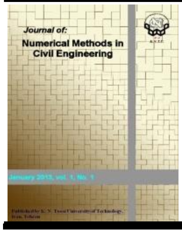


Numerical Methods in Civil Engineering

Journal Homepage: https://nmce.kntu.ac.ir/

Development of a fragility model for low-rise steel and reinforced concrete buildings in Iran

Ali Maghsoudi-Barmi*, Mohammad Reza Soghrat**

ARTICLE INFO

RESEARCH PAPER

Article history:
Received:
April 2023
Revised:
December 2023
Accepted:
May 2024

Keywords:
Fragility,
Low-rise building,
Steel,
reinforced concrete,
damage estimation

Abstract:

Low-rise buildings in Iran, particularly in rural areas, constitute a significant portion of the country's total buildings. Given this issue, in conjunction with the high level of seismic activity in the country and the necessity for decision-makers to formulate effective risk mitigation plans, it is imperative to conduct a centralized investigation into the estimated losses of these buildings in different earthquakes. To achieve this goal, the development of fragility curves can be highly beneficial. Therefore, this study aims to compile newly developed fragility models from the literature pertaining to low-rise steel and RC structures, with a specific focus on models designed for Iranian buildings. Additionally, in order to minimize uncertainties, the gathered fragility curves are consolidated, and new models are proposed for the buildings under examination. Various factors such as design/construction quality, structural system, and infill effects are taken into account. The comparison of the proposed curves with the observed damages from previous earthquakes indicates the validity of the results, particularly for cases involving low-level design/construction quality.

1. Introduction

Iran is situated in one of the most seismically hazardous regions globally and has endured numerous catastrophic earthquakes throughout its history, resulting in substantial financial and human losses. In the realm of seismic loss estimation and risk assessment, fragility curves play a pivotal role, influencing the ultimate outcomes significantly. While significant strides have been taken in this area, leading to the development of various models, persistent challenges underscore the necessity for further research and exploration in this domain, as well as the creation of innovative models. Bastami et al. (2022) outline some of these challenges as follows:

- The vulnerability of buildings is strongly related to the design and construction circumstances in the region. Hence, it is important to develop specific models for each specific field.
- The design and construction methods generally improve over time; hence the fragility/vulnerability models are time dependent and should be updated on a regular basis.
- Using advanced structural models which consider characteristics of a building more precisely, can provide a more precise seismic risk assessment. However, these models require data which is usually not available, or is costly to obtain.

When examining buildings in Iran, a significant portion of the country's structures, particularly in rural areas, consist of low-rise steel and reinforced concrete. As an example, as experienced in Sarpol-e Zahab-Ezgeleh Earthquake (MW 7.3 on November 12, 2017), and also reported by Hashemi et al. (2018) and Hashemi and Kiany (2018), most of the buildings affected by the earthquake were low-rise buildings. In this regard, a comprehensive model estimating the seismic losses in these buildings can assist decision-makers in developing effective risk mitigation plans. Although this practice is relatively new in the country, some studies have been done in this regard, partially addressing the issue. However, a specific comprehensive study considering low-rise buildings has not been conducted yet. Moreover, the existing studies incorporate specific assumptions and methods, in which a thorough review of the available methods would be effective in creating a complete

* *Corresponding author: PhD, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran.*
** *Assistant professor, Structural Retrofitting and Reconstruction Research Group, Natural Disasters Research Institute, Tehran, Iran.*

https://doi.org/10.61186/NMCE.2304.1019

understanding of the subject while addressing the aforementioned challenges.

In this regard, this paper aims to propose appropriate fragility curves for low-rise steel and reinforced concrete buildings in Iran. To achieve this, a comprehensive classification is defined. Furthermore, the literature was reviewed to collect the relevant fragility models. Finally, the collected models are combined to obtain the final models.

2. Building classification

Various parameters can be considered in the classification of the buildings, among which the most important ones are material, lateral force-resisting system, height, and the level of ductility, that are also widely adopted by other researchers (Fallah-Tafti et al., 2020). For the first one, two types of construction materials, namely steel and reinforced concrete, are considered according to the subject of the paper. Regarding the lateral force-resisting system, moment resisting frame (MRF), braced frame (BF), and reinforced concrete shear wall (RCSW), are the systems widely used in Iran. However, there is a common type of classification that only considers buildings in two categories of steel and reinforced concrete. Both of these classifications are adopted in this paper, resulting in Model 1 and Model 2 classifications, which are defined at the end of the current section.

The buildings included in this paper are low-rise buildings. Generally, the number of stories is used as a criterion in this regard, and buildings with one to three stories are classified as low-rise. The same definition is adopted in this study.

The level of ductility can be assumed to be equivalent to the level of seismic code requirements included in the design and construction process of the building. In this regard, based on the year of construction, buildings are generally categorized into three groups of (1) low-code, which are designed based on early versions of seismic codes, (2) mid-code, which require some degree of ductility level in the building, and (3) high-code, which includes buildings designed based on modern versions of seismic codes. A fourth group named pre-code is also used by some researchers, which includes buildings constructed before the development of seismic design codes. However, these buildings are not included in this study. The seismic code used in the above definition is different for various studies investigated in this paper. However, the general idea is the same as mentioned above. Moreover, for the researches regarding the Iranian buildings, which include a major share of all, Standard No. 2800 is mainly used.

Following the above parameters, and the mentioned classes, two models of classification were introduced and used in this paper, as they are presented in Table 1 and Table 2. In the first model, the lateral force-resisting system is not considered as a parameter, and considering the ductility level, all the buildings are classified into two main groups of steel and reinforced concrete, each one including three levels of ductility (a total of 6 groups). In the second classification, lateral force-resisting system is also included, and 10 different classes are covered. There is an exception for reinforced concrete shear wall, which is relatively a new system in Iran, and it is anticipated to provide a high-code level of ductility.

Table 1: Building classification considering materials of construction (Model 1)

No.	Class Name	Material	Ductility level
1	RCH	Reinforced concrete	High-code
2	RCM		Mid-code
3	RCL		Low-code
4	STH	Steel	High-code
5	STM		Mid-code
6	STL		Low-code

Table 2: Building classification considering lateral force-resisting system (Model 2)

	Class Name	Material	Lateral force-resisting system	Ductility level
1	RC-Frame-H	Reinforced concrete	Moment resisting frame	High-code
2	RC-Frame-M			Mid-code
3	RC-Frame-L			Low-code
4	ST-Frame-H	Steel	Moment resisting frame	High-code
5	ST-Frame-M			Mid-code
6	ST-Frame-L			Low-code
7	ST-Brace-H	Steel	Braced frame	High-code
8	ST- Brace -M			Mid-code
9	ST- Brace -L			Low-code
10	RC-SWall-H	Reinforced concrete	Reinforced concrete shear wall	High-code

3. Collecting fragility models

Fragility curves are defined as the probability of reaching or exceeding a specific damage state under a given earthquake excitation. A general state of the fragility curve is given in Equation 1, in the form of a conditional probability. Mathematically, a lognormal probability distribution function is usually used to express a fragility function.

$$P_f(a) = P(DM > DS \,|IM = a) \quad (1)$$

In this equation “DM” is the damage measure, “DS” is a damage state for the whole structural system or an element, “IM” is the earthquake’s intensity measure, and “a” is the recognized condition for the earthquake’s intensity measure. Using an appropriate IM is an important step in developing fragility curves. This issue has been the subject of discussion for a long time, as still it is. However, there is no comprehensive consensus on which parameter should be considered as a proper measure representing the IM. Today, the use of device intensity measures such as peak ground acceleration, velocity or displacement, spectral response, or some parameters derived from seismic energy dissipation principles, are more common.

There are various classifications for fragility curves. However, based on the method used for developing, fragility curves can be divided into five main categories, namely;

1) Expert-based/judgmental fragility curves
2) Empirical fragility curves
3) Experimental fragility curves
4) Analytical fragility curves
5) Hybrid fragility curves

Each of these fragility curves has its own advantages and downsides. Expert-based/judgmental fragility curves use one of the oldest and simplest methods, in which a group of experts are asked a series of questions regarding the different elements of the structure. This method is highly affected by the questionnaires, experience, and the number of experts. Moreover, most of these judgments may be biased and include uncertainties that are not clearly quantified in the development of vulnerability models. Empirical fragility curves are developed using the observed damage distribution after an earthquake. High levels of uncertainties exist in this method. Differences in the observations of different inspection teams add to the uncertainty of the developed curves. Experimental fragility curves are not common since large-scale experiments are costly, and not optimal yet. In the absence of sufficient data on damage, fragility functions can be developed using different analytical methods. This is a method widely employed by different researchers, although different methods of analysis, are used. Based on the assumptions and the methods used in the modeling and analysis process, the issue of uncertainty will be raised. Moreover, efforts to reduce uncertainties might be computationally costly. Lastly, to compensate for the shortcomings of the methods mentioned, researchers proposed the idea of hybrid fragility curves. The hybrid method tries to reduce computational efforts in analytical modeling, and also solves the issue of targeted bias in experts' judgment method (Kappos et al., 2006). Also, the hybrid method combines the results of large-scale experimental tests that can reasonably reflect the real response of the structure.

Following the above categorization, and also the classification proposed in section 2, different models existing in the literature were collected. The collected models were subjected to an initial screening and some suitable models were selected for use. The screening process was done based on the authors’ judgment using some predefined criteria. Among these criteria, the most important ones are being related to Iranian buildings or regions with similar building practice, using relatively reliable data and modeling techniques, and using compatible damage states. This led to the collection of110 different models proposed by 10 various researchers, using different assumptions. A brief description of the selected models is presented below.

Motamed et al. (2019 developed a probabilistic earthquake loss model for Iran in their study. To this aim, exposure models for the residential, commercial, and industrial building stock were developed using recent housing census information, socio-economic data, and the judgment of local experts. For each building class in the exposure model, using nonlinear time history analysis and ground motion records from the region, a set of fragility and vulnerability models was derived. 7 out of 23 building classes in this study are related to low-rise buildings. Two levels of ductility, including low and moderate/high are considered. Three main sources of uncertainty, including building-to-building, record-to-record, and damage criteria, were considered in the modeling process.

To provide reliable fragility curves for different types of buildings in Iran, Fallah-Tafti et al. (2020) generated 19 sets of fragility curves (6 were related to low-rise buildings). An empirical approach, incorporated with statistical analysis was adopted. To propose appropriate fragility curves, existing empirical fragility curves in Iran as well as those proposed for similar types of buildings in other countries were used. For this purpose, a statistical approach was adopted to weigh different curves based on the construction provisions and expert judgment. Biglari et al. (2021) investigated the damage data after November 12, 2017, Sarpol Zahab, Iran earthquake (Mw7.3), collected on 440 steel and reinforced concrete residential buildings. Damage probability matrix, vulnerability index, and empirical fragility curves were presented for three subgroups of these structures on the basis of (i) structural materials and seismic force resisting systems, without considering the height of structures; (ii) structural materials and height of structures, without considering the seismic force resisting systems (i.e. low and medium-height steel and RC structures); (iii) structural materials, without considering the seismic force resisting systems and height of structures (i.e. total data for steel and RC frames). Among these, the second subgroup was used in this study.

In another study, Kohrangi et al. (2021) focused on the exposure and fragility/vulnerability of the residential, mixed residential/commercial, and public building stock of the city of Isfahan, Iran. Considering the available georeferenced 2011 Census data, along with a local survey of the city, they classified the city's buildings into 27 construction classes characterized by age, height, and material/lateral-load-resisting system. An analytical method using nonlinear dynamic analysis of multiple equivalent single-degree-of-freedom systems was used. Both record-to-record and building-to-building variability rates were considered in this study.

Karim-Zadeh et al. (2022) devoted their study to developing specific fragility functions for the common building types in Iran. To this aim, they classified existing buildings into 31 categories regarding material, lateral-load-resisting system, height, and code level. Using collected structural and dynamic parameters for buildings in each class, a large set of backbone curves for Iranian buildings taxonomy was obtained. Then fragility functions were generated using non-linear time history analyses on the generic backbone curves and a large set of ground motion records.

Naseri et al. (2017) studied the fragility curves of RC structures with 3, 5, and 8 stories in Iran, where the first set is employed in this project. The structures which have been estimated in this article have the system of RC Intermediate Moment Frame which is designed by the third edition of Standard No. 2800 (Ministry of Road & Urban Development, 2005). These models were created in OpenSEES software, to conduct 3D non-linear analyses.

In another study, Omidian and Saffari (2017) evaluated the seismic behavior of regular and irregular reinforced concrete structures, 3, 6, and 9 stories high, under ten records for incremental dynamic analysis. Only the 3-story building model was selected in this project. Fragility curves, using the threshold of damage state of RC structure according to HAZUS in both regular and irregular structures have been investigated. Modeling has been done using Seismostruct software. Buildings in this study have been seismically loaded based on the Fourth Edition of Standard No. 2800 (Ministry of Road & Urban Development, 2014), and are assumed to have high code conditions.

Razmkhah et al. (2021) developed fragility curves for three-, five-, and eight-story moment-resisting steel frame structures, taking into account soft story and torsional irregularities during the earthquake mainshock to assess the probabilistic effects of irregularities in the plan and height of steel structures. The models were designed in accordance with the fourth Standard No. 2800 (Ministry of Road & Urban Development, 2014). 3D analytical models of steel structures were created using the OpenSees software platform, and Incremental Dynamic Analysis (IDA) was carried out. The maximum inter-story drift value was chosen as the demand parameter, and the capacity was determined based on the HAZUS-MH (HAZUS, 1999) limit states. Finally, the corresponding fragility curves were developed.

Villar-Vega et al. (2017) aimed to obtain a uniform fragility model for the most representative building classes in the Andean region (South America), for large-scale risk analysis. Sets of SDOF oscillators were created and subjected to a series of ground motion records using non-linear time history analyses, and the obtained damage distributions were used to derive fragility functions. Classification of the buildings used in this study is based on the model presented in the SARA project (Yepes et al., 2017), and only concrete moment resisting frames were employed in this project.

Lastly, Martins and Silva (2020) outlined the creation of an analytical fragility and vulnerability model that encompasses the most prevalent building classes on a global scale. Nearly five hundred functions were devised to encompass the majority of combinations of construction material, height, lateral load resisting system, and seismic design level. The fragility and vulnerability were determined through nonlinear time-history analyses on equivalent SDOF oscillators and a comprehensive set of ground motion records representing various tectonic environments.

Table 3 shows the details of the selected models for reinforced concrete (RC) and steel (S) buildings. For a better understanding and comparison, a uniform four-part nomenclature is defined and applied. The first part shows the name of the developer of the model, the second part shows the building's material type ("ST" stands for steel and "RC" stand for reinforced concrete), the third part shows the structural system ("MomentF" is the moment resisting frame in the general state, "BareF" is the moment resisting frame without the presence of infills, and "InfillF" is moment resisting frame with the presence of infills, "BracedF" is bracing resisting frame, "SWall" is shear wall, and "NC" means uncategorized and used for studies where the structural system is not a parameter and concrete and steel structures have been investigated in general), and the fourth part indicates the quality of construction or the level of code requirements controlled in the design process of the building ("LC" is low-code, "MC" is moderate-code, "HC" is high-code, and "NC" is related to studies that this parameter is not investigated).

Models mentioned in rows 44 to 66 have developed fragility curves for three cases of 1,2 and 3 stories, which is shown by “H=1,2,3” at the end of the models’ names.

As shown in Table 3, most of the models used analytical methods, although some empirical and hybrid fragility curves exist, as well. Out of 10 studies, only eight were specifically carried out for Iran buildings, while one is a global model and the other is for South America which adopt a building design practice close to the Iranian ones. Considering analytical models, almost all the models have incorporated nonlinear time history analysis (NLTHA) or incremental dynamic analysis (IDA) methods. The structural models were mostly equivalent to single degree of freedom systems (SDOF); however, some 3D finite element models were also proposed.

Table 3: List of gathered fragility models for low-rise steel and RC buildings

	Model	IM	Scope	Developing method	Additional details	Reference
1	Motamed-RC-MomentF-LC	PGA	Regional (Iran)	Analytical	Code criteria is considered in 2 categories, Low Code and Moderate to High code.	Motamed et al. (2019)
2	Motamed-RC-MomentF-M&HC	PGA				
3	Motamed-RC- SWall - M&HC	PGA				
4	Motamed-ST-MomentF-LC	PGA				
5	Motamed-ST-MomentF-M&HC	PGA				
6	Motamed-ST-BracedF-LC	PGA				
7	Motamed-ST-BracedF-M&HC	PGA				
8	Fallah-RC-NC-LC	PGA	Regional (Iran)	Hybrid	-	Fallah Tafti et al. (2020)
9	Fallah-RC-NC-MC	PGA				
10	Fallah-RC-NC-HC	PGA				
11	Fallah-ST-NC-LC	PGA				
12	Fallah-ST-NC-MC	PGA				
13	Fallah-ST-NC-HC	PGA				
14	Biglari-RC-NC-HC	PGA	Regional (Sare-Pole-Zahab)	Empirical	-	Biglari et l. (2021)
15	Biglari-ST-NC-HC	PGA				
16	Kohrangi-RC-InfillF-LC	S_a (0.2s)	Regional (Isfahan)	Analytical	-	Kohrangi et al. (2021)
17	Kohrangi-RC-InfillF-MC	S_a (0.2s)				
18	Kohrangi-RC-InfillF-HC	S_a (0.2s)				
19	Kohrangi-ST-BareF-LC	S_a (0.3s)				
20	Kohrangi-ST-BareF-MC	S_a (0.3s)				
21	Kohrangi-ST-BareF-HC	S_a (0.3s)				
22	Kohrangi-ST-BracedF-MC	S_a (0.2s)				
23	Karimzadeh-RC-BareF-LC	S_a (0.6s)	Regional (Iran)	Analytical	-	Karim Zadeh et al. (2022)
24	Karimzadeh-RC-BareF-MC	S_a (0.6s)				
25	Karimzadeh-RC-BareF-HC	S_a (0.6s)				
26	Karimzadeh-RC-InfillF-LC	S_a (0.3s)				
27	Karimzadeh-RC-InfillF-MC	S_a (0.3s)				
28	Karimzadeh-RC-InfillF-HC	S_a (0.3s)				
29	Karimzadeh-ST-BareF-LC	S_a (0.6s)				
30	Karimzadeh-ST-BareF-MC	S_a (0.6s)				
31	Karimzadeh-ST-BareF-HC	S_a (0.6s)				
32	Karimzadeh-ST-InfillF-LC	S_a (0.3s)				

continued on next page

Table 3 (continued)

	Model	IM	Scope	Developing method	Additional details	Reference
33	Karimzadeh-ST-InfillF-MC	S_a (0.3s)				
34	Karimzadeh-ST-InfillF-HC	S_a (0.3s)				
35	Karimzadeh-ST-BracedF-LC	S_a (0.3s)				
36	Karimzadeh-ST-BracedF-MC	S_a (0.3s)				
37	Karimzadeh-ST-BracedF-HC	S_a (0.3s)				
38	Naseri-RC-BareF-HC	PGA	Case study	Analytical	-	Naseri et al. (2017)
39	Omidian-RC-BareF-HC	PGA	Case study	Analytical	Regular	Omidian and Saffari (2017)
40	Omidian-RC-BareF-HC-Irregular	PGA			Irregular	
41	Razmkhah-ST-BareF-HC	PGA	Case study	Analytical	Regular	Razmkhah et al. (2021)
42	Razmkhah-ST-BareF-HC-SOS	PGA			Soft story	
43	Razmkhah-ST-BareF-HC-SOS&T	PGA			Soft story and Tortional irregularity	
44	Villar-RC-BareF-HC-H:1,2,3	S_a	Regional (South America)	Analytical	H is number of stories.	Villar-Vega et al. (2017)
45	Villar-RC-BareF-LC-H:1,2,3	S_a				
46	Villar-RC-BareF-LC-H:1,2,3-SOS	S_a			Soft story	
47	Villar-RC-Infillf-HC-H:1,2,3	S_a/PGA			H is number of stories.	
48	Villar-RC-Infillf-LC-H:1,2,3	S_a/PGA				
49	Martins-RC-InfillF-HC-H:1,2,3	S_a/PGA	Global	Analytical	H is number of stories, which 3 different cases of 1, 2, and 3 are applicable in this project.	Martins and Silva (2020)
50	Martins-RC-InfillF-MC-H:1,2,3	S_a/PGA				
51	Martins-RC-InfillF-LC-H:1,2,3	S_a/PGA				
52	Martins-RC-BareF-HC-H:1,2,3	S_a				
53	Martins-RC-BareF-MC-H:1,2,3	S_a				
54	Martins-RC-BareF-LC-H:1,2,3	S_a				
55	Martins-RC-SWall-HC-H:1,2,3	S_a/PGA				
56	Martins-RC-SWall-MC-H:1,2,3	S_a/PGA				
57	Martins-RC-SWall-LC-H:1,2,3	S_a/PGA				
58	Martins-ST-BracedF-HC-H:1,2,3	S_a				
59	Martins-ST-BracedF-MC-H:1,2,3	S_a				
60	Martins-ST-BracedF-LC-H:1,2,3	S_a				
61	Martins-ST-InfillF-HC-H:1,2,3	S_a/PGA				
62	Martins-ST-InfillF-MC-H:1,2,3	S_a				
63	Martins-ST-InfillF-LC-H:1,2,3	S_a				
64	Martins-ST-BareF-HC-H:1,2,3	S_a/PGA				
65	Martins-ST-BareF-MC-H:1,2,3	S_a (0.3s)				
66	Martins-ST-BareF-LC-H:1,2,3	S_a (0.3s)				

4. Developing fragility curves

In this section, the proposed fragility curves for low-rise steel and reinforced concrete structures are introduced. A hybrid method is employed for this purpose using the collected models. The collected fragility curves are combined with equal weighting for all models, as they were deemed to be equally reliable.

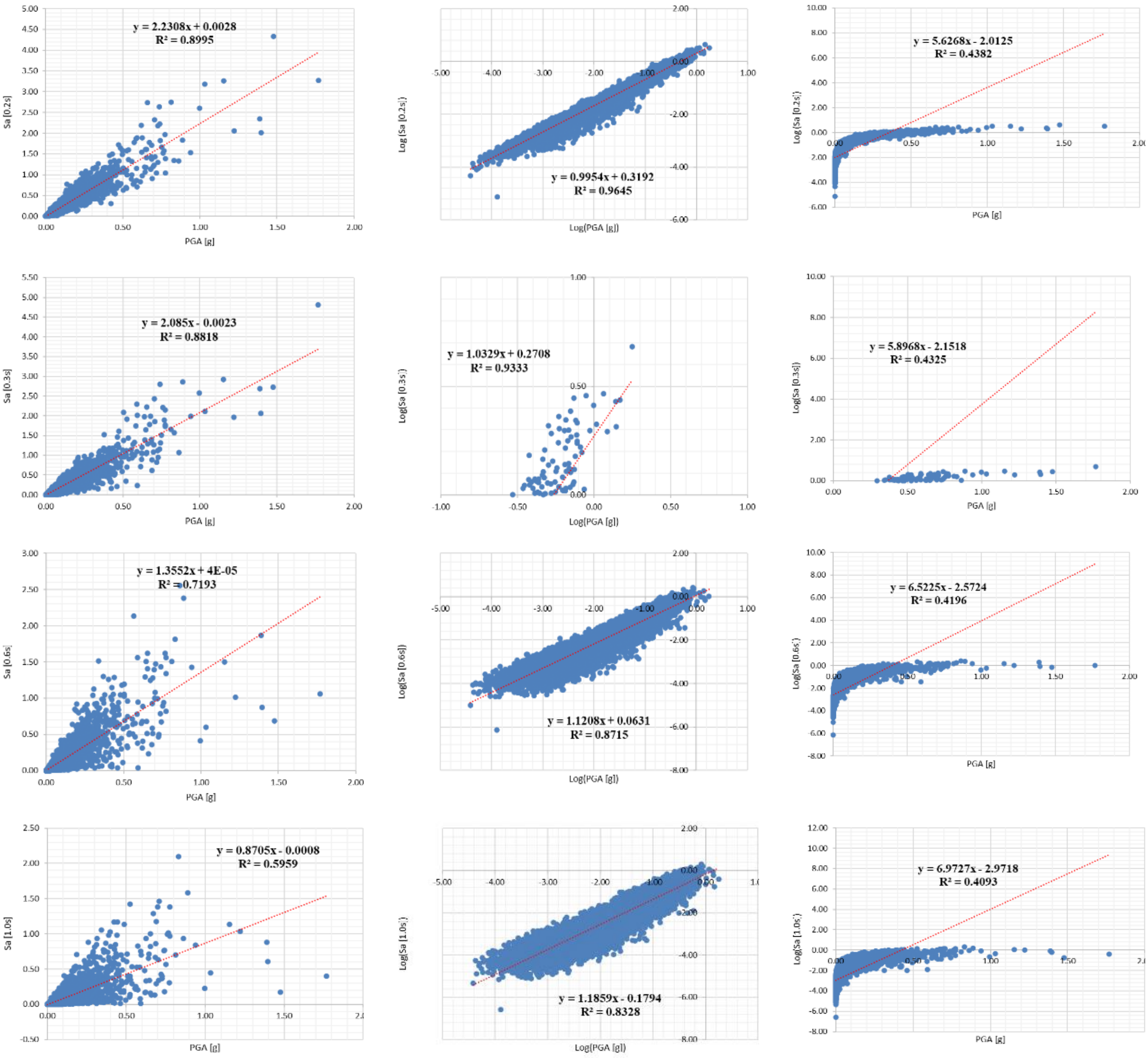
Collected models use different IMs, therefore to combine these models, it is necessary to convert various IMs to a specific one. In this study, due to its wide application, peak ground acceleration (PGA) was chosen as IM for developing fragility curves. To convert various IMs to PGA, more than 6200 selected ground motion records were investigated and some conversion relations were fitted, using linear, logarithmic, and semi-logarithmic methods. As presented in Figure 1, the logarithmic method provides a more accurate fitting. Final relations fitted for various required IMs are shown in Equation 2 to Equation 5.

$$Sa[0.2s] = 0.9954\ PGA + 0.3192 \tag{2}$$

$$\mathrm{Sa}[0.3\mathrm{s}] = 1.0329\ \mathrm{PGA} + 0.2708 \tag{3}$$

$$\mathrm{Sa}[0.6\mathrm{s}] = 1.1208\ \mathrm{PGA} + 0.0631 \tag{4}$$

$$\mathrm{Sa}[1.0\mathrm{s}] = 1.1859\ \mathrm{PGA} - 0.1794 \tag{5}$$



(a) **(b)** **(c)**

Fig. 1: Sa to PGA relation using various fitting methods. (a) Linear; (b) Logarithmic; (c) Semi-logarithmic

Regarding the damage states, all the selected fragility curves used a four-damage state model, including slight, moderate, extensive, and complete damage states; however, there are some minor differences in the definition of thresholds used. These differences are neglected in this study, and the proposed fragility curves are developed similarly using four damage states of slight, moderate, extensive, and complete damage.

In order to find an appropriate method to combine the collected models, three different methods were investigated. Assuming a log-normal distribution for all the models, which can be defined with a median (μ) and a standard deviation (σ), three averaging methods were defined as follows:

1) Direct averaging of the gathered curves at each value of IM (PGA).

2) Assuming a log-normal distribution by a median and standard deviation equal to the mean of the median and standard deviation of the gathered curves.

3) Assuming a log-normal distribution by a median and standard deviation equal to the median of the median and standard deviation of the gathered curves.

A comparison of the results based on these three methods is shown for RC buildings in Figure 2. As shown in this figure, the first method generally shows a more conservative result in comparison with the two other methods. Therefore, it was decided to use this method for the development of the rest of the fragility curves. Figure 3 also shows the fragility curves of reinforced concrete structures for the complete damage state, along with the distribution of the related collected curves used for the generation of each fragility curve. The broad variety of the collected curves and their high levels of variability are presented in this figure.

4.1 Fragility curves of Classification Model 1

Based on the previously outlined assumptions and methodology, fragility curves for low-rise steel and reinforced concrete structures were created. This section presents the results pertaining to Classification 1, where the structural system was not regarded as a parameter, and six categories were included. Fragility models used in each curve are also presented in Table 4. Fragility curves developed for these building classes are presented in Figure 4. A log-normal distribution is also fitted to these curves, relevant parameters of which are listed in Table 5.

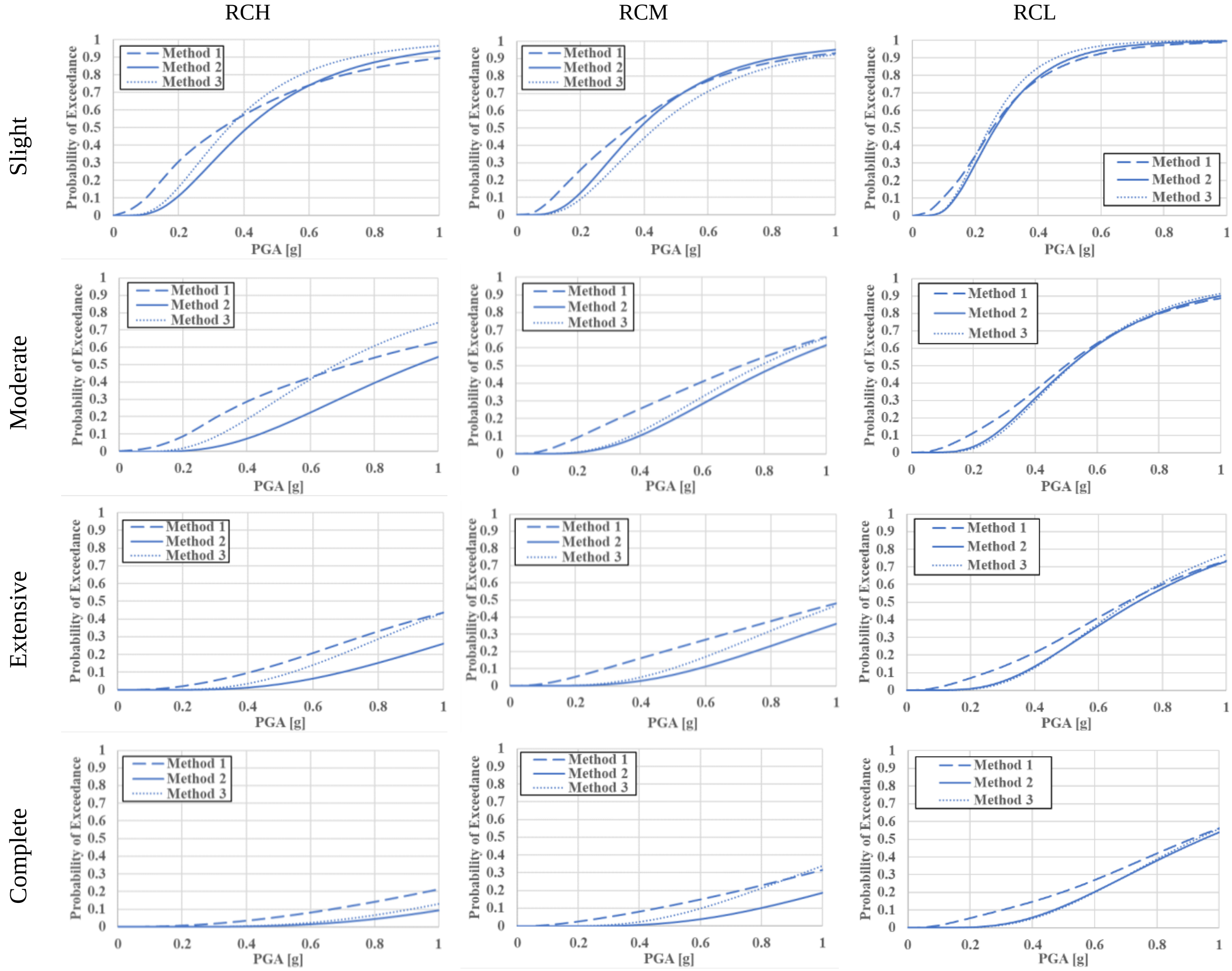


Fig. 2: Comparison of three methods of developing hybrid fragility curves using collected models

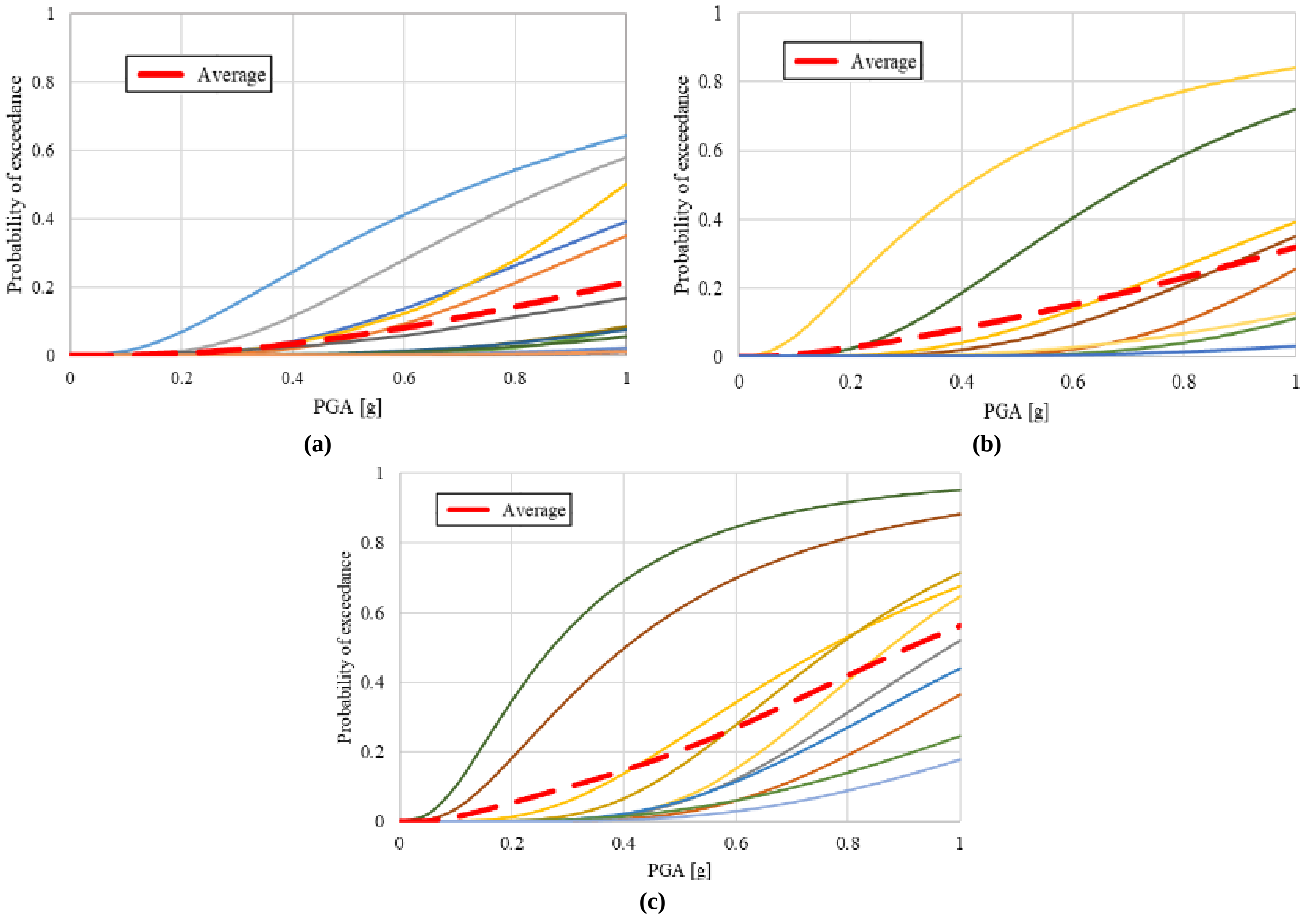


Fig. 3: Distribution of the related collected curves used for generation of RC structures' fragility curve at Complete DS. (a) RCH; (b) RCM; (c) RCL

Table 4: List of fragility curves combined in each building class (based on classification Model 1)

Building Class	No. of the curves used [a]
RCH	2,3,10,14,18,25,28,38,39,40,44(3[b]),47(3),49(3),52(3),55(3)
RCM	2,3,9,17,24,27,50(3),53(3),56(3)
RCL	1,8,16,23,26,45(3),46(3),48(3),51(3),54(3)
STH	5,7,13,15,21,31,34,37,41,42,43,58(3),61(3),64(3)
STM	5,7,12,20,22,30,33,36,59(3),62(3),65(3)
STL	4,6,11,19,29,32,35,60(3),63(3),66(3)

[a] The numbers utilized in this table correspond to those defined in the initial column of Table 3.

[b] The (3) in front of some numbers, indicates that three models of 1, 2 and 3 story are included.

Table 5: Log-normal distribution parameters for fragility curves developed for building classes in classification Model 1.

Building Type	Damage State							
	slight		Moderate		Extensive		Complete	
	μ	β	μ	β	μ	β	μ	β
RCH	0.33	0.99	0.72	0.97	1.13	0.78	1.95	0.84
RCM	0.33	0.78	0.70	0.90	1.08	0.98	1.65	0.99
RCL	0.24	0.67	0.47	0.68	0.66	0.72	0.93	0.80
STH	0.40	0.94	0.93	0.99	1.48	0.96	2.06	0.83
STM	0.39	0.77	0.84	0.99	1.16	0.99	1.53	0.99
STL	0.32	0.78	0.58	0.88	0.83	0.91	1.06	0.90

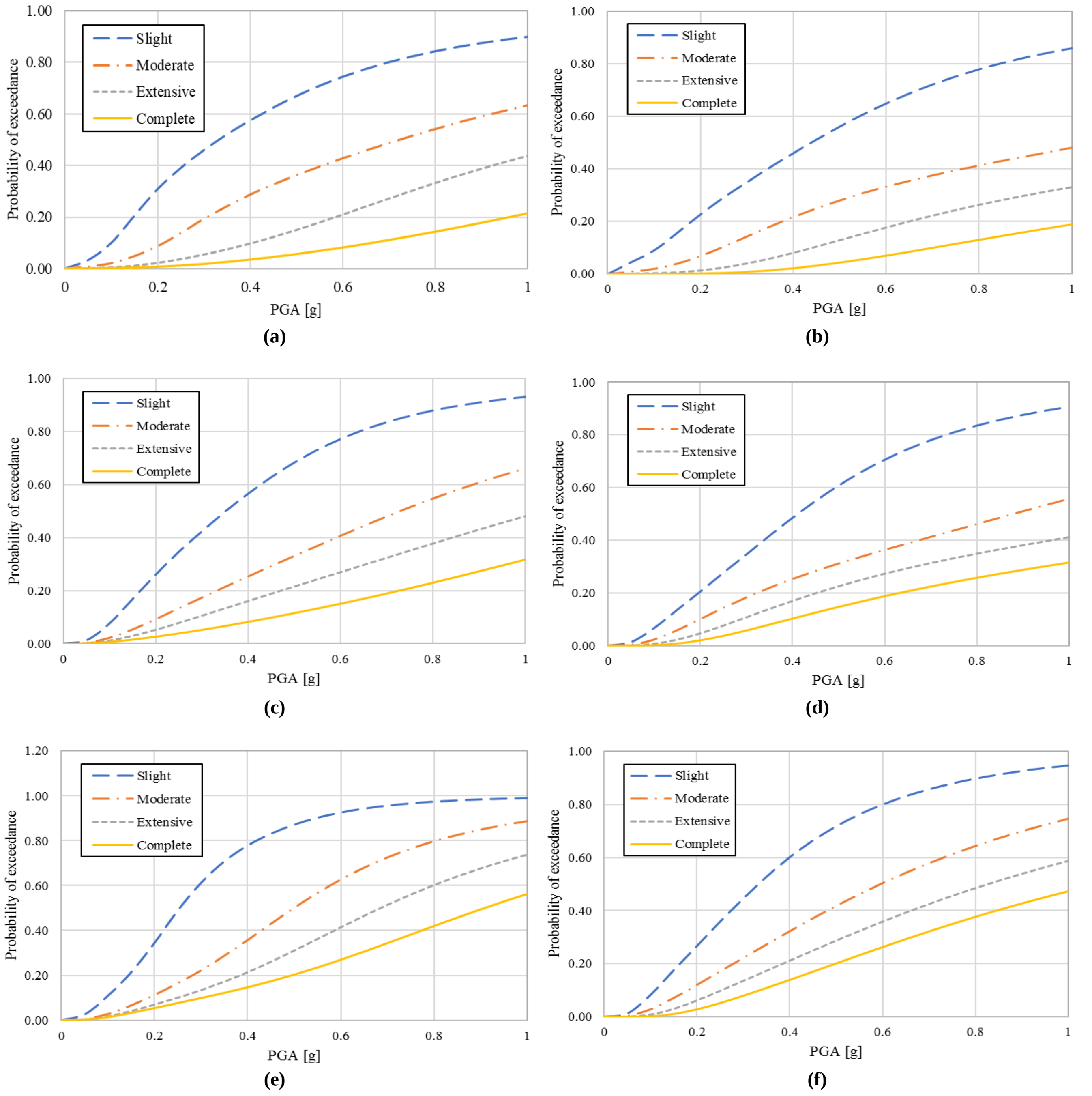


Fig. 4: Fragility curves developed for building classes in classification Model 1. (a) RCH; (b) STH; (c) RCM; (d) STM; (e) RCL; (f) STL

4.2 Fragility curves of Classification Model 2

Considering the structural system in classification Model 2, more accurate fragility curves are developed in this section. Fragility models used in each curve are also presented in Table 6. As shown in this table, the quantity of fragility curves for steel-braced structures and RC shear wall systems appears to be inadequate. Introducing new models in the future could enhance the reliability of the associated fragility curves. Fragility curves developed for these building classes are presented in Figure 5. The same as classification Model 1, a log-normal distribution is also fitted to these curves, and their parameters are listed in Table 7.

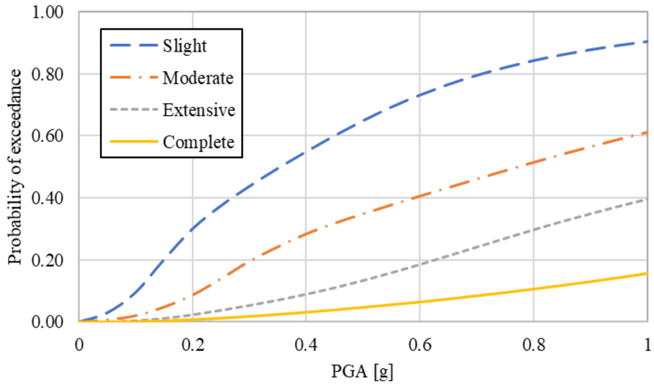
Table 6: List of fragility curves combined in each building class (based on classification Model 2)

Building Class	No. of the curves used [a]
RC-Frame-H	2,18,25,28,38,39,40,44(3[b]),47(3),49(3),52(3)
RC-Frame-M	2,17,24,27,50(3),53(3)
RC-Frame-L	1,16,23,26,45(3),46(3),48(3),51(3),54(3)
ST-Frame-H	5,21,31,34,41,42,43,61,64
ST-Frame-M	5,20,30,33,62,65
ST-Frame-L	4,19,29,32,63,66
ST-Brace-H	7,37,58
ST- Brace -M	7,22,36,59
ST- Brace -L	6,35,60
RC-SWall-H	3,55,56

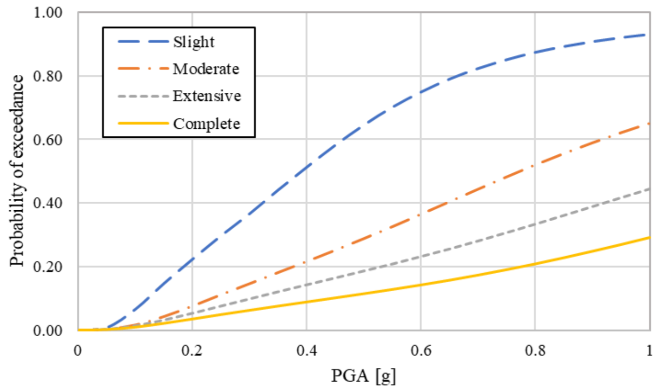
a Numbers used in this table, are the same as what is defined in the first column of Table 3.
b The (3) in front of some numbers, indicates that three models of 1, 2 and 3 story are included

Table 7: Log-normal distribution parameters for fragility curves developed for building classes in classification Model 2.

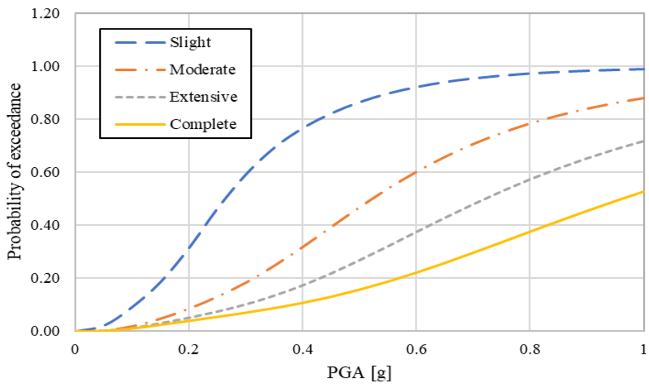
Building Type	**Damage State**							
	slight		**Moderate**		**Extensive**		**Complete**	
	μ	β	μ	β	μ	β	μ	β
RC-Frame-H	0.33	0.91	0.76	1.00	1.25	0.84	2.78	1.00
RC-Frame-M	0.37	0.76	0.77	0.84	1.21	1.00	1.75	1.00
RC-Frame-L	0.26	0.61	0.51	0.59	0.72	0.63	1.01	0.72
ST-Frame-H	0.43	0.85	1.00	1.00	1.53	0.94	2.22	0.83
ST-Frame-M	0.44	0.64	1.01	0.91	1.51	1.00	1.98	1.00
ST-Frame-L	0.32	0.70	0.62	0.79	0.89	0.92	1.14	0.94
ST-Brace-H	0.60	0.59	1.61	0.92	1.83	0.84	2.14	0.68
ST-Brace-M	0.40	0.93	0.80	1.00	1.07	1.00	1.36	1.00
ST-Brace-L	0.41	0.69	0.71	0.73	0.96	0.68	1.22	0.67
RC-Wall-H	0.49	0.89	1.24	0.91	1.65	0.85	2.18	0.70



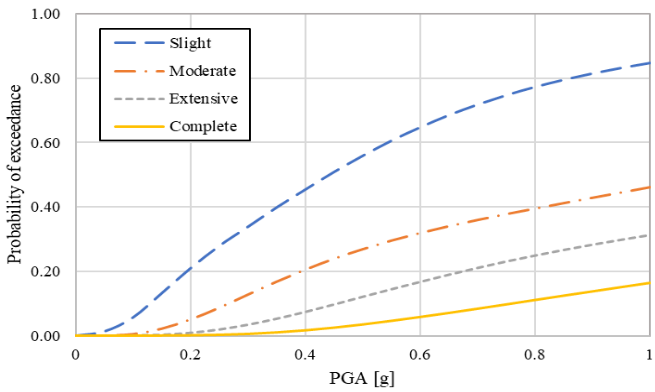
(5a)



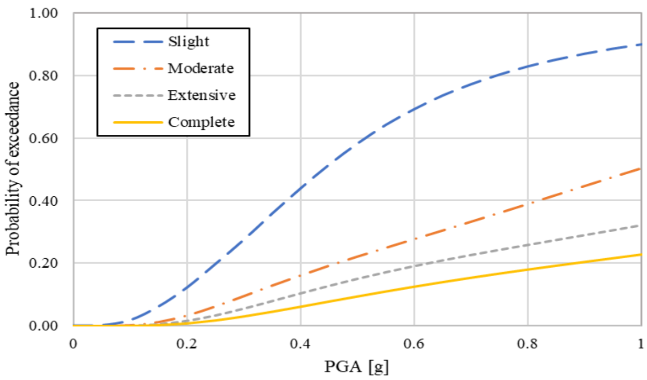
(5b)



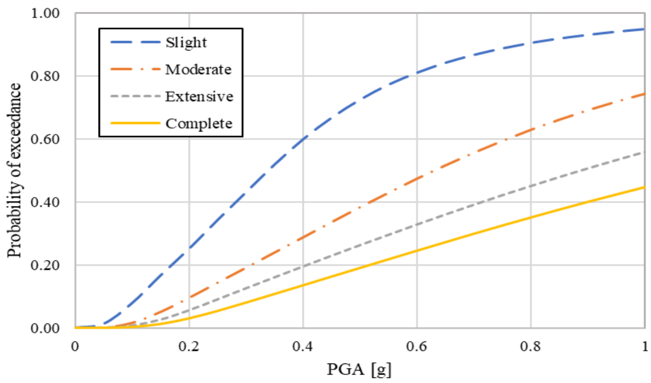
(5c)



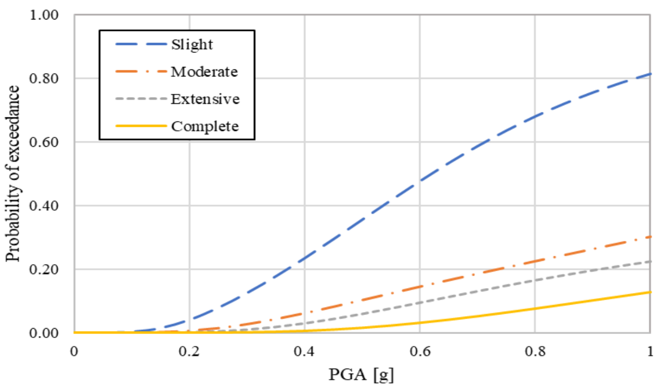
(5d)



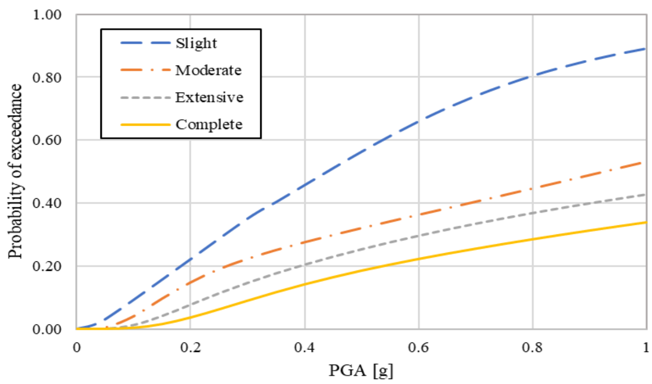
(5e)



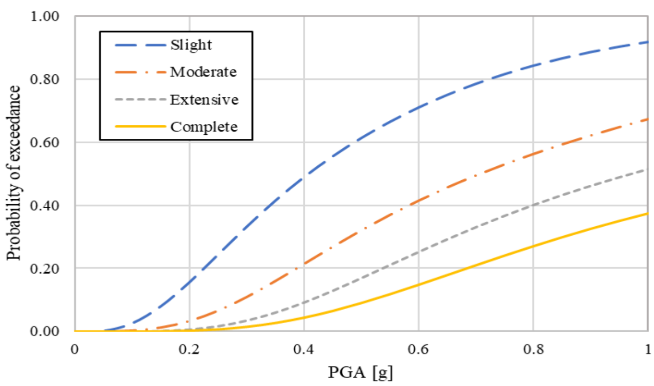
(5f)



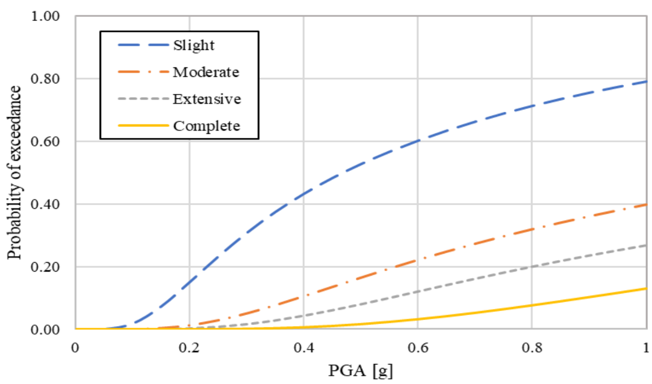
(5g)



(5h)



(5i)



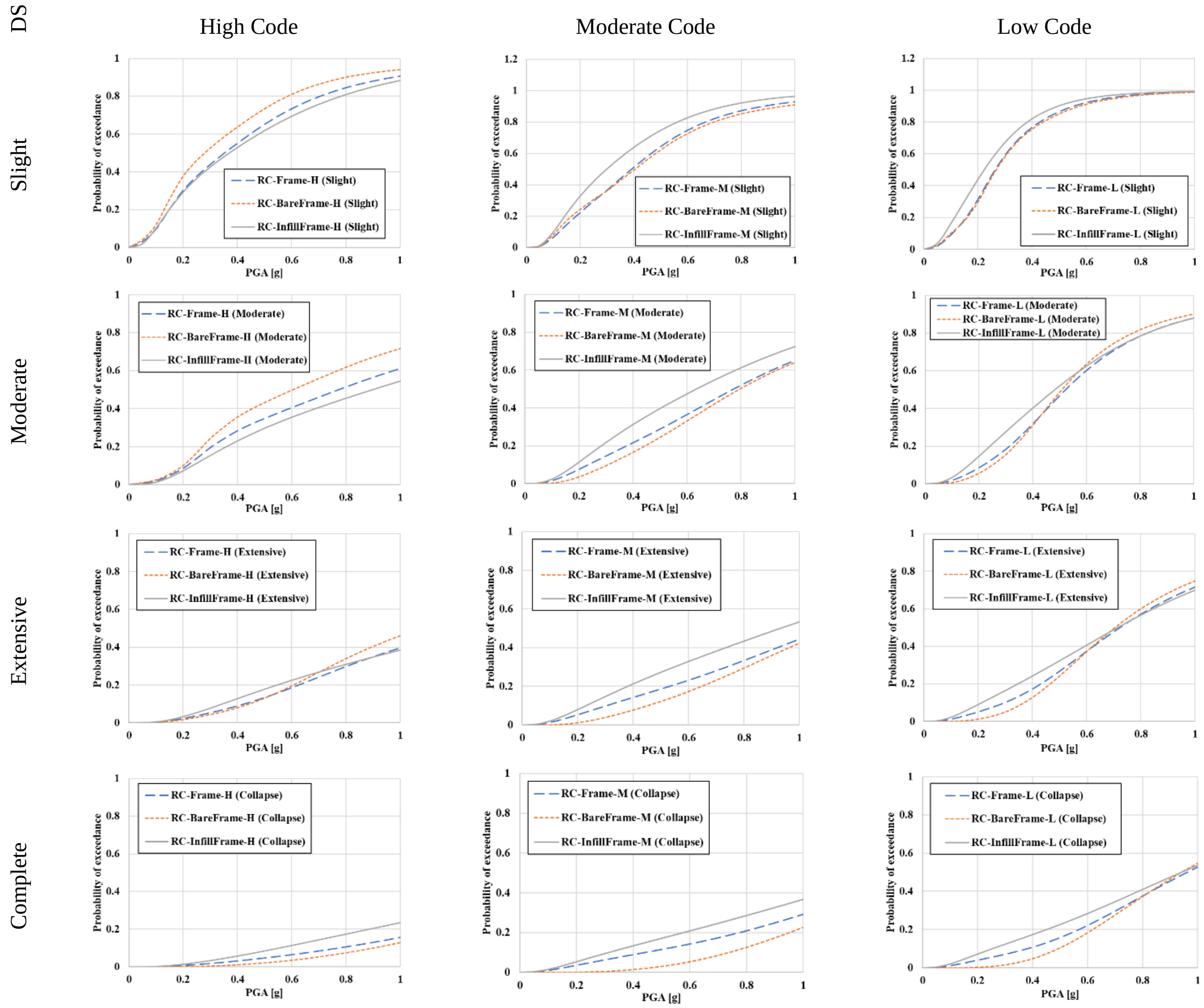
(5j)

Fig. 5: Fragility curves developed for building classes in classification Model 2. **(a)** RC-Frame-H; **(b)** RC-Frame-M; **(c)** RC-Frame-L; **(d)** ST-Frame-H; **(e)** ST-Frame-M; **(f)** ST-Frame-L; **(g)** ST-Brace-H; **(h)** ST-Brace-M; **(i)** ST-Brace-L; **(j)** RC-SWall-H

4.3 Infill effects

In Iran, buildings with MRF systems typically incorporate infills, which can significantly impact the overall seismic behavior of the structure. While these infills enhance the initial stiffness and strength of the system, their effect diminishes rapidly after failure, transitioning the system into a bare frame (Kohrangi et al., 2021). The fragility curves gathered in this study encompass scenarios with and without infills. Previously, the proposed fragility curves for concrete and steel MRF systems did not account for infill effects, treating both cases as MRF systems. To enhance the accuracy of the proposed curves and explore the impact of this factor, the fragility curves obtained from MRF systems were divided into two groups: "InfillF" and "BareF," representing scenarios with and without consideration of infill effects, respectively, and were analyzed separately. The results and the comparison made between the two cases and the previous case are shown in Figure 6 and Figure 7. As it is visible in these figures, the presence of infills has a significant effect on the proposed fragility curves, and ignoring this effect might result in crucial errors. Differences even up to 40% are observed in the probability of exceedance in various DS values, which is a notable indication of this effect.

Moreover, the results show that this effect may reduce or increase the probability of exceedance in different cases. In the case of RC structures that have higher stiffness, infill presence has shown its effect in the case of complete DS, and it seems that the failure of the infills and the sudden reduction in the stiffness of the building made the probability of failure higher. In other DS values, however, the presence of infills is effective and the probability of exceedance is reduced. In the case of steel structures, this effect is different, and among all DS values, the presence of infills has been able to reduce the probability of exceedance.



Fi. 6: Infill effects on fragility curves of reinforced MRF buildings.

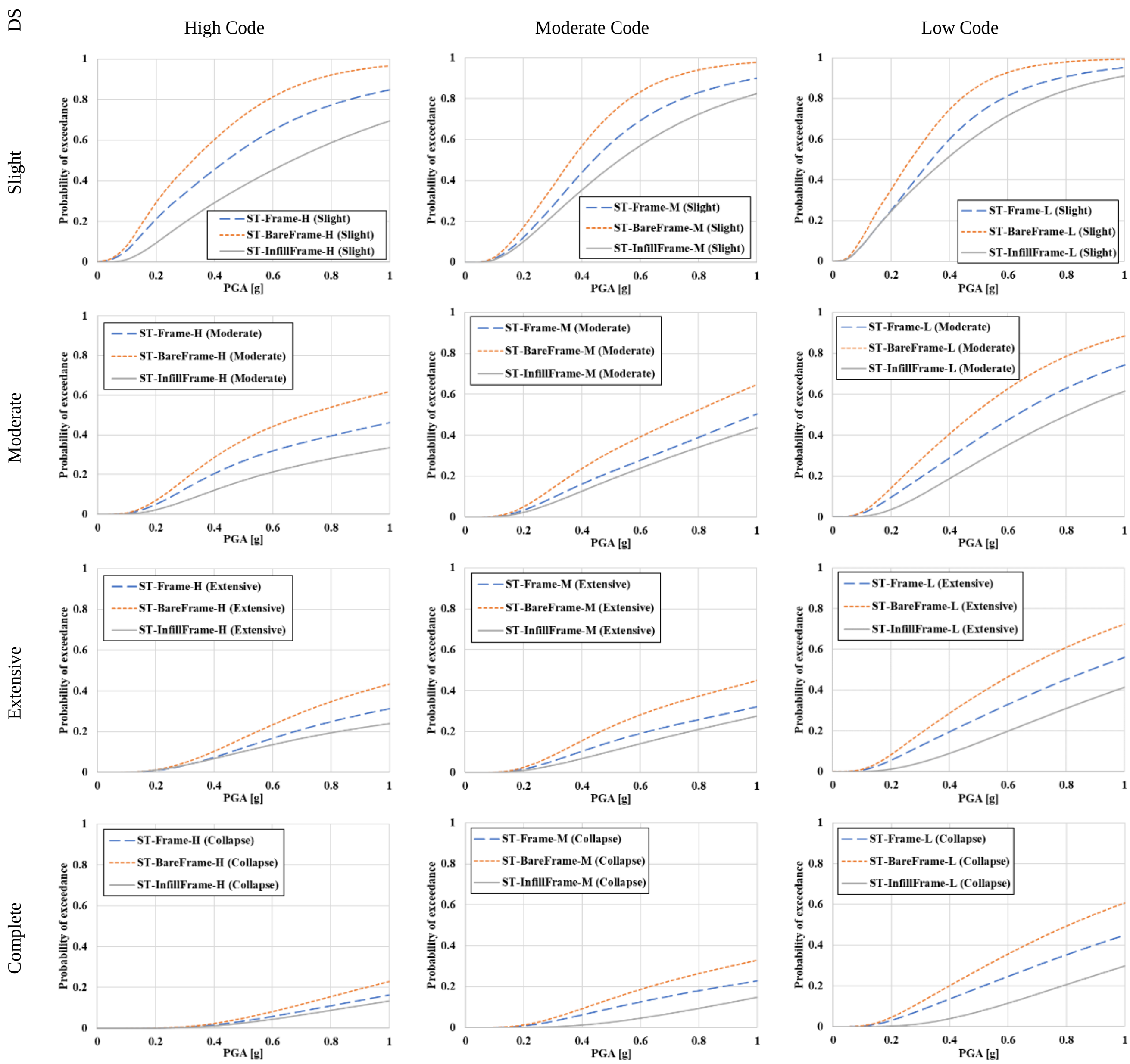


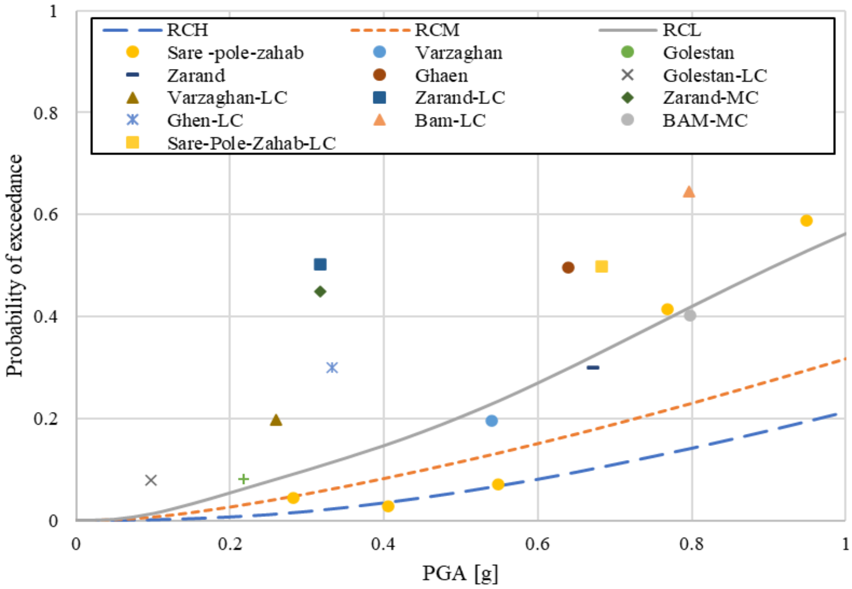
Fig. 7: Infill effects on fragility curves of steel MRF buildings

4.4 Verification of results

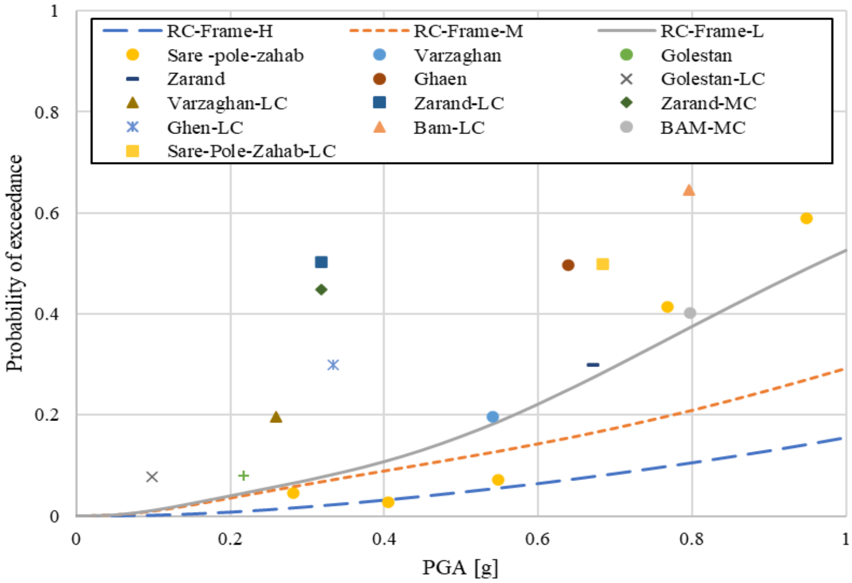
In order to control the accuracy and quality of the obtained results, a comparison between the observed and estimated results is made using the results and damage statistics from past earthquakes. To this aim, data presented by various researchers were collected through an adequate review of the literature. It is noteworthy that sufficient data for all the structural systems investigated in this paper are not available, but a partial comparison can also be a general confirmation of the presented fragility curves.

Considering that the collected data are mainly related to MRF buildings, the comparison is only made for this structural system. All related cases, including both classification Models 1 and 2, and also with/without infill effects are considered. Figure 8 and Figure 9 show the gathered damage data along with the proposed fragility curves for DS values corresponding to the complete damage, for both steel and reinforced concrete buildings. As it is clear in these figures, there is a good agreement between the proposed curves and the available data, especially in low quality mode for both steel and concrete buildings. This was anticipated, as the majority of the available data pertained to past earthquakes in areas with older buildings and low construction quality. Furthermore, a study by Biglari et al. (2021) found that the buildings examined after November 12, 2017, were engineered steel and RC structures constructed in accordance with the second and third editions of the Iranian code for earthquake-resistant buildings. However, these structures were often built with inadequate supervision and subpar materials. This could better explain why the observed damages from previous earthquakes closely align with the low-construction case in the developed fragility curves. As long as concrete structures are considered, the issue mentioned above is more evident. In these cases, the gathered damage data fit better with low-code fragility curves in all DSs. It seems to be due to the lower quality of the materials used, and also the less suitable construction practice of concrete structures that exist in Iran. On the other hand, in steel structures, the yellow data, which is related to low quality steel buildings, is consistent with the low-code case of the curves, and in contrast, the blue data, which is related to MRFSs, is consistent with the moderate code state.

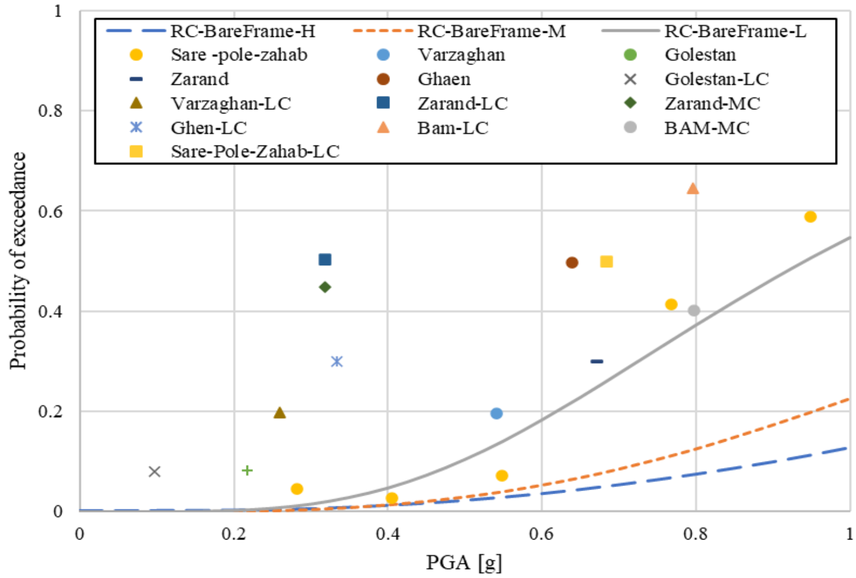
Finally, it can also be pointed out that the fragility curves developed by various researchers are generally created with specific engineering assumptions for the buildings, while in reality many of the assumptions may not be achieved. In this regard, some justifications were discussed above. In general, this case can be seen as one of the main reasons for the developed curves to underestimate the losses, in comparison with the actual loss data.



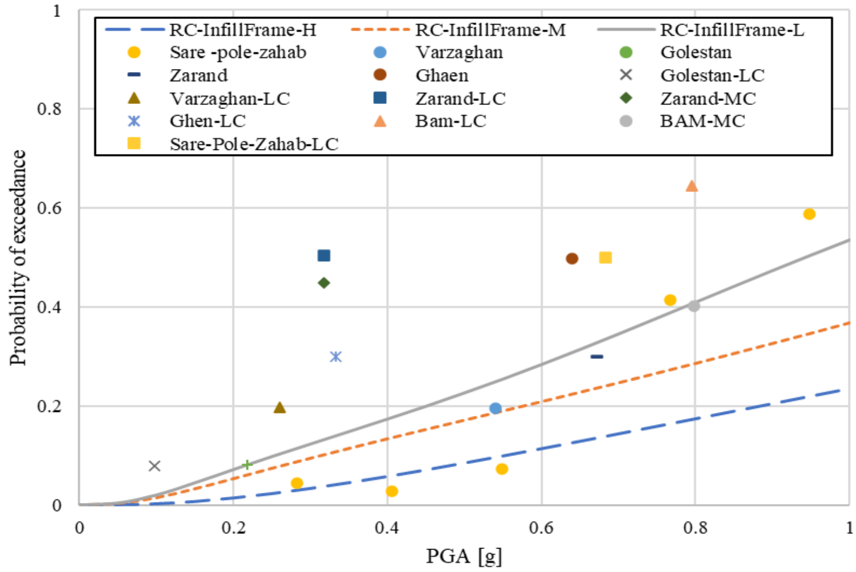
(8a)



(8b)

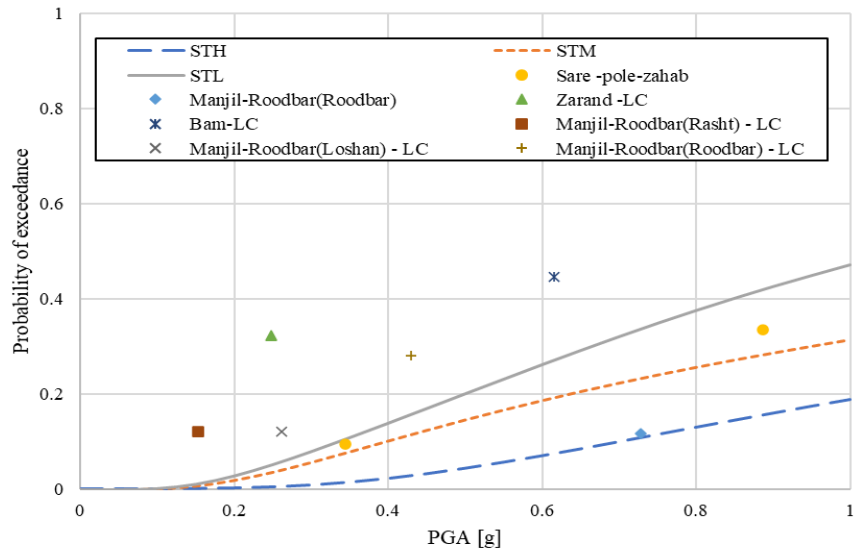


(8c)

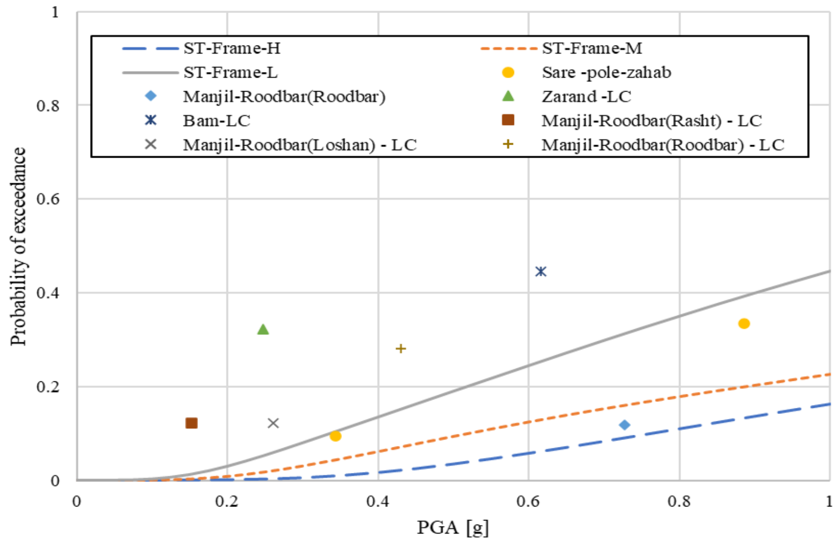


(8d)

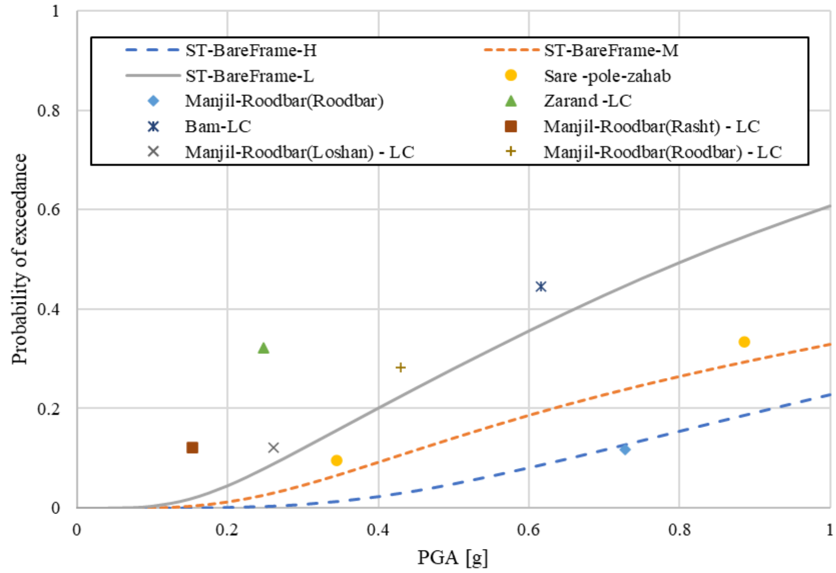
Fig. 8: Comparison of proposed fragility curves (Complete DS) with damage data of old earthquakes for RC buildings.



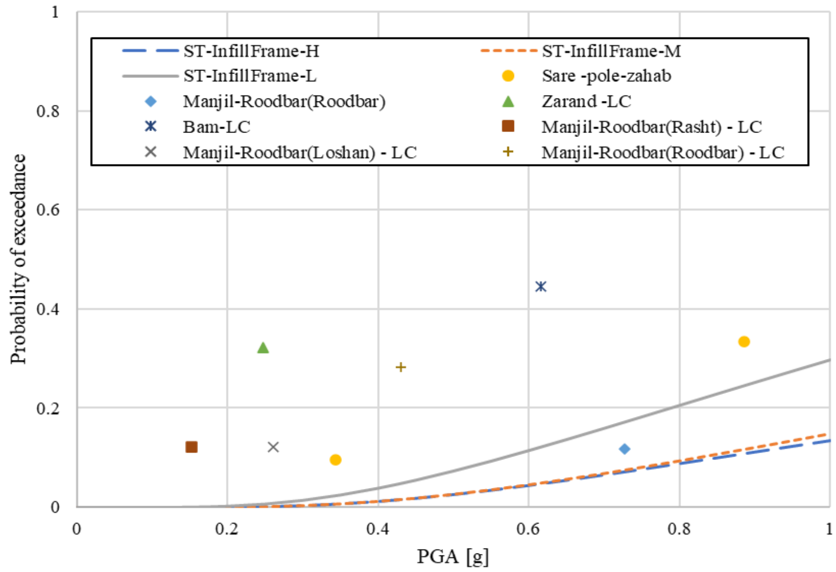
(9a)



(9b)



(9c)



(9d)

Fig. 9: Comparison of proposed fragility curves (Complete DS) with damage data of old earthquakes for steel buildings.

5. Conclusion

In this paper, a thorough review of national and international studies on fragility models was conducted. Various related models were collected and then integrated to propose suitable models for Iranian low-rise steel and reinforced concrete buildings, taking into account different parameters. To summarize the topic, the main results obtained in this study are briefly presented:

1- Through an adequate review of the existing studies, which dealt with the classification of Iran's buildings, a specific classification was proposed in this project. In terms of building materials, structural system, and the level of the quality of construction or design requirements, two classification models were proposed. The first one considers building materials, along with the quality of design/construction, resulting in the generation of 6 general categories. In the second classification, the structural system is considered as a parameter leading to a more detailed classification consisting of 10 categories.

2- According to the defined classification, a review of existing fragility models at both national and global scales was done. In an initial screening, only the models that were compatible with the project target were selected. In total, 115 fragility curves were collected and reported.

3- After gathering the fragility models, to reduce the existing uncertainties, the collected curves were combined to propose the new fragility model. Due to the initial filtering that was done, the same weight was used to combine these curves.

4- Due to the fact that the collected fragility curves used different intensity measures, using the data of about 6200 earthquake records, mathematical relations were employed to convert different measures into one, which is PGA. For this purpose, different methods of linear, logarithmic, and semi-logarithmic regressions were investigated. It was shown that the logarithmic method, provided the highest values of the correlation coefficient, and therefore it was used in this study.

5- Due to the possibility of the presence of infills in MRF buildings, the curves were specifically investigated with or without the effect of infills, and the results were compared. The results showed a significant impact on the probability of exceedance of damage reaching 40%, at times.

6- Comparison of the proposed curves with observed damages of the previous earthquakes indicated an acceptable agreement between them. However, it is worth mentioning that the damage data of past earthquakes are most consistent with the - LC case in the curves. The reason can be clearly mentioned in two cases, one is the old data and the low quality of the buildings (construction or design) in the past, and the second is related to the low quality of the materials used, the construction practice, and supervision on it, especially for the low-rise buildings in rural areas whith minimal supervision on their construction.

References

[1] Bastami, M., Abbasnejadfard, M., Motamed, H., Ansari, A., and Garakaninezhad, A. (2022), "Development of hybrid earthquake vulnerability functions for typical residential buildings in Iran", International Journal of Disaster Risk Reduction, 77.

[2] Ministry of Road & Urban Development (2014), Iranian Code for Seismic Design of Buildings (Standard No. 2800), 4th ed., Tehran: Roads, Housing & Urban Development Research Center. (In Persian)

[3] Ministry of Road & Urban Development (2005), Iranian Code for Seismic Design of Buildings (Standard No. 2800), 3rd ed., Tehran: Roads, Housing & Urban Development Research Center. (In Persian)

[4] Biglari, M., Formisano, A., and Hashemi, B.H. (2021), "Empirical fragility curves of engineered Steel and RC residential buildings after Mw 7.3 2017 Sarpol-e-zahab earthquake", Bulletin of Earthquake Engineering, 19:2671–2689. https:// doi. org/ 10. 1007/ s10518- 021- 01090-4.

[5] Fallah Tafti, M., Amini Hosseini, K., and Mansouri, B. (2020), "Generation of new fragility curves for common types of buildings in Iran", Bulletin of Earthquake Engineering, 18:3079–3099. https:// doi. org/ 10. 1007/s10518- 020- 00811-5.

[6] Hashemi, B.H., and Kiany, B.K. (2018), "Performance of Steel Structures and Associated Lessons to be Learned from November 12, 2017, Sarpol-e Zahab-Ezgeleh Earthquake (MW 7.3)", Journal of Seismology and Earthquake Engineering, 20(3): 33-46.

[7] Hashemi, B.H., Kiany, B. K., and Farshchi, H. (2018), "Performance of RC Structures and Associated Lessons to be Learned from November 12, 2017, Sarpol-e Zahab-Ezgeleh Earthquake (MW 7.3)", Journal of Seismology and Earthquake Engineering, 20(3): 19-32.

[8] HAZUS (1999), Earthquake loss estimation methodology-Technical manual, Federal Emergency Management Agency and National Institute of Building Science.

[9] Kappos, A.J., Panagopoulos, G., Panagiotopoulos, C. et al. (2006), "A hybrid method for the vulnerability assessment of R/C and URM buildings", Bulletin of Earthquake Engineering, 4: 391–413. https://doi.org/10.1007/s10518-006-9023-0.

[10] Karim Zadeh, Z., Ghafory-Ashtiany, M., Kalantari, A. et al. (2022), "Development of analytical seismic fragility functions for the common buildings in Iran", Bulletin of Earthquake Engineering, 20: 5905–5942. https://doi.org/10.1007/s10518-022-01411-1.

[11] Kohrangi, M., Bazzurro, P. and Vamvatsikos, D. (2021), "Seismic risk and loss estimation for the building stock in Isfahan. Part I: exposure and vulnerability", Bulletin of Earthquake Engineering, 19: 1709–1737. https://doi.org/10.1007/s10518-020-01036-2.

[12] Martins, L., and Silva, V. (2020), "Development of a fragility and vulnerability model for global seismic risk analyses", Bulletin of Earthquake Engineering, 19: 6719–6745. https:// doi. org/ 10. 1007/ s10518- 020- 00885-1.

[13] Motamed, H., Calderon, A., Silva, V. et al. (2019), "Development of a probabilistic earthquake loss model for Iran", Bulletin of Earthquake Engineering, 17: 1795–1823. https://doi.org/10.1007/s10518-018-0515-5.

[14] Naseri, A., Pahlavan, H., and Ghodrati Amiri, G. (2017), "Probabilistic seismic assessment of RC frame structures in North of Iran using fragility curves", Journal of Structural and Construction Engineering, 4(4): 58-78. doi: 10.22065/jsce.2017.78827.1095 (in Persian).

[15] Omidian, P., and Saffari, H. (2017), "Seismic vulnerability assessment of regular and irregular concrete structures using fragility curves", Journal of Structural and Construction Engineering, 5(3):124-144. doi: 10.22065/jsce.2017.84305.1168

[16] Razmkhah, M. H., Kouhestanian, H., Shafaei, J., Pahlavan, H., and Shamekhi Amiri, M. (2021), "Probabilistic Seismic Assessment of Moment Resisting Steel Buildings Considering Soft-story and Torsional Irregularities", International Journal of Engineering, 34(11): 2476-2493. doi: 10.5829/ije.2021.34.11b.11

[17] Villar-Vega, M., Silva, V., Crowley, H., Yepes, C., Tarque, N., Acevedo, A., Hube, M., Coronel, G., and Santa-María, H. (2017), "Development of a fragility model for the residential building stock in South America", Earthquake Spectra, 33(2):581–604.

[18] Yepes-Estrada, C., Silva, V., Valcárcel, J., et al. (2017), "Modeling the Residential Building Inventory in South America for Seismic Risk Assessment", Earthquake Spectra, 33(1):299-322. doi:10.1193/101915eqs155dp.