



TOWARD A VULNERABILITY MODEL FOR SICHUAN, CHINA: RC INDEX BUILDINGS DEFINITION AND CAPACITY CURVES

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Abstract

Although probabilistic seismic risk assessment is now consolidated enough to escape academic boundaries and become widely used in several practical applications, China has fallen behind the state-of-art in developing tools for its practical implementation, particularly from the perspective of seismic vulnerability assessment. Research in other countries, for instance in the US and in Southern European countries, can be adopted as a reference to advance models and tools for assessing seismic vulnerability in China. Specifically, using the Global Earthquake Model (GEM) Analytical Vulnerability framework, this study describes the first steps in deriving a robust procedure for obtaining fragility and vulnerability functions for structures in China. The first part of this paper looks at developing an inventory of typical building types in the Sichuan Province by deriving data from the latest 2010 Chinese Census. This allows the definition of a set of 21 index buildings to be used in the fragility assessment of low-rise and mid-rise reinforced concrete (RC) structures. The index buildings of 2-storey, 5-storey and 8-storey are designed following the detailing characteristics representative of the Sichuan construction practice. Different versions of Chinese seismic design codes e.g., GBJ11-1989, GB50011-2001, GB50011-2010 are considered in the definition of the archetype buildings. Nonlinear static analysis is performed on detailed 3D models of the buildings to generate capacity curves. These curves constitute the first step in the ongoing development of a generic framework for constructing a state-of-the-art vulnerability model for China, properly accounting for structural and ground motion uncertainties.

Keywords: Exposure, Vulnerability, Chinese building stock, RC structures



1. Introduction

At least one damaging earthquake occurs every year in China, albeit in disparate areas of the country. In fact, China has endured some of the world's most disastrous earthquake, including the deadliest event in world history, which occurred in 1557 when an M 8.0 (est.) earthquake struck the Shaanxi Province. It is estimated that the quake killed more than 800,000 people. The deadliest earthquake in the 20th century also occurred in China in 1976, when the M 7.8 Tangshan earthquake is estimated to have caused more than 200,000 deaths. Recently, the M 7.9 Wenchuan earthquake (2008), the M 7.1 Yushu earthquake (2010), the M 7.0 Lushan earthquake (2013), and the M 6.5 Ludian earthquake (2014) have caused extensive damage and loss of life and property.

The country's earthquake hazard is widespread as well as severe. Damaging earthquakes have occurred within a very large area that stretches over nine million square kilometers, from the Himalayan mountain range in the west to the eastern part of the country. Historical records dating as far back as 2300 BC indicate that massive earthquakes with magnitudes on the order of 8.0-9.0 occurred in several areas throughout the country. This severe hazard is due to the unique tectonic environment: China is situated along the India-Eurasia plate boundary, which is the largest seismic zone in the world and it is responsible for most, if not all, of the crustal deformation in China. On the other side, China's very rapid urbanization and accompanying building boom have led to rapidly growing concentration of residential and commercial exposure. Due to lack of strict building codes and code enforcement before 1978, even moderate earthquakes have caused heavy losses in China, particularly to residential buildings. Similarly, the potential economic loss due to future events is still very high. Recent major construction projects have increased awareness of earthquake risk; however, much of the research related to earthquake risk assessment in China to date has focused on quantifying the possible risk to individual buildings. Hence, it is crucial to develop a robust earthquake loss prediction model for China, where the information can be used by many stakeholders, such as policy makers, insurers, and real-estate developers, need to make risk informed decisions for a region or portfolio of geographically-distributed buildings.

In this paper, in order to fill this gap, the Global Earthquake Model (GEM) Analytical Vulnerability framework [1] is applied to the Sichuan Province to develop a detailed vulnerability model. The Sichuan Province is selected as case-study due to of its geologic and geographic conditions, with the Longmenshan Fault crossing the whole province and making that area highly exposed to earthquake events. Building exposure in this area is investigated and a number of reinforced concrete (RC) index buildings are selected. All index buildings are designed according to Chinese seismic design codes and follow the detailed local construction practice. The behavior of the structures under seismic excitation is assessed using non-linear static analysis. Capacity curves for the different index buildings are presented as a first step toward a state-of-the-art vulnerability model for China. The final sections of this paper discuss the results and offer some conclusions, highlighting the next steps in the study.

2. Building Exposure in the Sichuan Province

China is the world's most populous country and the fourth largest by area. Mainland China consists of 22 provinces, 5 autonomous regions, and 4 municipalities. Fig. 1 shows the Seismic ground motion parameters zonation map of China. Large earthquakes generally occur in the central and western parts of the country, where population is lower. However, there have been very damaging events in heavily populated areas around the country.

Sichuan is the fourth populous provinces in China with a population of more than 80 billion in 2010 [2]. It's also one of the most seismically active regions with a history of devastating earthquake events, e.g., the 2008 M 7.9 Wenchuan earthquake and 2013 M 6.6¹ Lushan earthquake. In particular, the 2008 Wenchuan earthquake (also known as the 2008 Sichuan earthquake or the Great Sichuan earthquake) is currently recorded as the 21st deadliest earthquake in history: almost 70,000 people died and over 18,000 people were reported missing [3]. Apart from the large amount of casualty, the building damage was severe, including critical infrastructure. For

¹ United States Geological Survey (USGS)



example, more than 7,000 schools were damaged and about 11,000 medical buildings (including hospital and healthcare facilities) were affected [4]. Many rural and urban residential buildings were severely damaged or collapsed.

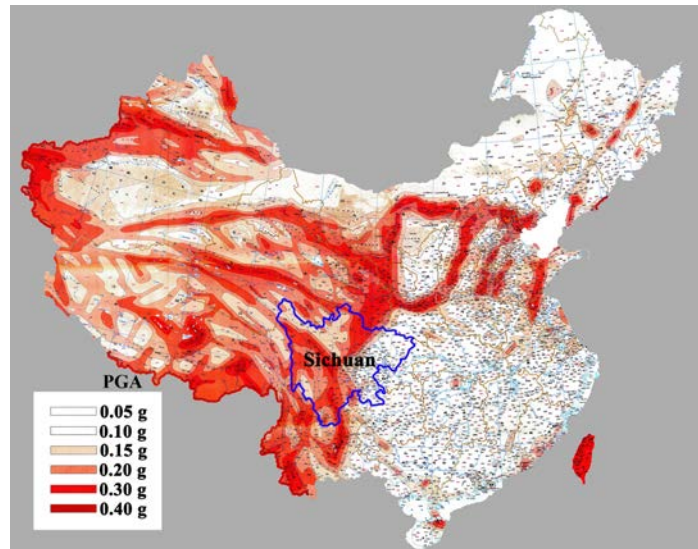


Fig. 1 Seismic ground motion parameters zonation map of China from GB18306-2015 [5]

In this study, the 6th National Population Census of the People's Republic of China (also referred to as the 2010 Chinese Census [2]) conducted by the National Bureau of Statistics of the People's Republic of China is used as a main reference to provide an overall view of the general building stock inventory in the Sichuan Province. The national population census is conducted every ten years. Building data from the census are collected based on the unit of family household in three main administrative divisions for different provinces: prefecture, county, and township. Among these, the prefectural level areas mainly stand for cities, consisting of sub-provincial-level cities, prefectural-level cities and prefectures; the county level areas contain district, county-level city and county; the township level areas can represent the rural areas including sub-district, township and village.

The information in the 2010 Chinese Census presents the total family household numbers divided by construction type, number of storeys and construction period separately. It is important to point out that the census forms were filled out by residents who were not professionally trained in collecting the building information. As a result, data uncertainties are supposed to be unavoidable, especially for recording the exact construction period and types of bearing systems which can affect the accuracy of the result for total loss estimation [6].

Construction types

The 2010 Chinese Census classifies the Chinese building types into 4 main categories, namely 'Reinforced Concrete and Steel Structure', 'Composite Structure', 'Masonry and Timber Structure' and 'Other Structure'. Among these, the 'Reinforced Concrete and Steel Structure' category includes RC buildings, steel buildings and composite steel-concrete buildings. The 'Composite Structure' category refers to buildings with a combination of bearing elements made by RC, masonry or timber; for instance, structures consisting of RC beams and brick bearing walls or of timber beams and RC columns, etc. The 'Masonry and Timber Structure' category includes masonry and timber buildings. The 'Other Structure' category includes all the construction types not include in the previous categories.

Fig. 2 summarizes the distribution of construction types in the Sichuan Province according to the 2010 Chinese Census. Based on the data extracted from the Census, 'Composite Structure' is the most common construction type in the Sichuan Province, followed by 'Masonry and Timber Structure' and 'Reinforced Concrete and Steel Structure'. Indeed, in China, the dominant construction types have historically been unreinforced masonry made from adobe or brick, or brick with light wood frame. However, when it comes to different administrative divisions, i.e. prefecture, county, and township, the distribution of construction types exhibits some different



trends (Fig. 2, right panel). For example, the proportion of 'RC and Steel Structure' at the prefecture level is almost 7 times bigger than that of 'Masonry and Timber Structures'. At township level, 'Masonry and Timber Structure' takes up the largest percentage with 'RC and Steel Structure' being the least common construction type. In general, with the increase of the urbanization extent, construction types gradually change to more engineered typologies (e.g., 'Reinforced Concrete and Steel Structure' or confined masonry).

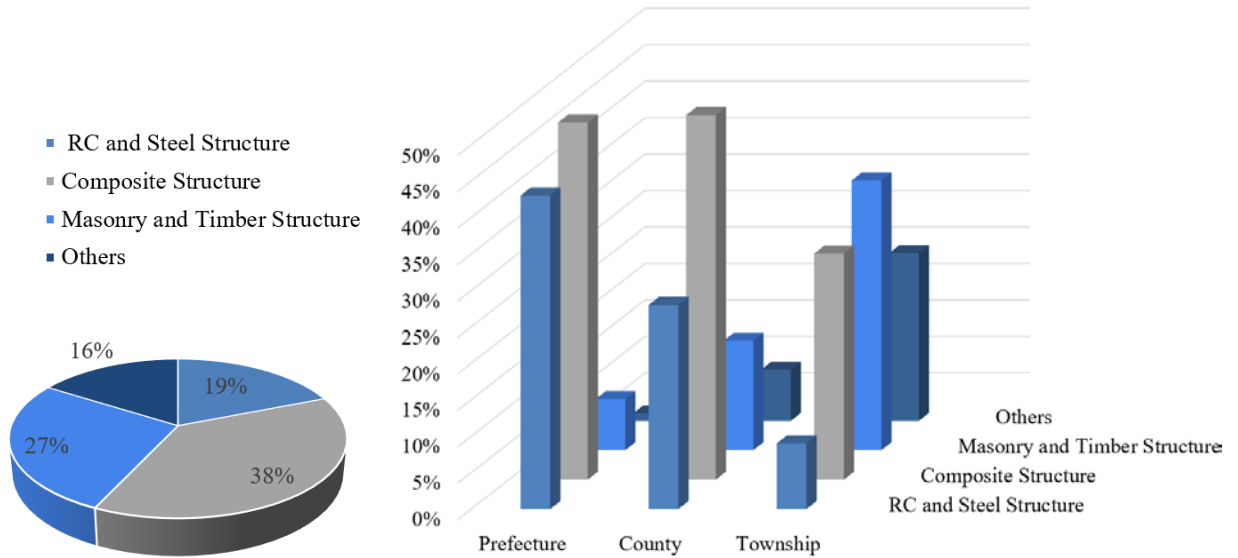


Fig.2 - Distribution of construction types in the Sichuan Province (left), and distributions of construction type by main administrative divisions (right) according to the 2010 Chinese Census.

Number of storeys

The 2010 Chinese Census also includes information on the number of storeys in the buildings. The number of storeys is counted excluding basement and roof. Five categories are considered, namely is '1', '2-3', '4-6', '7-9' and 'over 10'. This information, which is a proxy for the building height, is particularly important in assessing the seismic vulnerability of a building.

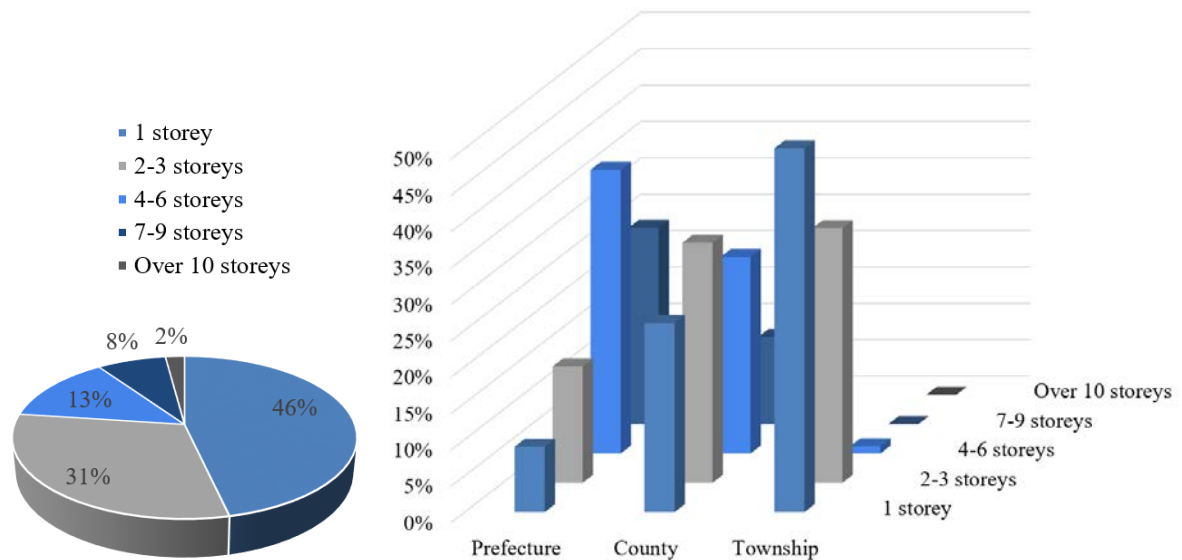


Fig.3 - Distribution of the number of storeys in the Sichuan Province (left), and distributions of the number of storeys by main administrative divisions (right) according to the 2010 Chinese Census.



Fig. 3 summarizes the distribution of the number of storeys in the Sichuan Province according to the 2010 Chinese Census. Based on the data extracted from the Census, almost half (i.e., 46%) of the total number of buildings has a single-story and about one third (i.e., 31%) of the building have '2-3' storeys. Buildings with 'over 10' storeys take just 2% of the total amount. Similar to the distribution of construction types, Fig. 3 (right panel) shows that the distribution of the number of storeys for different administrative divisions exhibits a different trend compared to the statistics for the whole province. For example, the total number of buildings with '4-6' and '7-9' storeys (i.e., mid-rise buildings) largely represents the majority of the buildings at the prefecture level (single-story and 'over 10' storeys building take similar, lower, percentages). On the other side, when looking at the county and township levels, buildings with '2-3' storeys and single-story buildings represent the majority of the building at county and township level respectively. In particular, 'low-rise' buildings (up to 3 storeys) take up 99% of the total number of building in rural areas.

Construction period

Finally, the 2010 Chinese Census includes information on the construction period of the buildings. In fact, the buildings are further classified into seven different groups, each corresponding to a decade, ranging from 1949 to 2000. The construction period (and thus the age of a building) is typically used as a proxy for changes in the building codes and the evolution of construction techniques. New building in China are incorporating advanced earthquake-resistant features in their design and are also subjected to better construction practices and more stringent code enforcement.

Fig. 4 summarizes the distribution of the construction periods in the Sichuan Province according to the 2010 Chinese Census, clearly reflecting China's very rapid urbanization and accompanying building boom in the last 40 years. Also, unlike the previous distributions (for construction types and number of storeys), there are no apparent differences among different administrative areas: different administrative divisions share the same trend with a growing number of buildings built in recent years. However, slightly differences still exist: a non-negligible number of buildings were built before 1989 at township level. During that period, seismic design codes were quite simplified and were not widely used in the construction practice, particularly in rural areas. In those areas, many buildings have been constructed by the households themselves, without conforming to specific building codes.

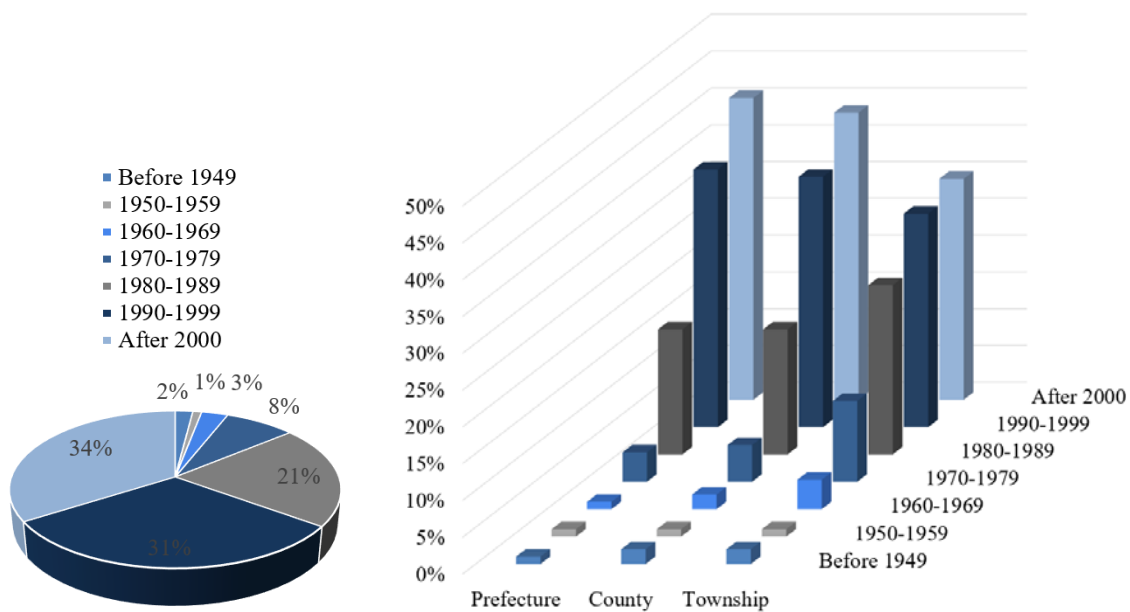


Fig.4 - Distribution of construction periods in the Sichuan Province (left), and distributions of construction periods by main administrative divisions (right) according to the 2010 Chinese Census.



3. Definition of RC index buildings

As discussed in the previous section, the majority of residential buildings in China, and particularly in the Sichuan Province, are masonry structures, with unreinforced masonry and other traditional materials still found in older buildings and rural areas. Looking at the damage extent based on the statistics derived from past seismic events, masonry structures are highly vulnerable to ground shaking, even to low-intensity tremors, constituting the largest portion of severely damaged or collapsed buildings in recent earthquakes [3]. On the other side, most urban dwellers live in mid-rise or high-rise apartment buildings, many of which have commercial establishments on the ground floor. These mid-to-high-rise building are often RC structures (particularly those built in recent years of China's rapid economic growth and urbanization) and tend to be better engineered to withstand ground shaking. Mid- and high-rise RC buildings have a paramount role in the urban framework, so damages to this kind of structures can have a large impact on communities, but also can lead to significant economic losses. RC is also very common in commercial and industrial buildings due to its relatively low-cost compared to other material (e.g., steel).

Building damage statistics from past earthquakes, particularly the 2008 Wenchuan earthquake, reveal some of the seismic deficiencies of RC frame, namely weak-column and strong-beam, soft-story, short columns, interaction between infills and the bounding RC frames, etc. These features have led to extensive and severe damage as well as catastrophic collapses, often causing a large death toll. Beyond the higher risk of human injury and casualties, the economic loss in urban area is much bigger than that in rural area. For example, in 2008 Wenchuan Earthquake, a field investigation team from the Institute of Geophysics, China Earthquake Administration (CEA), found that the average loss per household the rural areas of Dujiangyan was 1,500 China Yuan (CNY) with moderate building damage [7]. In the case of urban areas, the loss for each household ranged from 20,000 to 50,000 CNY with building severe damaged or collapsed [7]. Looking at the whole province, the total direct economic loss for rural residential buildings was 144.7 billion CNY, while for urban areas; the total loss reached 204.5 billion CNY [4].

Hence, assessing the seismic capacity and vulnerability of existing RC buildings becomes particularly significant and it is the focus of the study presented here. In particular, a set of 21 RC index buildings, categorized based on the date of construction (which has a direct relation with the design code level, as discussed above), number of storeys (height of the building) and seismic zonation (which affects the design of the buildings), is proposed here.

Different versions of seismic design code have been released over the years. The first two editions, TJ11-74 [8] and TJ11-78 [9] were overly simplified in defining the design seismic actions and the seismic detailing provision; thus, they failed in enforcing sufficient seismic performance. Since 1989, different performance objectives of seismic designed buildings have been adopted in the subsequent seismic design codes, i.e., GBJ11-1989[10], GB50011-2001 [11], and GB50011-2010 [12]. Hence, to reflect the evolution in China's building code, this study considers four age bands, which coincide with periods during which code practices were distinctly different from one another. The first one, the 'pre-code' period (or 'no code' hereinafter), is before 1989 when Chinese seismic design theories and methods were mainly influenced by the codes of former Soviet Union. Statistics obtained from post-earthquake field investigations clearly shows that most structures built before 1989 were totally collapsed. Only in 1989, advancements in seismic design led to an amendment to the code (GBJ11-89) with more sophisticated materials and building practices ('moderate code' period). The code was revised again in 2001 (GB50011-2001; 'high-code' period) and 2010 (GB50011-2010; 'special-code' period) to accommodate further improvements in building practices in periods of very rapid economic growth.

Within these categories, different seismic zones are considered as recommended by CEA, by allocating the considered region to different seismic fortification intensities (SFIs). In Chinese codes, SFI is regarded as criterion of seismic design requirements, corresponding to basic seismic intensity. The basic seismic intensity of a certain region in China is defined as the impact of the earthquake with 10% probability of exceedance in 50 years (i.e., with a return period of 475 years), divided into 12 degrees. Each SFI is associated to different design peak ground acceleration (PGA), resulting in six groups: 6 (0.05g), 7 (0.10g), 7 (0.15g), 8 (0.20g), 8 (0.3g) and 9 (0.4g). As shown in Fig. 5, in the Sichuan Province, a SFI of 6 (0.05g) is assigned to 63 out of 167 prefectures while a SFI of 7 (0.1g) is assigned to 67 prefectures according to GB50011-2001. After the 2008 Wenchuan



earthquake, the SFI levels for the Sichuan Province were increase; specifically, in GB50011-2010, a SFI of 6 (0.05g) is assigned to 51 prefectures while a SFI of 7 (0.1g) is assigned to 69 prefectures. The prefectures characterized by these two SFIs take up more than 70% of the total areas listed in the code, i.e., more than 70% structures have been designed and built according to these SFIs. Thus, in this study, SFI of 6 (0.05g) and SFI of 7 (0.01g) are considered in defining the index buildings.

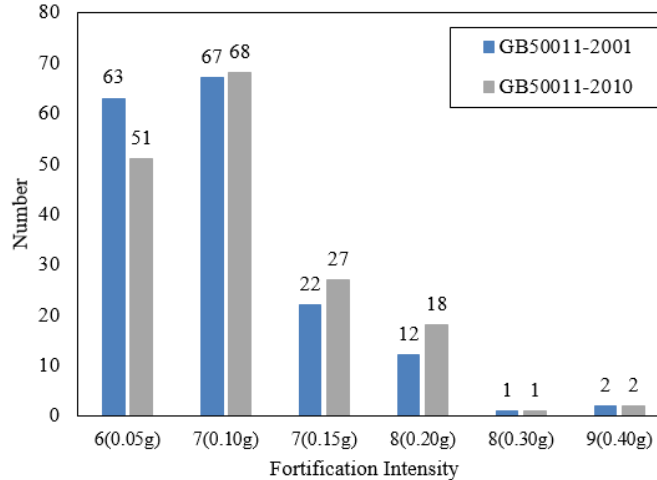


Fig. 5 - Number of prefectures with different seismic fortification intensities in the Sichuan Province according to GB50011-2001 and GB50011-2010

Regarding the number of storeys, three categories are considered to represent low-rise, mid-rise and high-rise structures respectively. According to the data derived from the 2010 Chinese Census (previous section), 2-, 5-, 8- can be selected as typical number of storeys representative for prefecture, county, and township areas. The combination of these 3 essential factors results in 21 RC index buildings to be analyzed and summarized in Table 1.

Table 1 - Summary of selected RC index buildings.

Index Building	ID	No. of storeys	SFI	Reference code
1	Code10-6(0.05g)-2	2	6(0.05g)	GB50011-2010
2	Code 10-6(0.05g)-5	5	6(0.05g)	GB50011-2010
3	Code 10-6(0.05g)-8	8	6(0.05g)	GB50011-2010
4	Code 10-7(0.1g)-2	2	7(0.1g)	GB50011-2010
5	Code 10-7(0.1g)-5	5	7(0.1g)	GB50011-2010
6	Code 10-7(0.1g)-8	8	7(0.1g)	GB50011-2010
7	Code 01-6(0.05g)-2	2	6(0.05g)	GB50011-2001
8	Code 01-6(0.05g)-5	5	6(0.05g)	GB50011-2001
9	Code 01-6(0.05g)-8	8	6(0.05g)	GB50011-2001
10	Code 01-7(0.1g)-2	2	7(0.1g)	GB50011-2001
11	Code 01-7(0.1g)-5	5	7(0.1g)	GB50011-2001
12	Code 01-7(0.1g)-8	8	7(0.1g)	GB50011-2001
13	Code 89-6-2	2	6*	GBJ11-1989
14	Code 89-6-5	5	6*	GBJ11-1989
15	Code 89-6-8	8	6*	GBJ11-1989
16	Code 89-7-2	2	7*	GBJ11-1989
17	Code 89-7-5	5	7*	GBJ11-1989
18	Code 89-7-8	8	7*	GBJ11-1989
19	No code-2	2	Gravity Load	No seismic design
20	No code-5	5	Gravity Load	No seismic design
21	No code-8	8	Gravity Load	No seismic design

* For GBJ11-1989, different areas are only associated to different seismic fortification intensities (and related seismic load), without an explicit link to a design PGA as in GB50011-2001 and GB50011-2010.

4. Structural design and modeling

With the aim of getting realistic building models, a questionnaire has been prepared to collect the general design layout and other relevant design information of RC frames in China, for instance, number of frames, frame spacing, number of bays, bay length, material properties etc. Twenty-five practicing engineers from three major national design companies (China WuZhou Engineering Group, China Coal Xi'an Design Engineering Co., Ltd., and Institute of Shanghai Architectural Design and Research Co., Ltd.) and one construction company (China Railway 24th Bureau Group Shanghai Railway Co., Ltd.) in China were invited to fill the questionnaire. The engineers in these companies have rich experiences in building design and are familiar with Chinese codes and local standards. Some of them even participated in the field investigation in Wenchuan after the disastrous earthquake in 2008.

Based on the results from the survey, the index buildings are designed with 4 frames with frame spacing of 7.2m, 2.4m, and 7.2m, respectively, each with 5 bays of the same bay length (equal to 7.8m). The plan view is shown in Fig. 6. The interior bay is much narrower than the exterior ones to represent the typical regional practice of having a corridor running through the entire floor. The storey height is 3.6m for the ground floor and 3.3m for the upper floor. The slab thickness is 120mm at each floor.

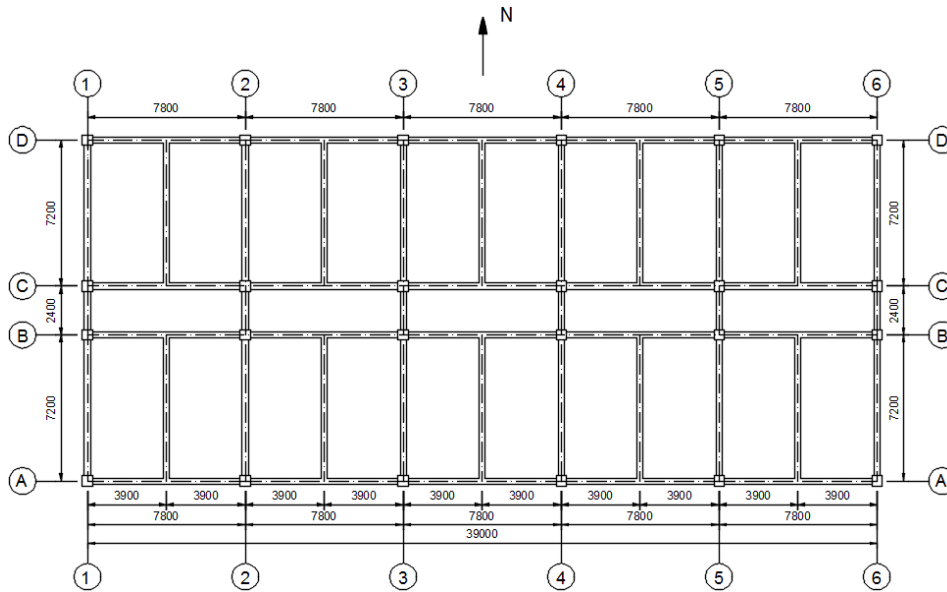


Fig. 6 - Typical RC building layout in the Sichuan Province

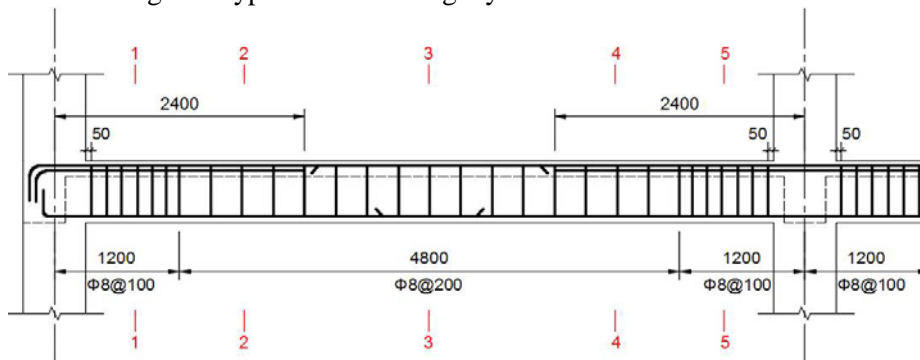


Fig. 7 - Example of reinforcement detailing for seismically designed beams.

The PKPM software, widely used in China's structural engineering industry, is used to design the index buildings. Different versions (PKPM 2005 and PKPM 2010) are used to design buildings corresponding to different construction periods. A class II soil is used, which represents medium-stiff soil site with equivalent shear wave velocity of 250-500 m/s and a site soil layer thickness greater than 5m [11][12]. A live load of 2 kN/m² and 0.5 kN/m² is considered for the floors and the roof separately. The dead load contains floor finishing,



thermal insulation and waterproof layers (which are designed based on the Sichuan local construction practice) and is equal to 3.8 kN/m² for the lower floors and 1.2 kN/m² for roof. Aerated concrete is used as the exterior walls and interior partitions. The infill loads on beams are 6.44 kN/m. Wind load of 0.3 kN/m² is also taken into consideration in this analysis. Fig. 7 illustrates an example of the reinforcement detailing for seismic designed beams, in which more hoops and longitudinal reinforcement are applied along column-beam joint. Since the buildings are constructed in different period, different materials are adopted in the index buildings. Table 2 shows the material used and structural member sections for each model.

All 21 index buildings are modelled using SeismoStruct finite element software [13]. The program allows the construction of 3D finite element models with consideration of both material inelasticity and geometric nonlinearities. It is able to predict the large displacement behaviour of framed structures under static or dynamic loadings. The prediction accuracy of SeismoStruct is demonstrated by many Blind Test Prediction Exercises (e.g.[14]). The Mander et al. [15] concrete model is implemented to account for the effect of confinement. Menegotto-Pinto (1973) stress-strain steel model is used in order to capture the hysteretic stress-strain relation of the reinforcement bars, calibrated to include strain-hardening effects [16]. In order to account for material's inelasticity, fibre approach is used. Thus, each RC section consisted of a total 150 steel, confined concrete and unconfined concrete fibres. The material parameters required are all based on Chinese standards which are shown in Table 3 and Table 4. All the structural members are modelled following the specific reinforcement detailing. For beams, five different sections are defined to represent the various bending reinforcements and shear reinforcements, as shown in Fig. 7. For columns, two sections are defined with different shear reinforcements.

Table 2- Basic design information for the index buildings

No. of storeys	Name	Concrete	Steel	Column Section (mm×mm)	Beam Section (mm×mm)
2	Code10-6(0.05g)-2	C30	HRB400	400×400	200×500
	Code 10-7(0.1g)-2	C30	HRB400		
	Code 01-6(0.05g)-2	C25	HRB335		
	Code 01-7(0.1g)-2	C25	HRB335		
	Code 89-6-2	C20	HRB335		
	Code 89-7-2	C20	HRB335		
	No code-2	C18	HRB335		
5	Code10-6(0.05g)-5	C30	HRB400	1st-3rd Floor: 500×500	300×600
	Code 10-7(0.1g)-5	C30	HRB400		
	Code 01-6(0.05g)-5	C25	HRB335	4th-5th Floor: 450×450	
	Code 01-7(0.1g)-5	C25	HRB335		
	Code 89-6-5	C20	HRB335		
	Code 89-7-5	C20	HRB335		
	No code-5	C18	HRB335		
8	Code10-6(0.05g)-8	1st Floor:C35 2-8th Floor:C30	HRB400	1st-3rd Floor: 600×600	300×600
	Code 10-7(0.1g)-8	1st Floor:C35 2-8th Floor:C30	HRB400		
	Code 01-6(0.05g)-8	C25	HRB335	4th-6th Floor: 500×500	
	Code 01-7(0.1g)-8	1st Floor:C30 2-8th Floor:C25	HRB335		
	Code 89-6-8	C20	HRB335		
	Code 89-7-8	C20	HRB335	7th-8th Floor: 450×450	
	No code-8	C18	HRB335		

There are certain limitations in the structural modeling herein that need to be pointed out. All the index buildings are assumed to be without basement and built on flat terrains. The seismic pounding effects between adjacent



buildings are neglected. Besides, the analysis is also carried out without consideration of elements with large stiffness, for instance elevator shafts and stairs.

Table 3 - Reinforcement Properties.

Steel	Material properties	HPB300	HRB335	HRB400
	Modulus of elasticity (E_s) [kPa]	$2.1 \cdot 10^8$	$2.0 \cdot 10^8$	$2.0 \cdot 10^8$
	Yield strength (f_y) [kPa]	300000	335000	400000
	Ultimate strain	0.1	0.1	0.1
	Specific weight (γ) [kN/m ³]	78	78	78

Table 4 - Concrete Properties.

Concrete	Material properties	C18	C20	C25	C30	C35
	Compressive strength (f_c) [kPa]	14000	13500	16500	20000	23500
	Tensile strength (f_t) [kPa]	1600	1550	1800	2000	2200
	Modulus of Elasticity (E_c) [kPa]	$2.6 \cdot 10^7$	$2.55 \cdot 10^7$	$2.8 \cdot 10^7$	$3.0 \cdot 10^7$	$3.15 \cdot 10^7$
	Strain at peak stress (ϵ_c)	0.002	0.002	0.002	0.002	0.002
	Specific weight (γ) [kN/m ³]	26	26	26	26	26



Fig. 8 - Structural member sections for (a) 2-storey, (b) 5-storey and (c) 8-storey index buildings.

Table 5 presents the structure periods for every model. Index buildings with the same height are almost with the same period. This is due to the models with the same floor numbers are designed with the same section. However, slightly difference can be found in Table 5. This is due to different material properties, such as young's modulus, can influence structural stiffness. As a result, the model periods are not exactly the same. With the increasing of building height, the periods increase.

Table 5 - Index buildings periods

Seismic Code	2-storey	5-storey	8-storey
Code 10-6(0.05g)	0.4940s	0.8596s	1.2593s
Code 10-7(0.1g)	0.4926s	0.8594s	1.2581s
Code 01-6(0.05g)	0.5072s	0.8831s	1.3073s
Code 01-7(0.1g)	0.5038s	0.8850s	1.2969s
Code 89-6	0.5131s	0.8987s	1.3287s
Code 89-7	0.5113s	0.8990s	1.3264s
No code	0.5233s	0.9113s	1.3418s



5. Capacity curves

An incremental uniform rectangular lateral loading is applied in the E-W direction to each index building to examine the lateral deformation and damage pattern of each structure into the inelastic range of behavior. This loading pattern allows to obtain irregular response features such as soft-storey and is able to well reproducing the softening post-peak branch of the response. The capacity curves of the index buildings are shown in Fig. 9. For these curves, the base shear is normalized with respect to the total seismic weight of the frame to obtain the base shear coefficient; the roof displacement is divided by the structural height to obtain the roof drift ratio. These curves provide a representative and visually effective illustration of the Sichuan RC building portfolio structural properties. As expected, significant variations can be found when comparing capacity curves for index buildings with the same number of storeys but designed based on different seismic design codes. In fact, buildings designed with more recent seismic design codes shows higher initial stiffness, higher base shear capacity and generally higher ductility. Fig.9 shows that 'pre-code' buildings are the most vulnerable ones compared with those designed according to more modern seismic codes. Generally, buildings designed with higher SFI, do not show significant differences in their seismic capacity. After the yielding point, the curve slope for the 2-storey buildings (with lower stiffness and yield strength) shows lower softening, i.e., they are characterized by higher seismic displacement demands. With the increasing of the number of stories, the structural damage vulnerability increases.

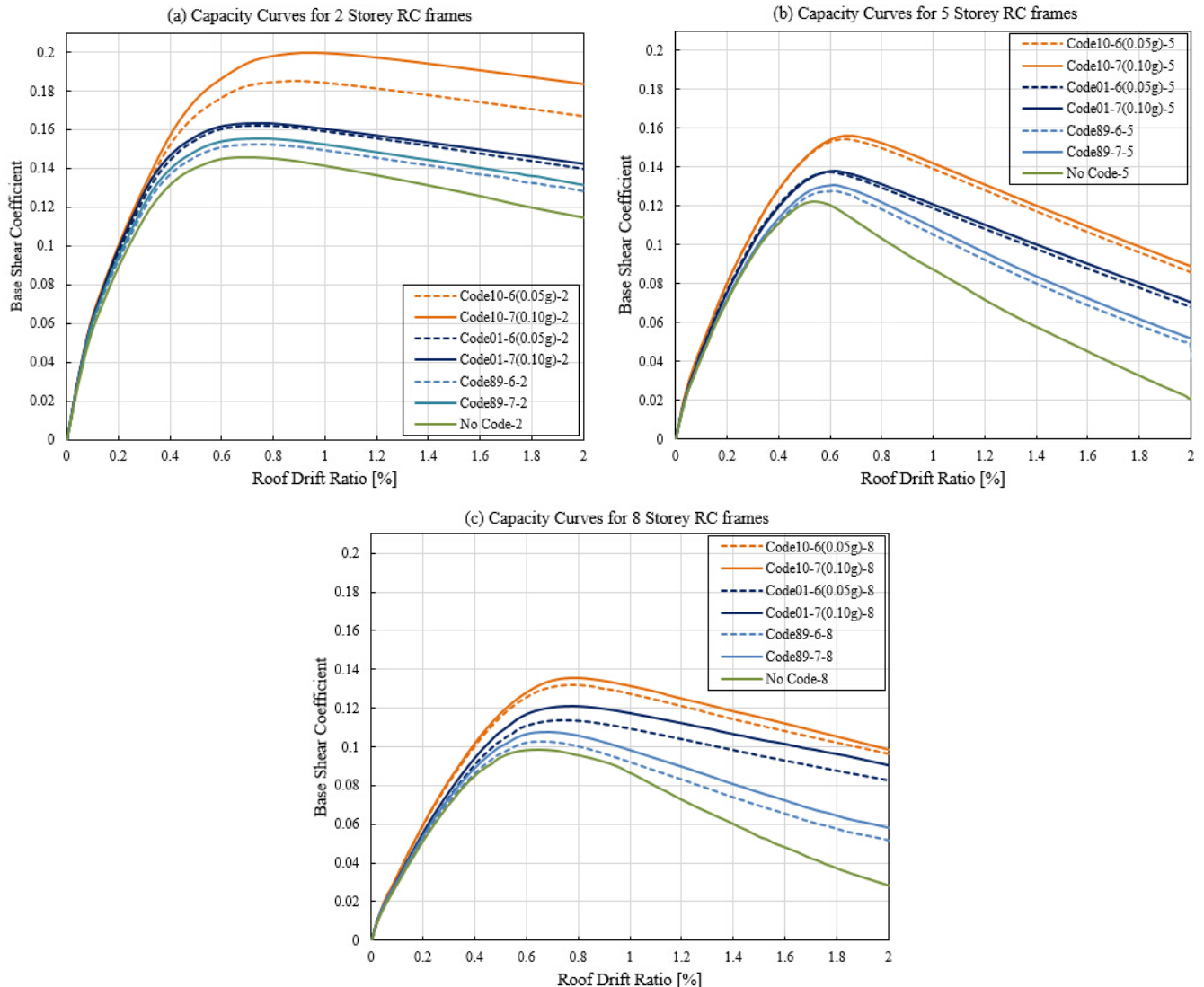


Fig.9 - Capacity curves for the RC index buildings



6. Conclusions

This paper first presented the building exposure in the Sichuan Province, China, and, focusing on reinforced concrete buildings, proposed 21 RC index buildings categorized based on design code level, number of storeys and seismic zonation (which affect the design of the building). Due to lack of detailed data regarding post-earthquake damage for this type of buildings in China, an analytical methodology has been adopted and detailed 3D nonlinear building models have been developed. With the aim of getting realistic building models, a questionnaire has been prepared to collect the general design layout and other relevant design information of RC frames in China. Twenty-five practicing engineers from three major national design companies and one construction company in China were invited to fill the questionnaire. The developed models are used as input to perform nonlinear static analysis and generate capacity curves for each case-study building.

The study presented in this paper only constitutes the first step in the development of a generic framework for constructing a state-of-the-art vulnerability model for China, properly accounting for structural and ground motion uncertainties. Such a vulnerability model is a fundamental tool to perform earthquake loss assessment as well as to evaluate buildings weakness and to quantitatively test effective strengthening strategies.

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