



# Empirical seismic vulnerability assessment model of typical urban buildings

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## Abstract

Evaluating the seismic vulnerability of regional group structures is essential for effectively quantifying the seismic resilience and risk analysis of regional cities. To study the degree of damage caused by a typical earthquake to the overall group of buildings in a specific area, this paper takes the field observation data of the Wenchuan earthquake on May 12, 2008, in China as the research background and makes empirical vulnerability statistics and classification on all the inspection data of structural groups in Dujiangyan city. The seismic risk experience database (8621 building samples) based on the overall regional group buildings is developed. Using nonlinear regression, probabilistic risk prediction, and a cumulative damage conditional probability model, the empirical vulnerability matrices of six typical groups of buildings in different seismic intensity zones are established. Considering the effects of seismic design, age, purpose, number of floors, and plane shape features on the seismic resilience and vulnerability of regional group structures, a multifactor vulnerability innovation comparison model based on updating the quantitative scale of vulnerability level is developed. Ultimately, an innovative seismic vulnerability update index domain assessment model is proposed to quantify the damage modes of regional group structures. Zonal fragility prediction models of six typical regional structure groups are established. In the analysis results of the multidimensional empirical vulnerability model, it is found that with the increase in the macroseismic intensity grade, the sample number distribution shows a decreasing trend. Additionally, an essential finding is that the damage of the regional reinforced concrete structure is relatively light, indicating that it has a certain seismic resilience. The empirical vulnerability database is used within the proposed model to obtain a seismic vulnerability index.

**Keywords** Urban agglomerate buildings · Empirical vulnerability · Seismic resilience of regional structures · Update vulnerability assessment model · Vulnerability strip judgment model

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## 1 Introduction

Earthquakes have seriously impacted the social economy, life, and property, especially on buildings in urban areas. In recent years, research on urban seismic resilience and vulnerability has become a hotspot in earthquake engineering. Seismic risk and empirical vulnerability assessment of regional structures is a valued index to effectively quantify and predict structural damage and resilience. The seismic risk model, reliability theory, and empirical evaluation equation are extensively used in the field of regional structural damage and seismic resilience prediction (Iervolino 2022; Iervolino et al. 2022; Lagomarsino and Giovinazzin 2006; Lagomarsino et al. 2022). A substantial number of structural seismic and vulnerability research scholars have used artificial intelligence technology, neural networks, support vector machines, deep learning, fuzzy membership judgment models, numerical simulation, vibration testing, remote sensing monitoring, probability risk, nonlinear model theory, mathematical statistics principles, and empirical vulnerability analysis methods to perform multidimensional damage mode evolution research on various typical building structures. An empirical vulnerability prediction model with significant theoretical and application significance has been developed, which has positively contributed to effectively reducing structural seismic risk, improving the ability of structures to resist earthquakes, and recuperating the seismic resilience of regional building groups.

With the rapid development of artificial intelligence technology, machine learning methods have been utilized to analyse structural earthquake fragility. The model analysis is conducted using the training set, the test set, and the verification set, and the intelligent model used to predict the structural earthquake failure mode is derived. Wen et al. (2022) selected the convolutional neural network model to develop a rapid prediction model of RC frame vulnerability based on five dependent variables. The reliability was verified using the field survey data of 162 RC structures. Stojadinović et al. (2022) demonstrated a random forest classification model using machine learning damage classification and representative sampling algorithms. They developed a vulnerability maintenance cost matrix considering the number of buildings in typical zones. Yu (2022) compared the backpropagation neural network, random forest, exploration tree, and linear and ridge regression algorithms. They established a data-driven model to evaluate the damage features of RC structures. After the 2015 earthquake in Nepal, the inspection data were selected by Ghimire et al. (2022), and combined with the innovative methods of artificial intelligence, a regional structure comparison prediction model based on testing multiple algorithms and automated machine learning (Chen and Zhang 2022) was developed and established.

Fuzzy set theory, the finite element method, dynamic testing, and remote sensing monitoring are ubiquitously used to analyse typical structures' seismic fragility and vulnerability. Combining undefined random variables, triangular fuzzy set theory, and the copula model, Guo et al. (2022) proposed a fuzzy global seismic vulnerability analysis framework to study the uncertainty of structural damage. The representative structures of typical earthquake regions were selected by Bernardo et al. (2022) and Rezvani et al. (2022), and three-dimensional finite element models of single structures and local components were established. Nonlinear and probabilistic modal analyses were performed using actual seismic loss detection and test data, and a vulnerability comparison curve was generated. Ferreira et al. (2017) employed the global geographic information system (GIS) to investigate buildings after the Azores earthquake in 1998 and established an empirical vulnerability model based on 192 buildings.

Considering the empirical fragility and statistical analysis of actual seismic damage observation data, the vulnerability characteristics of buildings in a certain zone can be obtained directly, excitably, and accurately. Demirel et al. (2022) conducted an on-site seismic loss inspection of the Samos earthquake in Greece on October 30, 2020, collected seismic damage data of typical RC structures in the Izmir region and developed an empirical vulnerability statistical model. Shafapourtehreny et al. (2022) contained the regional structural earthquake damage data of Istanbul city, Türkiye. They combined the machine learning calculation method to generate vulnerability regression and prediction curves based on typical earthquake damage sample data. Sheshov et al. (2022) conducted a field survey on 169 buildings in Dulles, Albania, in 2019, conducted a vulnerability rating according to EMS-98 (Zhong et al. 2022a, b), and developed statistical vulnerability models for brick structures and RC structures. Debnath et al. (2022) conducted field observations on the unreinforced masonry structure damaged in the 2017 Anbar earthquake in India and summarized the typical failure features. The 3D model was established with SAP2000, and incremental dynamic analysis was performed considering seven ground motion parameters. Misseri et al. (2020) demonstrated the element model of the wood-soil reinforced structure, gave the mechanical model considering the dynamic characteristic parameters, and selected the field inspection data of the Maule earthquake in Chile in 2010 to verify and compare the built model. Ebrahimiyan et al. (2022) presented the seismic loss data of RC structures under the action of typical near- and far-field earthquakes, established a damage model of adjacent buildings by using soft computing means (Yang et al. 2023), and conducted vulnerability analysis, generating vulnerability curve bundles.

The nonlinear dynamic features of building types and geometric structures were considered by Ptilakis and Petridis (2022), and the seismic vulnerability comparison curves of existing group RC structures under different site conditions were established with the peak ground acceleration (PGA) as the intensity measure. Chettri et al. (2021) and Gautam et al. (2022) summarized the survey data of two destructive earthquakes in Bhutan in 2009 and 2011, analysed the actual seismic loss features and mechanism of group masonry structures, and established three vulnerability mode comparison curves using the log-distribution function. Usta and Bozdağ (2022) conducted vulnerability analysis on the traditional himis buildings in Türkiye and constructed vulnerability regression curves considering different damage modes.

In Italy, research on empirical seismic vulnerability has been rapidly developed, and many remarkable scientific achievements have been derived, which have contributed significantly to the development of global seismic vulnerability research. Del Gaudio et al. (2017) made statistics on 7597 RC buildings in the 2009 L'Aquila earthquake in Italy, drew a PGA-based risk distribution map according to the building characteristic information from field observations, used EMS-98 to assess the vulnerability level of the data, and developed a statistical vulnerability distribution. Formisano and Chieffo (2022) studied the empirical vulnerability of ancient buildings in Morris, Italy, considering the site effect, and developed a statistical model of the relationship between the number of buildings and frequency according to age. Using the MCS and EMS-98 quantitative criteria, the spatial vulnerability layout of small building groups was drawn. Cardinali et al. (2022) discussed the empirical damage assessment method of masonry structures in Florence, Italy, in the XX century, combined with the original data of the archives. They performed empirical vulnerability and nonlinear static analysis on more than 300 structures. Angioli et al. (2022) made statistics on the field data of five earthquakes in central and northern Italy. They generated a typical failure feature analysis and statistical vulnerability chart of masonry structures. Zucconi et al. (2022a, b), Shabani et al. (2021) studied the field inspection data

of RC frame structures and unreinforced masonry structures in the 2012 Emilia and 2009 L'Aquila earthquakes in Italy, generated a distribution map of structural survey samples according to different vulnerability levels, took PGA as the intensity measure, and established a statistical and nonlinear regression model based on actual earthquake loss survey data. Scala et al. (2022) used the L'Aquila earthquake data established by the Italian Department of Civil Protection (DPC) to conduct empirical vulnerability research in many aspects (Longobardi and Formisano 2022), counted and obtained the actual seismic fragility distribution of masonry structure groups built at different ages, and developed regression curves based on the seismic damage index and intensity measures in multiple periods.

China is one of the countries with the highest earthquake frequency in the world (Li and Liu 2022a). A large number of researchers in the field of earthquake engineering have performed a variety of empirical vulnerability studies for typical earthquakes. Qu et al. (2015) and Sun et al. (2019) conducted an on-site structural investigation after the 2013 Lushan earthquake with Mw 7.0, obtained the seismic damage data of 3684 actual buildings, and obtained the empirical fragility matrix of the wooden roof truss structure, masonry structure, brick concrete structure, and RC frame structure. Gong et al. (2015) investigated the field structural earthquake loss in China's 2010 Mw 7.1 Yushu earthquake. They established empirical fragility databases of adobe, concrete block, RC frame, brick concrete, and bottom RC frame structures. Li et al. (2020, 2021a, 2022a; b), Li and Liu (2022b) investigated the actual structural damage caused by the 2008 Wenchuan earthquake in China. They developed empirical vulnerability curves and matrices of masonry structures, RC structures, bottom frame seismic wall structures, brick wood structures, and RC girder bridges based on the damage data of structures and bridges obtained from field observations. Li et al. (2021b), Li and Liu (2022c, d), Li (2022) gathered and sorted a large amount of historical seismic data in China and quantified the vulnerability level by using the Chinese seismic intensity standard (GB/T 17742 2008, 2020; Li 2023) and established a nonlinear vulnerability model based on the empirical vulnerability database of typical structures. Xi (2022) developed a model relationship between the organized building structure and economic vulnerability risk parameters from the perspective of the repair cost of the Dujiangyan regional structure groups after the Wenchuan earthquake using the vulnerability function and large-scale loss assessment method (Bianchi et al. 2022; d'Aragona et al. 2022).

The above research work has performed many fragility studies on various engineering structures using multidimensional analysis methods, established an effective quantitative relationship model of structural damage, and made significant contributions to the research field of structural seismic vulnerability. However, most of the research on the damage of a single structure model focuses on the dynamic response feature analysis of a building that was seriously damaged in the actual earthquake. The vulnerability model is challenging to extend to the group vulnerability field research. Regarding the empirical vulnerability of group structure, most studies use various methods to perform research based on group structure vulnerability. However, establishing a typical structure sample database commonly depends on sampling discrete survey points of typical earthquakes or specific inspection points in historical earthquakes, which cannot virtually and accurately measure the damage degree of all buildings in a particular area.

To more precisely estimate the seismic vulnerability and fragility features of various typical structure groups in typical earthquake regions, a relatively reasonable empirical vulnerability quantification model of group structures is developed. From July to September 2008, the *China Earthquake Administration* organized relevant earthquake and structural engineering experts to conduct a comprehensive on-site investigation in Dujiangyan

city (the authors participated in the complete field investigation). Dujiangyan city is located across multiple intensity zones, and the damage features of urban structure groups are significant. Therefore, this city was selected for comprehensive surveillance. In this study, 8,621 buildings in Dujiangyan city are quantified by using the latest version of the China intensity standard, and empirical fragility probability matrix models of six typical building groups (multistory masonry structure (MMS), RC structure (RC), bottom frame seismic wall masonry structure (BFM), single story RC workshop (SRCW), single story brick concrete column workshop (SBCW) and mixed structure (wood-masonry, adobe, wood roof truss structure and other combined structures, MS)) are established. Depending on the regional damage features of various structures, the traditional five damage grade quantitative standards are broken through, updated, and refined into nine vulnerability-level quantitative scales. According to the seismic design, age, purpose, number of floors, and plane shape, a comprehensive fragility assessment of six building group samples is performed, and innovative vulnerability matrix, plane, and surface models are developed. Using the calculation method of the nonlinear regression optimization model, the vulnerability comparison curve based on multidimensional influence factors is generated. A vulnerability index stripe model is proposed to evaluate the fragility of typical urban group buildings, and the rationality of the zonal assessment model is verified by using the established vulnerability update database of Dujiangyan Group buildings.

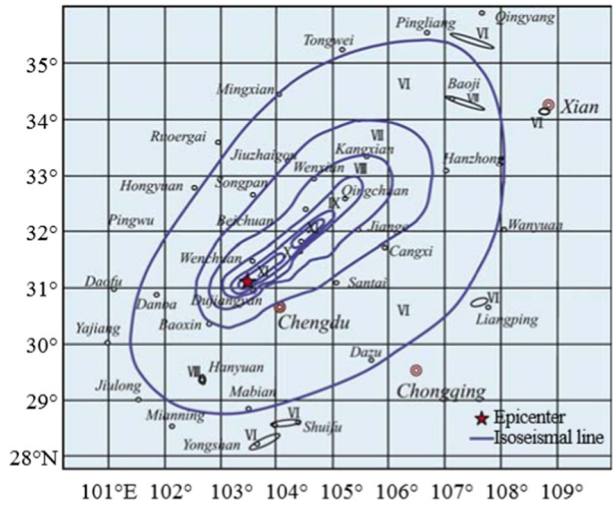
## 2 Empirical vulnerability assessment model of typical urban buildings

### 2.1 Empirical vulnerability statistical model of regional group structure

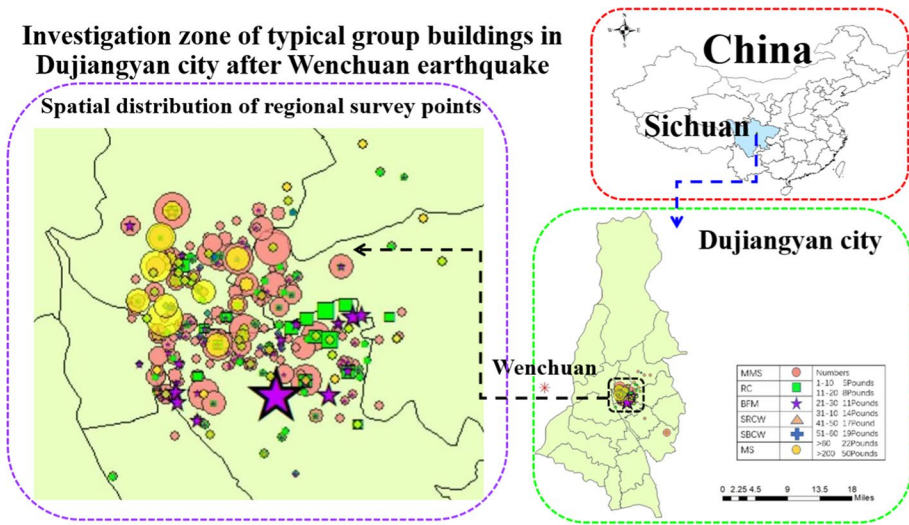
To study the damage mode features of typical destructive earthquakes on urban buildings, selecting typical urban buildings affected by actual destructive earthquakes as the research object and conducting empirical vulnerability research is one of the essential means to effectively quantify the seismic resilience of urban buildings. On May 12, 2008, China experienced the Wenchuan earthquake with Mw 7.9. The epicentre was located in Yingxiu town. The focal depth was less than 20 km, and the duration was 80–120 s. The impact scope involved ten provinces in China, and 48,810 villages in 4467 townships were affected (Li and Chen 2020; Li et al. 2021a). After the earthquake, the China Earthquake Administration (CEA) (Li et al. 2021a) immediately gave an intensity distribution map, as reported in Fig. 1.

The earthquake caused many buildings to collapse, and Dujiangyan city, 28.4 km away from the epicentre, suffered earthquake damage to varying degrees. Its administrative area has the features of spanning multiple intensity zones and diversified structural categories. In July 2008, CEA took the lead in organizing earthquake engineering experts from different regions to perform field structural earthquake loss observations in Dujiangyan city for several months, collecting almost all building samples in the city's main urban area. The location of the sample investigation region and the distribution of various types of buildings are presented in Fig. 2. To profoundly study the vulnerability and resilience characteristics of various types of building complexes in typical cities, this paper takes the actual earthquake damage inspection data of six typical building complexes in Dujiangyan city as the research object. It employs the Chinese macrointensity standard (GB/T 17742 2008, 2020) to evaluate and count the vulnerability level (no damage (DS1), minimal damage (DS2), moderate damage (DS3), extensive damage (DS4), and collapse (DS5)) of all

**Fig. 1** Seismic intensity distribution map of the Wenchuan earthquake (Li and Chen 2020; Li et al. 2021a)



### Investigation zone of typical group buildings in Dujiangyan city after Wenchuan earthquake



**Fig. 2** Seismic damage investigation zone and distribution map of structural groups in Dujiangyan after the Wenchuan earthquake

samples. Table 1 indicates the quantitative assessment scale of the structural vulnerability level based on the Chinese macroseismic intensity standard. Combining probability statistics and modal analysis methods, the statistical vulnerability matrix, point cloud, surface, and plane models of MMS, RC, BFM, SRCW, SBCW, and MS are obtained, as summarized in Table 2 and Fig. 3.

Depending on the statistics and induction of the sample database, the number and proportion of MMS are relatively large, accounting for nearly half of the total sample number, and the damage is rather heavy. The ensemble RC samples are relatively lightly damaged, and approximately 70% of the samples are at the DS1 and DS2 levels. The

**Table 1** Evaluation criteria and description of different vulnerability levels (Li et al. 2021a; GB/T 17742 2008, 2020; Li 2023)

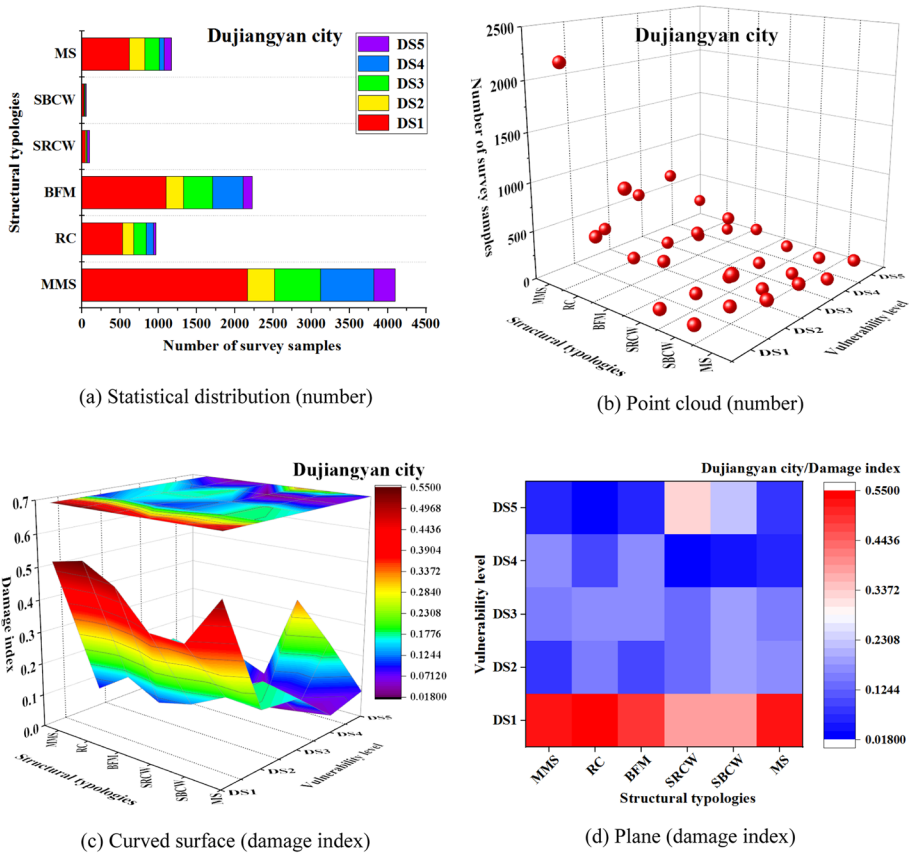
Vulnerability level	Description of evaluation criteria
DS1	Intact bearing and nonbearing components, or slight damage to individual nonbearing parts which can be used without being mended
DS2	Visible cracks in individual bearing components and evident cracks in nonbearing components
DS3	Slight cracks in most load-bearing components, some with obvious cracks, and severe damage to individual nonload-bearing components which can be used after general mend
DS4	Severe damage to most of the load-bearing components, and local failure of the nonload-bearing components render it difficult to mend the buildings
DS5	The collapse of buildings

**Table 2** Empirical fragility matrix of group buildings in the Wenchuan earthquake (Dujiangyan city (number/damage index (DI)), DI represents the number of buildings identified for the different vulnerability levels divided by the total number of buildings,  $DI = \frac{\text{Number}_{\text{different vulnerability levels}}}{\text{Number}_{\text{allsurveyed buildings}}}$ )

Structural typologies	Quantitative parameters	Vulnerability level					Total
		DS1	DS2	DS3	DS4	DS5	
MMS	Number	2162	359	601	699	279	4100
	Damage index	0.527	0.088	0.147	0.170	0.068	1
RC	Number	529	149	163	97	26	964
	Damage index	0.549	0.155	0.169	0.101	0.027	1
BFM	Number	1101	229	379	396	125	2230
	Damage index	0.494	0.103	0.170	0.178	0.056	1
SRCW	Number	39	13	13	2	34	101
	Damage index	0.386	0.129	0.129	0.020	0.337	1
SBCW	Number	21	10	10	2	12	55
	Damage index	0.382	0.182	0.182	0.036	0.218	1
MS	Number	617	206	186	64	98	1171
	Damage index	0.527	0.176	0.159	0.055	0.084	1
	Total						8,621/1

loss of BFM is slightly heavier than that of MMS and slightly lighter than that of RC. There are relatively more MS stocks, and the damage degree of the overall regional samples is less than that of BFM. Due to SRCW and SBCW being limited by their use functions and the stock being small, the widespread damage is relatively heavy.

Before 2008, no effective seismic monitoring stations were set up in Dujiangyan city, so it was impossible to obtain various ground motion parameter data. This study uses macroseismic intensity as an intensity measure, comprehensively considers the macro-intensity regional map reported by the CEA, evaluates and counts all sample databases, and develops an empirical vulnerability matrix, curved surface, and plane model of six typical building groups in different intensity regions by using probability and quantitative statistical calculation methods, as shown in Table 3 and Figs. 4, 5.



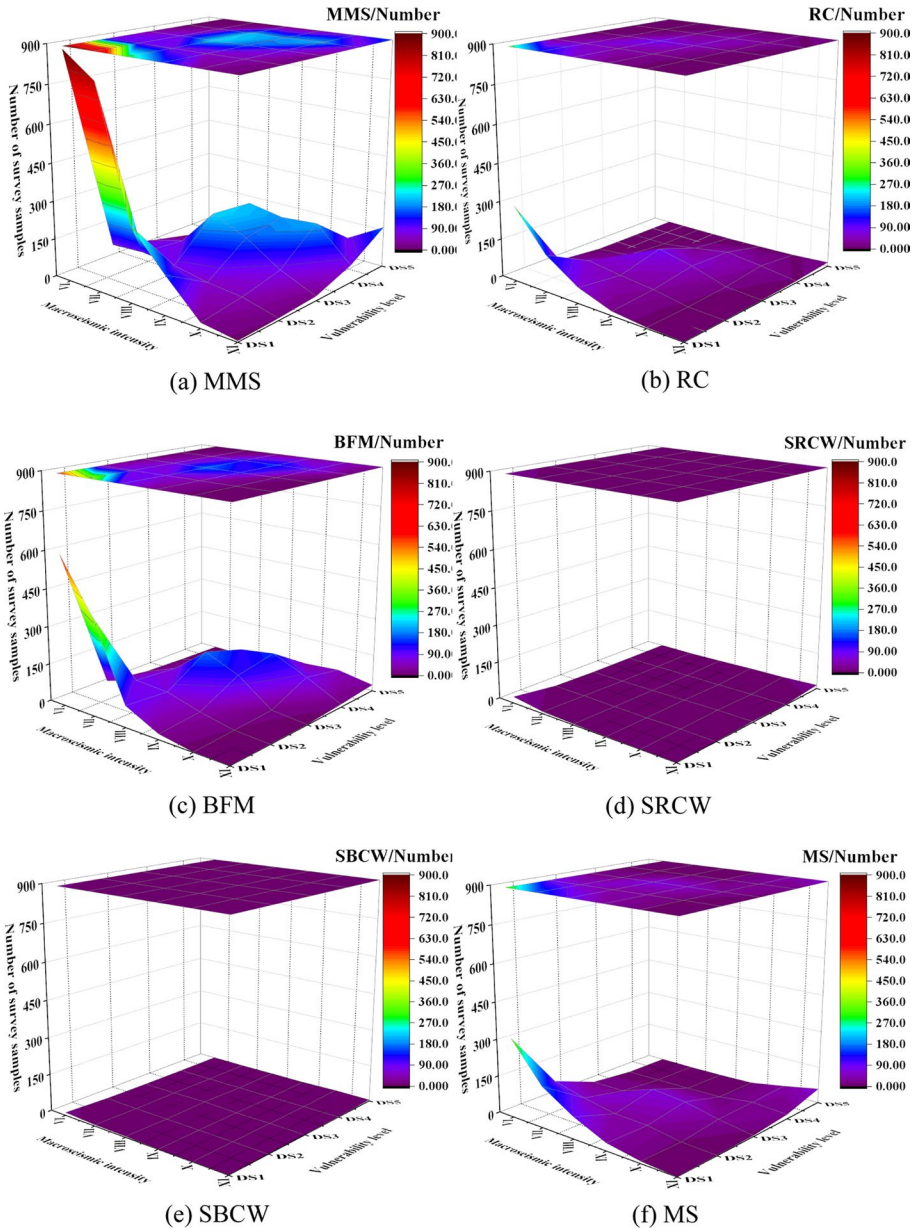
**Fig. 3** Multidimensional empirical vulnerability model considering regional typical structural groups

According to the analysis results of the multidimensional vulnerability model, the stock of various group structure samples demonstrates a decreasing trend with the increase in the macroseismic intensity zone, which is consistent with the reported macrointensity distribution map. The statistical results indicate that there are relatively few samples of DS2 damage to various structures in Dujiangyan city, and some regional buildings are at DS3 and above. In zone VI, the structural damage of multiple groups is relatively light, and RC and BFM are the most significant. After zone VIII, the damage to various structures is significantly aggravated, and the damage change of BFM is the most apparent. In zones X and XI, local failure or collapse occurred in a large proportion of various structures. It is worth noting that a certain proportion of RC structures are still damaged at the DS3 and DS4 levels in the extreme earthquake region, which indicates that this type of structure has sensible seismic resilience.

### 2.2 Vulnerability prediction and evaluation model of a typical urban group structure

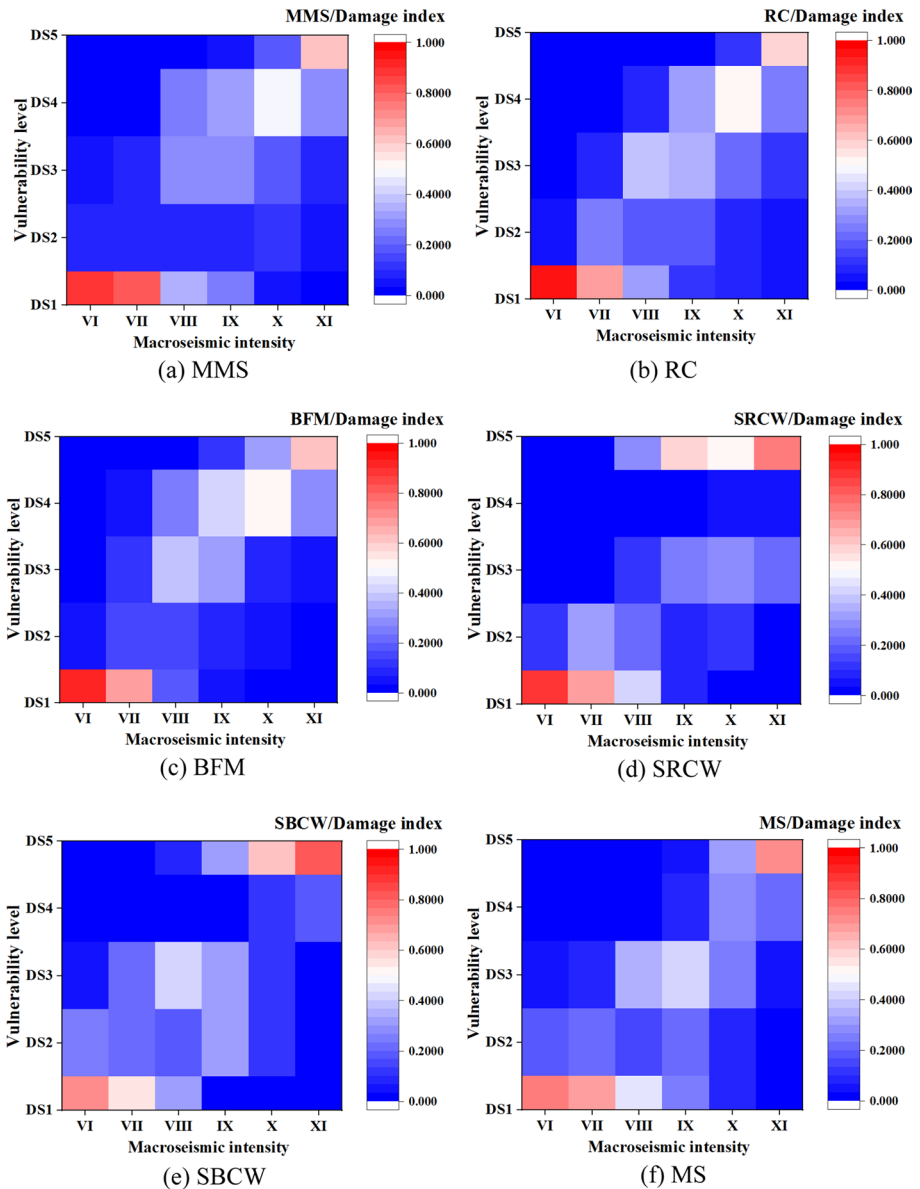
It is the core of empirical vulnerability research to conduct field investigations on structural damage affected by actual typical earthquakes and perform damage mode evolution analysis





**Fig. 4** Empirical vulnerability surface models of typical group buildings in different macroseismic intensity zones (number)

based on structural failure data. Using various nonlinear regression models and probabilistic risk analysis methods, researchers conducted multidimensional damage modal analysis on the group building empirical data of typical earthquake attacks and developed many structural vulnerability models. Del Gaudio et al. (2017) summarized the database of 7597 RC structures



**Fig. 5** Empirical vulnerability plane models of typical group buildings in different macroseismic intensity zones (damage index)

damaged by the L'Aquila earthquake in Italy. They proposed a group structure vulnerability prediction function model based on the exponential distribution function model (EDFM), as expressed in Eq. 1.

$$P[VG \geq VG_i | PGA] = \alpha_1 e^{\alpha_2 VG} + \alpha_3 e^{\alpha_4 VG} \tag{1}$$

**Table 3** Vulnerability matrix of typical group buildings considering different macrointensity zones (Dujingyan city (number/damage index))

Structural typologies	Macroseismic intensity	Vulnerability level					Total
		DS1	DS2	DS3	DS4	DS5	
MMS	VI	891/0.88	82/0.081	39/0.039	0/0	0/0	1012/1
	VII	795/0.806	91/0.092	75/0.076	25/0.025	0/0	986/1
	VIII	296/0.36	79/0.096	226/0.275	213/0.259	9/0.011	823/1
	IX	153/0.259	55/0.093	165/0.279	189/0.32	29/0.049	591/1
	X	22/0.052	43/0.102	78/0.184	201/0.475	79/0.187	423/1
	XI	5/0.019	9/0.034	18/0.068	71/0.268	162/0.611	265/1
RC	VI	299/0.937	19/0.06	1/0.003	0/0	0/0	319/1
	VII	146/0.67	57/0.261	15/0.069	0/0	0/0	218/1
	VIII	62/0.305	40/0.197	81/0.399	20/0.099	0/0	203/1
	IX	17/0.12	27/0.19	52/0.366	43/0.303	3/0.021	142/1
	X	4/0.074	5/0.093	11/0.204	27/0.5	7/0.13	54/1
	XI	1/0.036	1/0.036	3/0.107	7/0.25	16/0.571	28/1
BFM	VI	599/0.923	35/0.054	11/0.017	4/0.006	0/0	649/1
	VII	393/0.693	78/0.138	64/0.113	32/0.056	0/0	567/1
	VIII	86/0.185	72/0.155	172/0.369	123/0.264	13/0.028	466/1
	IX	22/0.062	35/0.099	115/0.326	143/0.405	38/0.108	353/1
	X	1/0.006	8/0.052	15/0.097	82/0.529	49/0.316	155/1
	XI	0/0	1/0.025	2/0.05	12/0.3	25/0.625	40/1
SRCW	VI	26/0.867	4/0.133	0/0	0/0	0/0	30/1
	VII	8/0.667	4/0.333	0/0	0/0	0/0	12/1
	VIII	4/0.4	2/0.2	1/0.1	0/0	3/0.3	10/1
	IX	1/0.083	1/0.083	3/0.25	0/0	7/0.583	12/1
	X	0/0	2/0.118	5/0.294	1/0.059	9/0.529	17/1
	XI	0/0	0/0	4/0.2	1/0.05	15/0.75	20/1
SBCW	VI	12/0.706	4/0.235	1/0.059	0/0	0/0	17/1
	VII	5/0.556	2/0.222	2/0.222	0/0	0/0	9/1
	VIII	4/0.333	2/0.167	5/0.417	0/0	1/0.083	12/1
	IX	0/0	1/0.333	1/0.333	0/0	1/0.333	3/1
	X	0/0	1/0.125	1/0.125	1/0.125	5/0.625	8/1
	XI	0/0	0/0	0/0	1/0.167	5/0.833	6/1
MS	VI	322/0.756	85/0.2	18/0.042	1/0.002	0/0	426/1
	VII	167/0.687	54/0.222	19/0.078	3/0.012	0/0	243/1
	VIII	88/0.456	31/0.161	66/0.342	6/0.031	2/0.01	193/1
	IX	31/0.244	27/0.213	54/0.425	9/0.071	6/0.047	127/1
	X	9/0.091	7/0.071	25/0.253	27/0.273	31/0.313	99/1
	XI	0/0	2/0.024	4/0.048	18/0.217	59/0.711	83/1

$P[VG \geq VG_i|PGA]$  represents the conditional probability that the actual damage of the structure reaches or exceeds the specific vulnerability level (VG) under the influence of the given intensity parameter (PGA),  $VG_i \in [1, 5]$ .  $\alpha_1, \alpha_2, \alpha_3,$  and  $\alpha_4$  are undetermined coefficients of exponential regression.

Zucconi et al. (2022b) processed the field investigation databases of the Emilia and L'Aquila earthquakes in Italy, counted the damage data of the MMS, RC, steel frame, and MS, and proposed a log-distribution function model (LDFM) to evaluate the vulnerability of regional population structures, as expressed in Eq. 2.

$$P[VG \geq VGi|PGA] = \Xi\left(\frac{\ln(PGA) - \mu}{\sigma}\right) = \frac{\beta_1}{VGi} e^{-\frac{-(\log(VGi) - \beta_2)^2}{\beta_3}} \quad (2)$$

$\Xi(\cdot)$  is a lognormal distribution function, and  $\mu$  and  $\sigma$  indicate log-mean and standard deviation, respectively.  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ , and  $\beta_4$  are undetermined coefficients of log-distribution regression.

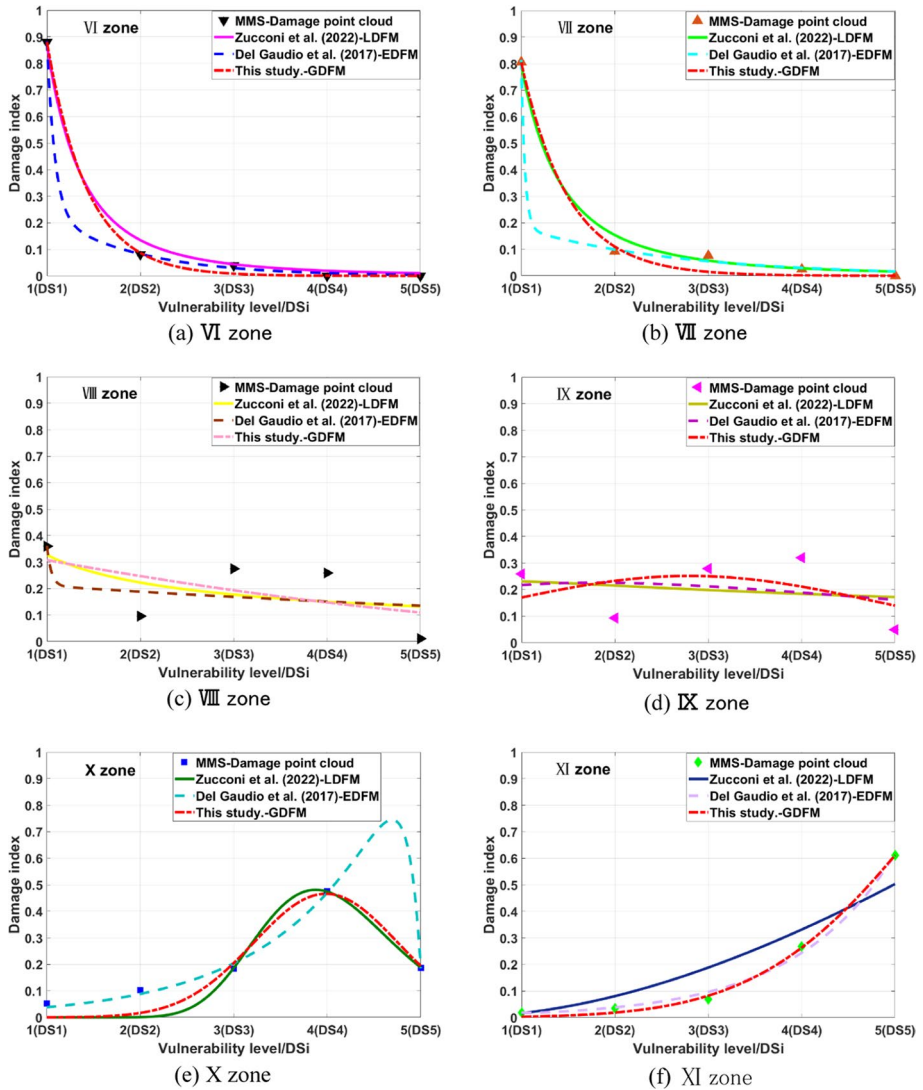
To obtain a relatively reasonable distribution model for fragility prediction and assessment of regional group structure, this paper comprehensively considered the mature analysis methods of nonlinear prediction models (Gaudio et al. 2017; Zucconi et al. 2022b; Li and Liu 2022c, d; Li 2022), updated the traditional exponential and logarithmic distribution models, and combined with Gaussian regression calculation theory, proposed a vulnerability function model (GDFM) for prediction and assessment of regional group buildings, as expressed in Eq. 3.

$$P[VG \geq VGi|MI] = \theta_1 e^{-\left(\frac{VGi - \theta_2}{\theta_3}\right)^2} \quad (3)$$

$MI$  denotes the macroseismic intensity;  $\theta_1$ ,  $\theta_2$ ,  $\theta_3$ , and  $\theta_4$  are the regression uncertainty coefficients of the Gaussian distribution.

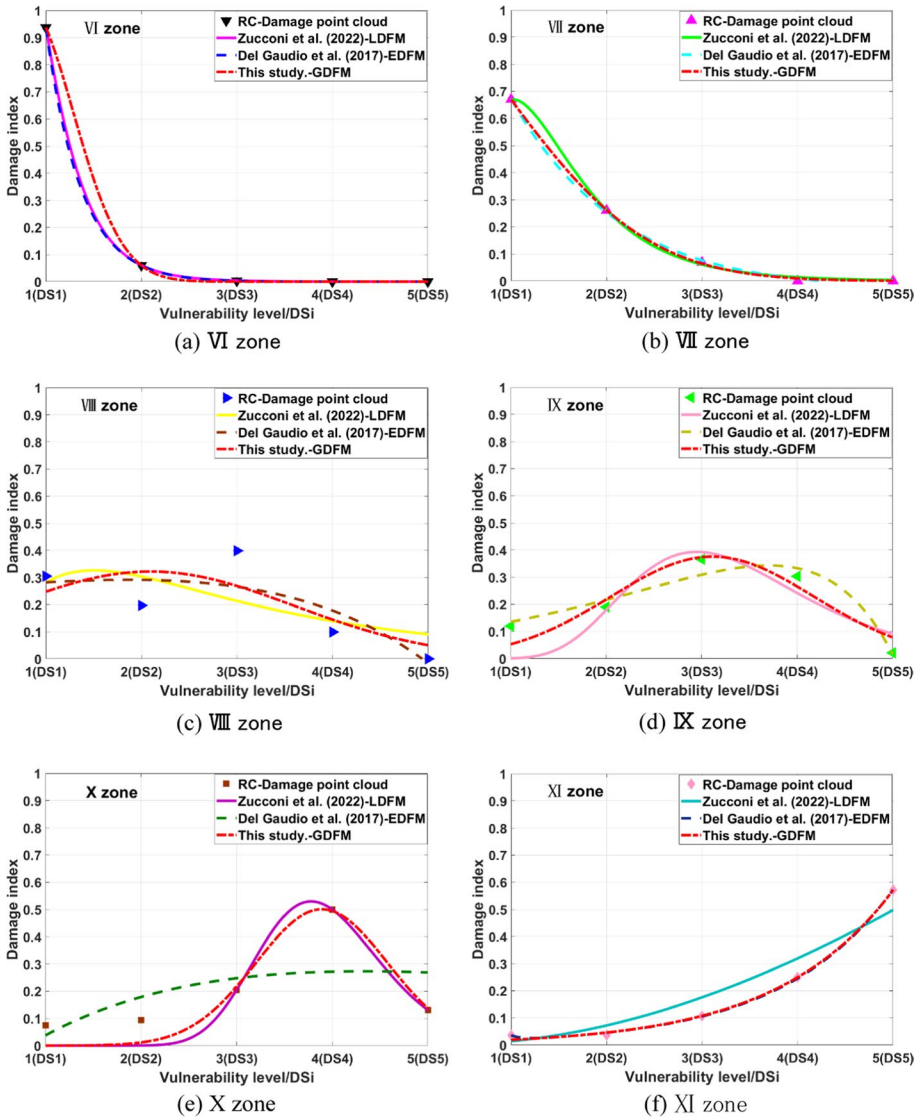
In this study, the empirical earthquake loss investigation database of six types of buildings in Dujiangyan city is comprehensively summarized to explore the fragility features of urban buildings under the influence of typical earthquakes. The established structural vulnerability database and matrix are regressed and compared using the multidimensional nonlinear regression model. Combined with the proposed GDFM (Eq. 3) and nonlinear model regression method, six typical structural vulnerability curves considering macroseismic intensity measures are developed, which can be used to evaluate the mean damage grade of regional group structures. The comparison curve and parameter matrix model of typical structural vulnerability prediction models based on different intensity regions are developed, as shown in Figs. 6, 7, 8, 9, 10 and 11 and Table 4.

According to the comparison of multidimensional nonlinear prediction models of six types of regional group buildings, MMS and SRCW are relatively light in damage in zones VI and VII, and all prediction models have high goodness of fit. It is worth noting that the peak values of RC and BFM in zone VII are significantly lower than those in zone VI, and the damage of MMS is relatively light, indicating that it has better seismic resilience. The injury to the SBCW and MS is rather serious in the lower intensity zones. In zones VIII and IX, the earthquake damage degree of all structures has obviously increased. The difference between the three prediction models of MMS is small, and the curve is gentle, indicating that many samples have been damaged at the DS3 and DS4 levels. The RC seismic damage is relatively light. The prediction models of VIII and IX show inapparent anomalies, and the curve reaches the peak around DS3, which indicates that the RC structure has excellent seismic toughness, which is in favorable agreement with the author's field investigation. The damage to the SRCW is relatively heavy in zone VIII and further aggravated in zone IX. However, it is worth noting that the damage was alleviated in zone X, demonstrating that this type of structure has a certain resilience ability to resist high-level earthquake action. The DS5 samples of SBCW in zone IX increased meaningfully. Nevertheless, the



**Fig. 6** Comparison of empirical vulnerability prediction models considering typical urban buildings (MMS)

prediction curve did not surge significantly, which is related to the small sample number of this type of structure, and the influence of model overfitting was considered. The damage of MS is relatively small. The mixed structure samples include many brick wood and concrete wood frame buildings. The wood frame systems of these structural groups have positive seismic resilience. In the extreme earthquake zone (X and XI), the bulk of group buildings was damaged at the DS5 and DS4 levels. Alternatively, there are still a certain number of MMS, RC, and BFM samples in DS4 and DS3, which have proficient seismic resilience. Depending on the established database information, most of the group buildings with excellent seismic resistance are newly built or have undergone seismic design, which



**Fig. 7** Comparison of empirical vulnerability prediction models considering typical urban buildings (RC)

indicates that seismic design and construction age factors directly affect the fragility features of structures.

According to the analysis of the vulnerability regression parameters of six types of structures, the goodness of fit of various nonlinear regression models is relatively low in the higher intensity zones, especially in zones VIII and IX. This study determined a relatively moderate regression model and the regression parameters in zone VIII to avoid nonlinear model overfitting and low applicability. In zone IX, the essential factor for the low goodness of fit of models of various structures is the relatively

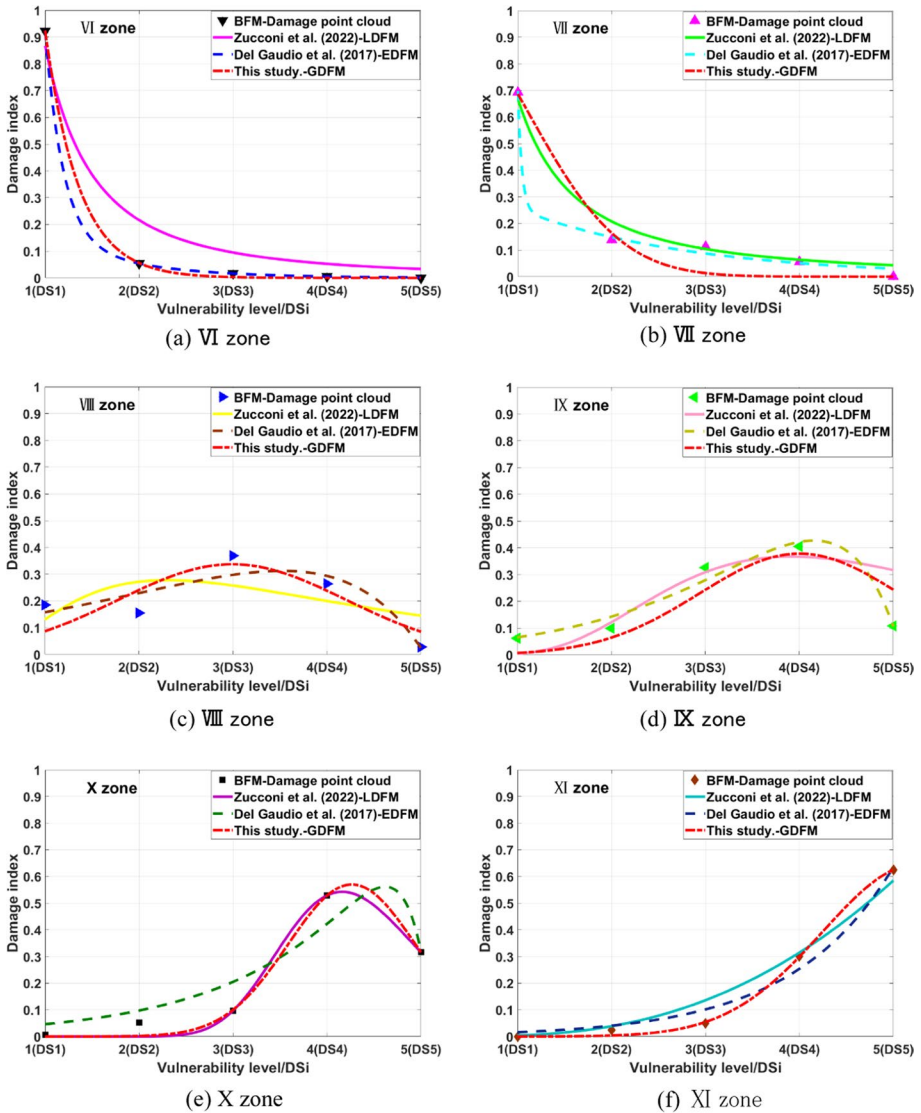


Fig. 8 Comparison of empirical vulnerability prediction models considering typical urban buildings (BFM)

small number of seismic damage sample data that can be used for model regression. In particular, the stock of SBCW in the Dujiangyan area is relatively small, which leads to low model fitting. Optimizing the model should consider increasing the necessary number of samples in similar seismic zones in the future to supplement the established structural vulnerability database and to update, optimize and improve the model’s goodness of fit.

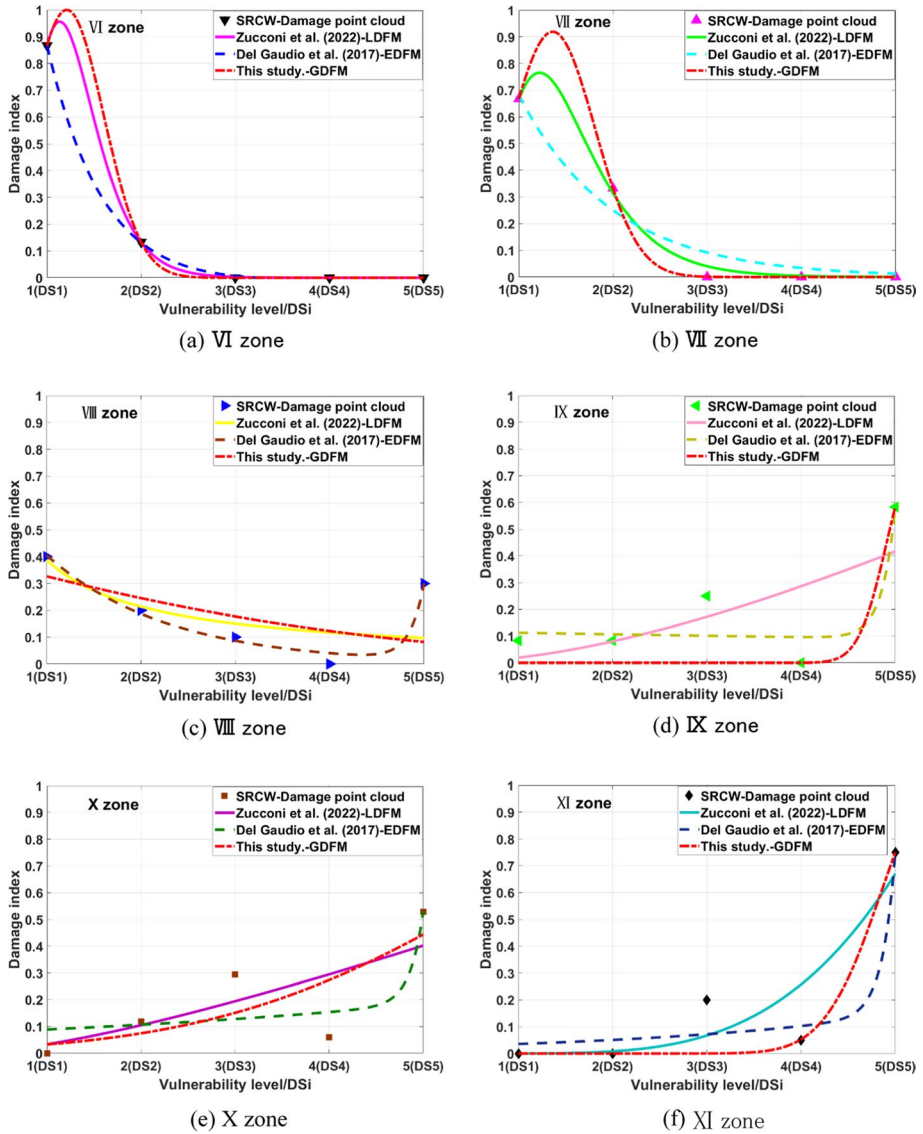
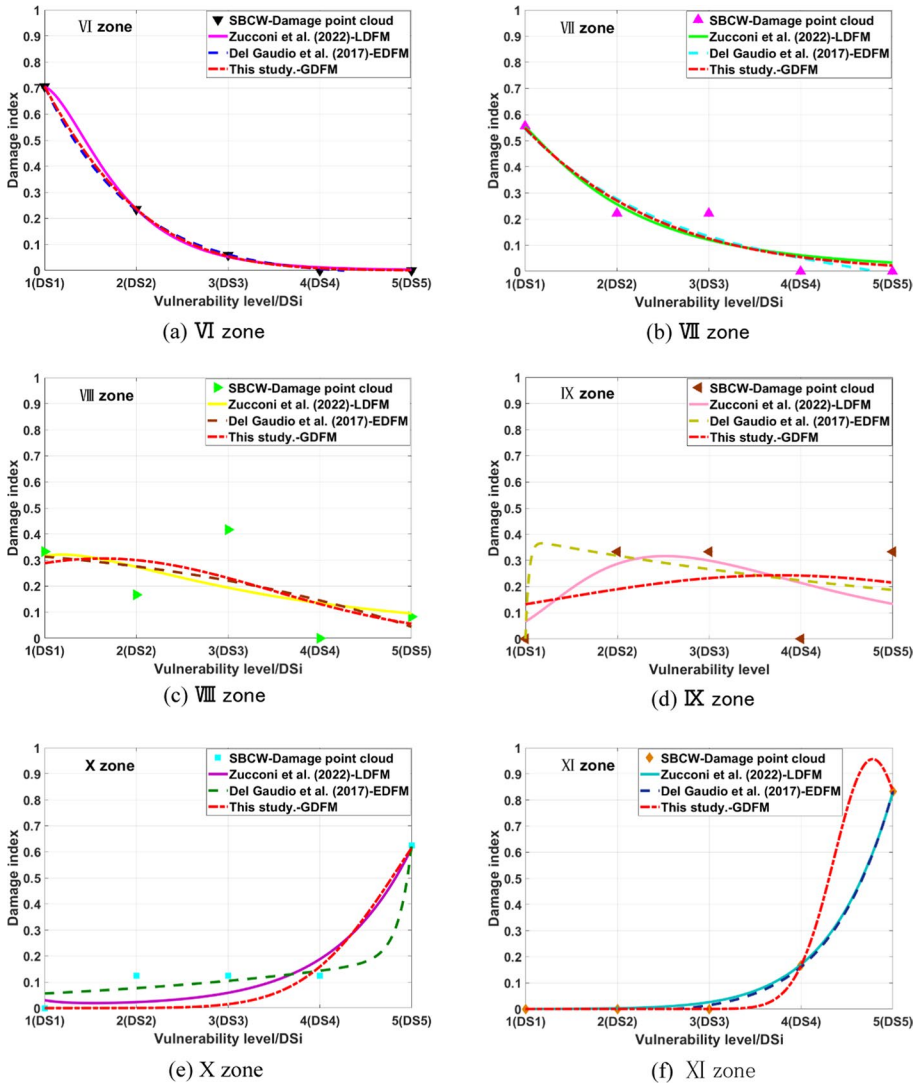


Fig. 9 Comparison of empirical vulnerability prediction models considering typical urban buildings (SRCW)

### 3 Vulnerability assessment model of urban group buildings considering essential influence factors

According to the umbrella observation and sampling of typical urban group buildings by the field reconnaissance team, the seismic vulnerability of structures is not only affected by intensity measures (macroseismic intensity) but also profoundly affected by a variety of pivotal impact factors, such as seismic design, construction age, functional requirements,

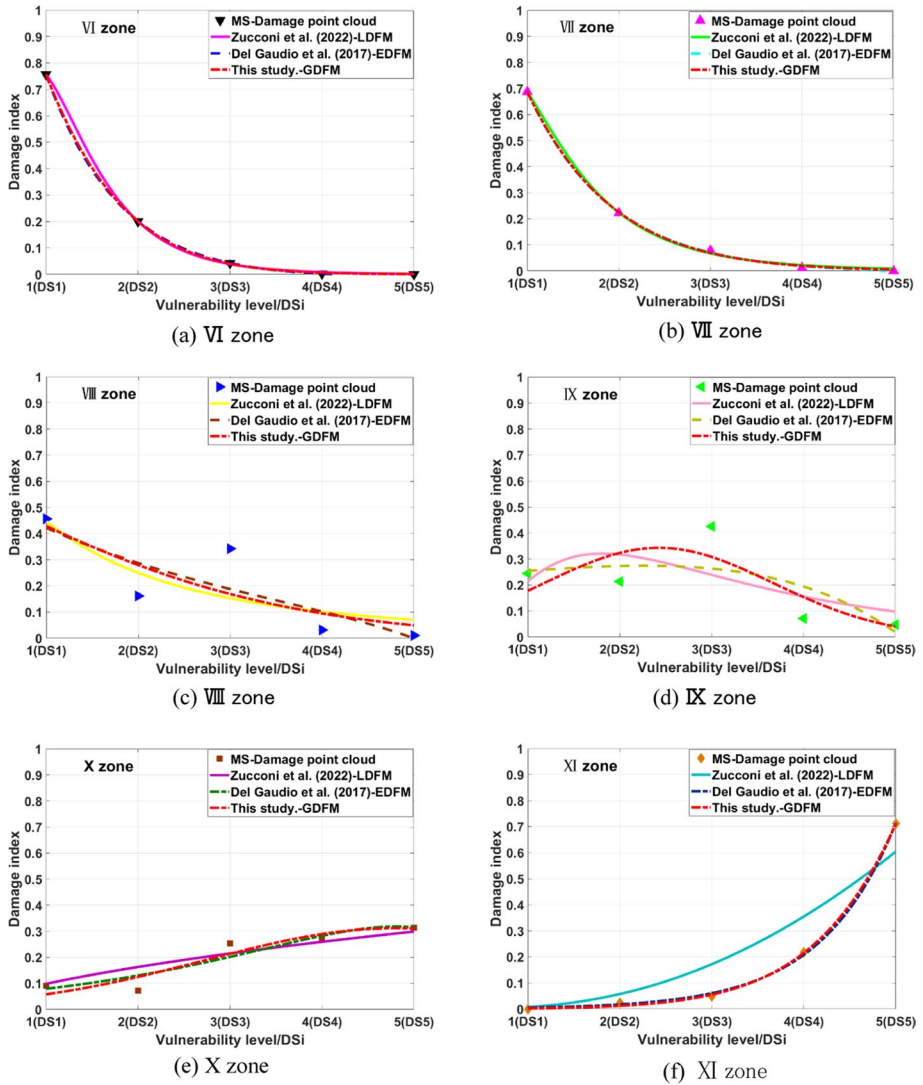




**Fig. 10** Comparison of empirical vulnerability prediction models considering typical urban buildings (SBCW)

number of floors and plane shape. It is worth emphasizing that during the field inspection, it was found that the DS3 and DS4 ratings showed a large dissimilarity in structural damage.

To achieve the actual damage degree of regional buildings more accurately, after the study and judgment of experts from the China earthquake damage field reconnaissance command center, it was decided to subdivide DS3 and DS4 into three grades (DS3d, DS3m, DS3u, DS4d, DS4m, and DS4u) to circumstantially evaluate the vulnerable features of various groups of buildings. The division scale and principle pay more attention to the damage level of structural and nonstructural members. DS3a, DS3m, and DS3u indicate



**Fig. 11** Comparison of empirical vulnerability prediction models considering typical urban buildings (MS)

that the nonstructural members of the building have suffered slight, moderate, and severe damage, respectively, and the structural members have universally suffered slight damage. DS4a, DS4m, and DS4u indicate that the nonstructural members of the building have suffered significant damage, and the structural members have suffered slight, moderate, and severe damage, respectively.

This study creatively expanded the traditional five-level damage quantification standard to nine levels, re-evaluated all the earthquake damage observation data in Dujiangyan city, and updated the old sample database. The comparative damage analysis is conducted for the key influencing factors that affect the vulnerability of group buildings.

**Table 4** Vulnerability regression parameter matrix of typical group buildings

Type	Nonlinear regression model										Goodness of fit				
	Zucconi et al. (2022a; b)					Dei Gaudio et al. (2017)						Goodness of fit			
	LDFM/ $\alpha_n$					EDFM/ $\beta_n$									
$\alpha_1$	$\alpha_2$	$\alpha_3$	Goodness of fit		$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	Goodness of fit		$\theta_1$	$\theta_2$	$\theta_3$	Goodness of fit	
MMS	VI	$1.544 \times 10^4$	-11.92	14.53	0.9939	0.6385	-1.022	$8.871 \times 10^4$	-11.82	0.9996	$2.49 \times 10^{69}$	-137.8	10.98	0.9967	
	VII	1714	-11.57	17.44	0.9901	$8.335 \times 10^{10}$	-25.61	0.324	-0.5919	0.993	$3.401 \times 10^{129}$	-299.7	17.4	0.9901	
	VIII	184.1	28.11	124.8	0.345	$2.575 \times 10^8$	-21.27	0.2347	-0.11	0.4223	0.6929	-6.899	8.768	0.3305	
	IX	3.168	5.472	11.44	0.04434	2636	-0.328	-2636	-0.3281	0.07965	0.2516	2.798	2.873	0.1709	
	X	1.896	1.389	0.069	0.8797	0.01652	0.8374	$-1.334 \times 10^{-16}$	7.29	0.9926	0.4659	3.985	1.086	0.9018	
	XI	$1.247 \times 10^5$	9.25	5.4	0.8715	0.00596	0.9276	184	-10.75	0.9943	1.266	7.13	2.497	0.9972	
	RC	VI	1.092	-0.2489	0.4042	1	-0.7569	-1.87	14.24	-2.604	1	1.035	0.7696	0.7292	1
		VII	0.7694	0.2603	0.4892	0.9991	334.8	-0.6141	-333.1	-0.613	0.9988	1.139	-0.5072	2.069	0.9996
		VIII	0.65	0.9712	1.128	0.4436	-603.3	0.3252	603.6	0.3251	0.6663	0.3222	2.094	2.131	0.5998
		IX	1.217	1.177	0.1909	0.6905	99.63	0.757	-99.55	0.7571	0.9333	0.3758	3.113	1.507	0.869
		X	2.028	1.357	0.0561	0.7701	$1.37 \times 10^4$	-0.2837	$-1.37 \times 10^4$	-0.2837	0.3297	0.5005	3.891	0.9746	0.899
BFM	XI	$7.188 \times 10^5$	10.13	5.777	0.9177	245.4	-9.609	0.008387	0.8446	0.9995	$9.354 \times 10^9$	62.37	11.83	0.9981	
	VI	$5.084 \times 10^4$	-22.22	44.96	0.9407	146.1	-5.244	0.4595	-1.108	1	$2.496 \times 10^{17}$	-28.12	4.597	0.9996	
	VII	2205	-23.94	70.76	0.9763	$1.017 \times 10^{10}$	-23.86	0.4316	-0.5329	0.9946	1	0.1603	1.368	0.9565	
	VIII	0.8061	1.297	0.9236	0.2739	75.25	0.6584	-75.15	0.6587	0.8097	0.3369	2.993	1.711	0.66	
	IX	1.59	1.568	0.4073	0.4856	26.07	1.062	-26.04	1.062	0.954	0.3782	4.002	1.504	0.6833	
	X	2.293	1.457	0.06233	0.9858	$-7.392 \times 10^{-10}$	4.101	0.0219	0.7457	0.861	0.57	4.264	0.9589	0.9868	
	XI	$1.006 \times 10^6$	8.471	3.693	0.9667	0.06253	0.9169	0.0002284	0.913	0.981	0.6463	5.262	1.438	0.9983	
	VI	1.129	0.2075	0.1628	1	-6.438	-1.209	11.04	-1.376	0.9998	0.9996	1.21	0.5663	1	
	VII	1	0.3362	0.2757	0.9944	0.7933	-1.004	1.065	-0.9997	0.9528	0.919	1.36	0.6355	1	
	VIII	356.6	98.46	1421	0.4206	0.8772	-0.7729	$6.709 \times 10^{-16}$	6.734	0.98	0.8	-5.712	7.095	0.2397	
	IX	$5.735 \times 10^5$	9.335	5.839	0.447	$3.297 \times 10^{-16}$	6.988	0.1188	-0.05406	0.8482	0.7328	5.199	0.4161	0.6478	
X	$4.639 \times 10^5$	12.06	8.837	0.5484	$1.179 \times 10^{-16}$	7.122	0.074	0.1826	0.7573	1	8.807	4.223	0.5818		
XI	$1.756 \times 10^4$	4.96	1.311	0.834	0.02521	0.3498	$1.215 \times 10^{-16}$	7.229	0.9432	0.9999	5.456	0.8493	0.9014		

**Table 4** (continued)

Type	Nonlinear regression model															
	Zucconi et al. (2022a; b)					Dei Gaudio et al. (2017)					This study					
	LDFM/ $\alpha_n$					EDFM/ $\beta_n$					GDFM/ $\theta_n$					
	$\alpha_1$	$\alpha_2$	$\alpha_3$	Goodness of fit		$\beta_1$	$\beta_2$	$\beta_3$	$\beta_4$	Goodness of fit		$\theta_1$	$\theta_2$	$\theta_3$	Goodness of fit	
SBCW	0.7614	0.1973	0.5142	0.9994	0.9998	99.98	-0.749	-98.03	-0.7444	0.9997	2.185	-1.48	2.333	0.9997		
VII	0.5806	0.2684	1.471	0.921	-0.001303	-0.001303	0.7245	1.061	-0.6617	0.9346	23.79	-10.17	5.753	0.9267		
VIII	0.5843	1.022	1.696	0.332	-848.1	-848.1	0.1318	848.4	0.1317	0.3872	0.3063	1.632	2.578	0.3947		
IX	0.9113	1.197	0.5448	0.3005	0.4527	0.4527	-0.1768	-7.404 × 10 <sup>11</sup>	-28.3	0.4304	0.2429	3.757	3.54	0.09327		
X	0.02679	0.2254	-0.404	0.9166	0.04119	0.04119	0.3115	1.017 × 10 <sup>-16</sup>	7.196	0.9737	0.88	5.845	1.412	0.8785		
XI	1.184 × 10 <sup>-6</sup>	-1.999	-0.8639	0.9986	-0.01042	-0.01042	0.9931	0.006367	1.18	0.9993	0.9567	4.78	0.5906	1		
MS	0.7742	0.1109	0.5151	0.9999	-0.4801	-0.4801	-0.6808	3.08	-1.126	0.9999	9.102	-3.195	2.66	0.9999		
VII	0.695	0.09786	0.8097	0.9991	-0.001704	-0.001704	0.3417	2.078	-1.104	0.9997	2714	-14.34	5.331	0.9995		
VIII	0.5007	0.5845	2.958	0.656	-0.0009003	-0.0009003	0.9372	0.6132	-0.3692	0.6967	1.173	-4.152	5.135	0.6687		
IX	0.7206	1.027	0.8686	0.3961	-0.3135	-0.3135	0.4116	0.535	0.3061	0.5043	0.3426	2.425	1.757	0.5998		
X	1.439 × 10 <sup>7</sup>	21.4	24.35	0.7912	0.09715	0.09715	0.6606	-0.05066	0.7654	0.8713	0.3115	4.802	2.927	0.8821		
XI	8.991 × 10 <sup>4</sup>	7.81	3.732	0.8678	0.001499	0.001499	1.233	0.0003671	-0.7167	0.9991	26.5	11.52	3.43	0.9994		

### 3.1 Seismic design factor

Depending on the summary of the updated structural earthquake damage database (8621 buildings), the seismic design factor directly impacts the damage of six types of group buildings. Considering the seismic design factor, the umbrella data's vulnerability grade is evaluated using the updated vulnerability level quantitative standard. The empirical vulnerability matrix based on the element is established, as summarized in Table 5. Using the calculation method of probability and statistical modelling, the empirical vulnerability statistical distribution based on the damage index of six typical group structures is generated, as shown in Fig. 12.

According to the vulnerability assessment and statistical distribution of six typical structures, among the samples considering seismic design, the damage to RC structures is relatively light, and many samples are distributed at the DS1 and DS2 levels. The damage of MMS was slightly lighter than that of BFM and MMS, and the deterioration of SRCW and SBCW was similar. The damage of various structures without considering the seismic design is obviously heavier, the damage of SRCW and SBCW is relatively heavier, the damage of MMS is obviously lighter than that of BFM, and the damage of MS and RC is relatively close. It is worth emphasizing that there is no remarkable discrepancy in whether to consider the MS damage of seismic design, which is related to the existence of a myriad of wood frame structures with excellent seismic resilience in MS.

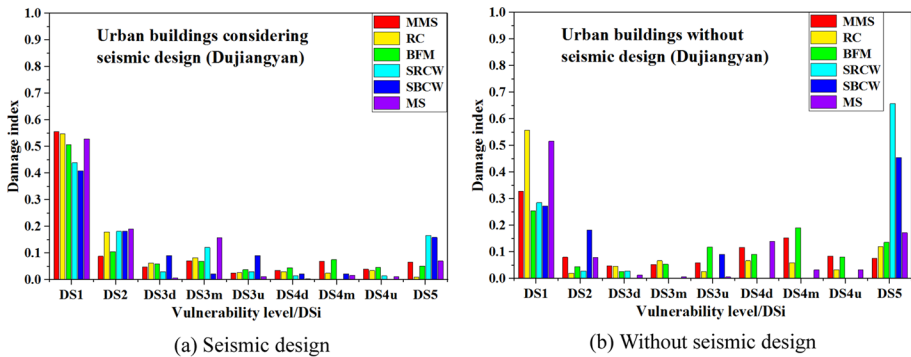
### 3.2 Age factor

Under the attack and influence of earthquakes, buildings built of different ages indicate remarkable damage discrepancies. A great deal of field observation data and studies have verified the impact of age factors on structural vulnerability (Li and Liu 2022c, d; Li 2022). To study the vulnerability and seismic resilience of building groups in typical urban areas under the influence of the construction age factor, this study classifies and counts the sample databases according to different ages (before 1978, 1979–1989, 1990–2001, and after 2002), establishes an empirical vulnerability matrix based on the age influence factor (Table 6), and generates a vulnerability distribution of building vulnerability in urban areas based on this influence factor, as shown in Fig. 13.

According to the empirical vulnerability matrix and statistical damage distribution of six types of structures of different ages, it can be concluded that the seismic capacity of group structures has been significantly improved with the advancement of age. Before 1978, six types of structures suffered relatively heavy damage, and 66.7% of RC were at the DS3d level, indicating that most of the nonstructural members of buildings were damaged. In MMS samples, 17.8% suffered from DS5 level damage, and MS was slightly lighter than BFM. The damage of SRCW is obviously heavier than that of other structures, and 55% of the samples are at the DS5 level. From 1979 to 1989, the damage caused by MS was relatively light, and BFM was slightly heavier than MMS. The seismic damage of the SBCW and RC is relatively significant. The survey data indicate that the seismic design was not considered for some buildings of the two types of structures in this era, which is the main reason for the heavy damage. From 1990 to 2001, the damage of MMS, RC, and MS was relatively light, the damage of SRCW was significantly heavier than that of BFM, and the deterioration of SBCW was similar to that of MMS. After 2002, according to the statistics of the established regional structure vulnerability database, the seismic capacity of various

**Table 5** Empirical vulnerability matrix of urban group buildings considering the seismic design factor (Duijiangyan city (number/damage index))

Structural typologies	Seismic design	Vulnerability level/DSi										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5		
MMS	Y	1990/0.556	317/0.089	175/0.049	254/0.071	88/0.025	126/0.035	246/0.069	142/0.04	239/0.067	3577/1	
	N	172/0.329	42/0.08	25/0.048	28/0.054	31/0.059	61/0.117	80/0.153	44/0.084	40/0.076	523/1	
RC	Y	446/0.547	146/0.179	52/0.064	68/0.083	22/0.027	25/0.031	20/0.025	28/0.034	8/0.01	815/1	
	N	83/0.557	3/0.02	7/0.047	10/0.067	4/0.027	10/0.067	9/0.06	5/0.034	18/0.121	149/1	
BFM	Y	1073/0.506	224/0.106	128/0.06	148/0.07	81/0.038	96/0.045	161/0.076	99/0.047	110/0.052	2120/1	
	N	28/0.255	5/0.045	3/0.027	6/0.055	13/0.118	10/0.091	21/0.191	9/0.082	15/0.136	110/1	
SRCW	Y	29/0.439	12/0.182	2/0.03	8/0.121	2/0.03	1/0.015	0/0	1/0.015	11/0.167	66/1	
	N	10/0.286	1/0.029	1/0.029	0/0	0/0	0/0	0/0	0/0	23/0.657	35/1	
SBCW	Y	18/0.409	8/0.182	4/0.091	1/0.023	4/0.091	1/0.023	1/0.023	0/0	7/0.159	44/1	
	N	3/0.273	2/0.182	0/0	0/0	1/0.091	0/0	0/0	0/0	5/0.455	11/1	
MS	Y	539/0.528	194/0.19	70/0.007	162/0.159	13/0.013	4/0.004	17/0.017	12/0.012	72/0.071	1,020/1	
	N	78/0.517	12/0.079	2/0.013	1/0.007	1/0.007	21/0.139	5/0.033	5/0.033	26/0.172	151/1	



**Fig. 12** Empirical fragility statistical distribution of typical group buildings considering seismic design factor

structures was significantly improved. MS, MMS, BFM, and RC damage is relatively light, and the damage of SBCW is heavier than that of SRCW. It is worth noting that the sample distribution of the SBCW is only at the DS1 and DS5 levels, which leads to the feature of a large dispersion of structural damage. The main reason is that the sample stock of this type of structure is relatively small.

### 3.3 Function factor

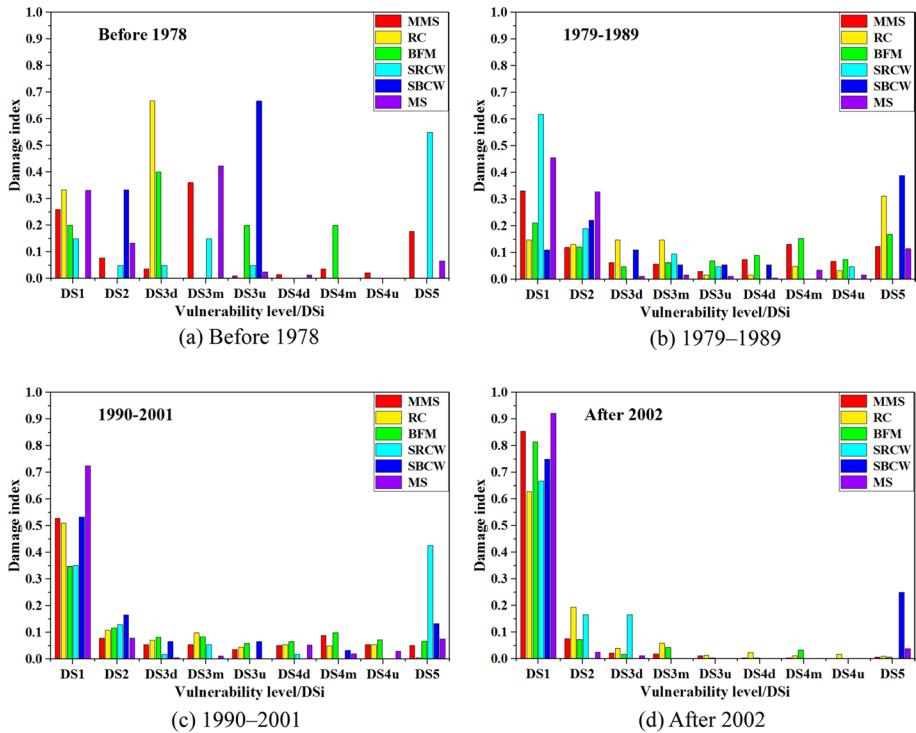
The reconnaissance data indicate that the damage suffered by various types of group buildings with different functions is a discrepancy, directly influencing the fragility and seismic resilience of urban group buildings. To understand the impact of different functional demand factors on the vulnerability of six types of structures, the sample database is classified and counted according to building functions (residential, commercial, residential and commercial, government, school, hospital, and other), and the empirical fragility matrix of urban group buildings based on this factor is established, as summarized in Table 7. Using the calculation method of probability and statistical modelling, a typical structural vulnerability statistical distribution considering the influence of different functional factors is generated, as shown in Fig. 14.

The number of MMS residential buildings and residential and commercial occupancies is relatively large, and the damage to the hospital, commercial, and other functional buildings is relatively light. Depending on the structural vulnerability statistical distribution, the damage to schools is relatively serious, and the earthquake loss of government buildings is slightly heavier than that of residential buildings. The difference between various functional damages to RC structures is inapparent, the damage to residential buildings is light, and the damage to government buildings is relatively heavy. The damage to commercial occupancies and government buildings with BFM structures is relatively light, and the damage to hospitals is slightly heavier than that to schools. The vulnerability distribution of some functional buildings in the SRCW structure has noticeable gradients resulting from the refinement of vulnerability levels. The damage features of such structures with different damage levels can be directly obtained. The residential, commercial, and school buildings using SBCW structures have similar damage peculiarities because the number of building samples used for the above functions is relatively small. The government, hospital, and commercial buildings with MS structures show excellent seismic resistance. Earthquake

**Table 6** Empirical vulnerability matrix of urban group buildings considering age factor (Duijiangyan city (number/damage index))

Structural typologies	Date of construction	Vulnerability level/DSi										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5		
MMS	Before 1978	70/0.26	21/0.078	100/0.37	97/0.361	3/0.011	4/0.015	10/0.037	6/0.022	48/0.178	269/1	
	1979–1989	311/0.332	112/0.12	59/0.063	54/0.058	28/0.03	70/0.075	124/0.132	63/0.067	116/0.124	937/1	
	1990–2001	1117/0.528	167/0.079	114/0.054	116/0.055	79/0.037	110/0.052	189/0.089	116/0.055	109/0.051	2117/1	
	After 2002	664/0.855	59/0.076	17/0.022	15/0.019	9/0.012	3/0.004	3/0.004	1/0.001	6/0.008	777/1	
	Before 1978	1/0.333	0/0	2/0.667	0/0	0/0	0/0	0/0	0/0	0/0	3/1	
RC	1979–1989	9/0.148	8/0.131	9/0.148	9/0.148	1/0.016	1/0.016	3/0.049	2/0.033	19/0.311	61/1	
	1990–2001	202/0.51	43/0.109	28/0.071	39/0.098	18/0.045	22/0.056	20/0.051	22/0.056	2/0.005	396/1	
	After 2002	317/0.629	98/0.194	20/0.04	30/0.06	7/0.014	12/0.024	6/0.012	9/0.018	5/0.01	504/1	
	Before 1978	1/0.2	0/0	2/0.4	0/0	1/0.2	0/0	1/0.2	0/0	0/0	5/1	
	1979–1989	40/0.212	23/0.122	9/0.048	12/0.063	13/0.069	17/0.09	29/0.153	14/0.074	32/0.169	189/1	
SRCW	1990–2001	447/0.348	151/0.118	107/0.083	109/0.085	77/0.06	86/0.067	127/0.099	93/0.072	87/0.068	1284/1	
	After 2002	613/0.815	55/0.073	13/0.017	33/0.044	3/0.004	3/0.004	25/0.033	1/0.001	6/0.008	752/1	
	Before 1978	3/0.15	1/0.05	1/0.05	3/0.15	1/0.05	0/0	0/0	0/0	11/0.55	20/1	
	1979–1989	13/0.619	4/0.19	0/0	2/0.095	1/0.048	0/0	0/0	1/0.048	0/0	21/1	
	1990–2001	19/0.352	7/0.13	1/0.019	3/0.056	0/0	1/0.019	0/0	0/0	23/0.426	54/1	
SBCW	After 2002	4/0.667	1/0.167	1/0.167	0/0	0/0	0/0	0/0	0/0	0/0	6/1	
	Before 1978	0/0	1/0.333	0/0	0/0	2/0.667	0/0	0/0	0/0	0/0	3/1	
	1979–1989	2/0.111	4/0.222	2/0.111	1/0.056	1/0.056	1/0.056	0/0	0/0	7/0.389	18/1	
	1990–2001	16/0.533	5/0.167	2/0.067	0/0	2/0.067	0/0	1/0.033	0/0	4/0.133	30/1	
	After 2002	3/0.75	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0.25	4/1	
MS	Before 1978	119/0.331	48/0.134	1/0.003	152/0.423	9/0.025	5/0.014	1/0.003	0/0	24/0.067	359/1	
	1979–1989	179/0.455	129/0.328	5/0.013	7/0.018	5/0.013	2/0.005	14/0.036	7/0.018	45/0.115	393/1	
	1990–2001	248/0.725	27/0.079	2/0.006	4/0.012	0/0	18/0.053	7/0.02	10/0.029	26/0.076	342/1	
	After 2002	71/0.922	2/0.026	1/0.013	0/0	0/0	0/0	0/0	0/0	3/0.039	77/1	





**Fig. 13** Empirical fragility statistical distribution of typical group buildings considering the age factor

damage to school buildings is relatively serious and should arouse vital concern. All kinds of essential functional buildings should be treated according to the code for seismic design to ensure the quality of building materials and appropriately increase seismic structural measures to improve available structures’ seismic resilience and capacity.

### 3.4 Floor factor

Due to the need for architectural design and function, the number of floors (building height) of urban buildings is diversified. A myriad of field structural earthquake loss inspection data indicate that the number of floors fundamentally impacts the fragility of regional group buildings. To explicitly study the vulnerability differences of various groups of buildings affected by this factor, this paper performs statistics and processing on the vulnerability database of six groups of buildings in Dujiangyan city after the Wenchuan earthquake according to the number of different floors and develops the empirical vulnerability matrix and distribution of typical group structures, as indicated in Table 8 and Fig. 15.

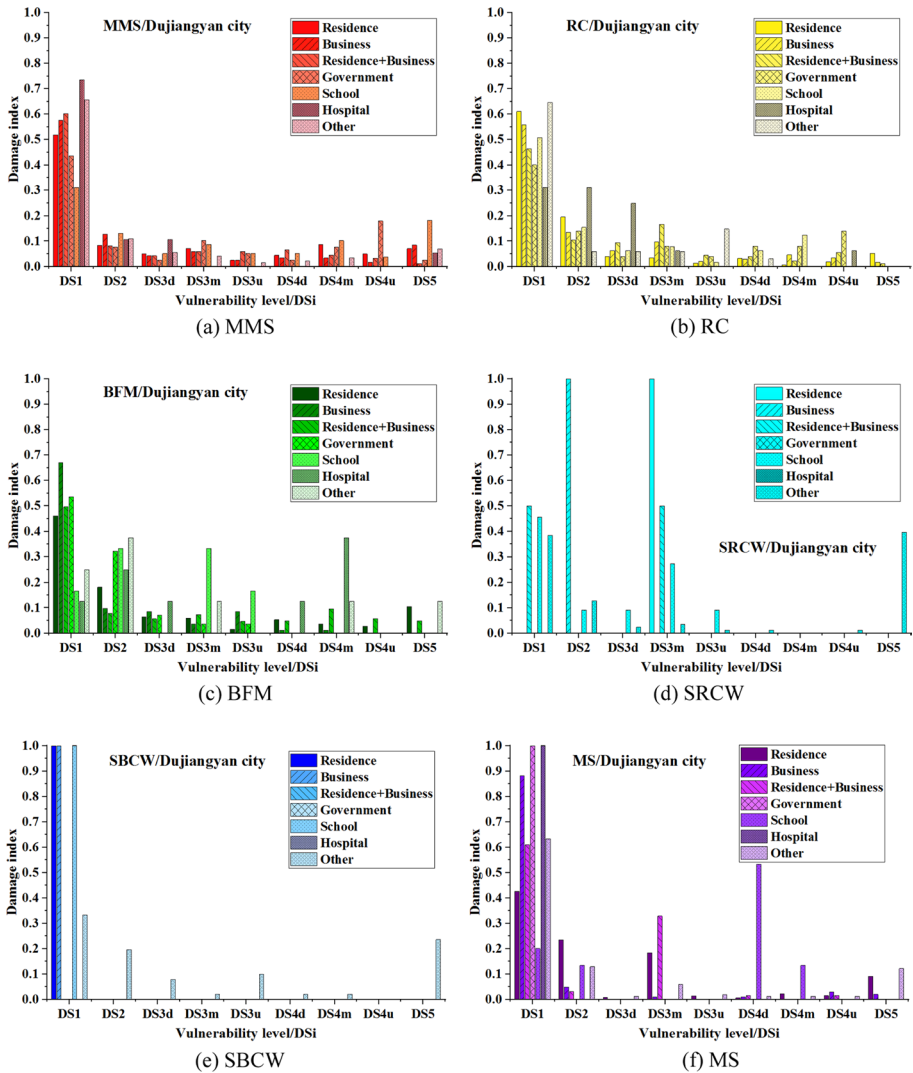
Depending on the damage analysis of six typical group buildings, the 2-story MMS and RC structures show sensible seismic performance with minor damage. The MMS (7-story) and RC structures (1-story and 7-story) are relatively damaged. The damage to the MMS (4-story and 5-story) and RC structures (4-story and 6-story) is similar. It is worth emphasizing that it is necessary to conduct in-depth research on the seismic performance of single-layer RC structures, appropriately increase the compelling

**Table 7** Empirical vulnerability matrix of urban group buildings considering the functional requirement factor (Dujiangyan city (number/damage index))

Structural typologies	Functional requirement	Vulnerability level/DSI										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5	DS5	
MMS	Residence	1668/0.519	2700/0.084	159/0.049	228/0.071	80/0.025	144/0.045	281/0.087	158/0.049	227/0.071	3215/1	
	Business	68/0.576	15/0.127	5/0.042	7/0.059	3/0.025	4/0.034	4/0.034	2/0.017	10/0.085	118/1	
	Residence + business	256/0.602	35/0.082	18/0.042	25/0.059	25/0.059	28/0.066	19/0.045	14/0.033	5/0.012	425/1	
	Government	17/0.436	3/0.077	1/0.026	4/0.103	2/0.051	1/0.026	3/0.077	7/0.179	1/0.026	39/1	
	School	43/0.312	18/0.13	7/0.051	12/0.087	7/0.051	7/0.051	14/0.101	5/0.036	25/0.181	138/1	
	Hospital	14/0.737	2/0.105	2/0.105	0/0	0/0	0/0	0/0	0/0	1/0.053	19/1	
	Other	96/0.658	16/0.11	8/0.055	6/0.041	2/0.014	3/0.021	5/0.034	0/0	10/0.068	146/1	
	Residence	232/0.611	74/0.195	15/0.039	13/0.034	5/0.013	12/0.032	2/0.005	7/0.018	20/0.053	380/1	
	Business	133/0.559	32/0.134	15/0.063	23/0.097	5/0.021	7/0.029	11/0.046	8/0.034	4/0.017	238/1	
RC	Residence + business	84/0.464	19/0.105	17/0.094	30/0.166	8/0.044	7/0.039	4/0.022	10/0.055	2/0.011	181/1	
	Government	20/0.4	7/0.14	2/0.04	4/0.08	2/0.04	4/0.08	4/0.08	7/0.14	0/0	50/1	
	School	33/0.508	10/0.154	4/0.062	5/0.077	1/0.015	4/0.062	8/0.123	0/0	0/0	65/1	
	Hospital	5/0.313	5/0.313	4/0.25	1/0.063	0/0	0/0	0/0	1/0.063	0/0	16/1	
	Other	22/0.647	2/0.059	2/0.059	2/0.059	5/0.147	1/0.029	0/0	0/0	0/0	34/1	
	Residence	181/0.461	71/0.181	25/0.064	23/0.059	6/0.015	21/0.053	14/0.036	11/0.028	41/0.104	393/1	
	Business	55/0.671	8/0.098	7/0.085	3/0.037	7/0.085	1/0.012	1/0.012	0/0	0/0	82/1	
	Residence + business	846/0.496	134/0.079	96/0.056	124/0.073	79/0.046	83/0.049	163/0.096	97/0.057	83/0.049	1705/1	
	Government	15/0.536	9/0.321	2/0.071	1/0.036	1/0.036	0/0	0/0	0/0	0/0	28/1	
SRCW	School	1/0.167	2/0.333	0/0	2/0.333	1/0.167	0/0	0/0	0/0	0/0	6/1	
	Hospital	1/0.125	2/0.25	1/0.125	0/0	0/0	1/0.125	3/0.375	0/0	0/0	8/1	
	Other	2/0.25	3/0.375	0/0	1/0.125	0/0	0/0	1/0.125	0/0	1/0.125	8/1	
	Residence	0/0	0/0	0/0	1/1	0/0	0/0	0/0	0/0	0/0	1/1	
	Business	0/0	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	
	Residence + business	1/0.5	0/0	0/0	1/0.5	0/0	0/0	0/0	0/0	0/0	2/1	
	School	5/0.455	1/0.091	1/0.091	3/0.273	1/0.091	0/0	0/0	0/0	0/0	11/1	

**Table 7** (continued)

Structural typologies	Functional requirement	Vulnerability level/DSi										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5		
SBCW	Other	33/0.384	11/0.128	2/0.023	3/0.035	1/0.012	1/0.012	0/0	1/0.012	34/0.395	86/1	
	Residence	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	
	Business	2/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/1	
	School	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	
MS	Other	17/0.333	10/0.196	4/0.078	1/0.02	5/0.098	1/0.02	1/0.02	0/0	12/0.235	51/1	
	Residence	287/0.426	158/0.234	6/0.009	124/0.184	9/0.013	4/0.006	15/0.022	10/0.015	61/0.091	674/1	
	Business	90/0.882	5/0.049	0/0	1/0.01	0/0	1/0.01	0/0	3/0.029	2/0.02	102/1	
	Residence + business	39/0.609	2/0.031	0/0	21/0.328	0/0	1/0.016	0/0	1/0.016	0/0	64/1	
	Government	4/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	4/1	
	School	6/0.2	4/0.133	0/0	0/0	0/0	16/0.533	4/0.133	0/0	0/0	30/1	
	Hospital	8/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	8/1	
	Other	183/0.633	37/0.128	3/0.01	17/0.059	5/0.017	3/0.01	3/0.01	3/0.01	35/0.121	289	



**Fig. 14** Empirical fragility statistical distribution of typical group buildings considering functional requirement factor

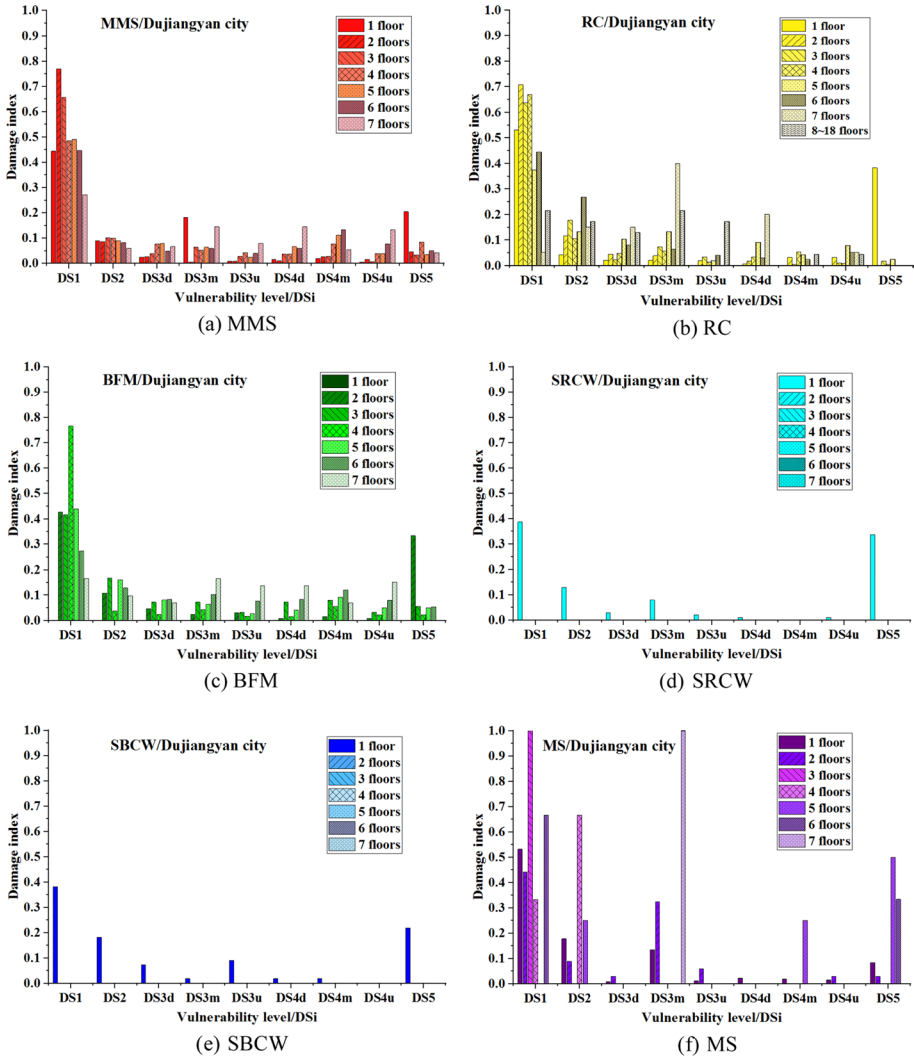
connection between infilled walls and structural systems, and improve lateral stiffness and structural integrity. The damage of BFM (4-story), MS (3-story and 4-story) is relatively light, the damage similarity of BFM (3-story and 5-story), SRCW of a single layer, and BFM (2-story) are relatively high, the damage of BFM (7-story) is rather heavy, and the damage of MS (5-story) is relatively heavy.

**Table 8** Empirical vulnerability matrix of urban group buildings considering the story number factor (Dujiangyan city (number/damage index))

Structural typologies	Story number	Vulnerability level/DSi										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5	DS5	
MMS	1	226/0.445	46/0.091	13/0.026	93/0.183	5/0.01	8/0.016	10/0.02	3/0.006	104/0.205	508/1	
	2	585/0.77	66/0.087	21/0.028	5/0.007	7/0.009	8/0.011	20/0.026	13/0.017	35/0.046	76/0/1	
	3	232/0.657	36/0.102	14/0.04	23/0.065	10/0.028	13/0.037	10/0.028	3/0.008	12/0.034	353/1	
	4	182/0.485	38/0.101	29/0.077	20/0.053	16/0.043	14/0.037	29/0.077	15/0.04	32/0.085	375/1	
	5	268/0.492	49/0.09	43/0.079	35/0.064	13/0.024	36/0.066	61/0.112	21/0.039	19/0.035	545/1	
	6	624/0.448	114/0.082	69/0.049	82/0.059	55/0.039	84/0.06	187/0.134	109/0.078	70/0.05	1394/1	
	7	45/0.273	10/0.061	11/0.067	24/0.145	13/0.079	24/0.145	9/0.055	22/0.133	7/0.042	165/1	
RC	1	25/0.532	2/0.043	1/0.021	1/0.021	0/0	0/0	0/0	0/0	18/0.383	47/1	
	2	109/0.708	18/0.117	7/0.045	6/0.039	3/0.019	1/0.006	5/0.032	5/0.032	0/0	154/1	
	3	111/0.638	31/0.178	4/0.023	13/0.075	6/0.034	3/0.017	1/0.006	2/0.011	3/0.017	174/1	
	4	138/0.67	22/0.107	10/0.049	12/0.058	3/0.015	7/0.034	11/0.053	2/0.01	1/0.005	206/1	
	5	62/0.376	22/0.133	17/0.103	22/0.133	3/0.018	15/0.091	7/0.042	13/0.079	4/0.024	165/1	
	6	78/0.446	47/0.269	14/0.08	11/0.063	7/0.04	5/0.029	4/0.023	9/0.051	0/0	175/1	
	7	1/0.05	3/0.15	3/0.15	8/0.4	0/0	4/0.2	0/0	1/0.05	0/0	20/1	
BFM	8~18	5/0.217	4/0.174	3/0.13	5/0.217	4/0.174	0/0	1/0.043	1/0.043	0/0	23/1	
	2	55/0.426	14/0.109	6/0.047	3/0.023	4/0.031	1/0.008	2/0.016	1/0.008	43/0.333	129/1	
	3	52/0.416	21/0.168	9/0.072	9/0.072	4/0.032	9/0.072	10/0.08	4/0.032	7/0.056	125/1	
	4	600/0.766	29/0.037	19/0.024	33/0.042	13/0.017	12/0.015	43/0.055	17/0.022	17/0.022	783/1	
	5	197/0.44	72/0.161	36/0.08	28/0.063	12/0.027	18/0.04	41/0.092	22/0.049	22/0.049	448/1	
	6	185/0.275	86/0.128	56/0.083	69/0.103	51/0.076	56/0.083	81/0.12	53/0.079	36/0.053	673/1	
	7	12/0.167	7/0.097	5/0.069	12/0.167	10/0.139	10/0.139	5/0.069	11/0.153	0/0	72/1	
SRCW	1	39/0.386	13/0.129	3/0.03	8/0.079	2/0.02	1/0.01	0/0	1/0.01	34/0.337	101/1	
	1	21/0.382	10/0.182	4/0.073	1/0.018	5/0.091	1/0.018	1/0.018	0/0	12/0.218	55/1	
MS	1	598/0.532	200/0.178	8/0.007	151/0.134	12/0.011	25/0.022	21/0.019	16/0.014	94/0.084	1125/1	
	2	15/0.441	3/0.088	1/0.029	11/0.324	2/0.059	0/0	0/0	1/0.029	1/0.029	34/1	

**Table 8** (continued)

Structural typologies	Story number	Vulnerability level/DSi										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5		
	3	1/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1
	4	1/0.333	2/0.667	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3/1
	5	0/0	1/0.25	0/0	0/0	0/0	0/0	1/0.25	0/0	0/0	2/0.5	4/1
	6	2/0.667	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0.333	3/1
	7	0/0	0/0	0/0	1/1	0/0	0/0	0/0	0/0	0/0	0/0	1/1



**Fig. 15** Empirical fragility statistical distribution of typical group buildings considering the story number factor

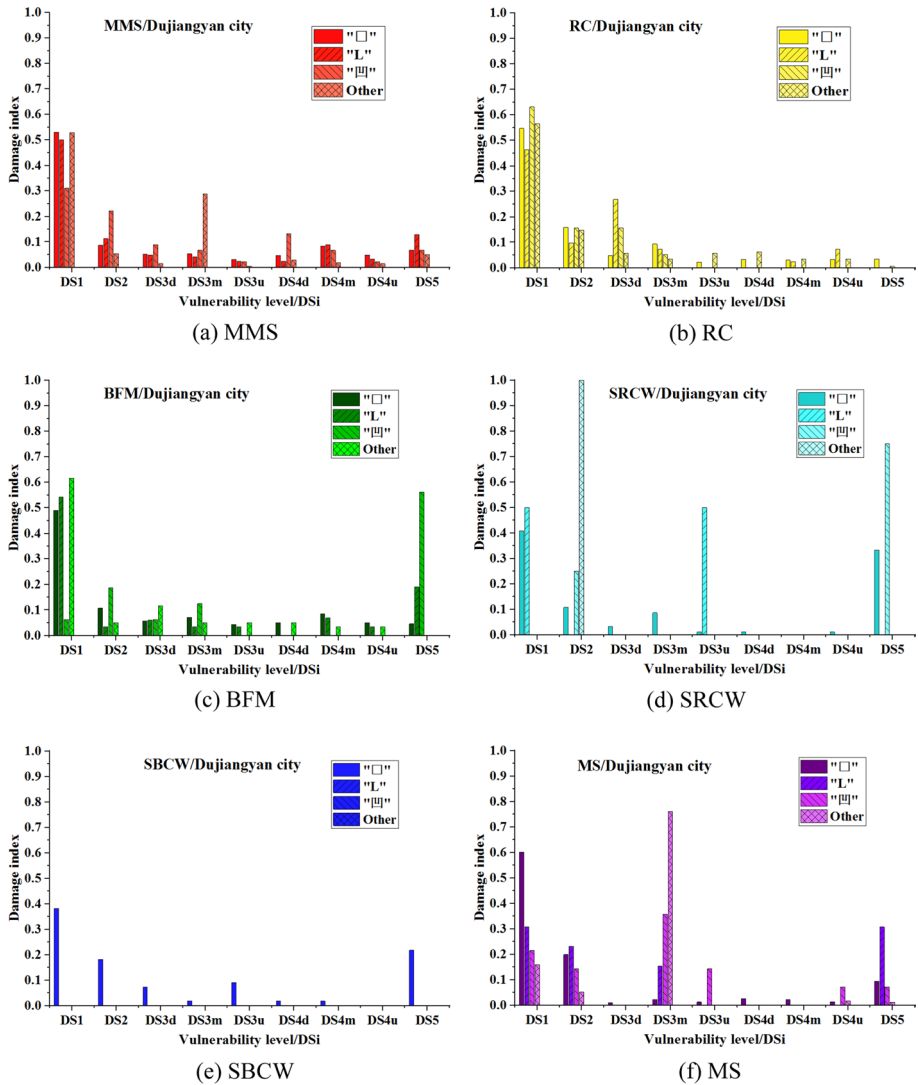
### 3.5 Planar shape factor

According to survey data and actual observations of historical earthquakes in China (Li and Liu 2022b, c, d; Li et al. 2021b; Li 2022), when a destructive earthquake attacks buildings in the same region, the damage caused by the plane shape of different structures has apparent anomalies. To analyse the structural vulnerability of different plane shapes, we conducted comprehensive statistics and processing on the structural damage database of Dujiangyan city in the Wenchuan earthquake according to different plane shapes (“□” type, “L” type, “田” type, and others) and established six types of group structural empirical vulnerability matrices, as summarized in Table 9. Probabilistic and statistical model

**Table 9** Empirical vulnerability matrix of urban group buildings considering the plane shape factor (Dujiangyan city (number/damage index))

Structural typologies	Plane shape	Vulnerability level/DSI										Total
		DS1	DS2	DS3d	DS3m	DS3u	DS4d	DS4m	DS4u	DS5		
MMS	□	1938/0.531	320/0.088	186/0.051	193/0.053	114/0.031	170/0.047	307/0.084	177/0.048	246/0.067	3651/1	
	L	62/0.5	14/0.113	6/0.048	5/0.04	3/0.024	3/0.024	11/0.089	4/0.032	16/0.129	124/1	
	▣	14/0.311	10/0.222	4/0.089	3/0.067	1/0.022	6/0.133	3/0.067	1/0.022	3/0.067	45/1	
	Other	148/0.529	15/0.054	4/0.014	81/0.289	1/0.004	8/0.029	5/0.018	4/0.014	14/0.05	28/0.1	
RC	□	399/0.547	116/0.159	35/0.048	68/0.093	16/0.022	24/0.033	22/0.03	24/0.033	25/0.034	729/1	
	L	19/0.463	4/0.098	11/0.268	3/0.073	0/0	0/0	1/0.024	3/0.073	0/0	41/1	
	▣	12/0.632	3/0.158	3/0.158	1/0.053	0/0	0/0	0/0	0/0	0/0	19/1	
	Other	99/0.566	26/0.149	10/0.057	6/0.034	10/0.057	11/0.063	6/0.034	6/0.034	1/0.006	175/1	
BFM	□	1000/0.491	219/0.107	116/0.057	145/0.071	87/0.043	103/0.051	172/0.084	102/0.05	94/0.046	2038/1	
	L	63/0.543	4/0.034	7/0.06	4/0.034	4/0.034	0/0	8/0.069	4/0.034	22/0.19	116/1	
	▣	1/0.063	3/0.188	1/0.063	2/0.125	0/0	0/0	0/0	0/0	9/0.563	16/1	
	Other	37/0.617	3/0.05	7/0.117	3/0.05	3/0.05	3/0.05	2/0.033	2/0.033	0/0	60/1	
SRCW	□	38/0.409	10/0.108	3/0.032	8/0.086	1/0.011	1/0.011	0/0	1/0.011	31/0.333	93/1	
	L	1/0.5	0/0	0/0	0/0	1/0.5	0/0	0/0	0/0	0/0	2/1	
	▣	0/0	1/0.25	0/0	0/0	0/0	0/0	0/0	0/0	3/0.75	4/1	
	Other	0/0	2/1	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2/1	
SBCW	□	21/0.382	10/0.182	4/0.073	1/0.018	5/0.091	1/0.018	1/0.018	0/0	12/0.218	55/1	
	□	582/0.601	192/0.198	9/0.009	22/0.023	12/0.012	25/0.026	22/0.023	13/0.013	91/0.094	968/1	
MS	L	4/0.308	3/0.231	0/0	2/0.154	0/0	0/0	0/0	0/0	4/0.308	13/1	
	▣	3/0.214	2/0.143	0/0	5/0.357	2/0.143	0/0	0/0	1/0.071	1/0.071	14/1	
	Other	28/0.159	9/0.051	0/0	134/0.761	0/0	0/0	0/0	3/0.017	2/0.011	176/1	





**Fig. 16** Empirical fragility statistical distribution of typical group buildings considering the plane shape factor

theories are comprehensively considered, and the typical structural vulnerability distribution considering the damage index parameter is developed, as shown in Fig. 16.

According to the classification, statistics, and damage analysis results of urban earthquake damage data, the MMS stock of the “□” type is relatively large, the damage is similar to the “L” type structure, and the earthquake slightly damages the MMS of the “凹” type. The damage index value of the “凹” type RC structure at the DS1 level reaches approximately 0.64, which indicates positive seismic resistance. There is no remarkable discrepancy in fragility features between “□”, “L”, and other types of structures. The “凹” BFM structure is relatively damaged, and the “L” structure is slightly more damaged than

the “□” structure. The damage to the “凹” SRCW structure is heavier than that of other types of structures. The samples of “L”, “凹” and other types are small, and the damage is concentrated. The damage of the “□” type MS is relatively light, the structural damage of other types is heavy, and the structural damage of the “凹” type is slightly heavier than that of the “L” type.

#### 4 Vulnerability strip assessment model of a typical urban group structure

The seismic risk and vulnerability analysis of urban buildings are vital factors in measuring the seismic resilience of regional structures. Hence, a large number of researchers in the field of seismic engineering have conducted multidimensional quantitative analysis. An assessment model for assessing the vulnerability of regional groups of buildings was proposed by Chieffo et al. (2022), as expressed in Eqs. 4–5. The evaluation model has been applied to the structural seismic risk analysis of typical regions in Italy, and the actual earthquake damage data have verified the rationality of the model.

$$V_I = \sum_{i=1}^{15} M_i P_i \tag{4}$$

$$SF_I = \left[ \frac{V_I - \left( \sum_{i=1}^{15} M_i \cdot P_{\min} \right)}{\left\| \sum_{i=1}^{15} \left[ \left( M_i \cdot P_{\max} \right) - \left( \sum_{i=1}^{15} M_i \cdot P_i \right) \right] \right\|} \right] \tag{5}$$

where  $V_I$  is the vulnerability index.  $M_i$  and  $P_i$  represent the type score and weight of the  $i$ th factor affecting the vulnerability of a typical regional structure.  $SF_I$  is the standardized vulnerability index of the typical regional structure.  $P_{\min}$  and  $P_{\max}$  denote the minimum and maximum scores of each influencing factor.

Taking ground motion parameters (PGA and PGV) as intensity measures, a traditional vulnerability index quantification model has been developed. Combined with a large number of ground motion feature parameters and macrointensity relationship equations (GB/T 17742 2020), a regional structure vulnerability quantification model based on macroseismic intensity has been established, as expressed in Eq. 6. This model can virtually achieve the damage evolution and dynamic catastrophe evaluation of regional group buildings under different macroseismic intensities and has been broadly used (Lagomarsino and Giovinazzin 2006).

$$\mu_D = 2.5 \cdot \left[ 1 + \tanh \left( \frac{MSM + 6.25SF_I - 13.1}{\lambda} \right) \right] \tag{6}$$

where  $\mu_D$  is the intensive vulnerability index and  $MSM$  is the macroseismic intensity measure.  $\lambda$  is the toughness factor.

Gong et al. (2015), Sun et al. (Li 2023), Li et al. (2021a, 2022a; b), Li and Liu (2022d) and Li (2022) proposed a quantitative model of regional structural vulnerability based on structural damage grade by using the risk matrix probability model analysis

method, as expressed in Eq. 7. They analysed the rationality of the model by using historical earthquake loss inspection data in China.

$$V_{ij} = \sum_{j=1}^5 U_j \cdot P(DS_p|I) \tag{7}$$

$V_{ij}$  is the structural vulnerability parameter of the  $j$ th macrointensity zone under the  $i$ th vulnerability level.  $U_j$  represents the average damage index under the influence of intensity  $j$  (value from 0 to 1).  $P(DS_p|I)$  denotes the conditional probability of the regional structure suffering from damage to the  $DS_p$  level under the influence of seismic intensity  $I$  ( $p \in [1, 5]$ ).

The above research aimed to assess the vulnerability of regional structures and used the vulnerability index to virtually and accurately achieve the vulnerability features of group structures, which made meaningful contributions to the field of urban seismic risk. However, with the update of the macrointensity standard and the revision of the fragility index to quantify different structural categories, there are specific differences in the vulnerability assessment results of regional group buildings. This study fully considered the updated version of China’s macrointensity scale (CMIS-2020), combined with the macrointensity and the number of structural empirical surveys, and proposed a vulnerability update index model (VUI) to evaluate the vulnerability of various groups of buildings in the seismic region, as expressed in Eq. 8.

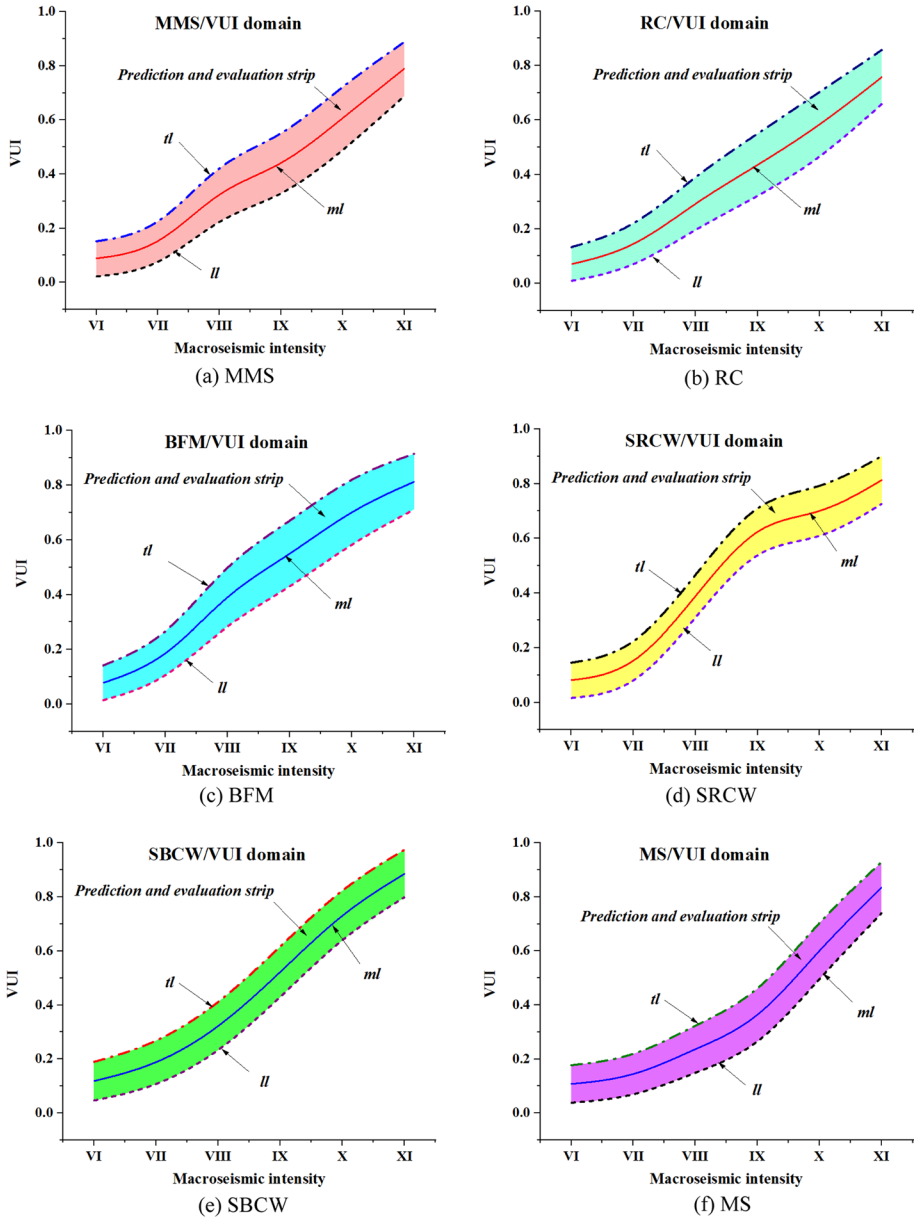
$$VUI = \sum_{i=1}^5 DI_i \cdot \frac{N_{i,regional\ buildings}}{N_{Total,regional\ buildings}} \tag{8}$$

$VUI$  is the vulnerability update index of regional group structures, and  $DI_i$  denotes the damage quantification coefficient of the  $i$ th vulnerability level ( $i \in \{1, 2, 3, 4, 5\}$ ).  $N_{i,regional\ buildings}$  and  $N_{Total,regional\ buildings}$  are the damage quantity and total quantity of regional group buildings at vulnerability level  $i$ , respectively.

This study compares and analyses China’s macroseismic intensity standards (GB/T 17742 2008, 1999, 1980) in different periods, updates the limits of structural damage index parameters in the author’s previous work (Li and Chen 2020; Li et al. 2021a), comprehensively combines the latest version of China’s macroseismic intensity scale quantification criteria (GB/T 17742 2020), and develops the damage quantification coefficient matrix ( $DI_i$ ) used to evaluate the buildings of six typical groups in the seismic region, as summarized in Table 10 ( $tl$ ,  $ml$ , and  $ll$  are the upper limit, mean limit and lower limit, respectively). Based on the empirical vulnerability matrix (Table 3) of the Dujiangyan regional group buildings and the VUI model, strip and curve models that can be used to evaluate the vulnerability of typical group structures are developed, as shown in Fig. 17.

**Table 10** Seismic damage coefficient matrix (GB/T 17742 2020)

Limit value	Damage quantification coefficient				
	DS1	DS	DS3	DS4	DS5
<i>tl</i>	0.12	0.31	0.54	0.85	1
<i>ml</i>	0.06	0.215	0.425	0.695	0.925
<i>ll</i>	0	0.12	0.31	0.54	0.85



**Fig. 17** Empirical fragility assessment strip model of urban group buildings

According to the strip analysis model of a typical group structure, the vulnerability features of various types of structures can be predicted visually and quickly. The established domain model for vulnerability prediction and assessment of six typical regional structures is in favorable agreement with the field observations. The developed empirical vulnerability zone prediction and assessment model of a typical group structure breaks through

the traditional vulnerability curve and matrix analysis mode. Using the proposed regional assessment model, it develops an innovative model that can evaluate the fuzzy damage quantification of buildings in urban areas.

Comparatively, Lagomarsino and Giovinazzi (2006) considered the macroseismic intensity, vulnerability, and ductility index and proposed a calculation model of the mean damage index (Eq. 6) with values ranging from 0 to 5, which has been widely used. Chieffo et al. (2022) and Formisano and Chieffo (2022) creatively proposed a vulnerability index calculation model (Eq. 4) that considers multiple influencing factors. This method provides an effective calculation measure for seismic vulnerability assessment of regional group structures. This paper proposes a VUI model with a value from 0 to 1, which fully combines the quantitative scale of China's macrointensity, the actual field survey data of structures, and the vulnerability level of buildings, and develops a model that can be used to assess the vulnerability of regional group structures from another dimension. The VUI model is utilized to develop the vulnerability strip and curve model of six types of structures based on the typical earthquake zone (Dujiangyan City).

## 5 Conclusion

This study takes the actual earthquake damage of group buildings in Dujiangyan city of the Wenchuan earthquake in China as the research background, innovatively develops a quantitative model to evaluate and predict the vulnerability of typical urban group buildings, and establishes the empirical fragility evaluation and regression comparison model of typical group buildings in different macrointensity zones. The traditional vulnerability level is expanded and refined, and establishing the vulnerability innovation model of regional group buildings is based on multidimensional influencing factors. Ultimately, a new strip model that can evaluate and predict the vulnerability of regional group buildings is proposed and verified by the established sample data. The following essential conclusions are obtained:

1. The regional earthquake damage observation samples (8621 buildings) of Dujiangyan city after the Wenchuan earthquake are comprehensively counted. Using the matrix, point cloud, curved surface, and plane models and theoretical analysis methods, multidimensional statistical models of multistory masonry structures (MMSs), reinforced concrete structures (RCs), bottom frame seismic wall masonry structures (BFMs), single-story reinforced concrete workshops (SRCWs), single-story brick column workshops (SBCWs) and mixed structures (MSs) are established. This set of models can accurately show the fragility features of typical urban group buildings.
2. Taking the macroseismic intensity as the intensity measure, the empirical vulnerability matrix, curved surface, and plane model of six types of group buildings are developed. We selected 8621 buildings (MMS: 4100; RC: 964; BFM: 2230; SRCW: 101; SBCW: 55; MS: 1171) with six types of structures in Dujiangyan city for regression model analysis. A nonlinear regression model (Eq. 3) is proposed to predict and evaluate the fragility of group buildings, and the vulnerability comparison curve and parameter matrix of multidimensional damage modes are derived. Table 4 indicates that various structures' goodness of fit ( $R^2$ ) is relatively reasonable. It is recommended to be used to assess and predict the vulnerability of similar regional buildings. It is worth emphasizing that the regression model of some structures in zone VIII is overfitted. To ensure the

applicability and generalization of the model, we determined a moderate goodness of fit. Additionally, the number of samples in zone IX is insufficient, which leads to a low fitting degree. The model's goodness of fit can be improved in the future by adding the number of structural samples in the same or similar seismic zones.

3. The vulnerability level is refined and expanded to nine levels. The effects of seismic design, age, functional requirements, number of floors, and plane shape factors on structural vulnerability are considered. Using the theory of transcendence and the conditional probability calculation model, the vulnerability comparison curves of six types of group buildings are developed. The established multidimensional parameter quantitative vulnerability model can provide a reference for the seismic design of regional buildings.
4. A strip model is proposed to evaluate the vulnerability of group buildings in urban areas, and the Dujiangyan damage database verifies the rationality of the model. This model can obtain the fragility features of various groups of buildings in typical earthquake areas more instantaneously. Compared with the commonly used vulnerability index calculation model, the proposed vulnerability update index model fully considers the impact of the actual structural seismic damage survey data, the latest version of China's macroseismic intensity scale and the structural vulnerability level and develops a novel method to assess the vulnerability of regional buildings from another dimension.

The vulnerability database, nonlinear evaluation model, damage model influenced by multidimensional factors, and vulnerability strip domain of typical urban regional group buildings established in this study can provide a valuable reference and contribute to the research of seismic resilience and empirical vulnerability of urban structures.

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## Declarations

**Conflict of interest** The authors declare no conflict of interest, ethics, or otherwise. Confirm informed consent.

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