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# Interview of Natural Hazards and Seismic Catastrophe Insurance Research in China

Jian Zhu

## Abstract

In order to solve the increasingly serious threat of natural disasters in western Pacific coastal region, a new life-cycle cost analysis method is presented to evaluate the possible loss of natural disasters in the future in China. At the same time the research also lays a foundation for the promotion and establishment of earthquake catastrophe insurance in China. The estimation of earthquake losses for example RC buildings and industrial buildings based stochastic method models is the focus of the research. An assembly-based mixture fragility framework is firstly adopted for modeling and seismic loss estimation. The damage of the structural and non-structural which connected into response of the structures under given stochastic motions use nonlinear incremental time-history analysis to estimate in a detailed. Description of the uncertainty of all parameters in life-cycle cost (LCC) research through appropriate probability distributions to reach quantification of the LCC expected value. Moreover, the study is also to give the expected seismic catastrophe insurance premium (CIP) for two types of typical buildings in high seismic intensity areas of China based probabilistic seismic risk assessment in its service lifetime.

**Keywords:** natural hazard, life-cycle analysis, seismic catastrophe insurance premium, multi-storey RC buildings, single-storey industrial buildings, seismic fragility analysis, Monte Carlo samplings, stochastic simulation

## 1. Introduction

Recent the natural disasters such as earthquakes and hurricanes worldwide, especially those in the Pacific rim region such as Wenchuan Earthquake (2008), Nepal Earthquake (2015) and Indonesia Earthquake & Tsunami (2005, 2018), have demonstrated that the insufficient structural performance of buildings may lead to high disaster vulnerability on human society. Post-disaster recovery and reconstruction also test a country's disaster response capacity and economic strength. The direct loss of Wenchuan Earthquake in Western China (Ms8.0) was 845.1 billion Yuan in 2008, and only 1.66 billion Yuan was paid out by insurance, which can only rely on the huge amount of free economic assistance from the central government. But people in other Asian disaster regions are not always so lucky, Earthquake and tsunami heavily hit local society and economy in some Asian countries such as

Nepal or Indonesia which has no catastrophe insurance, and often leading to long-time local economic decline.

Most of Asian-Pacific regions located around the Pacific Rim seismic activity zone. High seismic intensity leads more high vulnerability to natural disasters due to particular geographic location. Since current building technology cannot avoid the negative effects of natural disasters such as earthquake, typhoons tsunami and atmospheric corrosion on the engineering economic loss, environment loss and human fatalities in whole society. It is necessary to evaluate the severity of the effects of various natural disasters. Such assessment study is not only aimed at the impact of a single disaster, but also should be based on the impact of long-term factors such as the life-cycle performance of engineering products.

Building structures are important places for human to work and live. Its durability, safety and comfort need to be guaranteed during life-cycle service. Building structure is located in the earth's natural environment, so during the service of the inevitable from the nature of wind, sunshine, rain, smog and other external factors. Some of the influences of these external environmental factors on civil engineering structures are beneficial. For example, mild air is beneficial to the strength growth of concrete in the long run, but most of the environmental influences from nature are harmful to the performance of buildings. Some external factors on the impact of buildings are potential and long-term adverse effects, such as due to global greenhouse gas emissions caused by the carbonization of concrete, acid gas corrosion of reinforcement, waves corrosion of Marine engineering structures. Which influence the modern civil engineering life-cycle sustainability. Other natural hazardous factors such as earthquake, typhoon, flood and tsunami are more dangerous and sudden affection. Human have defines such natural hazard as natural disasters. Now with the rapid development of economy in Eastern Asian coastal land, more population flow into metropolis, where infrastructures and buildings face huge pressure to long-term safe service in resisting natural hazards. For example the East Japan Earthquake (Ms9.0) on March 11, 2011 and the tsunami caused the damage of Fukushima nuclear power. The extremely serious accident of nuclear leakage, which caused extremely serious nuclear pollution to the Marine water environment of the western Pacific Ocean, caused long-term immeasurable loss.

According to U.S. risk analyst AIR Worldwide, direct earthquake insurance losses from Tohoku Earthquake caused by industrial and civil buildings, infrastructure amount to nearly \$35 billion, which is almost equal to the total disaster losses of the global insurance compensation in 2010.

Now three procedures have be titled to minimize their devastating effects by enhancing resilience in communities, that is, by reducing (1) system failure probability, (2) consequences of system failures, and (3) fee and time to recovery. So in the past several decades Load-and-resistance-factor design (LRFD) was used as the framework under which many new and existing structures are analyzed for seismic adequacy. This approach seeks to assure performance primarily in terms of failure probability of individual structural component, such as strong-column-and-weak-beam requirement. But unfortunately past seismic disasters revealed that LRFD design could not meet the above need for minimizing system failures probabilities and decreasing life and economic losses.

Performance-based earthquake engineering (PBEE) methodology finally was be developed in 2000 by Pacific Earthquake Engineering Research (PEER) shown in **Figure 1**. This approach involves combined numerical integration of all the conditional probabilities to propagate the uncertainties from one level of analysis to the next, resulting in probabilistic prediction of performance. The PBEE frame work consist of four steps, respectively is Hazard analysis, Structural analysis, Damage analysis and Loss analysis, The PBEE now has become future research basis spirit in

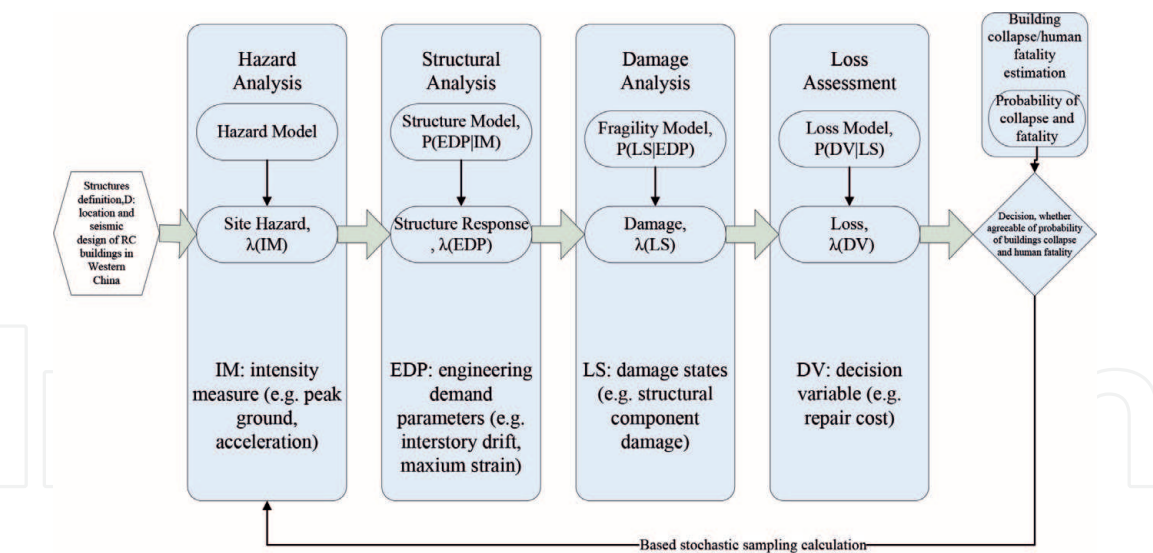


Figure 1.  
PBEE framework methodology by PEER.

civil engineering all of the world. Uncertainties are included and propagated through each step of the PBEE process [1].

At present for better approach above targets, many researchers further push the research performance-based engineering forward a great step over the entire life-cycle of the buildings. That is definitely exciting prospect but there also have several obstacles must be fronted at same time.

Seismic life-cycle research requires proper integration of following three factors: (i) probability approaches for treating the uncertainties related to the seismic hazard and to the structural dynamic behavior including structural and non-structural components in the buildings, (ii) recovery time and seismic loss estimation methodologies for evaluating the structural performance based random probability and socioeconomic criteria, (iii) algorithms for efficient evaluation of the resultant multidimensional integrals completely quantifying seismic fragility and loss are shown in Figure 2.

In 2013 December super typhoon Haiyan landed in Philippines, and resulted in 6300 life losses, millions people without shelter and \$2 billion in damage. So the most important mechanism is to rescue the refugees and compensate seismic loss from insurance companies. But how to determine buildings insurance premium ratio based seismic or typhoon loss estimation is a key problem in many Asia

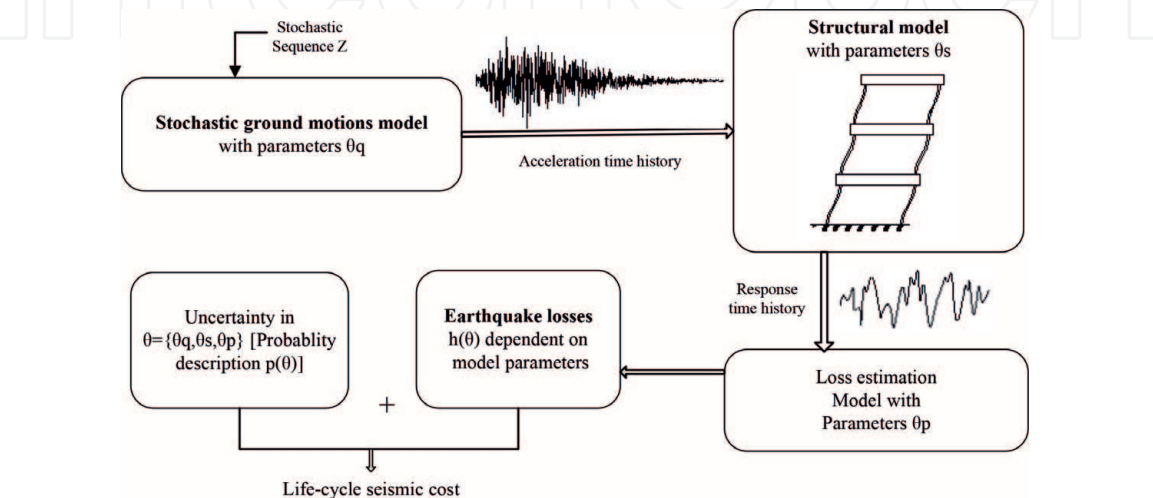


Figure 2.  
Stochastic parameters of PBEE framework methodology.



countries. Refugees’ buildings loss could not effective estimation because of absence reliable based research of life-cycle loss estimation. That is core reason why many Asia countries have not published normal disasters insurance policy at moment.

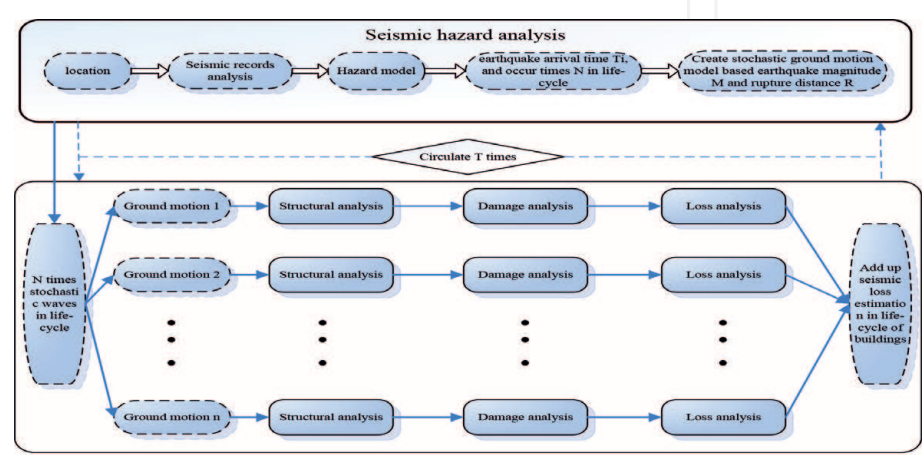
Earlier methodologies for seismic loss estimation mainly expressed seismic losses in terms of the global reliability characteristic of the structural system. Recent advances in PBEE quantify more appropriately repair cost, casualties, and down-time in relation to the structural or even on a detailed, component level (such as partitions, beams and columns) response [1], using seismic fragility curves to develop such a relationship. Nonlinear time-history as an more powerful analytical tool now accepted by many researchers in calculating seismic damage under a given earthquake excitation.

Nonlinear incremental time-history analysis is most popular methodology, which can facilitate such a description according local hazard levels through Intensity Measures (IMs) that represents the dominant features of the seismic excitation, and subsequent scaling of ground wave records to different IM values, as prescribed by a probabilistic seismic hazard analysis. Stochastic ground waves are chosen by fitting for response spectrum based China seismic code (GB50011-2010, 2] through online searching and selecting tool of PEER ground motion database, which represent samples of possible future ground waves for each hazard level of different regions in China. Additionally recent concerns related to ground motion scaling also in consideration into the stochastic ground wave model. The parameters of these ground wave, for example, duration of strong motion, can be related to earthquake (type of fault, moment magnitude and rupture distance) and site characteristics (shear wave velocity, local site conditions) by appropriate predictive relationship. Description of the uncertainty for the earthquake characteristics (moment and rupture distance) and for the predictive relationships, through appropriate probability models, to show a complete and detailed probabilistic description of potential future ground motion time waves. Therefore, the emphasis of primarily research is located in development of stochastic ground motion models.

In consideration of complexity and different regional characteristic about life-cycle seismic loss analysis, a whole set of innovated life-cycle analysis procedures based stochastic probability have been raised in this article based past PBEE research results.

The methodology indeed expand research time to life-cycle of buildings based PBEE, so basically it also consist of four steps same as PBEE framework. **Figure 3** shows the optimized methodology in research based PBEE.

This article is focus on a simulation-based, comprehensive research framework that aims to put the life-cycle loss estimation analysis into reality. Firstly life-cycle



**Figure 3.**  
*Optimized framework of life-cycle loss estimation in research.*

stochastic ground motion models including occurrence time point of every earthquake are adopted for the seismic hazard description in terms of detailed and versatile characteristic of seismic risk as well as balance in computation efficiency. Assembly-based vulnerability method is also used in evaluating seismic response of structural components based random probability in damage analysis. Therefore, life-cycle seismic cost is qualified by its expected value over the probability models and stochastic simulation is suggested for its evaluation. In the end, an revised probability life-cycle sensitivity analysis for identification of important risk factors for the life-cycle loss concept is also reviewed based former research results and stochastic sampling concepts. The analysis aims to identify the importance of the various risk-factors towards the overall performance of the structural system.

## 2. Seismic hazard analysis

Predictable ground motions in the special site firstly are considered in research as outer excitation to test structural system's performance. Yinchuan city which locate in high seismic hazard region in Western China was selected as sampling site in the research. A terrible earthquake (Ms8.0) was happened in Yinchuan district in 1739 and thousands of people died and earthquake disaster loss is very huge in record of local history. There are many NE-trending fault zones in the area. The local area is 180 km from north to south and 60 km from east to west. It is roughly 30 degrees northeast and has a total area of 7790 Km<sup>2</sup>. According to the Chinese Building Seismic Code (GB50011-2010) [2], the area is 8 degree seismic intensity design area, and the basic seismic acceleration value is 0.2 g. The area is a fault basin formed by the Cenozoic. The exposed strata are dominated by Quaternary sediments. The soil foundation is dominated by soft sand soil and is classified as II sites group, the site basic design period is 0.4 s. The thickness of the soil layer is generally between several hundred meters and 1 km, and the shear wave velocity of the soil layer  $V_{s30} = 150 - 300\text{m/s}$ .

Life-cycle model of a seismic hazard specifies (1) the random arrival times,  $T_1, T_2, \dots$ , of individual events at a site during a reference period  $\tau$ , and (2) the random properties of the ground motion hazards under considerations at  $T_1, T_2, \dots$ . The random properties involves: stochastic quantification of the earthquake intensity measure based precious activity matrix at the site and creating stochastic ground motions consistent with the intensity hazard.

Monte Carlo sampling algorithms can be used for generating samples of lifetime seismic hazard at a given site during a reference period  $\tau$ . Therefore, a life-cycle hazard sample consists of the arrival times of individual events and the properties defining their probability law.

Near-fault ground strong pulse is also considered into research based earthquakes survey recent years in many places of the world. So the final stochastic ground motion consist of low-frequency (long period) and high -frequency components and be combined to form the acceleration time history.

### 2.1 Activity matrix and event arrival

The activity matrix of seismic hazard at a given site delivers the annual rate of occurrence for events of the hazard corresponding to earthquake magnitude,  $M$ , and rupture distance,  $r$ . We can plot activity matrices against the properties which completely define the probability law of the hazard at the site. The plot of mean annual rate of occurrence of earthquake for all  $(M, r)$  at the site is called the site seismic activity matrix [3].

The average number of events per year irrespective of the values of  $(M, r)$  is

$$\nu = \sum_{i=M, r} v_{i_M, i_r} \quad (1)$$

We assume that the events in time according to a homogeneous Poisson counting process  $\{N(\tau), \tau \geq 0\}$  of intensity  $\nu$  so that

$$P(N(\tau) = n) = \frac{(\nu\tau)^n}{n!} \exp(-\nu\tau), n = 0, 1, 2, \dots \quad (2)$$

We note several properties of homogeneous Poisson counting process  $\{N(\tau), \tau \geq 0\}$ . First, the inter-arrival time  $T_k - T_{k-1}$ ,  $k = 1, \dots, N(\tau)$ ,  $T_0 = 0$ , are independent exponential random variables with rate  $\nu$  since  $P(T > \tau) = P(N(\tau) = 0) = \exp(-\nu\tau)$ . Second, conditional on  $N(\tau) = n$ , the unordered Poisson events  $\{s_1, s_2, \dots, s_n\}$  occurring in  $(0, \tau)$  have the probability density function  $1/\tau^n$ . Therefore, the unordered Poisson events are independent and uniformly distributed on  $(0, \tau)$  conditional on  $N(\tau) = n$ . The calculation method is based on the above properties to program. Samples of inter-arrival times are generated consecutively using their conditional distributions as long as the generated Poisson events remain in  $(0, \tau)$ .

## 2.2 High-frequency component

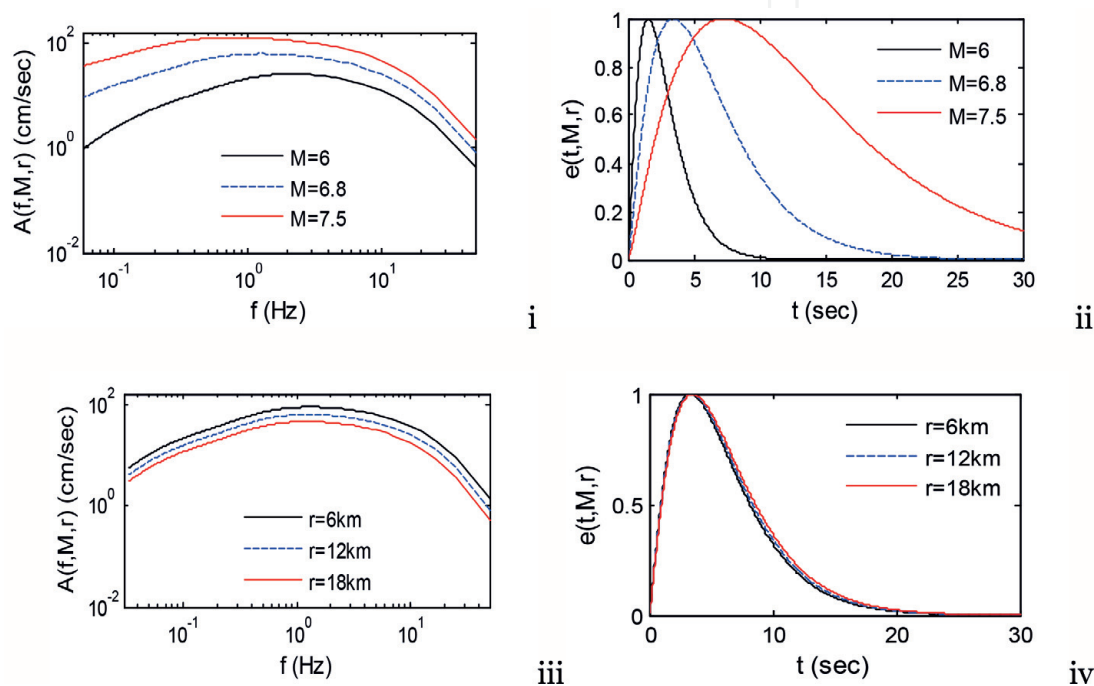
For the higher frequency component of ground motions in the seismic hazard model means the frequency of wave larger than 0.1–0.2 Hz here. The approach corresponds to a ‘source-based’ stochastic ground motion model, developed by considering the type of the fault rupture at the source as well as of the propagation of seismic waves through the underground soil site till the structural foundation. It is based on a parametric description of the ground motion’s radiation spectrum  $A(f; M; r)$ , dependent on the earthquake magnitude,  $M$ , and rupture distance,  $r$ , and expressed as a function including the frequency  $f$  of seismic wave. This spectrum consists of many factors that account for the spectral effects from the source (source spectrum) as well as propagation through the earth’s crust. The duration of the ground motion is addressed through an envelope function  $e(t; M; r)$ , which is also depends on  $M$  and  $r$ . More details on them are shown in article [3]. These frequency and time domain function  $A(f; M; r)$  and  $e(t; M; r)$ , completely describe the earthquake motion model and their characteristics are provided by predictive relationships that relate them directly to the seismic hazard such as  $M$  and  $r$ .

The time history for a specific event magnitude,  $M$ , and rupture distance,  $r$ , is obtained according to this model by modulating a white-noise sequence  $Z_\omega = [Z_\omega(i\Delta t) : i = 1, 2, \dots, N_T]$  by  $e(t; M; r)$  and subsequently by  $A(f; M; r)$  through the following steps:

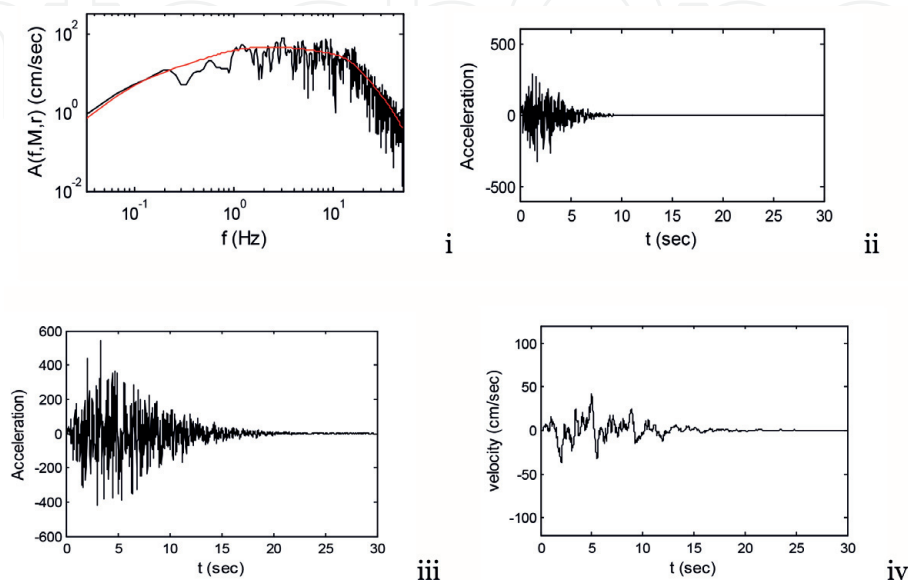
1. The sequence  $Z_\omega$  is multiplied by the time envelope function  $e(t; M; r)$ .
2. This modified sequence is then transformed to the frequency domain.
3. It is normalized by the square root of the mean square of the amplitude spectrum.
4. The normalized sequence is multiplied by the radiation spectrum  $A(f; M; r)$ .
5. It is transformed back to the time domain to yield the desired acceleration time history.

The model parameters include two seismological parameters  $M$  and  $r$ , describing the seismic hazard, the white-noise sequence  $Z_\omega$  and predictive relationship for function  $A(f; M; r)$  and  $e(t; M; r)$ . **Figure 4** shows  $A(f; M; r)$  and  $e(t; M; r)$  based functions for different values of  $M$  and  $r$ . It can be seen that as the moment magnitude increases the duration of the envelope function for strong component in motions also increases and the spectral amplitude becomes larger at all frequencies with a shift of dominant frequency content towards the lower frequency regime. As the epicenter distance increases, the spectral amplitude decreases uniformly and the envelope function also decreases, but at a relatively smaller amount.

**Figure 5** shows the detailed process of seismic wave fitting in view of different earthquake magnitude  $M$  and rupture distance  $r$ . And near-fault rupture influence

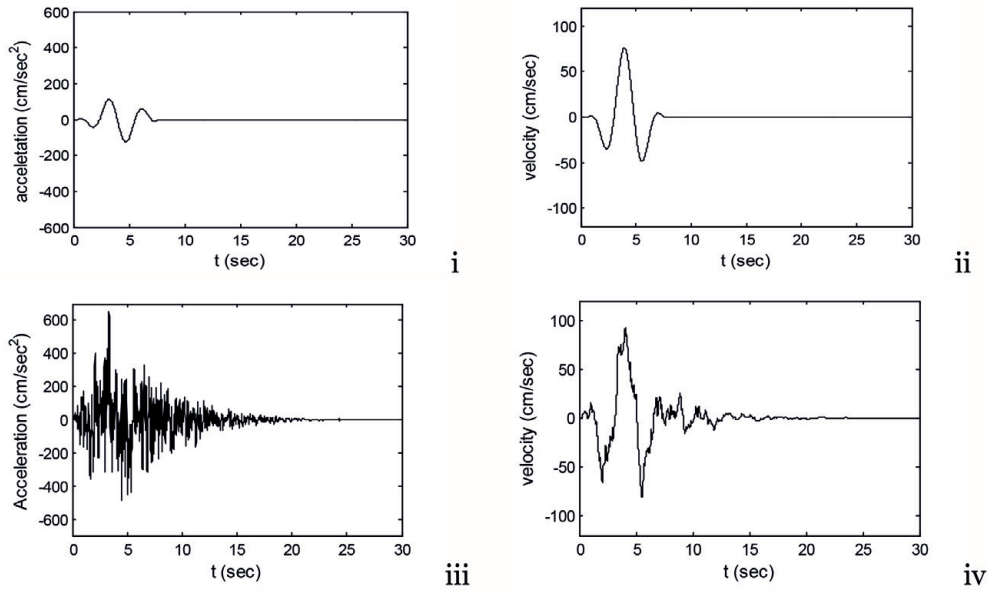


**Figure 4.**  
*Time and frequency envelope with different  $M$  and  $R$ .*



**Figure 5.**  
*Fitting process of stochastic time history wave.*





**Figure 6.**  
*Optimized wave in consideration of near-fault pulse.*

also be considered so as to reflect actual situation in most high seismic intensity areas in China as shown in **Figure 6**.

### 3. Classic buildings modeling

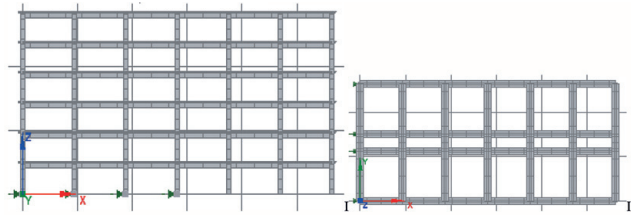
China is known as the country of the most population and the world's factory, so industrial construction plays an important role in China's economic growth. Two kinds of classic buildings were be considered in the research including public buildings and industrial buildings in the research.

#### 3.1 Multi-storey RC public buildings

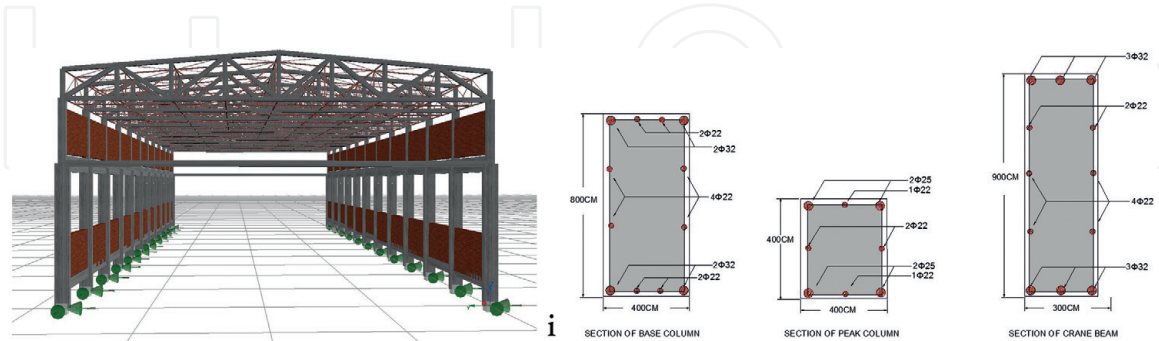
A classic six storey reinforced concrete (RC) moment resisting buildings have been constructed in order to obtain the seismic insurance ratio and influence of various sources of uncertainties on the life-cycle cost in select Western China region. Steel of class with yield stress of 335 Mpa and modulus of elasticity equal to 210 Gpa has been considered, while concrete of cubic strength of 25 Mpa and modulus of elasticity equal to 30 Gpa. The structural layout of the building represents six bay in longitudinal direction with 6–8 m span lengths and three bay in transverse direction with 6–2.5–6 m span lengths respectively. The storey height is 3.3 m. The column elements size is 0.5 m × 0.5 m ~ 0.5 m × 0.7 m. The beam size is 0.25 m × 0.6 m. The slab thickness is equal to 12 cm, while in addition to the self-weight of the beams and the slabs, a distributed permanent load of 2 kN/m² due to floor-finishing partitions and live load of 1.5 kN/m². For the analysis a three dimensional fiber model is created in Seismostruct software shown in **Figure 7**.

#### 3.2 Single-storey industrial buildings

A regular, single-storey industrial digital finite element model is chosen in **Figure 8** to represent the system. The model is designed according China seismic code [2] to the prescriptions for loading, material, member dimensioning and detailing of the seismic design and gravity load.



**Figure 7.**  
The representative RC frames- (i) front view (ii) plan view.



**Figure 8.**  
Industrial building model (i: Overview, ii: Section detail reinforcement).

The structure consists with general configuration of bent widths and bay widths of 6 m and 24 m respectively, so the construction area of whole building is  $1584 \text{ m}^2$  and which has 66 m long with 12 columns and 24 m width, structure is symmetrical in plan and elevation, and rectangular reinforced concrete track beam ( $0.30 \times 0.90 \text{ m}^2$ ) on the bracket of two side longitudinal columns of the building. At the same time RC bent frame columns are variable cross-section columns, reinforcement ratio of down columns ( $0.40 \times 0.80 \text{ m}^2$ ) is 1.86% ( $4\phi32 + 8\phi22$ ) which is under the bracket and up-columns ( $0.40 \times 0.40 \text{ m}^2$ ) is 1.96% ( $4\phi25 + 4\phi22$ ) which is on the bracket. Track beams are confined frame element array on the brackets along the interior side of the building between bent frame columns. The roof of building which height is 9.6 m consist in reinforced concrete truss, the truss length is changed from 2.4 m in center to 1.5 m of two sides, moreover there are four kind of circular hollow steel bar be using with diameter from 0.03 m to 0.05 m, and thickness of bar' section is also verify from 2 to 3 mm.

The building's wall between columns generally consist of load-bearing infill masonry walls in China, confined by reinforced concrete bent frame columns and thickness of wall is 0.37 m commonly according China masonry code. Columns must have four 32 and 25 mm diameter longitudinal reinforcements, 8 mm diameter stirrups must be spaced 100 mm apart at the terminal and 200 mm at the center of the elements.

The masonry brick strength must at least MU15 and the mortar strength must at least M10 according to China masonry code, so typical masonry shear strength is 0.27–1 Mpa. Bilinear stress-strain relationships with strain hardening were used for reinforced members which yield strength is 335 Mpa [4]. Concrete axial compressive strength is 20–25 Mpa in considering of that many industrial frames in Western China regions. And coefficient with variation of 0.3 has been considered for steel and concrete respectively. Uniaxial nonlinear constant confinement concrete model that constant confining pressure is assumed throughout the entire stress-strain range is proposed by Mander to apply to element of concrete [5].

The roof live load of industrial frame usually was  $1.0 \text{ kN/m}^2$ , which is typical for an industrial building including snow load. And dead load is  $2.0 \text{ kN/m}^2$  which considering worst condition.

## 4. Incremental dynamic damage analysis

In the seismic assessment of buildings a wide range stochastic ground motions from PEER strong motion database and seven seismic hazard level (HL) be considered in order to take into account the uncertainties. The main objective of IDA method is to define a curve through a relation between the seismic intensity level and the corresponding maximum response of the structural system. The intensity level and the structural response are described through an intensity measure (IM) and an engineering demand parameters (EDP) which refers also as damage index (DI). Incremental analysis are implemented through the following steps in this research: (i) Construct the local typical digital finite element model for performing nonlinear dynamic analyses; (ii) select a group of stochastic ground motion fitted with local response spectrum; (iii) select a proper intensity measure and an engineering demand parameter; (iv) employ an appropriate algorithm for selecting the record scaling factor in order to obtain the IM-EDP curve by performing the least required nonlinear dynamic analyses and (v) employ a summarization technique for exploiting the multiple waves results. In this work, the  $S_a(T_1, 5\%)$  for damping equal to 5% is selected as IM indicator, since it is the most commonly used intensity measure in practice today for the analysis of buildings. At the same time, two kind of damage index: the maximum inter-storey drift  $\theta_{\max}$  and maximum floor acceleration are chosen as EDPs, which are based on the maximum deformation of different damage state.

Actually scale factors is a key setting through IM in incremental analysis. The maximum inter-storey drift is recommended by FEMA-350 as the most suitable performance criterion for frame structures and is used in the research [6]. Depending on the problem and the performance that is needed to be calculated different intensity measures and performance factors can also be used. In this work two types of scaling be used: scaling all ground motion records in the same value of spectral acceleration or using a common scaling factor for all ground motion records. The  $S_a(T_1, 5\%)$  is calculated from the hazard curve of the area of interest, such as Yinchuan of western China in this work shown in Eq. (3).

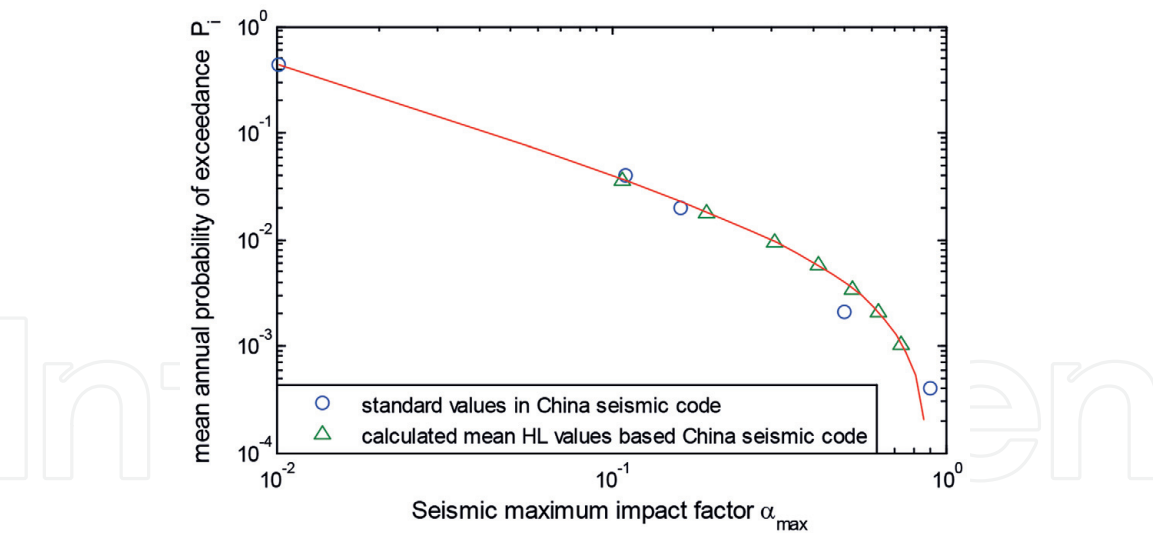
$$\bar{P}(DI > DI_i) = \frac{\gamma}{k^* \alpha_{\max}} + c \quad (3)$$

Where  $\gamma = 1.3253$ ,  $k = 2.9771 \times 10^{-2}$ ,  $c = -0.005$  in the function and the result was also shown in **Figure 9**.

$P_{50\%}$  is the exceedance probabilities in 50 years, and  $\bar{P}_i$  is annual exceedance probabilities. IDA nonlinear procedure has been chosen for detect structural seismic vulnerability including structural damage and non-structural damage. So we set suggested 7 damage limit states (LS) in calculation on the base of post research. And emphasis of LS is been located in moderate damage and heavy damage corresponding to the damage ratio between 20–45% based structural damage condition. At the same time nonstructural damage also can be classify with 7 HL or LS using peak ground acceleration. Damage scale indicators in IDA have been shown in **Table 1**.

### 4.1 Damage analysis of multi-storey RC buildings

The IM scaling factor increase from 1 to 7.2 in IDA analysis. The whole damage LS of maximum inter-storey drift ratio (ISD%) and maximum floor acceleration (MFA) of every storey are shown in **Table 2**. That means all kind of seismic intensity waves have impacted on RC buildings in life-cycle period. So the



**Figure 9.**  
The regression fitting curve for calculating the earthquake impact factor  $\alpha_{\max}$  based China seismic code.

No.	Typical sample buildings in Research					
	Hazard level	Limit states	$\bar{P}_i$	$\alpha_{\max}$	$P_i^{DI}\%$	Scaling factors
1	72/50	Slight damage	2.513	0.148	1.81	1.3
2	38/50	Light damage	0.951	0.307	0.379	2.1
3	25/50	Moderate damage I	0.574	0.415	0.227	3.7
4	16/50	Moderate damage II	0.348	0.525	0.139	4.7
5	10/50	Heavy damage I	0.21	0.627	0.107	6.2
6	5/50	Heavy damage II	0.103	0.739	0.063	7.2
7	2/50	Major damage	0.0404	0.824	0.040	9.0

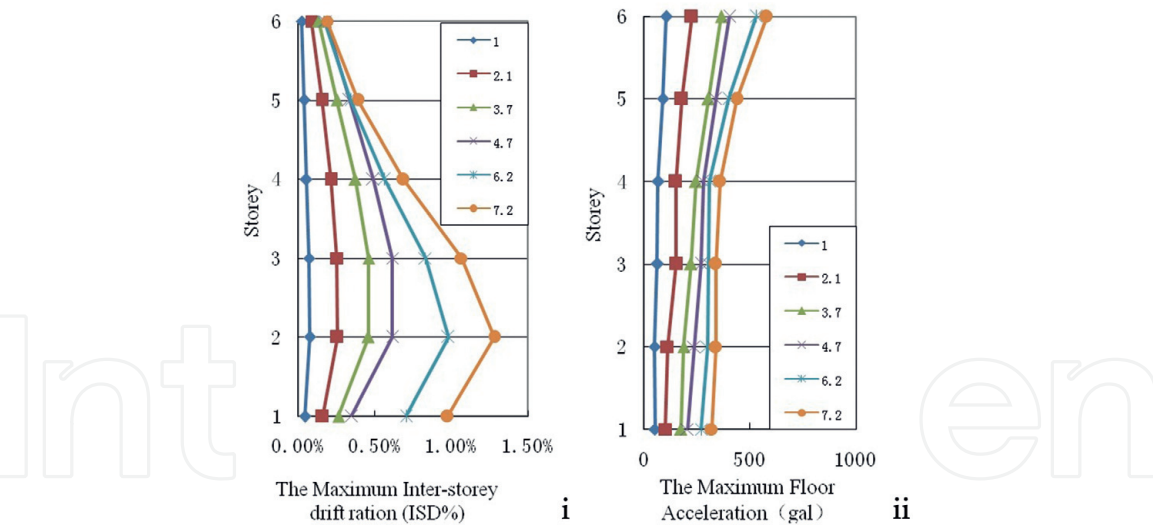
**Table 1.**  
Damage impact indicator in IDA.

Limit states	$\theta_{isd}(\%)$	$a_{\text{floor}}(g)$
(I)-None	$\theta \leq 0.1$	$a \leq 0.05$
(II)-Slight	$0.1 < \theta \leq 0.2$	$0.05 < a \leq 0.10$
(III)-Light	$0.2 < \theta \leq 0.28$	$0.10 < a \leq 0.16$
(IV)-Light II	$0.28 < \theta \leq 0.4$	$0.16 < a \leq 0.20$
(V)-Moderate I	$0.40 < \theta \leq 0.55$	$0.20 < a \leq 0.30$
(VI)-Moderate II	$0.55 < \theta \leq 0.90$	$0.30 < a \leq 0.50$
(VII)-Heavy	$0.90 < \theta \leq 1.70$	$0.50 < a \leq 0.75$
(VIII)-Major-Ma	$\theta > 1.70$	$a > 0.75$

**Table 2.**  
Drift ratio and floor acceleration limits for RC buildings in Yinchuan.

structural and non-structural damage of every floor of RC buildings must be detected based the two EDPs parameters. The maximum ISD% locates in second floor and the MFA in the top floor at the same time. That means the most structural damage lie in second floor and the severe non-structural damage in top storey,





**Figure 10.**  
The damage analysis based two EDPs parameters in IDA for Friuli Italy-02 (i: ISD%; ii: MFA).

which are shown in **Figure 10**. The tendency of the seismic vulnerability changed more obvious than ever.

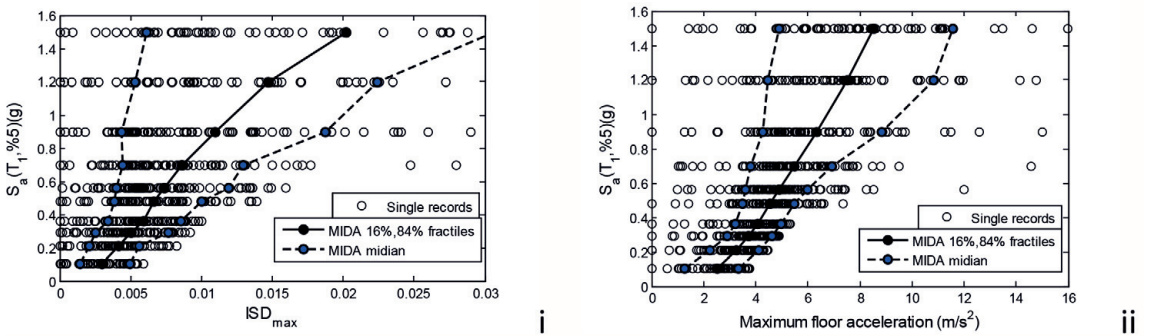
The relation between the drift ratio limits with the limit state. Employed in this study is partly based on the work of Ghobarah [7] for ductile RC moment resisting frames, and at the same time vast stochastic sampling based Monte Carlo method based local construction code in Western China also impact the limit state setting in this research. The relation of the limit state with the values of the floor acceleration is partly based on the work of Elens and Meskouris [8].

The damage scatter distribution of multi-storey RC buildings is shown in **Figure 11**. The middle black curve means median values of whole damage data and blue curves means  $\pm 15\%$  deviation limit.

#### 4.2 Damage analysis of industrial buildings

Damage, in the context of life-cycle cost assessment, refers not only to structural damage but also to non-structural damage. The latter including the case of architectural damage, mechanical, electrical and plumbing damage and also the damage of furniture, equipment and other contents in factory buildings. The maximum inter-storey drift has been considered as the structural damage response parameter. On the other hand, the peak ground acceleration (PGA) is associated with the loss of contents, like furniture and equipment which located in ground.

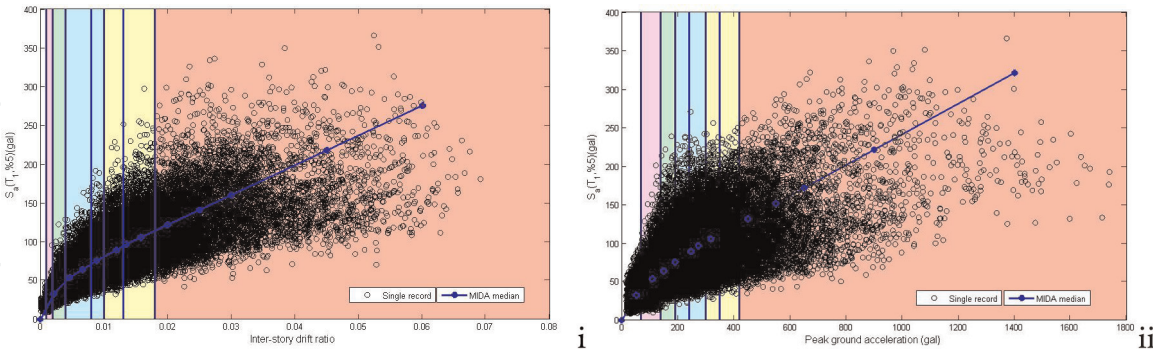
Five thousand times stochastic calculation has been made using Monte Carlo sampling method consideration of random materials and structural variables and



**Figure 11.**  
The damage scatter distribution of RC buildings.

stochastic damage scattered points can be viewed in **Figure 12** with different color stripe, which represent limit state has shown in **Table 3**.

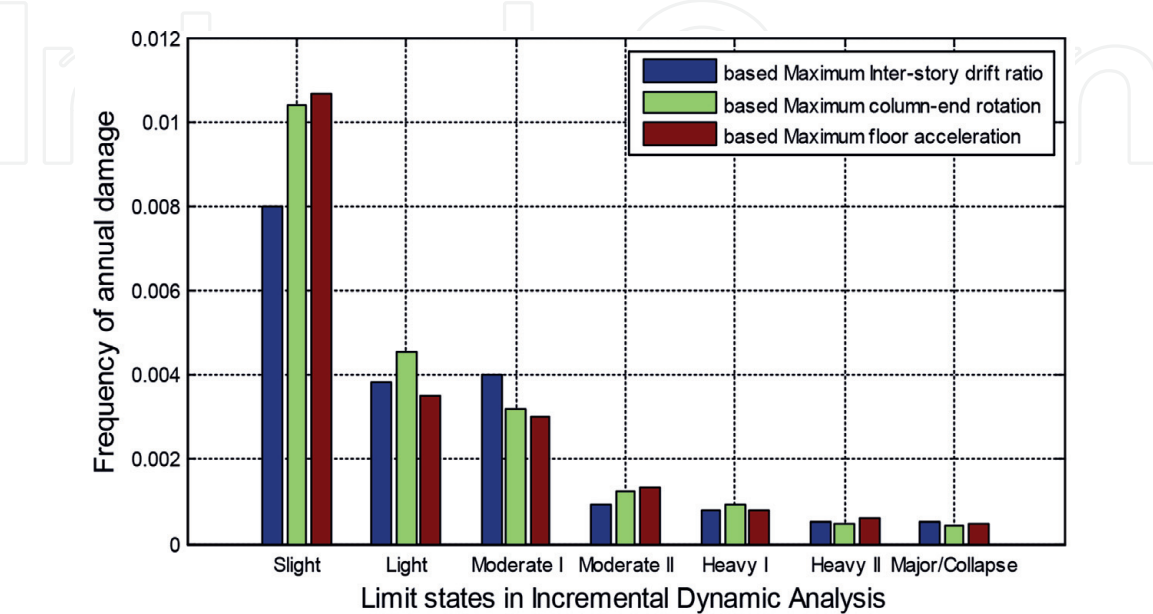
The damage zone of limit state can be represented from left to right respectively: none damage, slight damage, light damage, moderate damage, heavy damage and major damage or collapse. Statistics mean values and median values also be drawn



**Figure 12.**  
*Damage scattered distribution based limit states (i: ISD, ii: PGA).*

No.	Single-storey industrial buildings		
	Limit state	Inter-storey drift ratio%	PGA (g)
1	(I) None	$\theta \leq 0.11$	$\alpha \leq 0.07$
2	(II) Slight	$0.11 < \theta \leq 0.21$	$0.07 < \alpha \leq 0.10$
3	(III) Light	$0.21 < \theta \leq 0.31$	$0.10 < \alpha \leq 0.14$
4	(IV) Moderate I	$0.31 < \theta \leq 0.45$	$0.14 < \alpha \leq 0.18$
5	(V) Moderate II	$0.45 < \theta \leq 0.66$	$0.18 < \alpha \leq 0.23$
6	(VI) Heavy I	$0.66 < \theta \leq 1.12$	$0.23 < \alpha \leq 0.30$
7	(VII) Heavy II	$1.12 < \theta \leq 2.55$	$0.30 < \alpha \leq 0.45$
8	(VIII) Major	$\theta > 2.55$	$\alpha > 0.45$

**Table 3.**  
*Limit state drift ratio, floor acceleration of factory buildings.*



**Figure 13.**  
*The annual seismic column vulnerability in 50 years.*

as blue line in scatter diagram. The trend of scatters has clearly radial and diverging pattern like a slant bell mouth and every circle point in figure means single time history wave.

The object of life-cycle seismic cost estimation is provide high reliable seismic insurance premium data for spread industrial buildings seismic catastrophe insurance of high seismic hazard region of China in consideration of multiple undetermined factors.

The basic calculation equations are based on the work of Lagaros and Mitropoulou [9] and background reference data come from our post research. So we can calculate statistical annual damage number according 7 limit states. Further the annual seismic column vulnerability according to 7 limit states after considering respective annual seismic exceedance probability at all Hazard levels shown in **Figure 13**.

## 5. Life-cycle seismic disaster insurance premium estimation

In the research the hazard levels are defined in accordance to the hazard curve transferred from China seismic code and of the city of Yinchuan, western of China (latitude(N)38.4°, longitude(W)106.2°). The life-cycle seismic cost (LCSC) was calculated finally through incremental dynamic analyses based on the post work of Jian Zhu [10, 11]. And then the seismic disaster insurance ratio is determined.

### 5.1 Seismic insurance ratio of RC buildings

The total cost  $C_{TOT}$  of a structure may refer either to the design life period of a new building or to the remaining life period of an existing or retrofitting one. The cost can be expressed as a function of time and the design vector  $s$  as follows Eqs. (4)–(11).

$$C_{TOT} = C_{IN}(s) + C_{LS}(t, s) \quad (4)$$

where  $C_{IN}$  is the initial cost of new or retrofitted buildings.  $C_{LS}$  is the present value of the limit state seismic damage cost, that means seismic loss of the RC buildings through different limit state to consider in the work.

$$C_{LS}^{i, \theta} = C_{dam}^i + C_{con}^{i, \theta} + C_{ren}^i + C_{inc}^i + C_{inj}^i + C_{fat}^i \quad (5)$$

$$C_{LS}^{i, a} = C_{con}^{i, a} \quad (6)$$

where  $C_{dam}^i$  is the damage repair cost,  $C_{con}^{i, \theta}$  is the loss contents cost due to the structural damage  $C_{ren}^i$  is the loss of rental cost,  $C_{inc}^i$  is the income loss cost,  $C_{inj}^i$  is the cost of injuries and  $C_{fat}^i$  is the cost of human fatality. These cost components are related to the damage of the structural system.  $C_{con}^{i, a}$  is the loss contents cost due to ground acceleration or floor acceleration.

Based on a Poisson process model of the earthquake occurrences and an assumption that damaged buildings are immediately retrofitted to their original intact conditions after every seismic damage due to seismic attack.

$$C_{LS} = C_{LS}^{\theta} + C_{LS}^a \quad (7)$$

$$C_{LS}^{\theta}(t, s) = \frac{\nu}{\lambda} (1 - e^{-\lambda t}) \sum_{i=1}^N C_{LS}^{i, \theta} \cdot P_i^{\theta} \quad (8)$$

$$C_{LS}^a(t,s) = \frac{\nu}{\lambda} (1 - e^{-\lambda t}) \sum_{i=1}^N C_{LS}^{i,a} \cdot P_i^a \tag{9}$$

where  $C_{LS}^\theta$  and  $C_{LS}^a$  is respectively the seismic loss cost for the  $i$ th limit state violation calculated based  $ISD_{max}$  and  $PGA$  according to Eqs. (4) and (5). The annual monetary discount rate  $\lambda$  is taken constant and equal to 5%.

The probabilities  $P_i^\theta$  and  $P_i^a$  of Eqs. (7) and (8) are calculated as follows:

$$P_i^{DI} = P(DI > DI_i) - P(DI > DI_{i+1}) \tag{10}$$

where  $DI_i, DI_{i+1}$  are the lower and upper bounds of the  $i$ th limit state for the two damage indices considered, while  $P(DI > DI_i)$  is the exceedance probability given occurrence of the earthquake for every limit state given by the following expression:

$$P(DI > DI_i) = \frac{-1}{\nu t} \cdot \ln [1 - P_t(DI > DI_i)] \tag{11}$$

where  $P_t(DI > DI_i)$  is the exceedance probability over a period  $[0,t]$ ; and  $t$  is the service life, which is almost 50 years in China.

A more detailed description of the different damage rate and cost evaluation for each limit state cost can be found in **Tables 4** and **5**. The basic cost refers to the first component of the calculation formulas. While they are given in monetary units Yuan. The values of the mean damage index, loss of function, down time, expected minor injury rate, expected serious injury rate and expected death rate used in this study are based on [12]. Death rate denotes the number of persons that may die at a specific limit state and it is defined as the number of occupants  $\times$  death rate. **Table 4** provides the revised limit state parameters of cost evaluation in this work on the base of FEMA-227 limit state dependent damage consequence severities.

After study local statistics data of construction engineering in Yinchuan, which located in high seismic hazardous region of western China. In this research  $2500Yuan/m^2$  is considered as  $C_{IN}$ , meantime  $\pm 10\%$  variance is also included (**Figure 14**).

The statistics median covered area of typical RC building is  $3600\text{ m}^2$ . The annual average LCC is  $2.06\text{ Yuan}/\text{m}^2$  after calculation using above procedure, and annual median LCC is  $1.89\text{ Yuan}/\text{m}^2$ . There will add up 25% additional fee if insurance companies will establish catastrophe insurance at moment. The final insurance

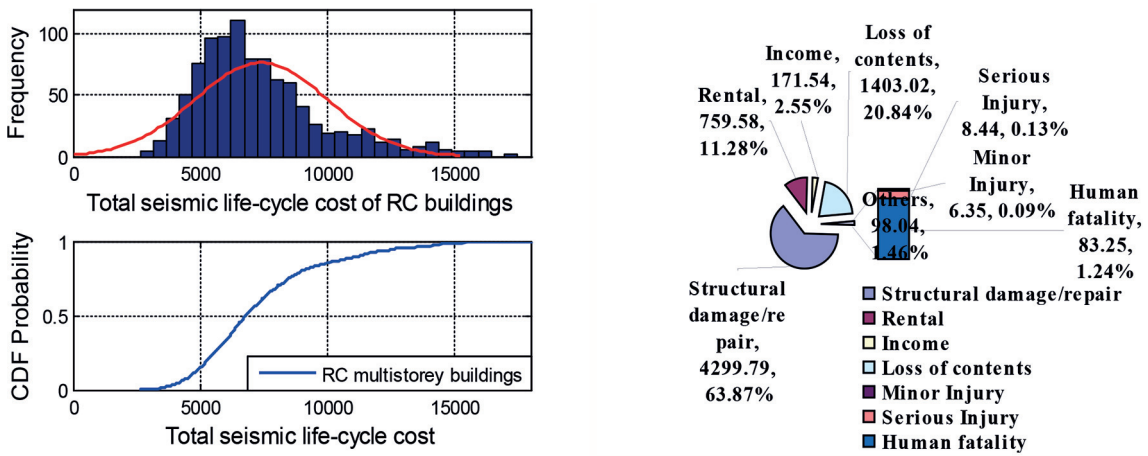
Limit state	Calculate index based FEMA-227 [12]			
	Mean damage index %	Expected minor injury rate	Expected serious injury rate	Expected death rate
N	0	0	0	0
S	0.5	$3.0 \times 10^{-5}$	$4.0 \times 10^{-6}$	$1.0 \times 10^{-6}$
LI	2	$1.3 \times 10^{-4}$	$1.8 \times 10^{-5}$	$0.4 \times 10^{-5}$
LII	5	$3.0 \times 10^{-4}$	$4.0 \times 10^{-5}$	$1.0 \times 10^{-5}$
MI	9	$1.4 \times 10^{-3}$	$1.6 \times 10^{-4}$	$0.4 \times 10^{-4}$
MII	20	$3.0 \times 10^{-3}$	$4.0 \times 10^{-4}$	$1.0 \times 10^{-4}$
H	45	$3.0 \times 10^{-2}$	$4.0 \times 10^{-3}$	$1.0 \times 10^{-3}$
Ma	80	$3.0 \times 10^{-1}$	$4.0 \times 10^{-2}$	$1.0 \times 10^{-2}$

**Table 4.**  
*Limit state parameters for cost estimation.*



Cost category	Basic cost
Damage/repair ( $C_{dam}$ )	1200 Yuan/ $m^2$
Loss of contents ( $C_{con}$ )	300 Yuan/ $m^2$
rental ( $C_{ren}$ )	20 Yuan/month/ $m^2$
Income ( $C_{inc}$ )	400 Yuan/year/ $m^2$
Minor injury ( $C_{inj,m}$ )	2000 Yuan/person
Serious injury ( $C_{inj,s}$ )	$2 \times 10^4$ Yuan/person
Human fatality ( $C_{fat}$ )	$8 \times 10^5$ Yuan/person

**Table 5.**  
Limit state costs-calculation formula.



**Figure 14.**  
The probability characteristics and constitution of RC buildings' LCC.

payment per people is about 70.9–77.2 Yuan annually in considering of local life endurance in this research on base of average living space per person equal 30  $m^2$ . The result is complete acceptable level for local people in Yinchuan city of western China as research sample region finally and have applied into local insurance policy successfully.

### 5.2 Seismic insurance ratio of industrial buildings

Then we can use the Eqs. (4)–(11) based data of **Table 6** to calculate life-cycle seismic cost of factory buildings in selected region in consideration of random variables from ground vibration, material character and time cost.

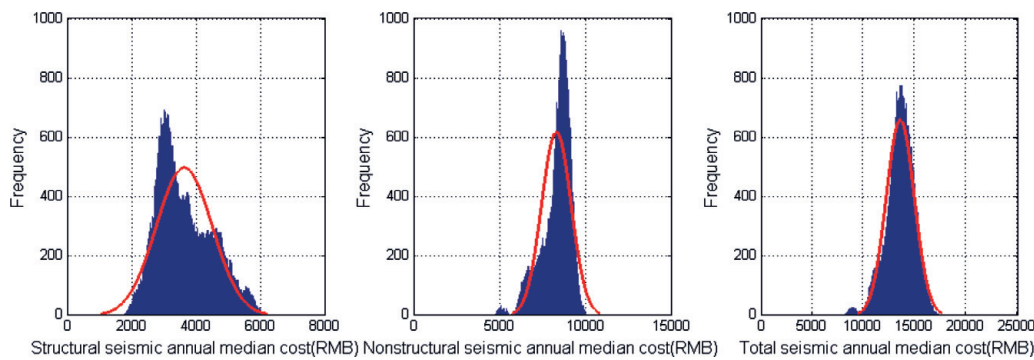
The initial unit construction cost of the building is estimated ¥1200/ $m^2$  and  $\pm 10\%$  deviation is considered in calculation. The cost of machines and non-structural contents is supposed as ¥3000/ $m^2$  and ¥300/ $m^2$  respectively in research.

The annual median seismic cost of structural damage of industrial buildings is ¥3419 and corresponding annual median value of non-structural damage including machine and facilities in factory buildings is ¥8505 in **Figure 15**. The average and median values of every cost category are shown in **Table 7**.

Insurance is a highly legal business. Relevant insurance matters are regulated by the laws of various countries. Generally, the calculation formula of seismic catastrophe insurance premium rate is as follows.

Single-storey industrial buildings		
Cost category	Calculation formula	Basic cost
Damage/repair	Replacement cost × FA* × DI*	¥1200/m <sup>2</sup>
Loss of machine & contents	Unit cost × FA* × DI*	¥3300/m <sup>2</sup>
Rental	Rental rate × FA* × LF*	¥30/mo/m <sup>2</sup>
Income	Rental rate × FA* × LF*	¥2000/ye/m <sup>2</sup>
Minor injury	MI per cost × FA* × OR* × rate	¥2000/per
Serious injury	SI per cost × FA* × OR* × rate	¥2 × 10 <sup>5</sup> /per
Human fatality	HF per cost × FA* × OR* × rate	¥5 × 10 <sup>5</sup> /per
*FA = floor area, DI = damage index, LF = loss function, OR = occupancy rate.		

**Table 6.**  
Limit state costs-calculation formula.



**Figure 15.**  
The annual median SLCC probability distribution of factory buildings (from left to right: Structural damage, non-structural damage and total).

Cost category	Average value CNY	CoV (%)	Median value CNY	CoV (%)
Damage/repair	3603	5.67	3419	5.65
Rental	599	57.66	497	52.35
Income	742	63.35	603	57.12
Loss of contents	8286	1.24	8505	1.34
Minor & Serous Injury	39	186.2	27	156.7
Human fatality	221	189.8	155	157.7
Total seismic cost annually	13,491	1.11	13,577	1.12

**Table 7.**  
LCC statistics results comparison.

$$p = \frac{\bar{L}}{1 - r - e}, e = e_1 + e_2 + e_3 + e_4 \tag{12}$$

Where  $p$  is insurance premium rate,  $\bar{L}$  is expected loss rate,  $r$  is discount rate,  $e$  is additional charges rate including  $e_1$  special reserve rate for claims,  $e_2$  is commission rate,  $e_3$  is development fund rate and  $e_4$  is other fee rate. In research refer to Taiwan seismic insurance rate,  $e_1 = 4\%$ ,  $e_2 = 12.5\%$ ,  $e_3 = 0.5\%$ ,  $e_4 = 22\%$ ,  $r = 5\%$ . So the

insurance premium rate  $p = 1.785$ , and seismic catastrophe insurance of industrial buildings is ¥15.21–15.30 Yuan/year.m<sup>2</sup> in selected sampling region of China.

## 6. Conclusion

In this work a seismic risk & loss assessment procedure is proposed for a quantitative estimation of the seismic vulnerability and seismic catastrophe insurance premium of two types of typical buildings located in western China subjected to seismic actions. The numerical study was performed on 3D digital industrial modeling structures with two kind of roof structural system with different material. The life-cycle seismic cost estimation is examined on the basis of stochastic simulation with the big data buildings damage sampling. The most important findings of this study can be summarized as follows:

Double damage indicators including (ISD% & PGA) are imported into life-cycle seismic cost estimation firstly in inner research. The loss of non-structural cost is more than 60 percent in total LCC value and found more higher than the loss of structural damage.

The moderate damage I is most frequency through comparing stochastic incremental dynamic analysis results of every limit state damage. And light damage and major damage is followed.

The unit CIP statistical value of industrial buildings is ¥15.21-15.30/year.m<sup>2</sup> in selected region. And in the future more precious results can be obtained through collecting buildings damage big data after large scale seismic investigation.

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## Author details


Jian Zhu<sup>1,2\*</sup>

1 Department of Transportation and Civil Engineering, Foshan University, Foshan, Guangdong, China

2 Department of Civil Engineering, Chang An University, Xi An, Shanxi, China

\*Address all correspondence to: zhuhoujian66@hotmail.com

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