-plane behavior modes are considered. Once again the results reveal that there is a strong correlation between seismic safety of URM buildings and the number of stories. While there exists an abundant number of buildings with three to five stories which has low values of VS in Table 4.2, these buildings now seem to be more vulnerable according to Table 4.3 with the contribution of out-of-plane failure modes. The change of distribution of the seismically vulnerable masonry buildings in terms of number of stories is also shown in Fig.4.5. It is observed that there is a drastic change in the distribution of the masonry buildings which have VS>0.7. With the contribution of the out-of-plane failure modes, the percentage of buildings exceeding this limit has increased from 38% to 46%.

Table 4.3. Relationship between VS and the number of stories by considering both in-plane and out-of-plane vulnerability

Vulnerability Score (VS)	Number of stories					Total
	1	2	3	4	5	
$0.0 \leq VS < 0.1$	0	0	0	0	0	0
$0.1 \leq VS < 0.2$	0	0	0	0	0	0
$0.2 \leq VS < 0.3$	293	0	0	0	0	293
$0.3 \leq VS < 0.4$	597	72	0	0	0	669
$0.4 \leq VS < 0.5$	752	486	37	0	0	1,275
$0.5 \leq VS < 0.6$	574	583	498	40	2	1,697
$0.6 \leq VS < 0.7$	27	175	406	460	76	1,144
$0.7 \leq VS < 0.8$	124	349	490	150	182	1,295
$0.8 \leq VS < 0.9$	79	531	173	499	148	1,430
$0.9 \leq VS \leq 1.0$	0	136	587	527	401	1,651
Total	2,446	2,332	2,191	1,676	809	9,454

5. CONCLUSIONS

This study is focused on the assessment of seismic vulnerability of populations of unreinforced masonry buildings in Turkey for both in-plane and out-of-plane behavior. The analysis tool that is used is fragility curves. Different sets of fragility curves have been generated for in-plane and out-of-plane action by using the same type of formulation. Both fragility curve sets have been compared with observed damage statistics and the results are quite satisfactory.

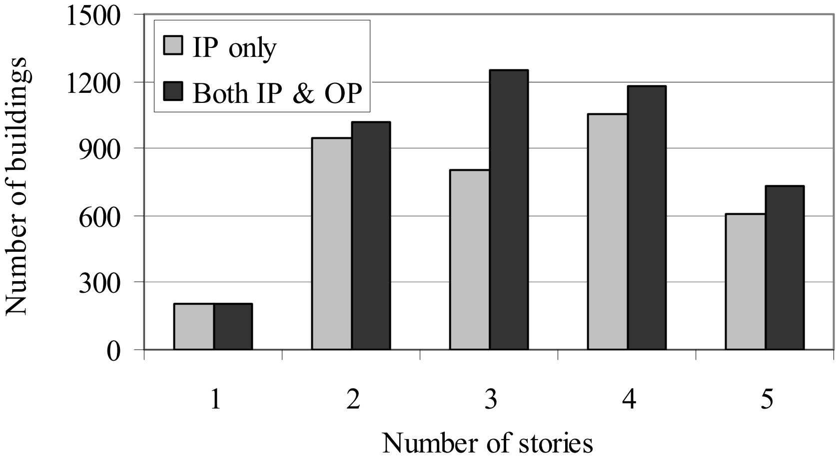

Figure 4. 5. The distribution of seismically vulnerable buildings (VS>0.7) in terms of number of stories.

The final part of the study is devoted to the seismic safety assessment of Turkish URM buildings in Fatih, Istanbul as a case study. First, all the buildings are examined by ignoring the out-of-plane vulnerability. In the second phase of evaluation, both in-plane and out-of-plane actions are taken into account by introducing the corresponding fragility curve sets. The assessment is carried out through a single-valued parameter, which is named as vulnerability score (VS). The results indicate that out-of-plane vulnerability plays an important role on the overall seismic safety of building populations.

The fragility based procedure developed in this study can provide an alternative for the seismic safety evaluation of URM buildings in Turkey. Using this procedure, it becomes possible to investigate a large population of masonry buildings located in regions of high seismic risk in a short period of time. The obtained results are valuable in the sense that they can be used as a database during the development of strategies for pre-earthquake planning and risk mitigation for earthquake prone regions of Turkey.

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