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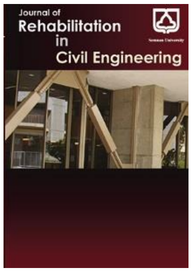

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Development of Fragility Curves for Brick Infill Walls in Steel Frames

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ABSTRACT

Brick infill walls are one of the most common types of nonstructural elements used in steel frame buildings. The recent earthquakes have shown that damage to masonry infill walls may endanger human lives and significant impact on economic losses. The damage estimation of masonry infill walls and the effects within the corresponding consequences of the performance-based earthquake engineering need fragility functions. The procedure implemented in this study is based on incremental dynamic analyses of two models, i.e. with and without brick infill walls. The primary objective is to develop fragility curves that permit the estimation of damage in masonry infill walls. Comparative analyses were conducted among the models considering four damage levels. The increase in the height has reduced the probability of damage to infill walls, so there was slight damage in drifts less than 3%. Therefore, with increases in stiffness, the probability of damages to the infill walls will increase. The fragility curves obtained by HAZUS show that there is a negligible variation in the infill walls seismic fragility estimated by the number of bays.

1. Introduction

Several previous studies have shown that probabilistic seismic performance estimation is an active field of research, with [1], [2] suggesting methodologies and approaches for seismic performance. The assessment of non-structural component capacity and the demand for a reliable analysis of the risks of collapse with a specified level of a safety margin against collapse is critical.

Several studies have been performed for full-scale experimental tests[3], a numerical study of the effects of infills on the global seismic behavior of frames, and sensitivity or

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fragility analysis of the consideration of uncertainty on the seismic capability of infilled frames [4]–[7]. Modeling infill walls as equivalent diagonal compressive struts first suggested in the early 1960s, by Polyakov and later developed by Holmes[8] Mainstone [9] Liauw and Kwan [10] and Panagiotakos and Fardis [11]. Tasnimi and mohebkhah. [12] and Abbasnejadfard et al. [13] Studied the behavior of infilled frames with openings. Cardone and Perone [14] and Sasun et al. [15] established the first drift-based fragility functions for infill walls without considering the effects of the presence of openings. Choizi et al. [16] used the experimental data based on lateral cyclic loading of masonry infilled frame specimens. The type of brick, the presence of openings, the compressive strength of the mortar and masonry prism used to develop the drift-based fragility function.

The evaluation of building seismic vulnerability is an essential step in preventing damages to the structural and nonstructural components such as infill walls, which can be evaluated by using the fragility curve [17], [18]. Fragility curve represents the possibility of achieving or exceeding structural damage states for a certain displacements range. Several approaches such as empirical, analytical, and hybrid methods have been suggested [19]. Whitman [20] by presenting a method for estimating the seismic loss, took the first steps in this course. After that, with the development of the nonlinear model for determining the behavior of buildings, research has been developed in this field. Anagnos et al. [21] , Shinozu`ka et al. [22] developed the fragility curves of the bridges through nonlinear dynamic analysis. Rossetto and Elnashai [23] employed the empirical method from collected data of damaged structures in previous earthquakes. Rwey-Hua [24] conducted an initial analysis on the fragility curves of steel structures in Taipei by using nonlinear static analysis for existing buildings. Del Gaudio et al. [25] derived the fragility curves for RC structures after the L'Aquila earthquake based on damage information to single building components, according to EMS-98. Tavakoli and Tavakoli [26] carried out the first analysis of seismic fragility curves in Iran using the Manjil-Rudbar earthquake data in 1990. Mostafaei and Kabeyasawa [27] used the Bam Earthquake Damage data to illustrate damage statuses for several Bam's structures.

Mansouri et al [28] compared the data obtained from HAZUS and the statistical methodologies in steel and RC frames. For RC frames with infill walls, Choudhury et al [29] provided fragility curves by considering uncertainty in response based on variations in the properties of ground motion. Razi et al. [30] evaluated fragility curves for special steel moment-resisting frame (SSMRF) structures, under near-fault pulse-like and far-fault ordinary ground motions. The result reveals that the increase in the height increases the drift demands toward upper stories. Khodadai et al. [31] rehabilitated the vulnerable moment resistant frames by using three different methods and presented the fragility curves for three performance levels to analyze the effect of different retrofitting models. The differences in designing and construction between different countries can substantially affect the fragility curves [32].

Trapani et al. [33] presented the probabilistic assessment framework for defining out-of-plane fragility curves of masonry infills walls with considering the peak ground acceleration as intensity measure and damage measure. The result shows that the infill walls at the higher stories undergo major spectral acceleration and masonry infill walls at lower stories undergo major in-plane damage. Xianxin et al. [34] critically reviewed the damage state determining methods to estabish in-plane fragility functions for full-scale masonry-infilled reinforced concrete. The greatest crack widths approach produced the minimum dispersion, but the other two methods produced significant dispersions. Di Sarno et al. [35] evaluated the fragility assessment of existing low-rise steel moment-resisting frames with masonry infill walls with considering the effects of multiple earthquakes and aftershocks. Lu et al. [36] proposed a resilient infill wall to enhance the building resilience. To that purpose, cyclic loading was applied to a resilient infill wall specimen and an ordinary infill wall specimen, and the results indicate that the seismic performance of resilient infill wall has been improved.

Despite extensive prior research on the effect of masonry infill on steel frames, very few studies have been performed to involve the development of fragility curves for brick infill walls in steel frames. The objective of the work mentioned in this paper is to develop the fragility curves for brick infill walls. The HAZUS methodology was used to determine the nonstructural damage state for infill walls [12]. The next section discusses the prototype building model and subsequently clarifies the damage state definitions adopted in this work.

2. Modeling

2.1. Selecting the prototype building model

In this paper, the 3 and 6 story building with 3 and 5 bays have been designed in three dimensions and analyzed by using Etabs software 2016 Editing version. The plan is presumed to be square and symmetrical, length of the bay and the height of floors, namely 5 meters, 3.5 meters. The building design is intended based on the criteria given in the tenth issue of National Building Regulations for Steel Structures. Dead and live load of levels and roof namely 600 kg/cm^3, 200 kg/cm^3, 650 kg/cm^3, 150 kg/cm^3 is considered based on the sixth national regulations. The load of the masonry wall was calculated separately and applied to the structure. The buildings in all models are assumed in residential buildings thus based on the Department of Buildings Regulations 2800 will be placed in the Mid-importance category.

Substitution of the equivalent diagonal element is the common method in modeling infill in the valid regulations all around the world such as FEMA356, FEMA273, and EC8. In this study, the method of single-diagonal brace is used to modeling the behavior of infill walls. Two Hypotheses are made regarding the configuration of the infill walls:

Case 1: uniform infill distribution in the frame (Fully infilled frame, 33IO, see Fig. 1).

Case 2: no infill panel is present (Bare frame).

The thickness of the infill wall is 23 cm. Openings and the soft story were ignored.

Table 1. 3 story beam and column.

Story	Beam	Column
1	PG-W350*10-F270*25	BOX250*25
2	PG-W350*10-F270*25	BOX250*25
3	PG-W350*10-F270*25	BOX250*25

Table 2. 6 story beam and column.

Story	Beam	Column
1	PG-W350*10-F300*20	BOX400*30
2	PG-W350*10-F300*20	BOX400*30
3	PG-W350*10-F300*20	BOX400*30
4	PG-W350*10-F300*20	BOX350*25
5	PG-W350*10-F300*20	BOX350*25
6	PG-W350*10-F300*20	BOX350*25

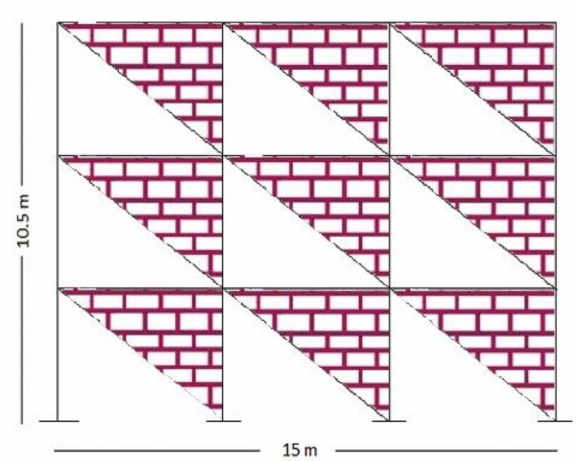

Fig. 1. 3 story fully infilled frame.

The OpenSEES software (2.5.0 Editing version) is used to perform incremental dynamic analyses. The Pinching4, employed to model material nonlinearity in brick infill and Truss elements for behavior of corresponding diagonal struts.

2.2. Selection of ground motions

One of the most important factors in the incremental dynamic analysis is to define the records since the results of the analysis have much dependence on the record that imposes to the structure, so choosing the record type of subject is sensitive and effective in the results. Therefore, six natural ground motion records with various hazard levels are used to perform Incremental dynamic analysis and the maximum inter-story drift regarded as a response parameter. IDA analysis was done with considering 0.1 PGA as a time step. The ground motion record is presented in Table 3.

Table 3. Ground motion records.

Earthquake	year	M_w	PGA (g)	Tm (s)	Station	V_s (m/s)	Rjb(km)	Hazard level
Tabas	1978	7.35	0.047	24.2	Ferdows	302.64	89.76	**low**
Landers	1992	7.28	0.017	23.7	LA - N Figueroa St	364.91	148.7	**low**
Loma Prieta	1989	6.93	0.09	13	Gilroy Array	17.92	663.31	**medium**
San fernando	1971	6.61	0.1	11.3	Santa Anita Dam	30.7	667.13	**medium**
Bam	2003	6.6	0.35	15.9	Bolvard	224.93	352.05	**high**
Friuli	1976	6.5	0.35	10.4	Barcis	49.13	496.46	**high**

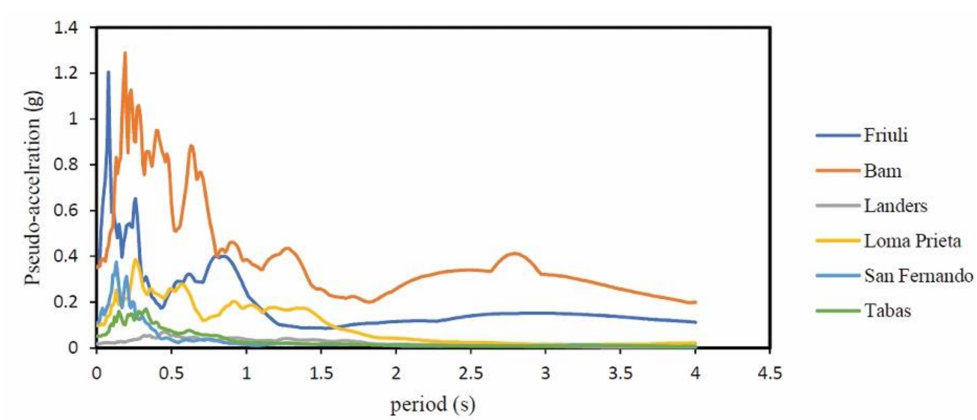

Fig. 2. spectrum of selected earthquake records.

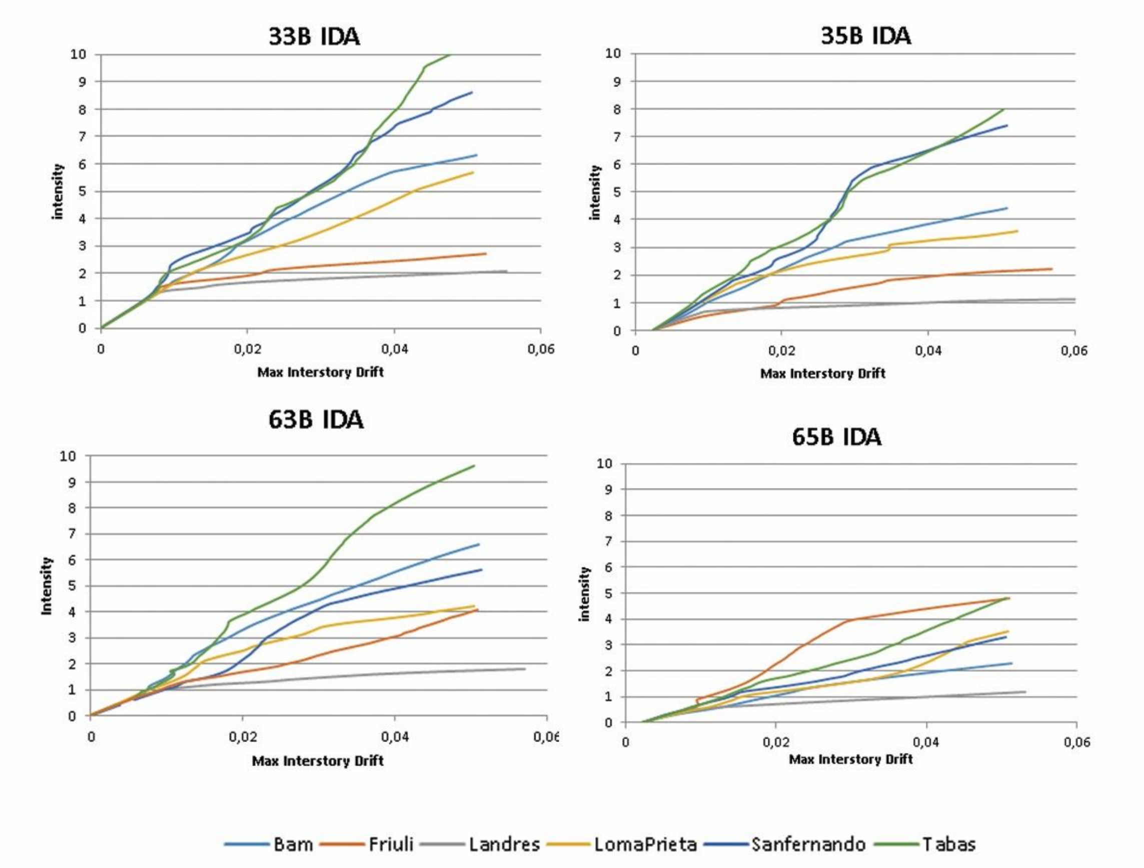

Fig. 3. IDA data for 3 & 6 story frames.

2.3. Model verification

To contrast the outcomes of the research with experimental work done by Tasnimi and Mohebkhah, a single-story, single-bay frame with and without infill wall modeled in OpenSees software. The pinching 4 materials are used as an infill wall material. For more information, see Tasnimi et al. [12]. Fig.2 and 3 illustrate the load-displacement relation for the bare frame and solid infilled frame compared with the experimental analysis.

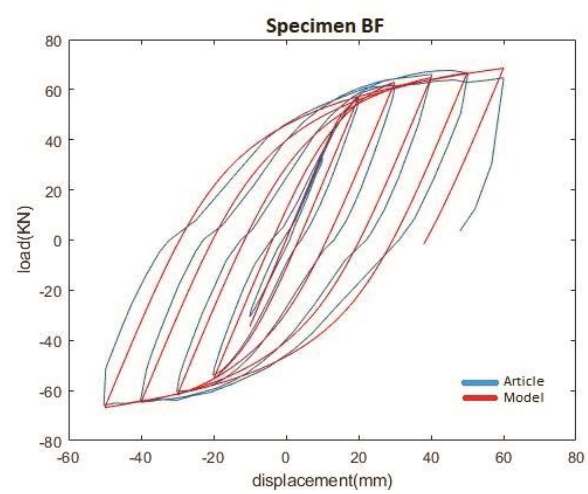

Fig.4. load–displacement relation for bare frame.

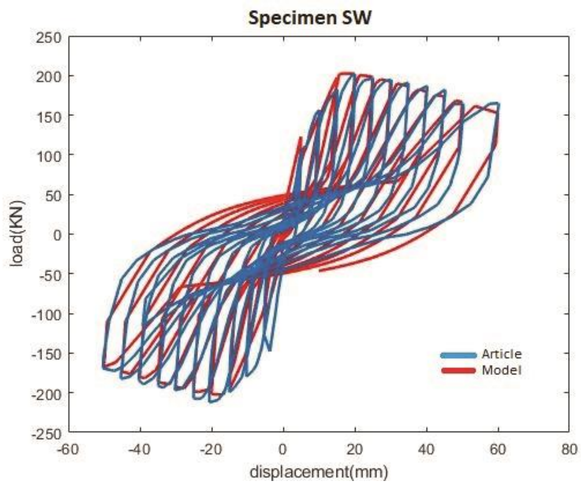

Fig. 5. load–displacement relation for solid infilled frame.

3. Damage states definition

Different descriptions of performance limit states for masonry infill walls have been established by a few experimental research results in the past. Mehrabi and Shing, [14] have proposed 12 Limit States for infilled RC frames. Calvi and Bolognini [10] have considered four limit states with levels of damage (“LS1”: fully operational, “LS2”: operational, “LS3”: life safety, “LS4”: life danger). Hak et al. [15] have assumed three limit states due to the increasing levels of damage observed during experiments (“Operational limit state”: no damage, “Damage Limitation limit state”: light damage and repairable, and a “Life Safety limit state”: very heavy damage but lives are not threatened). The concept of different performance levels especially related to the damage states in structural and nonstructural components is defined in seismic design codes. Cardone et al. defined damage states based on observations of cracking severity, and brick unit failure. In general, four distinct damage states are described as follow:

DS1: Light diagonal crack between the infill and the frame less than 1 mm.

DS2: Extensive diagonal cracking between 1 and 2 mm.

DS3: Corner crushing, brick spalling, sliding in the mortar joints.

DS4: Inplane or out of plane collapse.

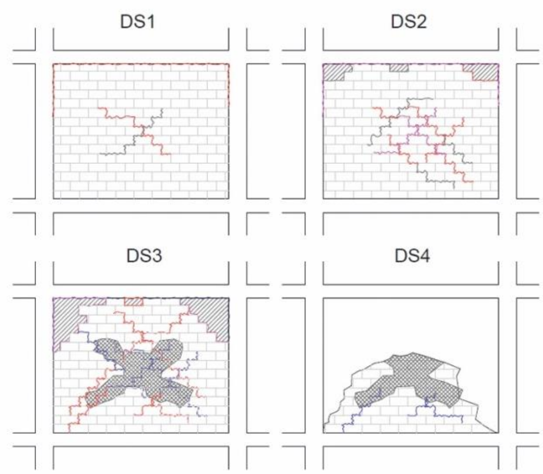

Fig. 6. Damage states of masonry infills [14].

Chiozzi et al. consider three damage states (DS1: cracks up to 2 mm wide, DS2: considerable cracks, more than 2 mm wide, DS3: larger than 4 mm). Susan et al. adopted four damage states (DS1: Operational limit state, DS2: Damage Limitation limit state, DS3: Life Safety or Severe Damage Iimit state, DS4: Near Collapse limit state) due to the results of cyclic in-plane testing on RC and steel frames from the performance of a single masonry infill. Hazus proposed four damage states for nonstructural drift-sensitive components (slight, moderate, extensive and complete). FEMA E-74 [18], assumed three types of risk: Life Safety, Property Loss, Functional Loss. In FEMA 273 [19] three different performance criteria applied for structural elements and unreinforced masonry infill walls are included: Immediate Occupancy, Life Safety and Collapse Prevention. Based on the general requirements provided by international standards.

In this study, four damage states have been considered and inter-story drift limits for different damage states are considered from Hazus.

4. Fragility curves

Fragility curves provide details about the probability of infilled walls damage increases with increasing peak ground acceleration. In HAZUS methodology building damage functions divided in four states, and for each one, regarding the levels of seismic design, the fragility curve is determined. Previous studies indicate that the use of fragility curves for masonry infill walls developed by Cardone et al. These curves were further developed by Chiozzi et al.

Table 4. Infill wall performance levels used in the fragility analysis.

Damage state	IDR
slight	0.004
moderate	0.008
extensive	0.025
complete	0.05

The fragility functions used in this work for masonry infill are assumed as follow:

$$P\ [ds|\ IDR] = \phi\ \left[\frac{1}{\beta_{ds}} \ln \left(\frac{IDR}{S_{d,ds}} \right) \right] \quad (1)$$

where P [ds| Sd] is a conditional probability of achieving or exceeding a specific damage state in the infill at a certain IDR value. $S_{d,ds}$ is demand capacity value and β, Φ respectively, indicate the central tendency and the cumulative standard normal distribution.

5. Results and discussion

It must be mentioned that the results obtained from this study are based on 2-dimensional frames. According to previously done research and as it was expected, the presence of infill considerably leads to increase strength and stiffness of the frames. Ignoring the effect of infill in steel frames can lead to more errors in the estimation of the initial stiffness. The estimated infill walls fragility curves are shown in Fig 3 as a function of interstory drift, respectively for minor and major rates of damage.

Generally speaking, Fig 7 points out that at DS1 the probability of failure of a non-structural wall in a 3-story frame is 22% higher than that of a 6-story frame. According to the studies, if the inter-story drift is smaller than 0.05%, light cracking would not be likely to be observed in nonstructural walls, and if the inter-story drift is smaller than 0.5% it is almost certain to occur. Since the peak inter-story drift ratio is larger than 0.5%, the possibility of light cracking on nonstructural walls is about 80%.

Table 5. comparison between original and modified equivalent strut model.

Model	Periods
33B	0.42
33I_O	0.084
35B	0.45
35I_O	0.065
63B	0.64
63I_O	0.12
65B	0.64
65I_O	0.11

The main conclusions are as follows:

- The result shows that the frame period with infill wall relative to the bare frame has decreased by more than 50%.

- Comparison of fragility curves shows that the probability of receives or exceeding damages in DS4 is about 20%.

-The slope of the fragility curve is higher at 4% inter-story drift and smaller at higher inter-story drift.

- The increase in the number of bays doesn't change the probability of damages.

- The fragility curves obtained by HAZUS show that, given the number of bays, there is a slight variation in the seismic fragility evaluated for the infill walls.

- The probability of occur in the infill wall of a taller frame is less than 22%.

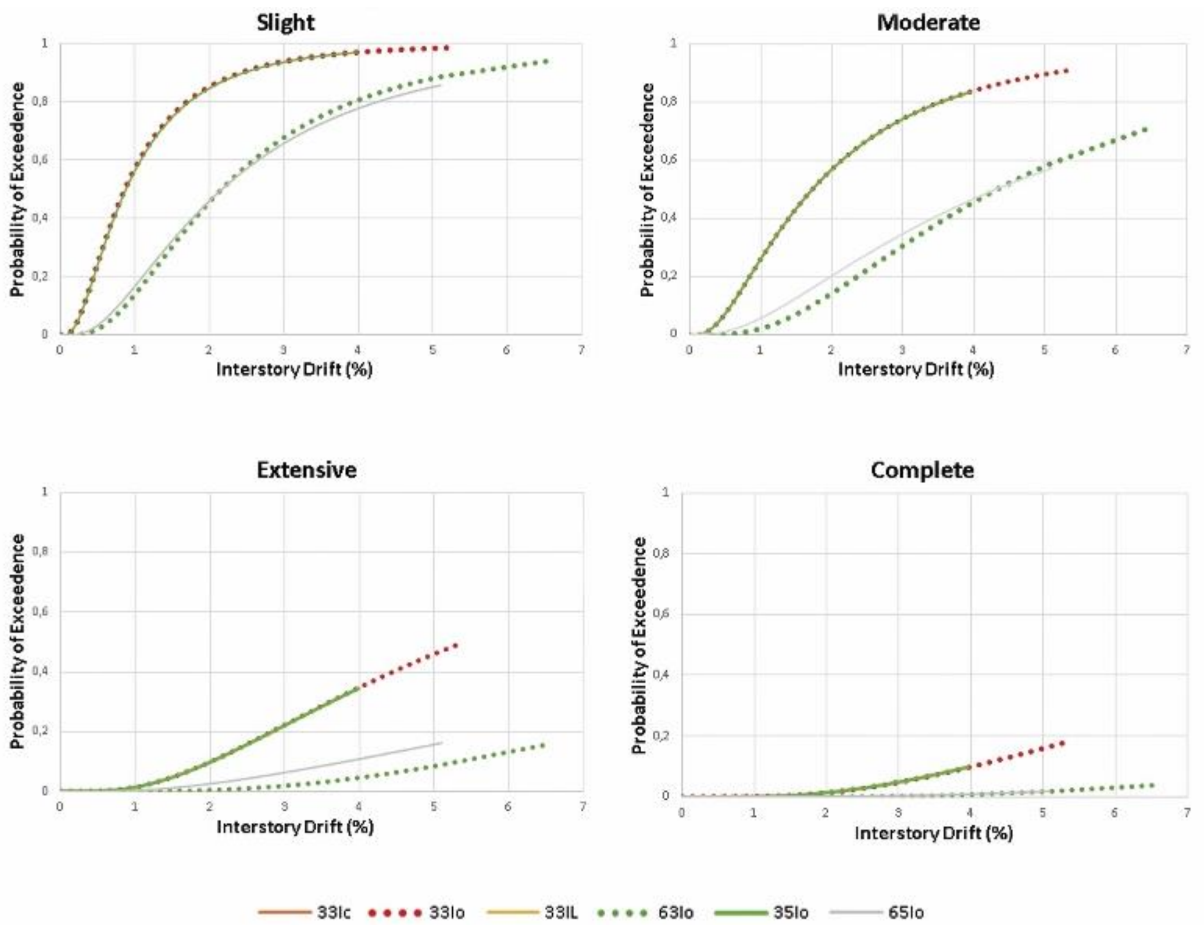

Fig. 7. Comparison of seismic fragility estimates considering the number of story and bay.

6. Conclusions

In the present work, the effect of infill walls in buildings has been studied and drift-based fragility curves of brick infill walls were developed. For this purpose, brick infill wall, and steel frame models were designed and analyzed. The drift capacity was identified from the damage evolution under increasing drift demand. Incremental dynamic analysis (IDA) was carried out, and the response component of each model includes maximum displacement, interstory drift, and base shear forces for the structures. Therefore, the fragility curves developed in steel frame buildings with infill walls.

The result can be summarized in the effect of parameters such as number of stories, number of bays, and Fundamental natural time on seismic behavior of brick infill walls. For masonry infilled steel frames, different recorded building typologies, such as HAZUS, are not adequate to estimate the effect of the number of bays. Therefore, the fragility curve obtained by HAZUS reveals that the seismic fragility estimated based on the number of bays in the infill walls has a negligible variation. On the other hand, considering the frame, the seismic fragility estimated increases with the increase in the number of stories and the number of bays. Also, the result indicates that increasing the overall stiffness of the structure leads to increasing the probability of received or exceeding damages in the infill walls. The increase in height has reduced the probability of damage to infill walls. The fundamental natural time period for the infilled frame is observed to be decreased in comparison with the bare frame for the first mode. Finally, it was cleared that the damage probabilities of slight, moderate and extensive damage state of infill frame are increased.

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