DOI: 10.2478/ace-2019-0042

ARCHIVES OF CIVIL ENGINEERING
Vol. LXV ISSUE 3 2019



# COMPARATIVE ANALYSIS OF THE EMPIRICAL SEISMIC VULNERABILITY OF TYPICAL STRUCTURES IN MULTIPLE INTENSITY ZONES

S. Q. LI[1], T. L. YU[2], Y. S CHEN[3]

Abstract. To study the difference in seismic vulnerability of multiple typical structures in multiple intensity zones, the seismic damage of 7099 buildings of Dujiangyan masonry structure (MS), reinforced concrete structure (RC) and bottom frame seismic wall masonry (BFM) in the 2008 Wenchuan earthquake in China is summarized and analysed. First, a statistical analysis of the data is carried out, the empirical seismic vulnerability matrix and model curves are established by considering the number of storeys, the age and the fortification factors.The vulnerability curves of the cumulative exceeding probability of the empirical seismic damage and the grade of the seismic damage in multiple intensity zones are shown. The mean damage index vulnerability matrix model is proposed and verified using the empirical seismic damage matrix of typical structures.

*Keywords*: Vulnerability comparison, Vulnerability analysis, Empirical seismic database, MDI, Typical structure

## 1. INTRODUCTION

On May 12, 2008, a magnitude Ms=8.0 earthquake struck Wenchuan, China, directly affecting 100,000 square kilometres [1].

[1] Assoc. Prof., PhD., Eng., Northeast Forestry University, School of Civil Engineering, Harbin 150030, China, e-mail: 79654127@qq.com

[2] Prof., PhD., Eng., Northeast Forestry University, School of Civil Engineering, Harbin 150030, China, e-mail: tianlaiyu@126.com………

[3] Assoc. Res., PhD., Eng., Institute of Engineering Mechanics, China Earthquake Administration, Harbin 150080, China, e-mail: chenys@iem.ac.cn………………..

The vulnerability grade of the structure was divided into four categories, and different survey sample points in the disaster area were classified and counted [1,2]. The seismic damage to5000 discrete structural investigation points in multiple cities and counties affected by the wenchuan earthquake was analysed. The statistics of the number of samples of the seismic damage investigated for 6 types of damaged buildings, such as ms, rc and bmf, are provided, and the vulnerability matrix is established considering the seismic fortification situation [3]. Based on the empirical data of seismic damage, the distribution of the failure ratio of ms and bfm damaged buildings in jiang you city, mian yang city and dey ang city is analysed, and structural failure characteristics of ms, rc and bfm are indirectly studied (the bfm is used in the bottom or bottom two stories of the building; due to the large space required for the use of functions, seismic walls are established along the vertical and horizontal directions. The upper stoerys are normally residences, using masonry walls with more vertical and horizontal walls as the load-bearing system; these are the characteristics of the bottom frame-seismic wall masonry buildings (bfm).). [4]. The information that generate the vulnerability curves of urban and rural areas are available from the survey data of ms damaged buildings in the area affected by the wenchuan earthquake, and the failure probability matrix was established [5,6]. The structural vulnerability research can use the rapid vulnerability analysis method of rc structures based on the svm to establish 6-story and 12-story structure models. Combining the pushover analysis and non-linear dynamic time history analysis, the seismic damage sample dataset is prepared, and the vulnerability curve is obtained [7,8]. the statistical analysis of vulnerability in the multiple intensity regions of the ms is established considering the mean damage index factor of the wenchuan earthquake [9]. Based on the survey data of the typical buildings damaged in several violent earthquakes worldwide, the vulnerability damage matrix considering the earthquake ground motion parameters is obtained by statistical analysis [10-16].

According to the global investigation of structural seismic damage and vulnerability research, most studies focus on the investigation of post-earthquake field seismic damage or on vulnerability research of a typical structure, while there are relatively few comparative analyses of the vulnerability of various widely used structural types in multiple intensity zones. It is quite difficult to analyse the vulnerability of a certain structure or a unique type of structure and to accurately and explicitly analyse the seismic damage in intensity zones. To study the seismic damage and vulnerability of the MS, RC and BFM buildings in multiple intensity zones, 7099 buildings in Dujiangyan city, which includes intensity zones VII-XI, are selected for vulnerability analysis. The difference in seismic vulnerability of the typical damaged buildings in the typical regions can be accurately obtained, which provide the necessary reference to revise the seismic intensity scales and, seismic codes and to investigate the seismic damage in practical engineering.

## 2. VULNERABILITY ANALYSES

To study the vulnerability of damaged buildings in different intensity regions, the seismic damage characteristics of MS, RC and BFM damaged buildings are analysed, and the seismic vulnerability matrix based on this strong earthquake is established. In July 2008, the China Earthquake Administration organized a comprehensive seismic damage field observation in Dujiangyan city, which spanned multiple intensity zones. The distribution of the structural types in this city is diverse and large in quantity. We select the overall observation samples, to better examine the vulnerability of damaged buildings in multiple intensity zones and relatively accurately establish the empirical seismic vulnerability matrix. The authors and relevant personnel have carried out a series of seismic damage investigations on the structure of the city. The overall sample for visual inspection includes 8625 buildings, including MS, RC, BFM, single-storey factory buildings (SSB), and other types of structures (OS). Figures 1 and 2 show the number and proportional distribution of each structure in the urban area, respectively. The MS, RC and BFM damaged buildings accounted for 82% of the holistic inspection samples and were extensively used in multiple intensity zones. Therefore, there is certain significance to examining the seismic damage characteristics of the MS, RC and BFM damaged buildings.

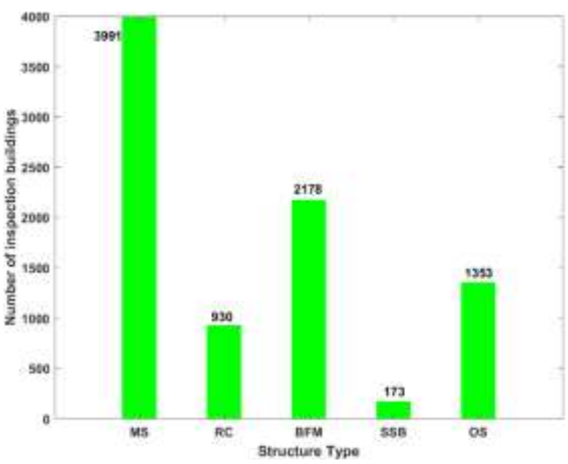



Fig.1 Statistics of the number of damage buildings of visually inspected in Dujiangyan city

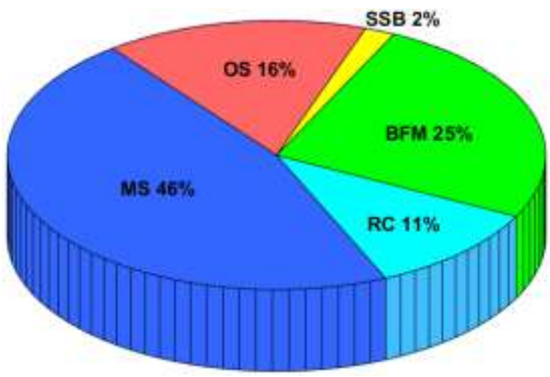



Fig.2 Sample to scale of the field inspection in Dujiangyan city

## 2.1. NUMERICAL ANALYSIS OF THE SAMPLE

According to the Chinese seismic intensity scale (GB/T 17742-1999) and the standard GB/T 1828.3-2000 appendix A1.2, the vulnerability grade (VG) of various structures is classified as basically intact (DS1), slightly damaged (DS2), moderately damaged (DS3), severely damaged (DS4), and destroyed (DS5). Combined with the empirical field inspection of seismic damage, the seismic damage grades (SDG) are expressed as 51, 43, 42, 41, 33, 32, 31, 21 and 11, among which the DS3 and DS4 are subdivided into 31, 32, 33 and 41, 42 and 43 to appraise the seismic damage condition in more detail. Figure 3 shows the distribution of multiple seismic damage grades for three typical damaged buildings. The numerical analysis of 7099 buildings with three structures is carried out. Due to the large differences in the field observation database samples, the editing of the regression model program highlights problems, such as the minimal fitting degree, large variance, poor robustness and lack of obvious regularity. It is difficult to explicitly express the seismic damage rules of structures in an urban area. By editing and comparing the non-linear function models, combined with the numerical and functional analysis principle, the exponential quadratic fitting (EQF) model successively approximates the discrete points (DP) of the investigation of seismic damage of numerous samples (NS) of three typical damage buildings. After we have adjusted the value, all $R^2$ values exceed 0.99. Therefore, a non-linear function model of the seismic damage grade ($\boldsymbol{S_D}$) and number of seismic damage investigation ($\boldsymbol{N_D}$) is established, as shown in formula (1). In the fitting model, $\boldsymbol{S_D}$ is only selected from 9 seismic damage grades in this section, $a, b, c, d$ are regression parameter factors, and the curves (EQFC) of the non-linear model of seismic damage for MS, RC and BFM are obtained, as shown in Figure. 4. The parameters are determined by regression with the empirical seismic damage survey database. Formula (2-4) show the non-linear function models of $N_{D_M}$, $N_{D_R}$ and $N_{D_B}$, respectively. By comparing and analysing the combined damage of the 3 typical structures in the urban area, the linear (LRC) and quadratic (QRC) nonlinear regression curves of the seismic damage based on the failure ratio (FR) factor are obtained in Figure 5. The RC structures are relatively light in multiple seismic damage grades, most of which are DS1 or DS2. However, The MS and BFM are approximations, and the empirical damage ratios of multiple seismic damage grades do not remarkable differ.

$$N_{\mathrm{D}} = ae^{(bS_{\mathrm{D}})} + ce^{(dS_{\mathrm{D}})} \quad (2.1) \qquad N_{\mathrm{D}_M} = 25540e^{(-0.233S_{\mathrm{D}})} + 110.8e^{(0.01658S_{\mathrm{D}})} \quad (2.2)$$

$$N_{\mathrm{D}_R} = 2652e^{(-0.1705S_{\mathrm{D}})} + 201.3e^{(-0.04903S_{\mathrm{D}})} \quad (2.3) \qquad N_{\mathrm{D}_B} = 14130e^{(-0.2469S_{\mathrm{D}})} + 184.3e^{(-0.01112S_{\mathrm{D}})} \quad (2.4)$$

## 2.2. COMPARATIVE ANALYSIS OF VULNERABILITY CONSIDERING MULTIPLE FACTORS

The structural seismic vulnerability is the probability of multiple degrees of structural damage under different seismic actions. The structural seismic vulnerability is mainly used to appraise the seismic capacity of structures and to calculate the conditional probability of structural capacity parameters, which are defined by the limit state when the structural response exceeds the limit state under seismic actions of multiple intensity. To obtain a more accurate vulnerability, the remarkable discrepancy of typical damage buildings and the vulnerability of MS, RC and BFM damage buildings were compared according to the characteristics of the seismic damage of Dujiangyan city and the effects of multiple factors.

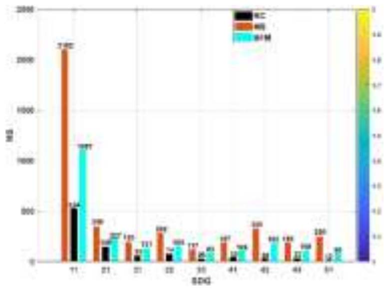


Fig.3 Sample statistics of a typical structural damage investigation in Dujiangyan

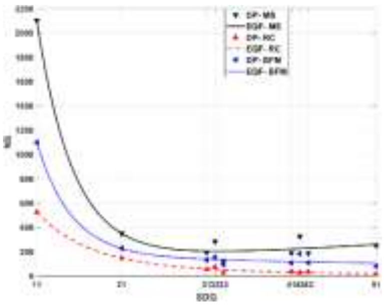


Fig.4 Comparison of the curves of the regression models for the seismic damage of typical structures

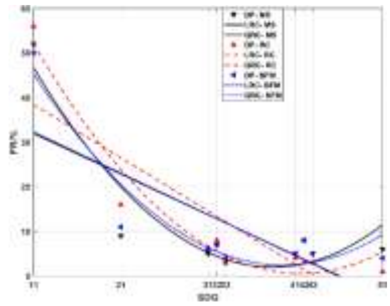


Fig.5 Comparison of the curves of fitting models for the seismic damage of typical structures

### 2.2.1. STOREY NUMBER FACTOR

According to seismic damage investigation data from the MS, RC and BFM structures, the effect of the storey numerical factor on structural damage exhibits apparent anomalies. This paper classifies 6985 buildings in Dujiangyan city (114 buildings are being strengthened or repaired and are not comparable to individual high-rise RC buildings, so they are excluded from the 7099 samples). The samples are divided into 1-7-storey buildings (SB) for statistical and numerical analysis, the empirical seismic vulnerability matrix is established based on this factor, as shown in Table 1, and the failure ratio curves of multiple storeys of the structures are provided. According to the theory of transcendental probability, the cumulative transcendental probability (CTP) vulnerability curves (CTPVC) based on the empirical seismic damage are obtained, as shown in Figure 6. The seismic damage of MS in 2SB is remarkable better than that of RC and BFM. The damage of BFM in 4SB is less severe than that of other structures. The damage of RC in 6SB is less severe, while that of

BFM is more severe. In the 7SB contrast map, the RC medium damage is more serious than that of the other structure, and the other storeys are relatively inapparent. It is necessary to rationally adjust the structure of relatively weak storeys in D4. The mechanism of structural damage based on the storey factor is relatively complex, and one must study it in depth by synthesizing various influencing factors.

Table 1. Empirical seismic vulnerability matrix of structures considering the storey number factors (number/percentage, N/%)

| SB | Type | DS1 | DS2 | DS3 | DS4 | DS5 | T/P |
|---|---|---|---|---|---|---|---|
| 1 | MS | 226/48 | 46/10 | 111/23 | 21/4 | 70/15 | 474/100 |
| | RC | 24/86 | 2/7 | 2/7 | 0/0 | 0/0 | 28/100 |
| | BFM | —— | —— | —— | —— | —— | —— |
| 2 | MS | 560/78 | 61/8 | 31/4 | 41/6 | 26/4 | 719/100 |
| | RC | 108/72 | 17/12 | 16/11 | 8/5 | 0/0 | 149/100 |
| | BFM | 45/62 | 14/19 | 9/12 | 4/6 | 1/1 | 73/100 |
| 3 | MS | 224/65 | 36/10 | 471/14 | 25/7 | 12/4 | 344/100 |
| | RC | 110/64 | 31/18 | 23/13 | 6/3 | 3/2 | 173/100 |
| | BFM | 54/43 | 21/17 | 22/18 | 23/18 | 5/4 | 125/100 |
| 4 | MS | 176/50 | 37/10 | 62/18 | 52/15 | 23/7 | 350/100 |
| | RC | 136/68 | 21/10 | 22/11 | 18/9 | 4/2 | 201/100 |
| | BFM | 599/77 | 28/4 | 65/8 | 70/9 | 15/2 | 777/100 |
| 5 | MS | 225/46 | 46/9 | 88/18 | 118/24 | 16/3 | 493/100 |
| | RC | 62/39 | 22/14 | 38/24 | 33/21 | 3/2 | 158/100 |
| | BFM | 197/44 | 72/16 | 76/17 | 81/18 | 21/5 | 447/100 |
| 6 | MS | 614/44 | 113/8 | 206/15 | 380/28 | 67/5 | 1380/100 |
| | RC | 78/45 | 47/27 | 31/18 | 17/10 | 0/0 | 173/100 |
| | BFM | 186/28 | 86/13 | 176/26 | 190/28 | 34/5 | 672/100 |
| 7 | MS | 43/27 | 10/6 | 47/29 | 55/34 | 7/4 | 162/100 |
| | RC | 1/5 | 3/15 | 11/55 | 5/25 | 0/0 | 20/100 |
| | BFM | 10/15 | 7/10 | 26/39 | 24/36 | 0/0 | 67/100 |

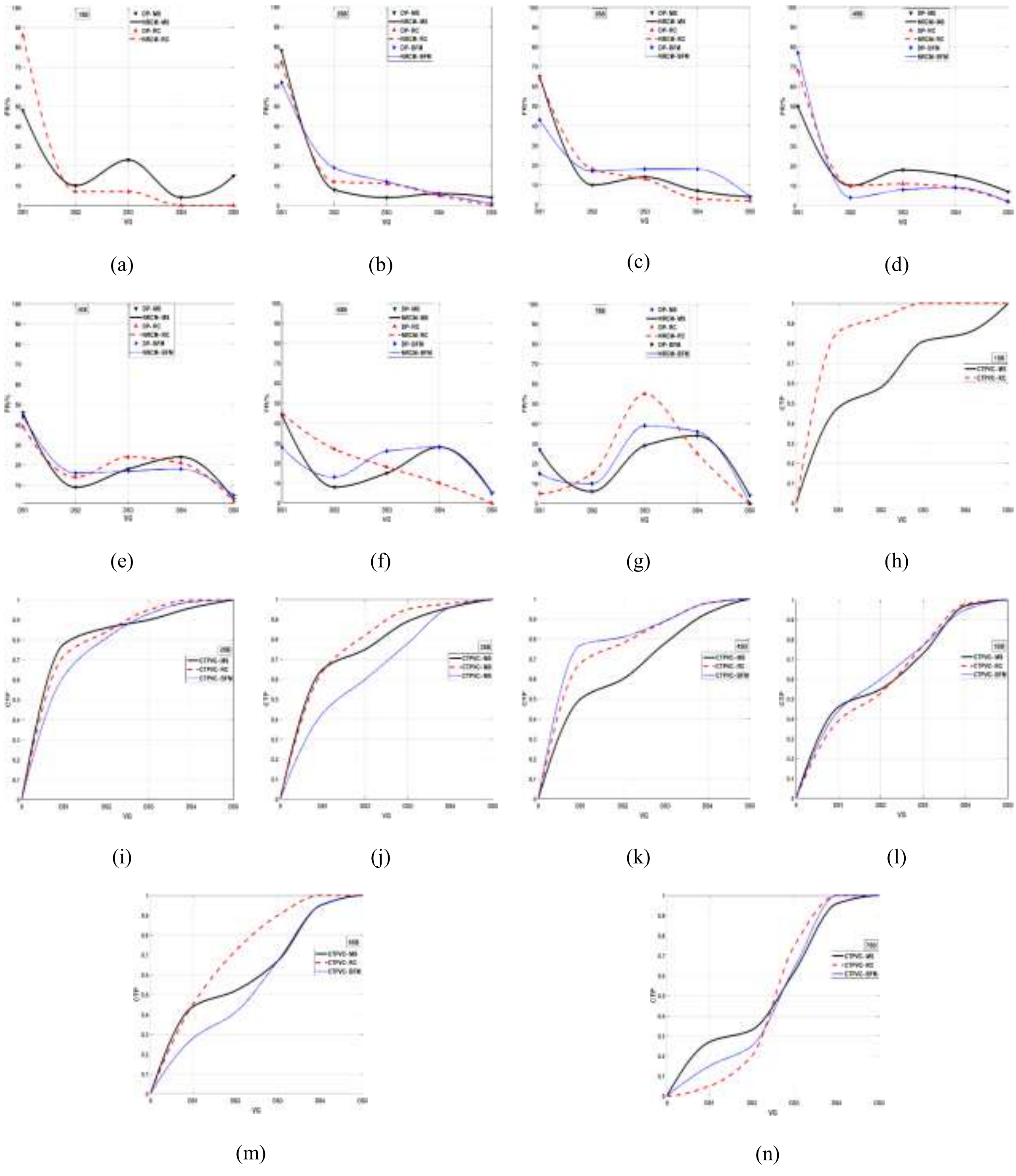


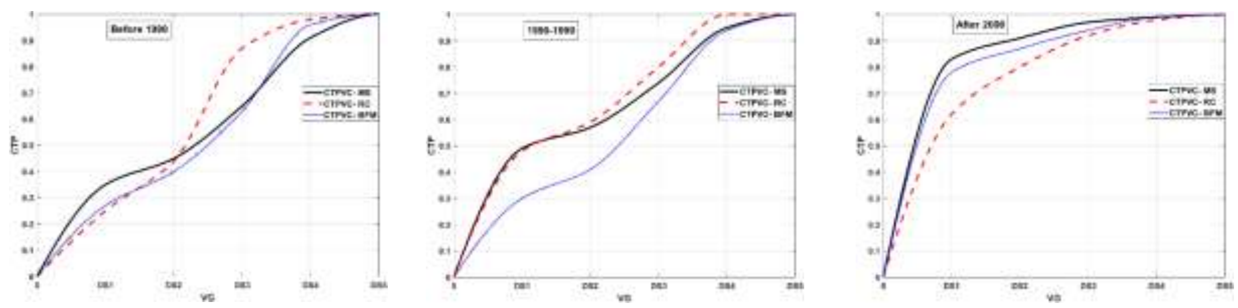

Fig. 6 Comparison of the vulnerability of different storeys of typical damage buildings: (a) - (g) failure ratio; (h) - (n) Cumulative transcendence probability

### 2.2.2. CHRONOLOGICAL FACTOR

The damaged buildings were constructed at multiple times and have been damaged to varying degrees. To study the effect of the age factor on the seismic damage of various damage buildings, 6906 buildings (excluding 193 unknown buildings from 7099 samples) were analysed according to the data before 1990, 1991-1999 and after 2000, and vulnerability matrices of MS, RC and BFM were established, as shown in Table 2. The vulnerability curves based on the age-dependent factors are provided. As shown in Figure 7, MS exhibits better seismic resistance in multiple years, especially after 2000. During 1991-1999, the damage of levels of RC and MS were relatively similar, and the damage of BFM was relatively serious. However, before 1990, the RC damage buildings suffered relatively serious seismic damage in DS3. The main reason is that no effective seismic measures were taken in RC damage buildings in the early years. Hence, from the overall damage ratio of the structures and the cumulative transcendental probability of seismic damage, the MS, RC and BFM constructed in multiple years show good seismic resistance, they have achieved the goal of not collapse during a violent earthquake.

Table 2. Empirical seismic vulnerability matrix of the damage buildings considering the age-dependent factors (number/percentage, N/%)

| Age | Type | DS1 | DS2 | DS3 | DS4 | DS5 | T/P |
|---|---|---|---|---|---|---|---|
| Before 1990 | MS | 511/35 | 150/10 | 289/20 | 372/26 | 137/9 | 1459/100 |
| | RC | 16/25 | 12/19 | 27/43 | 7/11 | 1/2 | 63/100 |
| | BFM | 64/27 | 30/13 | 54/23 | 79/33 | 10/4 | 237/100 |
| 1991-1999 | MS | 687/49 | 113/8 | 236/17 | 294/21 | 76/5 | 1406/100 |
| | RC | 123/48 | 28/11 | 53/21 | 50/20 | 1/0 | 255/100 |
| | BFM | 299/30 | 109/11 | 257/26 | 270/27 | 63/6 | 998/100 |
| After 2000 | MS | 844/83 | 82/8 | 61/6 | 23/2 | 11/1 | 1021/100 |
| | RC | 364/62 | 106/18 | 72/12 | 34/6 | 10/2 | 586/100 |
| | BFM | 729/78 | 83/9 | 66/7 | 46/5 | 7/1 | 931/100 |



(a) (b) (c)

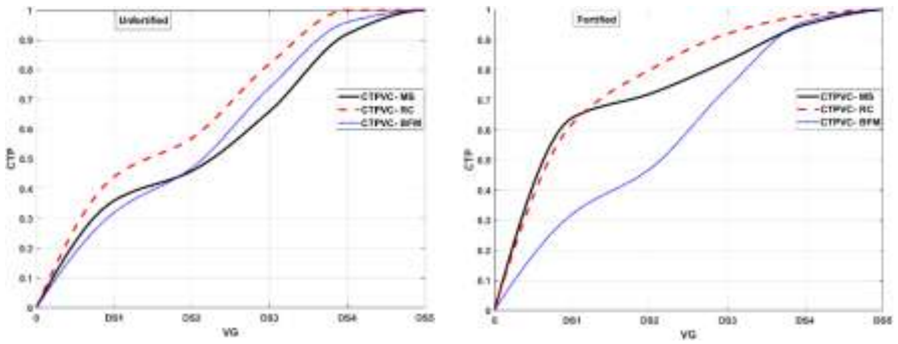
Fig.7 Comparison of the vulnerability of typical damage buildings with different ages

### 2.2.3. FORTIFICATION FACTOR

The seismic fortification factor is an important factor that affects the seismic damage of structures. Many factors are not considered or imperfect in the investigation and damage the structure to varying degrees.A statistical analysis was carried out on 7021 typical damage buildings (excluding 78 buildings with uncertain seismic fortification from 7099 samples), and a vulnerability matrix considering seismic fortification factors was established, as shown in Table 3. The vulnerability curve models of the structures based on the actual seismic damage field observation data are shown in Figure 8. According to the analysis results, the RC structure is relatively better than the MS and BFM structures when comparing the seismic damage without considering the imperfect seismic factors. RC structure is slightly higher than MS, while MS and BFM are relatively similar. The comparative analysis shows that the seismic damage of the RC structure is marginally worse than that of the MS structure.

Table 3. Empirical seismic vulnerability matrix of damage buildings considering the anti-seismic -dependent factors (number/percentage, N/%)

| Age factor | Type | DS1 | DS2 | DS3 | DS4 | DS5 | T/P |
|---|---|---|---|---|---|---|---|
| Unfortified | MS | 912/36 | 253/10 | 507/20 | 658/26 | 202/8 | 2532/100 |
| | RC | 230/44 | 68/13 | 131/25 | 94/18 | 0/0 | 523/100 |
| | BFM | 517/32 | 243/15 | 437/27 | 356/22 | 65/4 | 1618/100 |
| Fortified | MS | 909/64 | 114/8 | 156/11 | 171/12 | 71/5 | 1421/100 |
| | RC | 246/62 | 71/18 | 48/12 | 24/6 | 8/2 | 397/100 |
| | BFM | 312/59 | 58/11 | 85/16 | 48/9 | 27/5 | 530/100 |




(a) (b)

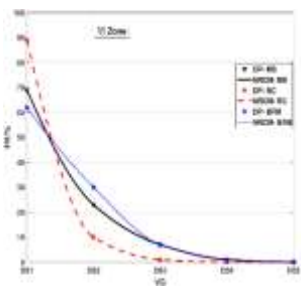
Fig.8 Comparison of the vulnerability of typical damage buildings considering the seismic factor

## 2.3. VULNERABILITY COMPARISONS IN MULTI-INTENSITY ZONES

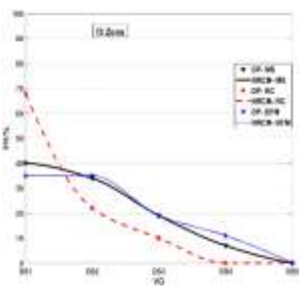
The degree of damage of the typical structure in multiple intensity zones exhibits a remarkable discrepancy. It is difficult to accurately appraise the vulnerability of the structure in the ensemble seismic region and determine the apparent anomalies of seismic damage in multiple intensity regions by analysing the damage of the structure in a certain intensity region. The methods of structural seismic vulnerability analysis are divided into empirical, judgement, analytical and mixed methods [18]. Empirical methods are mostly based on the statistical analysis of post-earthquake survey data; due to the substantial sample database, it does not have a comprehensive application. Judgement methods are generally founded on the experience of a single expert. Analytical methods generally uses a finite element numerical simulation for analysis [18], However, due to the remarkable discrepancy between the empirical seismic damage factors and the factors in the model, the numerical simulation results and actual earthquake damage often appear different. In this paper, a comprehensive method is utilized to analyse the vulnerability of typical damage buildings. The data samples from the ensemble field observation of Dujiangyan city are used for the statistical analysis. Based on the opinions of more than 20 experts from the investigation group and the numerical analysis method, the vulnerability matrix of typical damage buildings based on the multi-intensity zones is established, as shown in Table 4. The empirical seismic vulnerability curve is shown in Figure 9. Because of disputes about the delimitation of intensity zones in the seismic damage investigation, the seismic damage assessment in the region of degree VI has been added. The damage ratio of RC is relatively smaller in the VG and MS, which is slightly lower than BFM, in zones VI-VIII. The damage ratio of VG in zone IX sharply increases, the increase in BFM is larger, the proportion in RC damage grade is larger, and the increase of the MS damage grade is relatively mitigated. In the mega-earthquake zones X-XI, most damaged buildings are in DS4 or DS5, and some of these buildings have partially or completely collasped.

Table 4. Empirical seismic vulnerability matrix of typical damage buildings in different intensity regions (%)

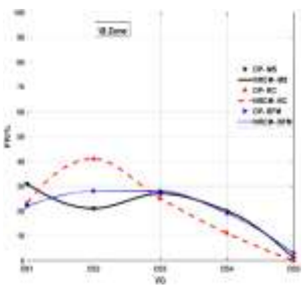
| Intensity zone | Type | DS1 | DS2 | DS3 | DS4 | DS5 |
|---|---|---|---|---|---|---|
| VI | MS | 69 | 23 | 7 | 1 | 0 |
| | RC | 89 | 10 | 1 | 0 | 0 |
| | BFM | 62 | 30 | 7 | 1 | 0 |
| VII | MS | 40 | 34 | 19 | 7 | 0 |
| | RC | 68 | 22 | 10 | 0 | 0 |
| | BFM | 35 | 35 | 19 | 11 | 0 |
| VIII | MS | 31 | 21 | 27 | 20 | 1 |
| | RC | 23 | 41 | 25 | 11 | 0 |
| | BFM | 22 | 28 | 28 | 19 | 3 |
| IX | MS | 11 | 10 | 32 | 30 | 17 |
| | RC | 10 | 15 | 21 | 43 | 11 |
| | BFM | 6 | 9 | 30 | 31 | 24 |
| X | MS | 2 | 7 | 7 | 21 | 63 |
| | RC | 6 | 8 | 12 | 22 | 52 |
| | BFM | 1 | 5 | 6 | 20 | 68 |
| XI | MS | 1 | 3 | 6 | 15 | 75 |
| | RC | 1 | 3 | 7 | 17 | 72 |
| | BFM | 0 | 2 | 6 | 14 | 78 |



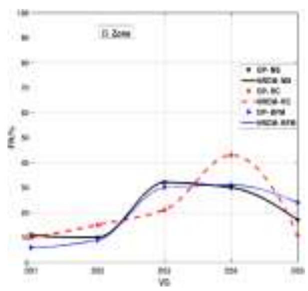
(a)



(b)



(c)



(d)

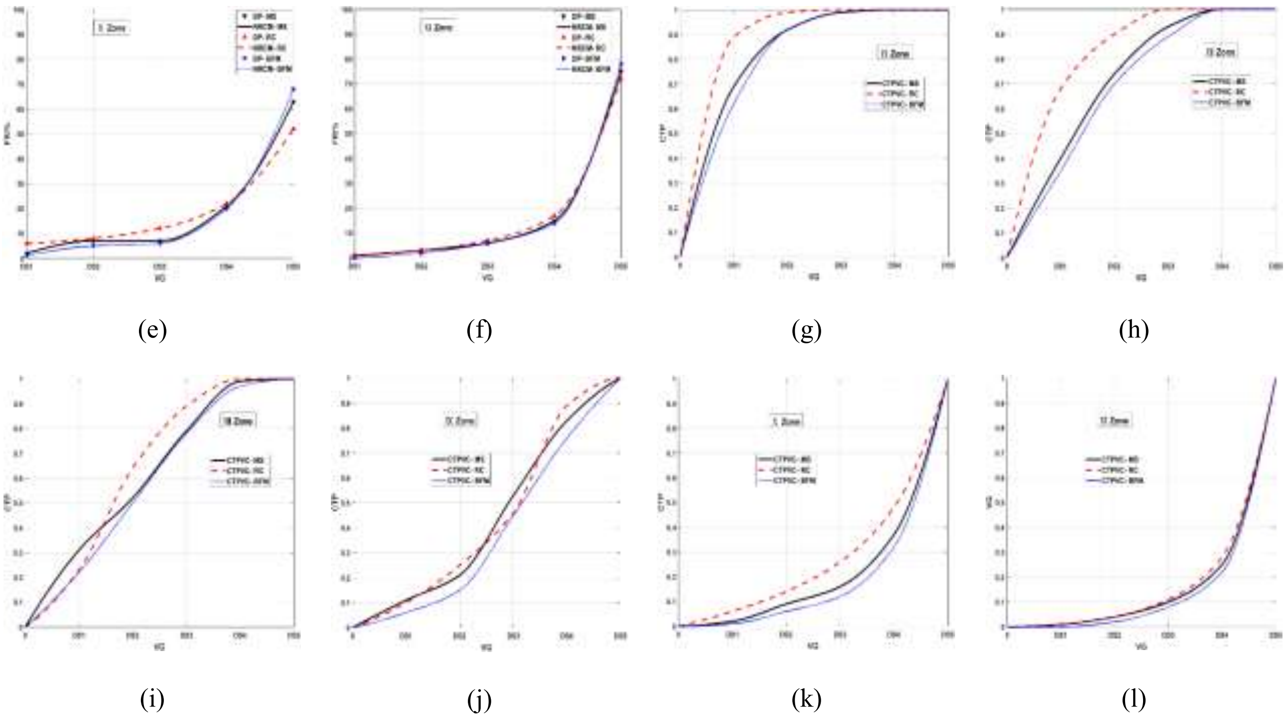


Fig.9 Comparison of the vulnerability of typical damage buildings in different intensity zones: (a) - (g) damage ratio; (h) - (n) Transcendental probability of seismic damage

## 2.4. COMPARISON OF THE MEAN DAMAGE INDEX (MDI)

In the appraisal of structural seismic vulnerability, to fully grasp the ensemble damage scenarios of a type of structure in a specific seismic zone, a seismic damage index (DI) is proposed to evaluate the damage degree of the structure in an urban area. Substantial structural seismic researchers have studied the DI in multiple studies. For example, based on the parameters of structural deformation, seismic energy and cyclic hysteresis characteristics, the DI models with diversification parameters were established using the correlation theory of numerical analysis, and the linear and quadratic regression models between diversify parameters are provided [19]. The DI is described as an integer of 1-7 to measure the structural damage in multiple grades. The vulnerability analysis of 3332 buildings in the Colima M7.4 earthquake in Mexico in 2003 was performed using the seismic damage field observation survey data, and the curve model of the DI and collapse ratio is established [20]. Considering the 4 elements of the structural system, irregular layout and interaction, storey factor and the related mode, and 14 parameters, the calculation model of DI is established, as shown in formula 5, where $I_v^*$ is the DI of parameters, $C_{vi}$ is the VG of the structure, and $p_i$ is the weight of the parameter. The vulnerability of more than 500 buildings in the old urban area of Seixal, Portugal, is analysed based on the DI. The vulnerability curves of MDI, transcendental probability and seismic intensity (EMS-98) are established [21]. Considering the structural damage characteristics of Dujiangyan city, this paper uses the continuous numerical value of the DI from 0 to 1 to represent the degree of the structural damage from light to heavy [22]. To obtain the ensemble damage scenario of a certain type of building in multiple intensity zones, the FR of buildings with different VG is a weighted average with the corresponding DI in multiple grades. The obtained parameters are the mean damage index (MDI), as shown in formula 6. In the formula, $[MDI]_T$ is the MDI of a type of T structure the in seismic zone; $d_i$ is the DI of VG for $i$, and its upper, median and lower limits are shown in Table 5; $\gamma_i$is the FR of the building structure with VG ($i$ = 1,2,3,4,5 ). To obtain the damage scenario of MS, RC and BFM in multiple intensity regions, with the empirical seismic vulnerability matrix, the matrix model of formula 6 is analysed, and the vulnerability matrix model based on the MDI is established, as shown in formulas 7-9. $\gamma_{ji}$ is the FR (failure number ratio) of the class-T structure subjected to the class-$i$ seismic damage in the intensity zone (j = 6,7,8,9,10,11); $MDI_j$ is the MDI of the T-type structure in intensity region j, $[MDI]_{T_S}$ is the MDI limit of the T-type structure (S takes the upper limit (u), mean value (m), and lower limit (d)). The model is validated with 7099 seismic damage samples. The MDI matrix of a typical structure in the seismic urban area is obtained, as shown in formulas 10-18, and the vulnerability comparison curves of the structure MDI are obtained, as shown in Figure 10. The results of the model calculation show that the MDI value of the RC structure is slightly lower than that of MS in the seismic zone. The increase in the amplitude after zone IX is relatively larger. The initial amplitude of MS increases relatively quickly in intensity zone VIII, while the MDI values of BFM in each intensity zone are relatively higher but slightly lower than MS.

$$I_v^* = \sum_{i=1}^{14} C_{vi} \times p_i \qquad (2.5)$$

$$[MSDI]_T = \sum_{i=}^{5} d_i \times \gamma_i \qquad (2.6)$$

$$[MDI]_T = [d_i] \times [\gamma_{ji}] \qquad (2.7)$$

$$[MDI]_T = \begin{bmatrix} d_1 \\ d_2 \\ \vdots \\ \vdots \\ d_i \end{bmatrix} \times \begin{bmatrix} \gamma_{61} & \gamma_{62} & \cdots & \cdots & \gamma_{6i} \\ \gamma_{71} & \gamma_{72} & \cdots & \cdots & \gamma_{7i} \\ \gamma_{81} & \gamma_{82} & \cdots & \cdots & \gamma_{8i} \\ \vdots & \vdots & \ddots & & \vdots \\ \vdots & \vdots & & \ddots & \vdots \\ \gamma_{j1} & \gamma_{j2} & \cdots & \cdots & \gamma_{ji} \end{bmatrix} \qquad (2.8)$$

$$[MDI]_{T_s} = \begin{bmatrix} MSDI_6 \\ MSDI_7 \\ MSDI_8 \\ \vdots \\ \vdots \\ MSDI_j \end{bmatrix} \qquad (2.9)$$

$$[MDI]_{MS_d} = \begin{bmatrix} 0.0495 \\ 0.1295 \\ 0.2205 \\ 0.4155 \\ 0.6790 \\ 0.7410 \end{bmatrix} \qquad (2.10)$$

$$[MDI]_{RC_d} = \begin{bmatrix} 0.0130 \\ 0.0520 \\ 0.1765 \\ 0.4080 \\ 0.6070 \\ 0.7295 \end{bmatrix} \qquad (2.11)$$

$$[MDI]_{BFM_d} = \begin{bmatrix} 0.0565 \\ 0.1525 \\ 0.2420 \\ 0.4735 \\ 0.7110 \\ 0.7600 \end{bmatrix} \qquad (2.12)$$

$$[MDI]_{MS_m} = \begin{bmatrix} 0.0810 \\ 0.1930 \\ 0.3000 \\ 0.5280 \\ 0.8190 \\ 0.8850 \end{bmatrix} \tag{2.13}$$

$$[MDI]_{RC_m} = \begin{bmatrix} 0.0240 \\ 0.0840 \\ 0.2590 \\ 0.5250 \\ 0.7380 \\ 0.8730 \end{bmatrix} \tag{2.14}$$

$$[MDI]_{BFM_m} = \begin{bmatrix} 0.0950 \\ 0.2230 \\ 0.3310 \\ 0.5950 \\ 0.8540 \\ 0.9060 \end{bmatrix} \tag{2.15}$$

$$[MDI]_{MS_u} = \begin{bmatrix} 0.1850 \\ 0.3060 \\ 0.4225 \\ 0.6420 \\ 0.8700 \\ 0.9205 \end{bmatrix} \tag{2.16}$$

$$[MDI]_{RC_u} = \begin{bmatrix} 0.1245 \\ 0.1890 \\ 0.3770 \\ 0.6460 \\ 0.8030 \\ 0.9130 \end{bmatrix} \tag{2.17}$$

$$[MDI]_{BFM_u} = \begin{bmatrix} 0.1990 \\ 0.3380 \\ 0.4515 \\ 0.7015 \\ 0.8990 \\ 0.9380 \end{bmatrix} \tag{2.18}$$

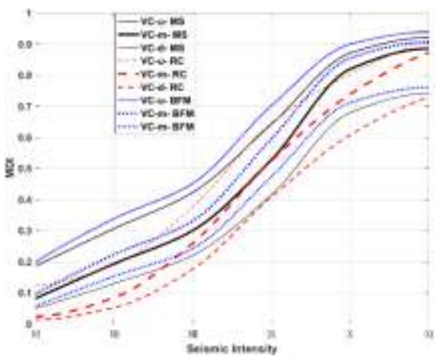


Fig.10 Comparison of the empirical seismic damage vulnerability of typical damage buildings under MDI parameters

## 3. CONCLUSION

Based on the investigation of 7099 MS, RC and BFM damaged buildings in Dujiangyan due to the Wenchuan earthquake, this paper compares and analyses the vulnerability of three typical damaged buildings and draws the following conclusions:

(1) The seismic damaged sample of 7099 buildings were statistically analysed. The exponential quadratic fitting model is established using numerical analysis theory. Combined with the empirical seismic damage sample data, the non-linear continuous function models and curves of MS, RC and BFM are obtained. The linear and non-linear quadratic fitting of the abovementioned seismic damage samples investigated is performed, and regression curves are obtained. Combined with functional models, typical damage buildings are analysed.

(2) The statistical and numerical analysis of the number of stories, age and seismic fortification factors, which have prominent effects on various structures, are carried out according to the empirical seismic damage investigation. The empirical seismic vulnerability matrix of the whole sample is given, and the vulnerability comparison model curves of multiple structural types are obtained.

(3) According to the characteristics of Dujiangyan,which spans multiple-intensity areas, the empirical seismic vulnerability matrices of MS, RC and BFM in zones VI-XI are established, and the vulnerability comparison curves, considering the failure ratio and CTP, are given. The difference in seismic vulnerability of the damaged buildings in multiple intensity zones is analysed based on the comparison curve.

(4) By analysing the research theory of the seismic damage index in the global territory, applying mathematical equation and functional theory and combining the probability matrix of empirical seismic vulnerability of Dujiangyan and the seismic intensity scale of China, we propose a calculation model of the MSDI matrix. The empirical seismic vulnerability matrix of each structure is embedded in the model, and the vulnerability curve models based on the MSDI parameters are obtained. All analysis results are within the vulnerability range delineated by the Chinese seismic intensity scale, which verifies the applicability of the model.

The main purpose of the comparative analysis of the seismic vulnerability of typical damage buildings in multiple intensity regions is to analyse the vulnerability of widely used buildings damaged in the Wenchuan Earthquake, compare the slight divergences, and provide a basic reference for the revision of the seismic design codes and the seismic intensity scale of structures. However, the comparison of structural seismic vulnerability is affected by the site conditions, seismic directionality, structural spatial arrangement and other factors. Many ground motion parameters (PGA, PGV), site effect analyses, ground motion release processes caused by fault rupture, geological exploration records and other factors should be further studied.

# 4. ACKNOWLEDGMENTS

The basic data used in this paper are from the Dujiangyan of seismic damage investigation team of the Institute of Engineering Mechanics, CAE, and the research group of china seismic intensity standards. The results of the research are benefited from the nearly two months on-site structural damage investigation of Du jiang weir and the research group of China Seismic Intensity Standards from more than 20 scientific research workers in universities and institutes nationwide. Thank you for the support of Natural Science Foundation Youth Fund of China (51608494) and Heilongjiang Science Foundation Face Project (E2018060).


## REFERENCES


1. Civil and Structural Groups of Tsing Hua University, XI Nan jiao tong University and Bei Jing Jiao tong University, "Analysis on seismic damage of buildings in the Wen chuan earthquake", Journal of building structures 29(4): 1-9, 2008.
2. H.N. Li, S.Y. Xiao, L.S. Huo, "Damage investigation and analysis of engineering structures in the Wen chuan earthquake", Journal of Building Structure 29(4): 10-19, 2008.
3. B.T. Sun, G.X. Zhang, "Statistical analysis of the seismic vulnerability of various types of structures in Wen chuan M8.0 earthquake", China Civil Engineering Journal 45(5): 26-30, 2012.
4. J.J. Sun, Y.H. Tang, Z.X. Sun, C. Zheng, H.B. Shi, L. Lin, "Damage to urban buildings in zones with intensity VIII or VII during Wen chuan earthquake and discussion on some typical damage", Journal of Earthquake Engineering and Engineering Vibration 29(6): 65-73, 2009.
5. L.S. Huo, H.N. Li, S.Y. Xiao, D.S. Wang, "Earthquake damage investigation and analysis of reinforced concrete frame structures in Wenchuan earthquake", Journal of Dalian University of Technology 49(5): 718-723, 2009.
6. H.Y. Gao, D.M. Bie, J.J. Ma, Q.G. Qu, "A research on vulnerability for brick-residence buildings in Wen chuan earthquake areas", World Earthquake Engineering 26(4): 73-77, 2010.
7. L. Su, H.J. He, "Seismic vulnerability assessment for RC frame structure based on SVM", J. Huazhong Univ. of Sci and Tech (Natural Science Edition) 46(5): 115-120, 2018.
8. C. Xu, Z.P. Wen, "Seismic vulnerability analysis of Reinforced Concrete frame structures based on ground motion parameters", China Earthquake Engineering Journal 38(2): 201-211, 2016.
9. B.T. Sun, G.X. Zhang, "Statistical analysis of seismic vulnerability for various types of building structures in Wenchuan earthquake", Key Engineering Materials. 452-453: 461-464, 2011.
10. S.L. Lin, S.R. Uma, A. King, "Empirical Fragility Curves for Non-Residential Buildings from the 2010–2011 Canterbury Earthquake Sequence", Journal of Earthquake Engineering 22(5): 749-777, 2018.
11. J. Schwarz, L. Abrahamczyk, M. Leipold, T. Wenk, "Vulnerability assessment and damage description for R.C. frame structures following the EMS-98 principles", Bulletin Earthquake Engineering 13(4): 1141-1159, 2015.
12. A. Rosti, M. Rota, A. Penna, "Damage classification and derivation of damage probability matrices from L'Aquila (2009) post-earthquake survey data", Bulletin Earthquake Engineering 16(9): 3687-3720, 2018.
13. E. Dumova-jovanoska, "Fragility curves for reinforced concrete structures in Skopje (Macedonia) region", Soil Dynamic and Earthquake Engineering 19(6): 455-466, 2000.
14. A.K. Eleftheriadou, A I. Karabinis, "Evaluation of damage probability matrices from observational seismic damage data. Earthquakes and Structures", 4(3): 299-324, 2013.
15. D. Gautam, G. Fabbrocino, F.S. De magistris, "Derive empirical fragility functions for Nepali residential buildings. Engineering Structures", 171, 617-628, 2018.

16. M. Naguit, P. Cummins, M. Edwards, H. Ghasemi, B. Bautista, H. Ryu, M. Haynes, "From Source to Building Fragility: Post-Event Assessment of the 2013 M7.1 Bohol, Philippines, Earthquake", Earthquake Spectra 33(3): 999-1027, 2017.
17. Q. Xu, S.S. Zheng, Y.Z. Han, "Steel frame seismic vulnerability based on a global structural damage index", Journal of Vibration and Shock 33(11): 78-106, 2014.
18. X.H. Yu, "Probabilistic seismic fragility and risk analysis of reinforced concrete frame structures", Doctor thesis, Harbin Institute of Technology, Harbin, 2012.
19. K. Faraji, M. Miri, "Correlation Between Damage Indexes in Knee Bracing Frames Subjected to Earthquakes" Advanced Materials Research 255-260, 2350-2354, 2011.
20. V.M. Zobin, F. Ventura-ramírez, C.L. Gutiérrez-andrade, L.H. Cruz, S. Santibáñez-ibáñez, "The Mw 7.4 Colima, Mexico, Earthquake of 21 January 2003: The Observed Damage Matrix in Colima City and its Comparison with the Damage Probability Matrix", Natural Hazards 38: 391-410, 2006.
21. T.M. Ferreira, R. Vicente, J.A.R. Mendesdasilva, H.V. Aníbalcosta, "Seismic vulnerability assessment of historical urban centres: case study of the old city centre in Seixal, Portugal", Bulletin Earthquake Engineering 11(5): 1753-1773, 2013.
22. GB/T 17742. The Chinese seismic intensity scale (in Chinese), 2008.

## LIST OF FIGURES AND TABLES:



*Received 02.07.2019*

*Revised 12.08.2019*