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Experimental vulnerability curves for the residential buildings of Iran

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Abstract   Iran is one of the most seismically active countries of the world located on the Alpine-Himalayan earthquake belt. More than 180,000 people were killed due to earthquakes in Iran during the last five decades. Considering the fact that most Iranians live in masonry and non-engineered houses, having a comprehensive program for decreasing the vulnerability of society holds considerable importance. For this reason, loss estimation should be done before an earthquake strikes to prepare proper information for designing and selection of emergency plans and the retrofitting strategies prior to occurrence of earthquake. The loss estimation process consists of two principal steps of hazard analysis and vulnerability assessment. After identifying the earthquake hazard, the first step is to evaluate the vulnerability of residential buildings and lifelines and also the social and economic impacts of the earthquake scenarios. Among these, residential buildings have specific importance, because their destruction will disturb the daily life and result in casualties. Consequently, the vulnerability assessment of the buildings in Iran is important to identify the weak points in the built environment structure. The aim of this research is to prepare vulnerability curves for the residential buildings of Iran to provide a proper base for estimating probable damage features by future earthquakes. The estimation may contribute fundamentally for better seismic performance of Iranian societies. After a brief review of the vulnerability assessment methods in Iran and other countries, through the use of the European Macroseismic method, a model for evaluating the vulnerability of the Iranian buildings is proposed. This method allows the vulnerability assessment for numerous sets of buildings by defining the vulnerability curves for each building type based on the damage observations of previous earthquakes. For defining the vulnerability curves, a building typology classification is presented in this article, which is representative of Iranian building characteristics. The hazard is described in terms of the macroseismic intensity and the EMS-98 damage grades have been considered for classifying the physical

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damage to the buildings. The calculated vulnerability indexes and vulnerability curves show that for engineered houses there is not any notable difference between the vulnerability of Iranian and Risk-UE building types. For the non-engineered houses, the vulnerability index of brick and steel structures is less than the corresponding values of the other unreinforced masonry buildings of Iran. The vulnerability index of unreinforced and masonry buildings of Iran are larger than the values of the similar types in Risk-UE and so the Iranian buildings are more vulnerable in this regard.

1 Introduction

Iran is one of the most seismically active countries of the world and frequently suffers destructive and catastrophic earthquakes that cause considerable death tolls and widespread damages. The Alpine-Himalayan earthquake belt, where Iran is located, extends from west Portugal eastward along Southern Europe, including Iran and southern East Asia, and then encircling the Pacific Ocean (Mirzaei Alavijeh and Farzanegan 2003).

More than 180,000 people were killed due to earthquakes during the last five decades (National Report of the Islamic Republic of Iran on Disaster Reduction 2005). The last four disastrous earthquakes include Boeen Zahra earthquake in 1961 with 10,000 deaths, Tabas earthquake in 1978 with 19,600 human losses, Manjil earthquake in 1990 with 35,000 deaths, and Bam earthquake with more than 30,000 death tolls (Khatam 2006). This shows that the country is vulnerable against earthquake and earthquake is a serious threat for it.

In order to manage a disaster such as an earthquake, an estimation of the extent and grade of destruction is important concerning two aspects. On the one hand, it is one of the essential needs of initial decision making and planning in response to an earthquake, and on the other hand, it has an important role in the preparation for earthquakes and allocation of resources. Therefore, developing a model for vulnerability assessment of buildings against earthquake is a must in disaster management.

The design of residential buildings in Iran that have been designed and constructed in recent decades predominantly comply with a certain level of seismic protection as specified by the building codes and/or standards in effect at the time of their construction. Considering the high seismicity of Iran and the fact that most Iranians live in masonry and non-engineered houses, the aim of this research is to provide vulnerability curves for residential buildings of Iran.

Vulnerability assessment methods are either qualitative or quantitative. Using these methods the vulnerability of the buildings can be evaluated based on different approaches including damage observation, expert judgment, and simplified-mechanical and analytical models.

Building vulnerability is the measurement of the damage a building is likely to experience when it is subjected to ground shaking of a specified level (for example, in terms of peak ground acceleration, peak ground displacement, or earthquake intensity). The dynamic response of a structure to ground shaking is very complex, and depends on a number of interrelated parameters that are often very difficult, if not impossible, to precisely identified. These include: the exact character of the ground shaking the building will experience; the extent to which the structure will be excited by and respond to the ground shaking; the strength of the materials in the structure; the quality of construction, condition

of individual structural elements and of the whole structure; the interaction between structural and non-structural elements; the live load present in the building at the time of the earthquake; and other factors. Most of these factors can be estimated, but they are never precisely known. Consequently, vulnerability curves should be developed within levels of confidence.

The experimental way to define an applicable methodology is to start from the observed damages by analyzing the damage assessment after earthquakes of different magnitudes. However, this is not possible for all types of buildings and for all intensity levels due to the lack of documented data from previous Iranian earthquakes. The data gathered after the 1990 Manjil earthquake can be used to assess the vulnerability of masonry buildings. Considerably more extensive data exist for the 2003 Bam earthquake.

This article describes how this method, which is applicable to Iranian towns, is derived from the European Macroseismic Scale (EMS-98) (Grunthal 1998). First, the standard vulnerability curves will be introduced. Building typology is defined to provide a methodology for classifying building data for urban seismic risk assessment in Iran and to identify and classify the specific features of the Iranian buildings: old buildings, specific building types, and building vulnerability data. Classification of buildings structural systems is suggested in terms of building typology matrix (BTM). The proposed vulnerability curves based on the European data will be adapted to the Iranian construction situation based on the observed damaged from previous earthquakes that have occurred in Iran, mainly the 1990 Manjil and 2003 Bam earthquakes. The proposed vulnerability curves are verified and compared with their counterpart in RISK-UE and JICA. The vulnerability index is also specified for each building type in BTM which can be used for monitoring the vulnerability status of different districts in urban areas. The proposed curves could be considered as a key component of seismic loss estimation studies in Iran and other neighboring countries with similar construction culture.

2 Literature review

2.1 Terminology

With the aim of a better understanding of the methodology that is described in this study, first some of the main vulnerability terms are defined below:

Damage   In modern macroseismic scales the damage is represented in a discrete form through damage grades D_k ($k = 0, 1, 2, 3, 4, 5$), which represent an apparent damage that can be ascertained in the emergency following an earthquake crisis. In the case of the European Macroseismic Scale (EMS-98), the five damage grades are listed in Table 1.

Seismic vulnerability   The seismic vulnerability for a built system is defined as its susceptibility to suffer a certain level of damage if subjected to an earthquake (Giovinazzi 2005).

Table 1 Definition of the damage grades in the European Macroseismic Scale (EMS-98) (Grunthal 1998)

Grade	0	1	2	3	4	5
Damage	None	Slight	Moderate	Heavy	Very heavy	Destruction

Mean damage grade If a set of buildings is considered, an earthquake of a given intensity should cause a different damage grade in each one of them, due to the specific seismic behavior. By considering the histogram of the damage grades that occur to the set of buildings, it is possible to define the mean damage grade (μ_D) as the representative parameter:

$$\mu_D = \sum_{k=0}^{5} p_k.k \quad 0 < \mu_D < 5 \tag{1}$$

where p_k is the probability of experiencing damage of grade k, in a set of buildings. It is necessary to remark that the mean damage grade μ_D is a continuous parameter, unlike the damage grades, which represents the distribution of damage to the building set.

Damage ratio (D_i) The damage can be measured in economic terms; the damage ratio parameter is defined as the ratio between the cost of repair and the reconstruction cost of buildings.

Damage probability matrix (DPM) DPM is a matrix that contains the seismic response of a set of buildings, by expressing the statistical distribution of damage grades for the different macroseismic intensities (Giovinazzi 2005).

Vulnerability index The vulnerability index (V_i) is a continuous parameter that quantifies the disposition of a building (or of a set of buildings) to be damaged by an earthquake; in other terms, the vulnerability index is a score that can be assigned to a building by means of the available information on the typology and other structural and constructive characteristics (Giovinazzi 2005). The larger the vulnerability index, the more the vulnerability of the structure. A relation between vulnerability index and damage grade is shown in Eq. 2. The Probabilistic distribution of different damage grades for different structural types could be calculated based on the calculated mean damage grade using Eq. 3 (Risk-UE 2004).

Vulnerability curves Vulnerability curves correlate to the hazard, in terms of macroseismic intensity I, with the damage, in terms of mean damage grade μ_D; the shape of the vulnerability curves that represent the behavior of any possible building is defined by only one parameter: the vulnerability index (Giovinazzi 2005).

Fragility curves The fragility curves for a given set of buildings give the probability of having a certain consequence (damage grades, economic losses, collapsed buildings, unfit for use buildings, dead people, homeless), as a function of the seismic aggression.

The fragility curves of the damage grades depend analytically on the vulnerability index. They could be derived from the vulnerability curves that offer the mean damage grade through the beta distribution (or another probabilistic distribution).

2.2 Vulnerability assessment methods

Considering how and on the basis of what knowledge the vulnerability curves have been derived, it is possible to build the fragility curves using three methods (Giovinazzi 2005):

2.2.1 Analytical methods, based on the mechanical calculation of the structural response of the building

An analytical approach for generating vulnerability curves is implemented when the actual earthquake damage data are limited and cannot provide sufficient statistical information.

Analytical fragility curves are developed from seismic response analysis of structures (Towashiraporn 2004). These types of vulnerability curves must be verified by the observed data. Mechanical vulnerability models for territorial scale analysis on classes of buildings can be defined on the basis of either traditional force-based procedures or displacement-based designed approaches. One of the well-known methods is HAZUS (1999). Developed by the Federal Emergency Agency specifically for the U.S. built environment (HAZard in U.S.), but is often applied in other regions too (Spence et al. 2003). The methodology is based on three fundamental concepts: capacity curve, performance point, and fragility curve. The displacement-based procedures, developed by Calvi (1999), are based on the assessment of the displacement capacity of a building corresponding to several limit states and of the displacement demand resulting from a displacement spectrum. The method allows for an evaluation of the probability of the occurrence of a certain limit state for a given displacement response spectrum (Giovinazzi 2005).

2.2.2 Expert judgment-based methods, based on observed damage data and corresponding earthquake intensity in the location of damaged structures after earthquakes in the urban areas

In the expert judgment methods, human judgment is used to replace the processing of observed data. When the required actual earthquake damage and building inventory data are not available, one can develop such data from experiences and judgments of earthquake engineering experts. These data are then processed statistically for earthquake damage estimates of the region (Towashiraporn 2004). These types of vulnerability curves must also be verified by the observed data if available. The first expert-based method was introduced by the Applied Technology Council (funded by FEMA Federal Emergency Management Agency) and summarized in the ATC-13 report (ATC 1985). Due to the uncertainty related to the opinion of experts, ATC-13 became the standard reference for earthquake damage and loss estimation study until the mid 1990s (Giovinazzi 2005).

Another approach for vulnerability assessment of buildings is based on visual inspection using score assignment procedures, in which expert judgment is employed to assign scores to the different structural deficiencies. A score assignment procedure, referred to as ATC-21 (1988), and a rapid visual screening procedure were proposed by the Applied Technology Council and sponsored by FEMA in 1988 as FEMA-154 (FEMA 1988). This is a method for single building vulnerability assessment. A method for vulnerability assessment and damage estimation based on score assignments has also been developed and applied successfully in Italy and is referred to as the GNDT II level approach (Benedetti and Petrini 1984).

2.2.3 Observed vulnerability methods (also referred to as the empirical approach or statistical methods), based on statistical observations of recorded damage data of past events as a function of the intensity felt

This method is based primarily on actual damage data obtained from field investigations after an earthquake. This kind of vulnerability curve is essentially close to exact results because it is derived directly from real structures and earthquakes. However, the quality is still limited by the limited numbers of damaged structures that are investigated. These

types of vulnerability curves are useful in characterizing the seismic performance of a collection of similar structures in an earthquake-prone area. Earthquake intensity data at each structure site and corresponding damage on the structure are collected following an earthquake. The raw data are then processed to generate vulnerability curves. This process usually requires a large number of data in order for reliable estimates of fragility. The empirical vulnerability curves are often used to calibrate the curves developed analytically (Towashiraporn 2004). Observed vulnerability methods can be summarized and represented via Damage Probability Matrices (DPM) (Whitman et al. 1973), and vulnerability or fragility curves (Lagomarsino and Giovinazzi 2006). DPMs are widely used for defining the probable distribution of damage through several methods, such as the GNDT Level I approach (Corsanego and Petrini 1994).

The observed vulnerability approach, employed in the framework of the Risk-UE project and referred to as the "macroseismic method" (Lagomarsino and Giovinazzi 2006; Giovinazzi 2005), was derived from the definitions provided by the EMS-98 macroseismic scale (Grunthal 1998). Based on the classical probability theory and on the fuzzy-set theory, numerical and complete DPM have been evaluated, in terms of EMS-98 intensities, IEMS-98, and damage grades (D_k, $k = 1$–5) for the set of EMS-98 vulnerability classes and building typologies (Risk-UE 2004).

3 Methodology

3.1 The form of vulnerability curves

An analytic expression calculates the mean damage grade μ_D as a function of the macroseismic intensity I and of the parameter V_i (vulnerability index). Figure 1 presents the vulnerability curves for vulnerability index values varying between 0.4 and 0.9. The vulnerability curves are expressed by the following formula (Risk-UE 2004):
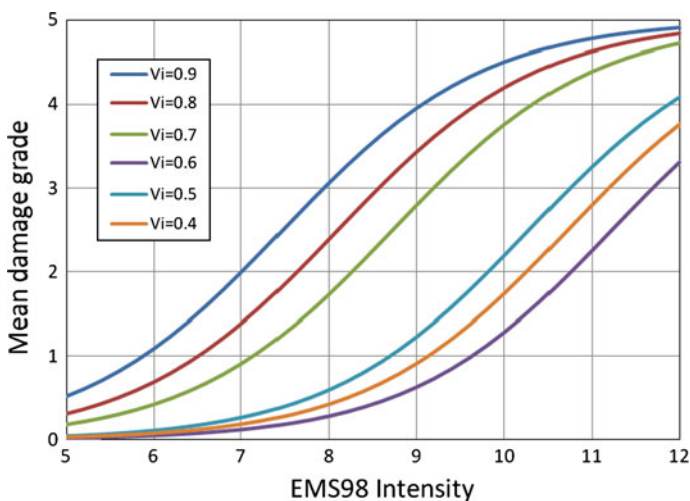

Fig. 1 Vulnerability curves relating to the vulnerability index (V_i), the EMS98 intensity, and the mean damage grade (μD) (Risk-UE 2004)

$$\mu_D = 2.5\left(1 + \tanh\left(\frac{I + 6.25 \times V_I - 13.1}{Q}\right)\right) \tag{2}$$

The value of the vulnerability index V_i determines the position of the curve; and the ductility index Q determines the rate of increase in the damage with intensity. The curves derived from EMS-98 scale are characterized by $Q = 2.3$ (Giovinazzi 2005).

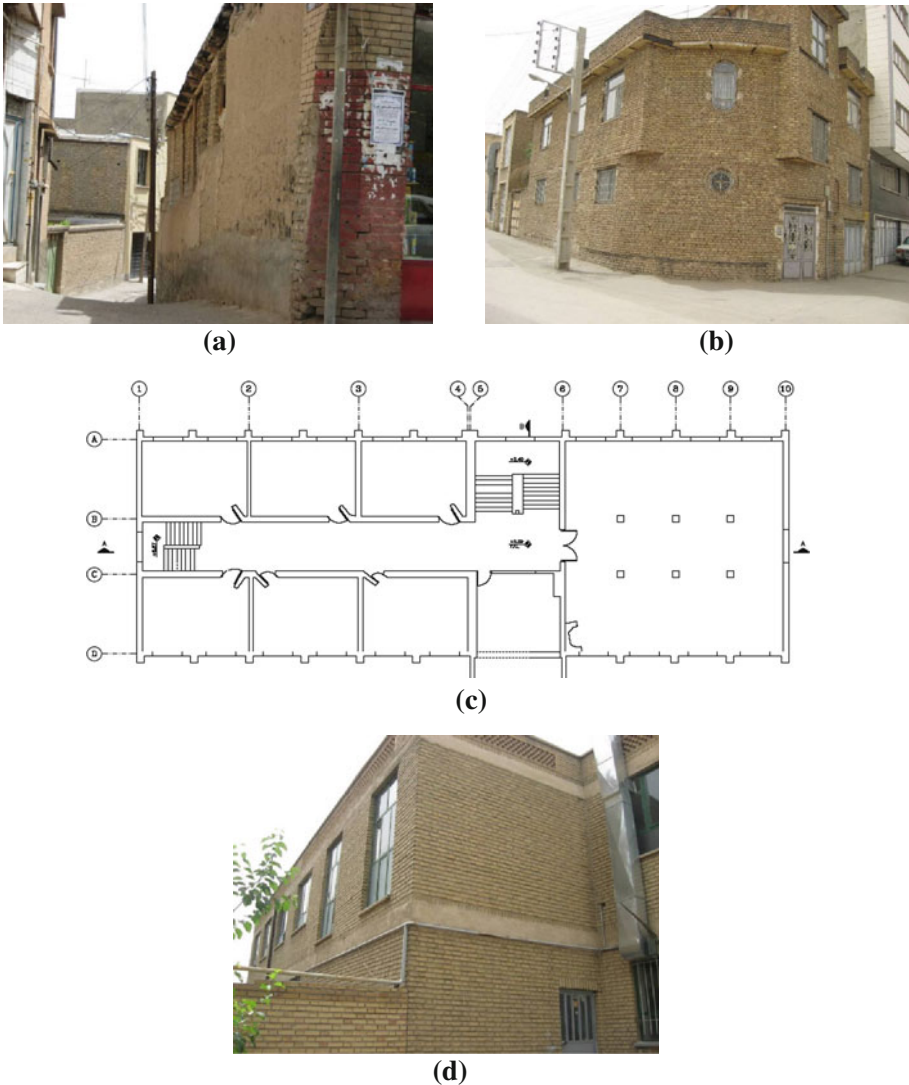The damage distribution is calculated using the beta distribution:

Fig. 2 Samples of masonry building types (Derakhshan 2009). **a** Brick walls and wooden beams. **b** Brick walls and steel beams. **c** Plan of a brick- and steel-type building. **d** Tied masonry

Fig. 3 Samples of Steel frame building types (Derakhshan 2009). **a** Simple steel frames without bracing. **b** Simple steel frames with bracing

Fig. 4 Samples of RC building types (Derakhshan 2009). **a** RC moment frames. **b** RC shear walls

$$\text{PDF:} \quad p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\Gamma(t-r)} \frac{(x-a)^{x-1}(b-x)^{(t-r-1)}}{(b-a)^{t-1}} \tag{3}$$

$$\text{CDF:} \quad P_\beta(x) = \int_a^x p_\beta(\varepsilon)d\varepsilon \tag{4}$$

where: $a = 0$; $b = 6$; $t = 8$; $r = t\,(0.007\,\mu_D^3 - 0.052\,\mu_D^2 + 0.2875\,\mu_D)$, a, b, t, and r are the parameters of the distribution, and x is the continuous variable which varies between a and b. The parameters of the beta distribution are correlated with the mean damage grade μ_D.

The discrete beta density probability function is calculated from the probabilities associated with damage grades k and $k + 1$ ($k = 0, 1, 2, 3, 4, 5$), as follows (Risk-UE 2004):

$$P_k = P_\beta(k) - P_\beta(k+1) \tag{5}$$

The fragility curve defining the probability of reaching or exceeding certain damage grade D_k is obtained directly from the cumulative probability beta distribution $P_\beta(k)$ as follows:

$$P(D \geq D_k) = 1 - P_\beta(k) \tag{6}$$

3.2 Building typology

This section presents the methodological framework for collecting physical data and focuses on the classification of buildings structural systems and suggests a matrix for building typology description (BTM).

The purpose of the building typology matrix (BTM) is to group the buildings with similar structural systems and behavior characteristics into a set of predefined building classes. Damage and loss prediction models can then be developed for the modeling of the building types that represent the average characteristics of the total population of buildings within each class.

The following primary parameters that affect building damage and loss characteristics are considered in developing the building typology matrix (10):

- Structural parameters affecting structural capacity and response
- Seismic design criteria (code level)
- Basic structural system (material and system)
- Building height (low-rise, mid-rise, high-rise)
- Non-structural elements that could cause non-structural damages.

Table 2 shows the different building types considered by BTM (Derakhshan 2009).

4 Case study

4.1 Adaptation of the Iranian data

Tavakoli and Tavakoli (1993) studied the damage to villages located near the epicenter of the 1990 Manjil earthquake in Iran (JICA 2000). They compiled the relationship between peak ground acceleration (PGA) and building damage for steel and brick structures as presented in Fig. 5. Non-engineered masonry buildings represent 83% of the studied structures (Derakhshan 2009). Thus, the proposed relationship can only be considered for this type of building.

Other post-seismic observations have been performed after the 2003 Bam earthquake (Mostafaei and Kabeyasawa 2004; Sanada et al. 2004). The data of these researches were used to build the vulnerability curves for the Iranian constructions (Tables 3 and 4).

The proposed form of vulnerability curves, which was introduced in previous section, must be adapted to the data of Iranian constructions. For this purpose, the existing damage data for Iranian cities have been analyzed. Unfortunately, there is little documented data of post-earthquake observations in Iran. Thus, the study focuses on the published results of the sustained damage after the Bam earthquake. The vulnerability curves proposed by JICA for Tehran city (JICA 2000) are also analyzed to complete this data.

Concerning the Bam earthquake, the observations of two studies were used: Mostafaei and Kabeyasawa work (Mostafaei and Kabeyasawa 2004), and the report of Sanada and his colleagues (Sanada et al. 2004). These papers present the data collected during the Bam

Table 2 Building typology matrix (BTM) (Derakhshan 2009)

Main type	Label	Description	Height	No. of stories	Specifications
Masonry	M1	Brick walls and wooden beams	Low-rise	1–2	Unreinforced masonry bearing walls and wooden beams (Fig. 2a)
	M2L	Brick walls and steel beams	Low-rise	1–2	Unreinforced masonry bearing walls and composite slabs made of steel beams and masonry vaults (Fig. 2b)
	M2M		Mid-rise	3–5	
	M3L	Brick and steel	Low-rise	1–2	Unreinforced masonry bearing walls in the lateral boundaries and some central steel columns, without frame (Fig. 2c)
	M3M		Mid-rise	3–5	
	M4L	Partially tied masonry (H)	Low-rise	1–2	Unreinforced masonry bearing walls with horizontal and vertical steel or RC ties (Fig. 2d)
	M4M	Partially tied masonry (V)	Mid-rise	3–5	
	M4H	Tied masonry	High-rise	6+	
Adobe	A1	Adobe	Low-rise	1–2	This type of construction can be found in many places where there are suitable clays
Steel	S1L	Steel frames without bracing	Low-rise	1–2	Steel columns and beams forming frames, not fully designed as moment-resisting frames (Fig. 3a)
	S1M		Mid-rise	3–5	
	S1H		High-rise	6+	
	S2L	Steel frames with bracing	Low-rise	1–2	Similar to steel frame buildings improved with bracing elements (Fig. 3b)
	S2M		Mid-rise	3–5	
	S2H		High-rise	6+	
	S3L	Steel moment frames	Low-rise	1–2	Steel columns and beams forming frames. Diaphragms transfer lateral loads to moment-resisting frames
	S3M		Mid-rise	3–5	
	S3H		High-rise	6+	
RC	RC1L	RC moment frames	Low-rise	1–2	RC columns, beams, and beam-column joints (Fig. 4a)
	RC1M		Mid-rise	3–5	
	RC1H		High-rise	6+	
	RC2L	RC shear walls	Low-rise	1–2	Reinforced concrete structural walls as the vertical components of the lateral-force-resisting system (Fig. 4b)
	RC2M		Mid-rise	3–5	
	RC2H		High-rise	6+	

post-earthquake building damage survey. The description type and the number of the buildings are presented in Table 3 for the first study and in Table 4 for the second one. The assumed types of buildings investigated in these researches and their relevant type labels are described in Table 3 and Table 4, respectively. The total number of buildings investigated using EMS98 is 624 in the first case and 94 in the second one.

By considering the data gathered after the Bam earthquake and presented in the first study, the damage probability matrix for Iranian building types is developed. The damage distribution for each building type is presented in Table 5. It can be observed that there are no buildings belonging to the VIII or lower intensity category. Another observation is that the number of inventoried buildings corresponding to each building type is different. For three
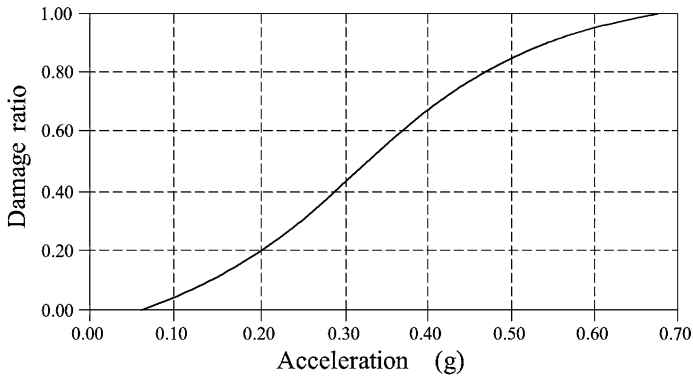
Fig. 5 Damage ratio of residential buildings during the Manjil 1990 Earthquake (steel and brick structures) (Tavakoli and Tavakoli 1993)

Table 3 Damaged buildings after Bam earthquake (Mostafaei and Kabeyasawa 2004)

Type	Description	Number of buildings investigated
Ad	Adobe	50
M&M-Ad	URM Masonry (with cement and mud-lime)	424
M-S	Reinforced masonry with steel frame ties/steel frame building with masonry brick walls	56
M-C	Reinforced masonry with RC ties	31
S-B	Steel frame with bracing	31
S-F	Moment-resistant steel frame	13
M-S-F	Steel frame with masonry walls	13
RC	Reinforced concrete building	6
Total number of investigated buildings	624	

Table 4 Damaged buildings after Bam earthquake (Sanada et al. 2004)

Type	Description	Number of buildings investigated
Adobe	Adobe masonry	22
SM	Simple masonry	24
S-frame + SM	Steel moment-resisting frame with simple masonry wall	27
S-brace + SM	Steel braced frame with simple masonry wall	14
RC-tie + SM	Simple masonry wall confined with reinforced concrete tie	1
RC-frame + SM	Reinforced concrete-resisting frame with simple masonry wall	1
S	Steel moment-resisting frame	1
Unknown		4
Total number of investigated buildings	94	

Table 5 Damage distribution for each building type described in Table 4 relating damage intensities and damage grades

	M&M-Ad					M-C				
	D1	D2	D3	D4	D5	D1	D2	D3	D4	D5
VII										
VIII	2		2	1						
IX	1	2		3	3					
X	6	8	14	13	32	8		7		
XI	2	11	17	30	280	2	8	16	2	
	Ad					**S-B**				
VII										
VIII			1							
IX			1		1					
X				11	8	6	2			
XI		1	1	2	21	7	4	3	6	0
	M-S					**S-F**				
VII										
VIII										
IX	1						1			
X	6	6	1	2	1	1	3	1	1	
XI	6	10	6	6	11	2		1		
	M-S-F					**RC**				
VII										
VIII										
IX										
X	3	1				2	1			
XI	3					3	2		1	1

structural types (Moment-resistant steel frame (S-F), Steel frame with masonry walls (M-S-F), and Reinforced concrete building (RC)), the number of inventoried buildings (<30) is not sufficient for the construction of reliable vulnerability curves. Therefore, the analysis is only concerned with the other construction types, namely: URM Masonry (with cement and mud-lime), Adobe, Reinforced masonry with steel frame ties/steel frame building with masonry brick walls, Reinforced masonry with RC ties, and Steel frame with bracing.

The calculated points of the mean damage grade for all intensities and for each Iranian building type are plotted in Fig. 6. The values of the vulnerability index are modified in order to fit the points of the mean damage grade obtained using the data collected from Bam. The least squares method is used for producing the vulnerability curves from the discrete values. The best vulnerability index for each building type is the one that has the minimum residual. The discrete values obtained for simple masonry and adobe buildings are positioned inside the vulnerability curves characterized by a vulnerability index that ranges between 0.7 and 0.9. For the reinforced masonry and braced steel frame buildings, the vulnerability index values range between 0.3 and 0.5.
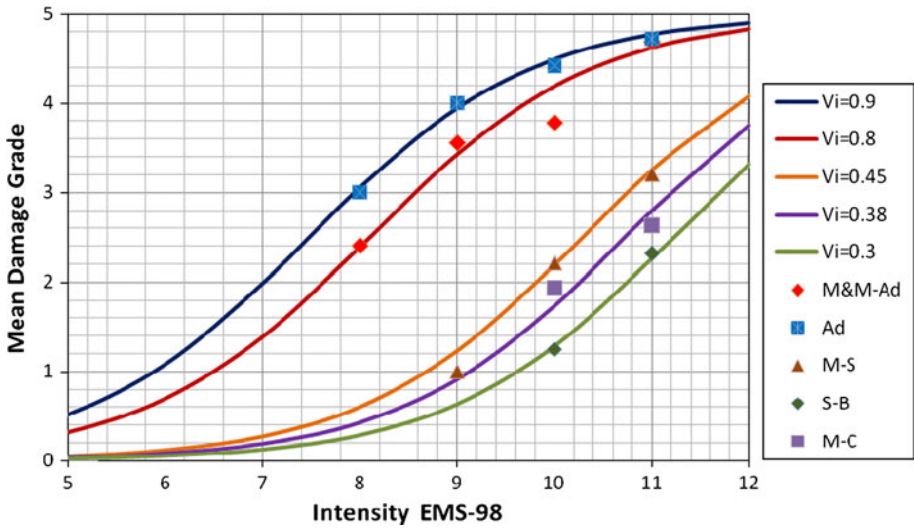
Fig. 6 Comparison between the Iranian discrete values and the vulnerability curves for each vulnerability index

4.2 Comparison between the Risk-UE vulnerability curves and Iranian discrete values

A second type of data that is used for verifying vulnerability curves is the JICA Report (JICA 2000). Vulnerability curves for a variety of building structures in Tehran were developed regarding the research on seismic hazards in Tehran in the framework of an overseas JICA research project. The curves were empirically obtained on the basis of the Manjil earthquake for which the relationship between the peak ground acceleration and the building damage ratio was investigated based on the damage data of the reference. In Fig. 7, the vulnerability curves for "brick and steel" (steel frame filled with brick walls), masonry, and adobe structures are represented. The damage of the structural types is represented in terms of the damage ratio and the aggression is expressed in peak ground
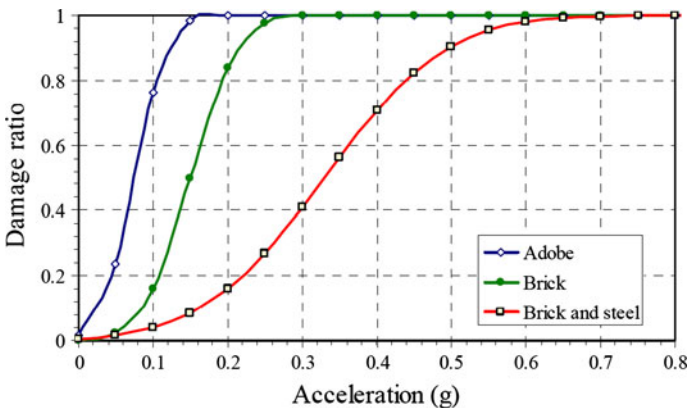
Fig. 7 Damage ratio for structures in Manjil area (Kuwata et al. 2005)
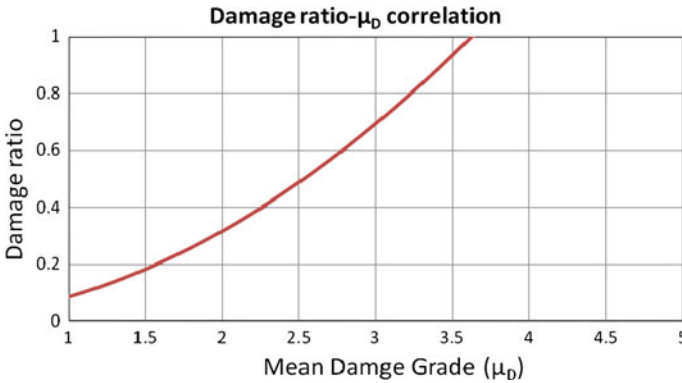
Fig. 8 Correlation between the mean damage grade μD and the damage ratio Di (Giovinazzi 2005)

acceleration PGA (g). The damage ratio is calculated by dividing the total cost of repair by the economic value of the building.

In order to compare the results of the JICA study and the developed vulnerability curves using the Bam data, the damage ratio (D_i) is correlated to EMS98 damage grades (μ_D) by using the following relationship (Giovinazzi 2005) (Fig. 8):

$$D_i = -0.0004\mu_D^3 + 0.0854\mu_D^2 + 0.0085\mu_D \tag{7}$$

There are many relationships correlating the intensity with specific physical parameters of ground motion in the literature. The most widely used relationships refer to the peak ground acceleration (PGA). Although these correlations are not very precise, their use is inevitable for correlating the macroseismic damage grade with the damage ratio. Figure 9 presents some of the more commonly used intensity-PGA relationships. This figure also
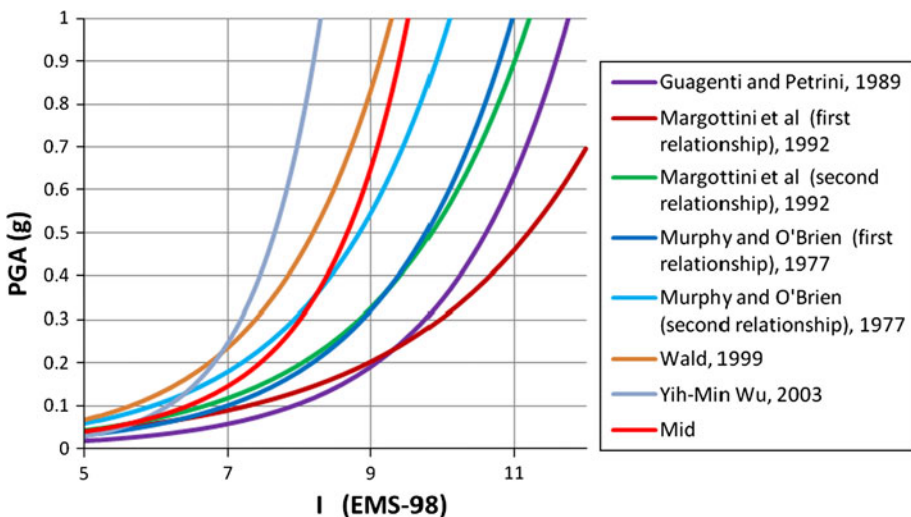
Fig. 9 Different correlation between peak ground acceleration and intensity

shows the huge scatter characterizing these correlations. The mean curve has been used in this article as Eq. 5.

$$I = 3.11 \times \log(\text{PGA}) - 0.24 \qquad (8)$$

Figure 10 shows the vulnerability curves (mean damage grade versus intensity) for masonry and adobe buildings converted to the damage ratio-acceleration format. This operation allows us to establish the vulnerability curve for brick and steel type buildings by fitting it in between the JICA discrete values. It also shows that the JICA values confirm the obtained vulnerability curves for the other building types.

4.3 Comparison between the Risk-UE vulnerability curves and Iranian discrete values

The comparison between the proposed Iranian vulnerability curves and the Risk-UE vulnerability curves for the unreinforced masonry and adobe structures is presented in Fig. 11. It can be seen that for the same type of building, the vulnerability index is higher for the Iranian construction for non-engineered buildings than the European buildings.
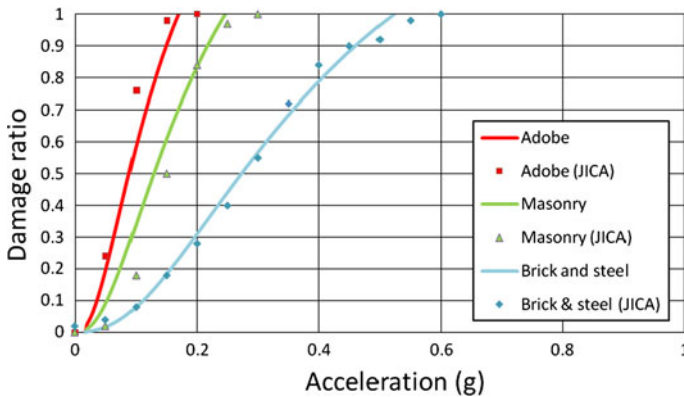
Fig. 10 Vulnerability *curves* converted into damage ratio-acceleration format
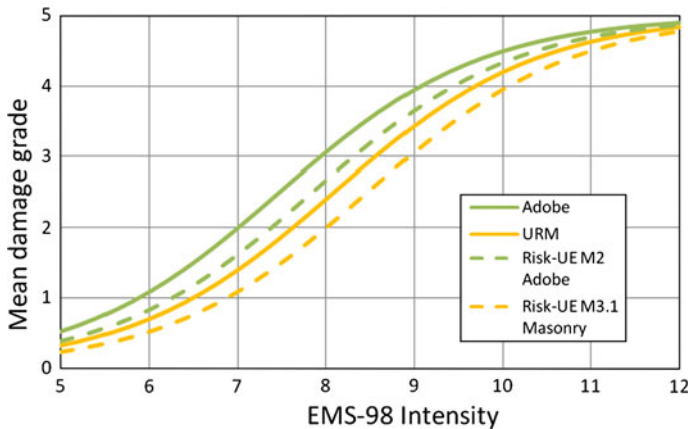

Fig. 11 Comparison between the Iranian data and the Risk-UE vulnerability *curves* for unreinforced masonry and adobe structures
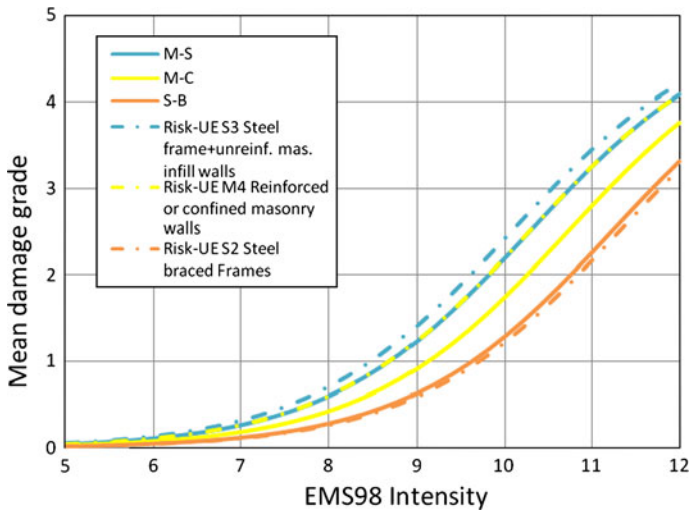
Fig. 12 Comparison between the Iranian data and the Risk-UE vulnerability curves for steel frames and reinforced masonry structures

As it can be seen in Fig. 10, the "Brick and Steel" structures, i.e., brick structure with load bearing walls with central steel columns, can present a much better seismic resistance than unreinforced masonry buildings. Because of the lack of such building type in the Risk-UE category, the vulnerability curve of the "Brick and Steel" structures is compared with the "URM" buildings of Risk-UE in Fig. 11.

For engineered buildings, the difference between the calculated curves and Risk-UE curves (Fig. 12) is less notable than the non-engineered buildings (Fig. 11).

For a conservative consideration, the Risk-UE vulnerability index for each building type could be considered as a lower limit for the proposed vulnerability index. Otherwise, the vulnerability indexes calculated in this study based on the observed damage data should be used (Table 6).

4.4 Establishment of vulnerability curves and probabilistic distribution of different damage grades

The selected vulnerability indexes are listed in Table 6.

Based on the assumed vulnerability indexes of Table 6, the vulnerability functions are developed for all building types considered in this article. Figure 13 presents the developed functions.

The probability of different damage grades (%) with respect to the different earthquake intensities (EMS) is shown in Figs. 14, 15, 16, 17 for each building type. These curves have been produced using the Eqs. 2 and 3 for k values from 0 to 5, and the proposed vulnerability indexes from Table 6.

5 Conclusion

Iran is one of the most seismically active countries of the world with more than 180,000 death tolls due to earthquakes in the last five decades. Considering the fact that most

Table 6 Vulnerability index (V_i) for different typologies

Main type	Description	Proposed V_i^*		Risk-UE project		Calculated V_i based on Mostafaei and Kabeyasawa data		Calculated V_i based on JICA data	
Masonry	Brick walls and wooden beams	M1	0.8	M3.1	0.74	M&M-Ad	0.8		
	Brick walls and steel beams	M2	0.74	M3.3	0.704	M&M-Ad	0.74		
	Brick and steel	M3	0.6					B&S	0.6
	Tied masonry	M4	0.451	M4	0.451	M-C	0.38		
Adobe	Adobe	A1	0.9	M2	0.84	Ad	0.9		
Steel	Steel frames without bracing	S1	0.484	S3	0.484	M-S	0.45		
	Steel frames with bracing	S2	0.3	S2	0.287	S-B	0.3		
	Steel moment frames**	S3	0.376	S1	0.363	M-S-f	0.376		
RC	RC moment frames**	RC1	0.455	RC1	0.442	RC	0.455		
	RC shear walls**	RC2	0.399	RC2	0.386	RC	0.399		

* For a conservative consideration, the Risk-UE vulnerability index for each building type is considered as a lower limit for the proposed vulnerability index

** For these building types, the number of inventoried buildings is < 30 and the proposed values may be considered as a guide
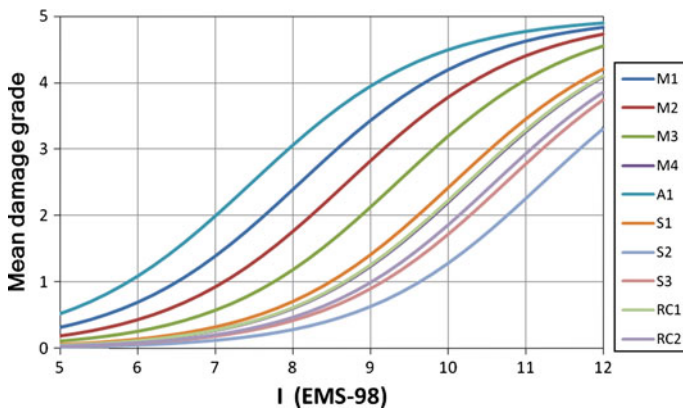

Fig. 13 Proposed vulnerability curves for different building typologies

Iranians live in masonry and non-engineered houses, having a comprehensive program for decreasing the vulnerability of society holds considerable importance.

Earthquake hazard analysis and vulnerability assessment are two principal components in seismic loss estimation studies. In the present study the experimental vulnerability curves for the residential buildings of Iran, as one of the essential parts of vulnerability assessment, were introduced. Due to the lack of such curves for the residential building of Iran, the results of this study seem to be a unique research in the field of seismic risk reduction in Iran. With the vulnerability curves adapted to the Iranian buildings, it will be easier to plan for strengthening and prevention programs.
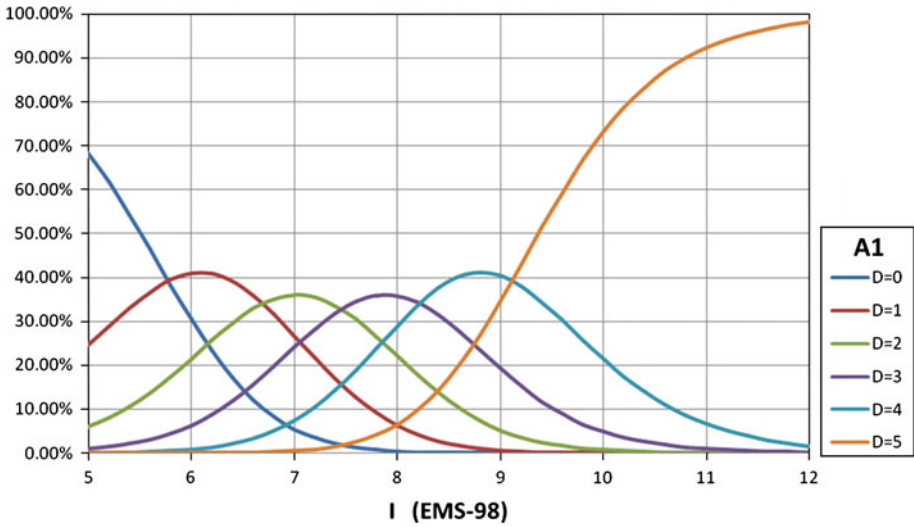
Fig. 14 Probabilistic distribution of different damage grades for Adobe buildings, $V_i = 0.9$
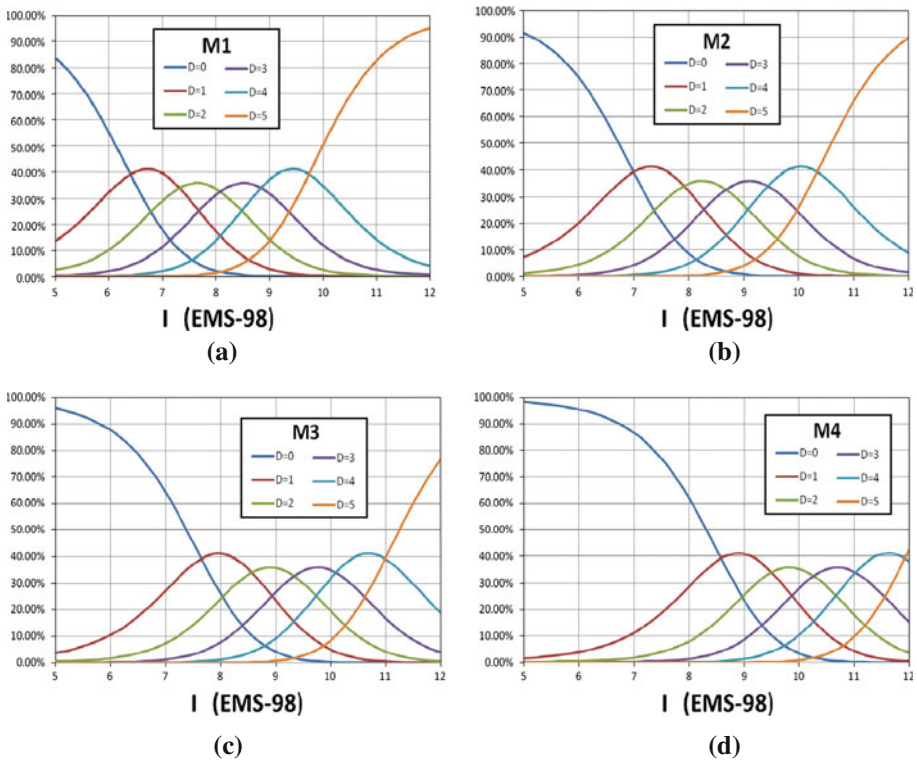

Fig. 15 Probabilistic distribution of different damage grades for Masonry buildings. **a** Brick walls and wooden beams, $V_i = 0.8$. **b** Brick walls and steel beams, $V_i = 0.74$. **c** Brick steel, $V_i = 0.6$. **d** Tied masonry, $V_i = 0.451$
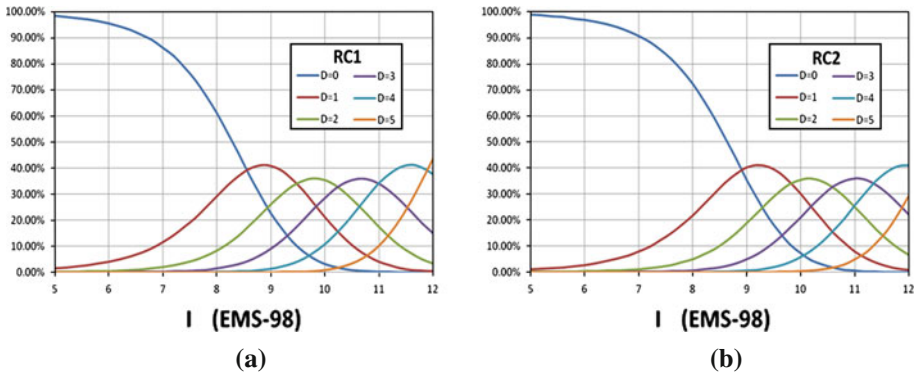
Fig. 16 Probabilistic distribution of different damage grades for RC buildings. **a** RC moment frame, $V_i = 0.455$. **b** RC shear walls, $V_i = 0.399$
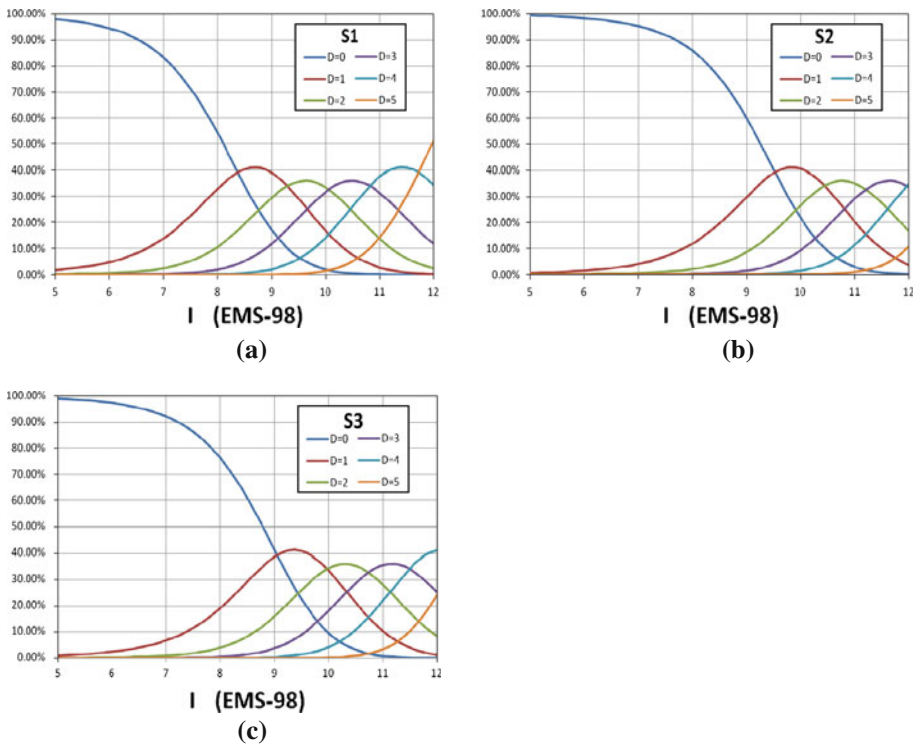

Fig. 17 Probabilistic distribution of different damage grades for steel frame buildings. **a** Steel frames without bracing, $V_i = 0.484$. **b** Steel frames with bracing, $V_i = 0.3$. **c** Steel moment frames, $V_i = 0.376$

For defining the vulnerability curves, a building typology classification representing the Iranian building characteristics was presented in this article. Through the use of the European Macroseismic method, a model for evaluating the vulnerability of the Iranian buildings was proposed. The different damage grades for buildings can only be estimated

by identifying their types. This method allows the vulnerability assessment for numerous sets of buildings in a regional sense by defining the vulnerability curves for each building type based on the damage observations of previous earthquakes. In order to find the vulnerability curves, the assumed form of the curves was fitted to the observed damage data and the relevant vulnerability indexes were established for each proposed building type using least square method.

By the use of the proposed vulnerability indexes, disaster managers can easily monitor the vulnerably of Iranian cities in a geographical information environment after identifying the geographical pattern of urban areas. On the other hand, the proposed vulnerability curves could be used in loss estimation studies in a regional sense. The estimated damages to the built environment based on an assumed earthquake scenario could also be used in designing of preparation and recovery phases of disaster management cycle. The efficiency of the vulnerability curves is based on the fact that the damage characteristic behavior of each building type can be estimated in different earthquake scenarios in a probabilistic manner and to derive empirical fragility curves for residential buildings in Iranian cities by a simple integration process. These curves are the necessary elements in preparing the mitigation and emergency plans before a disaster strikes.

The calculated vulnerability indexes and vulnerability curves show that for engineered houses there is not any notable difference between the vulnerability of Iranian and Risk-UE building types. For the non-engineered houses, the vulnerability index of brick and steel structures is less than the corresponding values of the other unreinforced masonry buildings of Iran. The vulnerability index of unreinforced and masonry buildings of Iran are larger than the values of the similar types in Risk-UE and so the Iranian buildings are more vulnerable in this regard.

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