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A Quantitative Method for Assessing and Monetizing the Failure Risk of Prefabricated Building Structures under Seismic Effect

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Abstract: As a new construction mode, the prefabricated building is the main direction of the transformation and upgrading process of the Chinese construction industry. In an earthquake area, prefabricated building damage is often reported; therefore, it is important to evaluate the failure risk of its structure under seismic effect. In this paper, combined with the vulnerability and building depreciation theory of prefabricated buildings, as well as a seismic hazard analysis of engineering sites, we propose a quantitative method for evaluating the structural failure risk of prefabricated buildings under seismic effect during their service life. In order to illustrate the proposed method, a residential prefabricated building as described in the previous study is used as a case study. The structural failure risk value and overall risk level of the case under seismic effect are calculated to verify the feasibility and effectiveness of the seismic risk evaluation method. The results demonstrate that the proposed method benefits and assists risk management in the decision making and disaster prevention and mitigation regarding prefabricated buildings.

Keywords: prefabricated building; vulnerability analysis; seismic hazard analysis; risk evaluation; disaster prevention and mitigation

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1. Introduction

In China, cities are characterized by their large number and scale, and most of them are located in seismic zones, where they are constantly exposed to the threat of earthquakes [1]. In particular, an earthquake can cause severe damage to building structures, which can lead to house cracking and even collapse. Statistics show that building damage is the main cause of human casualties and economic losses [2]. The Chinese construction industry is now in an important stage of transformation and upgrading, and the prefabricated building has been fully developed. But in China, prefabricated buildings rarely experience seismic hazards. Therefore, there is a lack of empirical studies on actual earthquake damage to prefabricated buildings [3]. On 17 June 2019, a 6.0 magnitude earthquake occurred in Changning County, Yibin City, Sichuan Province. In order to timely understand the earthquake damage to prefabricated buildings in the earthquake area and protect people's lives and properties, on 20 June 2019, the Sichuan Provincial Department of Housing and Urban–Rural Development organized a special earthquake damage survey of prefabricated buildings. Since prefabricated buildings may be severely damaged under the action of earthquakes, it is of practical significance to carry out research on the risk of the structural failure of prefabricated buildings under the action of earthquakes, to evaluate the risk of the structural design results at the end of the architectural design, to design reinforcement for prefabricated building structures with higher risk, and to design reinforcement for completed buildings. It is also of great significance to protect and reinforce the higher-risk prefabricated buildings for disaster prevention and mitigation.

In the field of structural failure analysis, most previous studies have focused on the probability of structural failure based on a fragility analysis rather than a risk assessment, which is a method based on a large amount of statistical data on different damage states of structures under the action of disasters to establish empirical fragility curves [4–7], as well as fragility matrices to reflect the average damage state of the structure itself under the action of disasters of different intensities [8]. Mahnoosh [9], based on the 7.3 magnitude earthquake in Iran in 2017 after 440 steel and reinforced concrete structures were damaged by the earthquake, established an empirical fragility curve with PGA as a variable. Li [10] summarized and statistically analyzed the data of 18,480 empirical earthquake damage samples in 33 towns affected by the Wenchuan earthquake (China) on 12 May 2008 and established a probability matrix model of empirical earthquake damage. Yao [11] investigated the typical structure of rural China from 1996 to 2013 and analyzed the vulnerability of the structures of these buildings and regional vulnerability through a beta probability distribution function. Another method is to analyze a specific structure according to the model, and the main steps are to import the finite element model of the structure into the structural analysis software, simulate the response of the structure under the action of different disasters through the software, perform a regression analysis of the resulting simulation data to obtain the function relationship between the disaster intensity and the response of the structure, and combine it with probability statistical theory to obtain the probability curve of different damage states [12–15]. Vamvatsikos and Cornell [16] first proposed the incremental dynamical analysis (IDA). This is a common method for assessing the structural vulnerability of buildings in the civil engineering field today. Zareian [17] simultaneously considered the uncertainty of ground shaking and the uncertainty of the model and carried out an earthquake vulnerability study. Dadkhah [18] pointed out that the method of IDA is one of the most accurate nonlinear seismic analyses and he used the discrete wavelet transform to solve the computationally time-consuming and labor-intensive problem.

In the field of building structural risk analysis, overall, previous scholars' research on building structural failure risk analysis has mainly been divided into two categories. Scholars in the field of engineering management often use comprehensive qualitative evaluation methods such as expert scoring and analytic hierarchy process to assess risk [19–22]. This method is more subjective and relies on historical experience. Another type of method is based on structural reliability theory, fragility concept, probability theory, and statistical theory, etc., considering the performance of the structure itself and the influence of external site factors, and calculating the probability of structural failure within the service life of the building—i.e., the fragility study of the structure—but this method often only studies the probability of structural failure and has not yet risen to the level of studying the risk of structural failure for the management of decision making. Based on these theories, Deierlein [23] proposed a framework for performance-based earthquake engineering, and someone also studied the structural damage risk of an ancient building based on this conceptual framework. The current research on building structural failure risk analysis under seismic effect is mainly divided into two categories. One is based on the hierarchical analysis method, which divides the primary and secondary factors affecting the failure of prefabricated buildings, and establishes a hierarchical model and matrix to determine the weights, ranks the factors after calculation, and finally calculates the failure risk index of prefabricated building structures according to the influence of each factor on the building structure. For example, Bahadori [24] proposed a comprehensive model for the seismic vulnerability assessment of residential buildings based on GIS and AHP. The other category is based on structural reliability theory, fragility concept, probability theory and statistical theory, etc., which integrates the performance of the structure itself and the influence of external site factors to calculate the expected loss of structural failure within the service life of the building, such as Janssens [25] assessment of the consequences of building failures within a risk-based robustness framework. Khalilian [26] evaluated the probabilistic life cycle costs of buildings with different structural designs. Luis [27] proposed a probability distribution function of economic loss from the perspective of economic loss, combining the seismic fragility of the structure, seismic hazard, and the cost required to repair the damaged elements. Athanasios [28] divided earthquake risk into three key components: hazard, structural vulnerability, and structural exposure, and then investigated how the uncertainty of the risk affects the risk management process and studied an insurance model for earthquakes. There are also articles that focused on regions and used GIS to show the level of risk and developed reliable risk maps [29–32]. The first method has a certain subjectivity in the division of factors, while the second method is more objective and accurate. At present, the risk analysis of building structure failure mainly consists of three aspects: structural fragility analysis, hazard risk analysis and loss estimation, but at present, few papers have considered the impact of building economic depreciation on loss estimates based on the time value of money.

However, it is thus clear that current studies have focused on the probability of damage, which is a topic of interest in the field of structural engineering, and that the assessment of risk is not yet sufficient, which is a topic of interest in the field of management. To take it a step further, if this risk could be monetized, then the results would be more intuitive, and decision making would become easier for structural designers and managers. The application of assembled shear wall structures in China is still in its infancy. They have not been tested by real earthquakes in recent years, and there has been much focus on the structural dynamic performance of assembled monolithic structures under earthquake effects. Many studies have focused on the nodes of individual assembled structures, while relatively little research has been performed on the overall structure containing assembled nodes, and few performance-based seismic risk analyses of assembled structures have been performed. In this paper, in the process of structure design, we consider the different levels of structural damage that may be caused by seismic hazards during the use phase of the prefabricated building design, proposing the concept of structural failure risk of prefabricated buildings. Then we use the maximum inter-story displacement angle value of the structure as the basis for classifying the degree of structural failure and the loss ratio. In this paper, the probability of the occurrence of different degrees of failure risk during the service life of a prefabricated building is obtained by multiplying the probability of the occurrence of a certain degree of hazard with the probability of the occurrence of a certain degree of failure of the structure under that degree of hazard. Then we combine the concept of the loss ratio to calculate the expected loss during the useful life for risk evaluation. To make the value of the building more accurate, we also place it under the concept of depreciation to calculate its value. It may help to keep the damage and economic losses of assembled structures within design expectations and reduce life-cycle costs. It also caters to the Chinese seismic design thinking: according to the actual situation in China—the economic strength has improved greatly, but still at the level of developing countries—appropriate seismic protection standards are proposed, which can rationalize the use of construction investment and at the same time achieve the requirements of seismic safety.

2. Theoretical Framework and Methods

2.1. The Concept of Structural Failure Risk

First appearing in economics in the late 19th century, risk is now also widely used in disciplines such as construction engineering and natural disasters. Risk is the combination of the likelihood (probability) of an event occurring and the degree of its impact [33]. Risk contains two layers of meaning: first, the appearance of risk implies the appearance of loss; second, the appearance or non-appearance of loss is uncertain. Additionally, the probability of the appearance of risk can be expressed in terms of probability [34].

In risk management theory:

$$R = L \times P \tag{1}$$

where R denotes the amount of risk (risk), L denotes the degree of loss (loss), and P denotes the probability of loss (possibility).

Thus, in order to calculate the value of risk, we need to calculate the likelihood of loss (probability) and the degree of loss.

Structural failure is one of the many risks faced by prefabricated buildings. The structural failure risk analysis of assembled structures is a research method for the quantitative analysis of structures based on structural reliability theory, probability and mathematical statistics theory, etc.

The probability and probability distribution of risk events are the basis for risk estimation [35], so an important aspect of estimating the risk of the structural failure of prefabricated buildings is to determine the probability distribution of structural failure. The risk of the structural failure of prefabricated buildings under earthquake action generally includes three aspects: one is the probability of damage to the structure itself under different earthquake actions, i.e., structural vulnerability, the second is the probability of occurrence of different earthquake intensities within a certain time, i.e., earthquake hazard, and the third is the degree of loss of prefabricated buildings under different degrees of damage.

In the risk of the structural failure of prefabricated buildings, the probability of structural failure is equal to the probability of the occurrence of a certain level of earthquake multiplied by the probability of structural failure under that level of earthquake intensity, i.e., vulnerability multiplied by seismic hazard. Combined with Equation (1), the risk of the structural failure of a prefabricated building under earthquake action can be expressed as:

$$R = \sum_i \sum_j L_j \cdot P\left(D_j / A_i\right) \cdot P(A_i) \tag{2}$$

where L_j is the degree of loss when the failure degree of the prefabricated building structure is D_j, in which $P\left(D_j / A_i\right)$ is the target of fragility analysis, which is the probability that the failure degree of the prefabricated building is D_j when an earthquake of grade A_i occurs, and $P(A_i)$ is the target of seismic hazard analysis, which is the probability that an earthquake of grade A_i occurs.

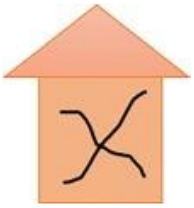
2.2. Division of Failure Degree of the Prefabricated Building Structure

Before classifying the degree of structural failure, it is necessary to determine the indexes characterizing the degree of structural damage and the indexes of ground shaking strength. There are many mainstream structural damage indexes, mainly including the maximum shear force at the bottom of the foundation, the top layer displacement of the structure, the maximum inter-story displacement angle of the structure, etc. The most commonly used one is the maximum inter-story displacement angle of the structure θ_{max}. This damage index can reflect the influence of structural material performance parameters, such as the reinforcement rate, concrete strength, etc., on the structural forces, and is directly related to the damage degree of the members and can reflect the elastic–plastic deformation of the nodes of the structure under the action of an earthquake [36].

The ground vibration strength index selected in the fragility analysis should reflect the intensity of the ground motion when the earthquake occurs, and the selection of a suitable ground vibration strength index is critical for the structural seismic fragility analysis. At present, one of the commonly used ground vibration parameters is peak horizontal seismic acceleration PGA; this parameter is relatively simple to use and easy to understand.

This paper refers to the classification of the structural failure degree in the established literature [37] and classifies the structural failure degree into five different classes: basically intact, slightly damaged, moderately damaged, severely damaged, and collapsed (completely damaged). In terms of the division of damage index limits, this paper refers to the inter-story displacement angles of high-rise assembled frame shear structures under load corresponding to various damage states given in the existing literature [38]. The parameters in the literature referenced in this paper apply to high-rise hybrid structures, and the case in this paper meets this requirement. The reference used the IDA method to analyze nine high-rise steel frame concrete core hybrid structures with different structural characteristics, proposed four performance levels for high-rise hybrid structures, and gave the corresponding maximum inter-story displacement angle range as the control index for seismic design based on performance design. It is the reference value for the case in this paper. These parameters are in line with the current specifications for high-rise concrete in China and can meet the requirements of different performance levels and performance targets. The corresponding relationship between the degree of structural damage and the loss ratio (the degree of loss divided by the value before the loss occurred) is tabulated as follows in Table 1:

Table 1. The relationship between the degree of structural failure and the maximum inter-story displacement angle and the loss ratio.

Degree of Structural Failure D_i	Illustration	Inter-Story Displacement Angle θ_{max}	Treatment Method	Average Loss Ratio
D_1: Intact		<1/900	No repair required	0
D_2: Slightly damaged		1/900~1/500	Needs a little repair	0.1
D_3: Moderately damaged		1/500~1/200	General degree of repair, take safety measures	0.4
D_4: Extensively damaged		1/200~1/100	Major repairs, partial reconstruction	0.8
D_5: Collapse		>1/100	Complete dismantling	1

2.3. General Approach to Building Fragility Curves

The vulnerability analysis is based on reliability theory, and the vulnerability curve is established by the vulnerability analysis to represent the probability of structural damage under different ground shaking intensities. The IDA (Incremental Dynamic Analysis) is often used for the vulnerability analysis of the structure [13,14,16,18].

In this approach, the probability of structural failure is usually expressed as:

$$P_f = \Phi\left(\frac{\mu_S - \mu_R}{\sqrt{{\sigma_R}^2 + {\sigma_S}^2}}\right) \tag{3}$$

The vulnerability analysis of prefabricated buildings refers to the conditional probability of different degrees of failure of their structures under the action of different earthquake intensities and is based on the following principles:

$$F(x) = P(a \geq b|IM = x) \tag{4}$$

where IM is the seismic intensity parameter, which in this paper is the peak ground acceleration of seismic waves, or PGA. The structural damage parameter in this paper is the maximum inter-story displacement angle, or θ_{max}.

According to the Section 2.2, for example, when θ_{max} exceeds 1/900, we say that the structure is beyond the slight failure state, so the probability that the structure is beyond slight damage can be expressed as:

$$P_f\left(\frac{S}{R} > 1\right) = P\left(\frac{\theta_{max}}{1/900} > 1|PGA\right) \tag{5}$$

In this method, a log-linear regression analysis of the two is usually performed, and a log-linear relationship between the maximum inter-story displacement angle θ_{max} and the seismic intensity (PGA) of the structure under the action of these seismic waves can be fitted as follows:

$$\ln \theta_{max} = c \ln PGA - d \tag{6}$$

From the literature, it is known that the structural seismic response and structural seismic capacity roughly obey a log-normal distribution [39,40], so it is assumed that these two parameters obey a log-normal distribution. Combining with Equations (3)–(6), the probability of a structure exceeding a certain damage state can be expressed as:

$$P_f\left(\frac{S}{R} > 1\right) = P\left(\frac{\theta_{max}}{D_i} > 1|PGA\right) = \Phi\left[\frac{ln\theta_{max} - lnD_i}{\beta_0}\right] \tag{7}$$

According to HAZUS99 [41], the value of β_0 can be taken as 0.5 when PGA is the ground shaking intensity index, and β_0 is taken as 0.4 when Sa(T1,5%) is the ground shaking intensity index. Therefore, the value of β_0 is taken as 0.5. Therefore, the transcendence probability of minor structural damage is:

$$P_{f_1} = \mathrm{P}\left(\frac{\theta_{max}}{D_1} > 1|PGA\right) = \Phi\left[\frac{\ln \theta_{max} - \ln D_1}{\beta_0}\right] = \Phi\left[\frac{c \ln PGA - d - \ln \frac{1}{900}}{0.5}\right] \tag{8}$$

So, the remaining three curves are:

$$P_{f_2} = \Phi\left[\frac{clnPGA - d - ln\frac{1}{500}}{0.5}\right] \tag{9}$$

$$P_{f_3} = \Phi\left[\frac{clnPGA - d - ln\frac{1}{200}}{0.5}\right] \tag{10}$$

$$P_{f_4} = \Phi\left[\frac{clnPGA - d - ln\frac{1}{100}}{0.5}\right] \tag{11}$$

2.4. Seismic Hazard Analysis

Cornell's study [42] in 1968 found that the seismic hazard curve (the probability that the seismic parameters at a site exceed A) can be expressed as:

$$P = H(PGA > A) = k_1 A^{k_2} \tag{12}$$

Taking the logarithm of both sides yields:

$$\log P = \log H(PGA > \mathrm{A}) = \log k_1 + k_2 \log A \tag{13}$$

Combining this theory and consulting the map of ground vibration parameter zones in China (http://www.gb18306.net/ (accessed on 5 December 2022)), for example, in the area where the design earthquake *PGA* = 0.1 g, under the 50-year exceeding probability specified in the building seismic code, the exceeding probabilities *P* corresponding to multiple encounter, basic, rare, and very rare are 63.00%, 10.00%, 2.00%, and 0.50%, and the *A* values of the four probability levels for different site categories can be calculated by clicking on the geographic location where the prefabricated building is located on the graph. After that, according to the data of these four points, importing the origin plot fitting can yield the values of k_1 and k_2, as well as plotting the seismic hazard curve.

2.5. Building Depreciation Model

The present value of the building product itself is not constant over its useful life; its present value depreciates over time. The depreciation of a building in terms of valuation is the loss in value of a building due to various reasons and is equal to the difference between the value of the building at the valuation point and its original cost. There are three main causes of building depreciation: physical depreciation, functional depreciation and economic depreciation. Physical depreciation is the loss of building value caused by physical aging, damage, etc.; functional depreciation is the loss of building value caused by the relative lack, backwardness or excess of building functions; economic depreciation is the loss of building value caused by various unforeseen unfavorable factors of the building itself. Depreciation in this article refers to both material depreciation and economic depreciation. Physical depreciation is due to the damage caused to the building by the earthquake, while economic depreciation refers to the decrease in value of the building as it is put into service for an increased period of time.

For economic depreciation, let the useful life of a building be *N* years, the present value of the building at the moment of the end of the year t is *V*, the salvage rate is γ, the salvage value is *S*, the discount rate is r, and the original cost of the building is *C*. The degree of loss is equal to the present value of the structure before failure multiplied by the loss ratio to obtain the full cost of the required expenditure. Depending on the depreciation method, the straight-line depreciation method, double declining balance depreciation method, and sinking fund depreciation method are mainly considered [43–45]:

Straight-line depreciation method:

$$V = C - (C - S)\frac{t}{N} \tag{14}$$

Double-declining balance depreciation method:

$$V = C\left(1 - \frac{2}{N}\right)^t \tag{15}$$

Debt service fund depreciation method:

$$V = C\,[1 - (1 - \gamma)\frac{(1 + r)^t - 1}{(1 + r)^N - 1} \tag{16}$$

For the straight-line depreciation method, the depreciation curve is a straight line, which is relatively simple to calculate, but the straight-line method does not consider the time value of money; the double declining balance method is generally used for the calculation of accounting depreciation; in fact, the study believes that the depreciation of the value of the building when it is first put into use should be slow first and then fast, while the double declining balance method is fast and then slow, which is inconsistent with the actual law of value change of the building. The sinking fund depreciation method considers the influence of interest, i.e., the time value of money, and is consistent with the objective law that depreciation slows down at the beginning and accelerates at the end, so this paper intended to use the sinking fund depreciation method to calculate the present value of the case assembly building. A diagram of the three different depreciation methods is shown in Figure 1:

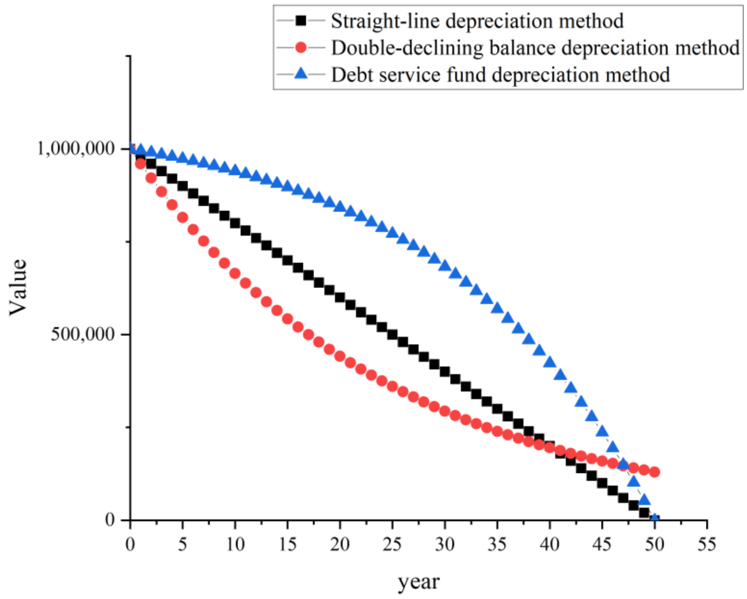


Figure 1. Comparison of different depreciation methods.

After considering depreciation, we can first calculate the annual material depreciation of the prefabricated building due to the earthquake R_A without considering the economic depreciation. Then, we can obtain the actual loss of the building every year based on economic depreciation and accumulate them to yield the total expected loss over the service life of the prefabricated building.

3. Case Studies

3.1. Case Overview

It should be noted that the cases in this paper are derived from paper [13]. The case is a residential building located in Nanjing, Jiangsu Province, with 27 floors above ground and 1 floor below ground, with a total building height of 80.75 m, and we assume it to be located in Xuanwu District. It was designed and built according to "Technical specification for concrete structures of high-rise buildings" JGJ3-2010, "Technical specification for precast concrete structures" JGJ 1-2014 and "Code for Seismic Design of Buildings" GB50011-2010. The main structure of the project adopts the assembled monolithic shear wall structure system, prefabricated sandwich heat preservation recombination clips walls are used for the east and west gable walls, the floor adopts a laminated floor slab, the balcony uses prefabricated balcony panels, the staircase employs prefabricated staircase sections, with a structural floor height of 2.9 m for the natural floor, 5.6 m for the basement floor and 5.95 m for the first floor, and the wall thickness is 0.2 m. The concrete grades are C45, C40, C35 and C30 in descending order as the floor height rises. The seismic intensity of Xuanwu District, Nanjing City, where the project is located, is 7 degrees, and the design basic seismic acceleration value is 0.1g, Class II site, T_g = 0.35s. The reinforced concrete shear walls of the first and second basement levels of the structure are cast-in-place. The east and west gable walls above the second floor are assembled shear wall structures with grouted sleeve connections, while the rest of the interior walls are all cast-in-place.

3.2. Calculation Process

The constitutive model for concrete and reinforcement is referenced from the literature [13]. The overall structure was modeled using MIDAS. The beams and columns adopted the rod unit element, and the shear walls adopted the 3D wall unit that comes with the software as shown in the Figure 2. The overall model of the structure is shown in Figure 3. A centralized plastic hinge model and clough hysteresis model were used in order to improve computational efficiency. Ten seismic waves were selected from PEER and China earthquake administration (CEA): El Centro, Northridge, Loma Prieta, Miyagi Coast, Hollywood, Kobe, Chichi, Imperial Vally, Tangshan and Tianjing. The finite element software MIDAS was used to perform dynamic elasto-plastic time analysis on each sample separately and obtain the maximum inter-layer displacement angle.

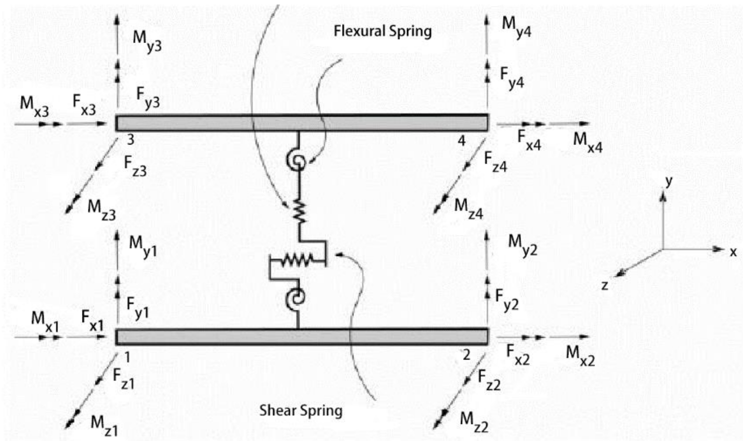
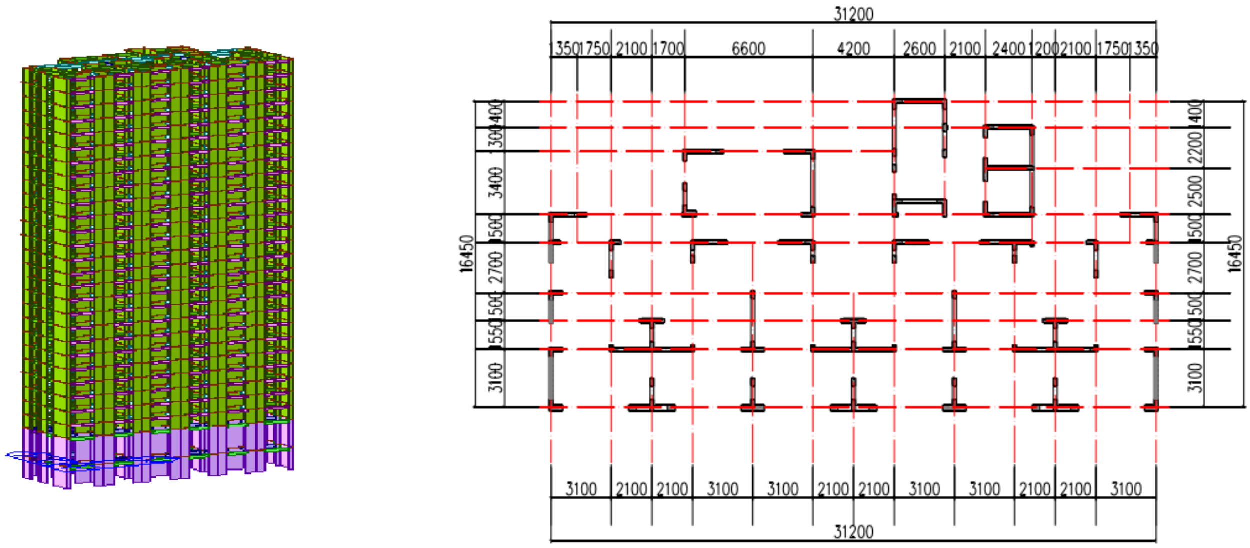


Figure 2. 3D wall unit.



(**a**) (**b**)

Figure 3. (**a**) Model of assembled shear wall structure; (**b**) Wall and column arrangement of the structure.

According to the existing literature's analysis of the case model, this paper obtained the maximum inter-layer displacement angle for the time course analysis [13], and in this paper, ten seismic wave data were taken from it, and the results were imported into the Origin plotting software to generate scatter plots. The maximum inter-layer displacement angle obtained in the above figure was taken as the natural logarithmic value $\ln d_i$ and filled in the Table 2:

Table 2. Natural logarithmic values of maximum inter-story displacement angles of structures under the action of seismic waves of different intensities.

Seismic Wave Number	PGA						
	0.1 g	**0.2 g**	**0.3 g**	**0.4 g**	**0.5 g**	**0.6 g**	**0.7 g**
A1	−7.1691	−6.5571	−6.1611	−5.864	−5.6158	−5.4081	−5.2269
A2	−6.8401	−6.2399	−5.8465	−5.5545	−5.3063	−5.0995	−4.9213
A3	−6.4695	−5.8465	−5.4491	−5.1499	−4.8995	−4.6907	−4.5117
A4	−5.8640	−5.2591	−4.8652	−4.5708	−4.3222	−4.1148	−3.9358
A5	−6.6377	−6.1013	−5.7169	−5.4081	−5.1277	−4.8915	−4.6853
A6	−7.0703	−6.5431	−6.1563	−5.8500	−5.5675	−5.3308	−5.1260
A7	−6.6377	−6.1013	−5.7169	−5.4081	−5.1277	−4.8915	−4.6853
A8	−6.2765	−5.7446	−5.3581	−5.0515	−4.7712	−4.5347	−4.3291
A9	−6.1563	−5.6296	−5.2438	−4.9378	−4.6575	−4.4220	−4.2165
A10	−7.3698	−6.8216	−6.4378	−6.1239	−5.8430	−5.6076	−5.4015

Then using the plotting software Origin2021b, the fitting operation was performed as shown in Figure 4:

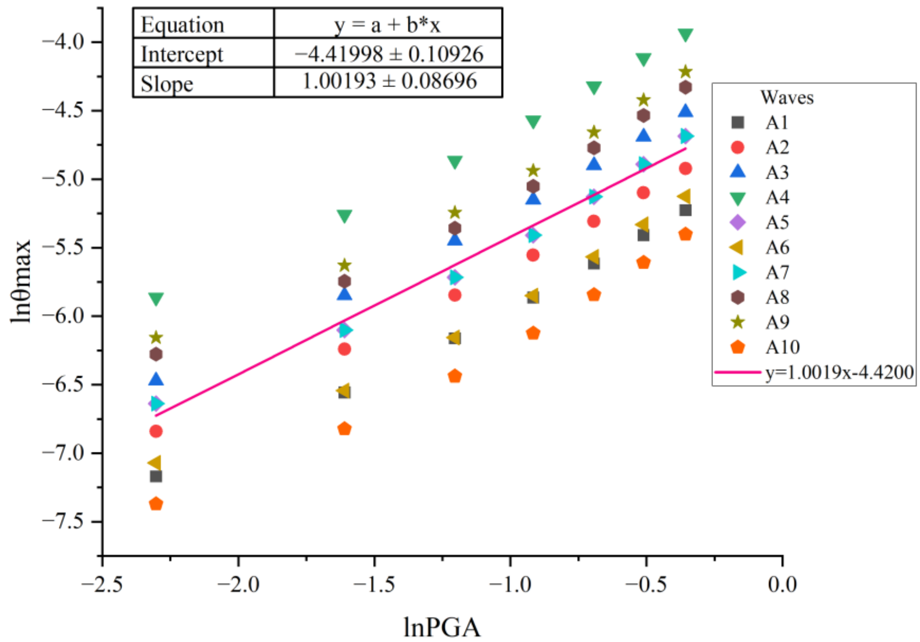


Figure 4. The fit of the $\ln\theta_{max}$ to the $\ln PGA$.

In this way, we can obtain the relationship between the *PGA* and the logarithmic value of the maximum inter-layer displacement angle:

$$\ln\theta_{max} = 1.0019 \ln PGA - 4.4200 \quad (17)$$

Now let us substitute Equation (17) into Equations (8)–(11); we can plot the earthquake vulnerability curve of the building as shown in Figure 5:

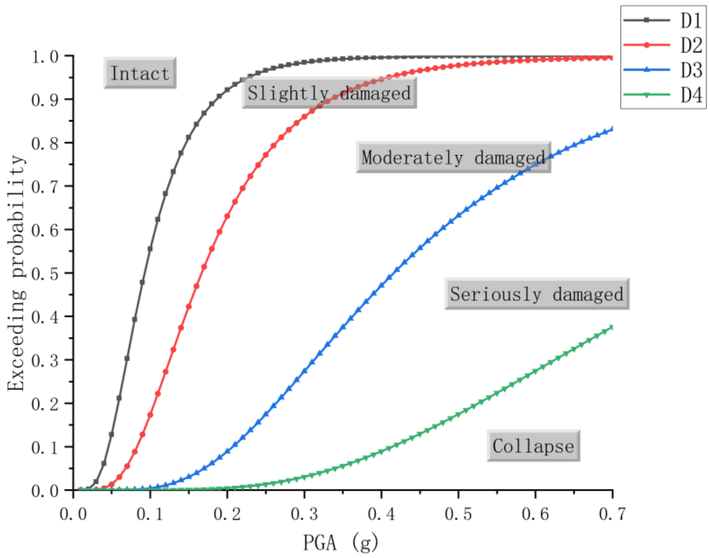


Figure 5. Probability of exceeding each failure state of prefabricated building structures at different PGA levels.

Referring to the zoning map of ground shaking parameters in China, it can be seen that the PGAs of the project site are 0.033 g, 0.100 g, 0.190 g and 0.300 g for multi-encounter ground shaking, basic ground shaking, rare ground shaking and very rare ground shaking, respectively.

The analysis curve shows that at a seismic intensity of 6 degrees and below (PGA < 0.05 g), the prefabricated building structure is basically in good condition; at a seismic intensity of 7 degrees to 8 degrees (0.1 g < PGA < 0.3 g), the probability of moderate damage to the prefabricated building structure gradually increases, and the probability of serious damage begins to increase; at the rare ground shaking level (0.19 g), the probability of collapse of the prefabricated building structure is only 0.00155, and even at the very rare ground shaking level (0.30 g), the probability of collapse of the prefabricated building structure is only 0.020567, which is also at a very low level.

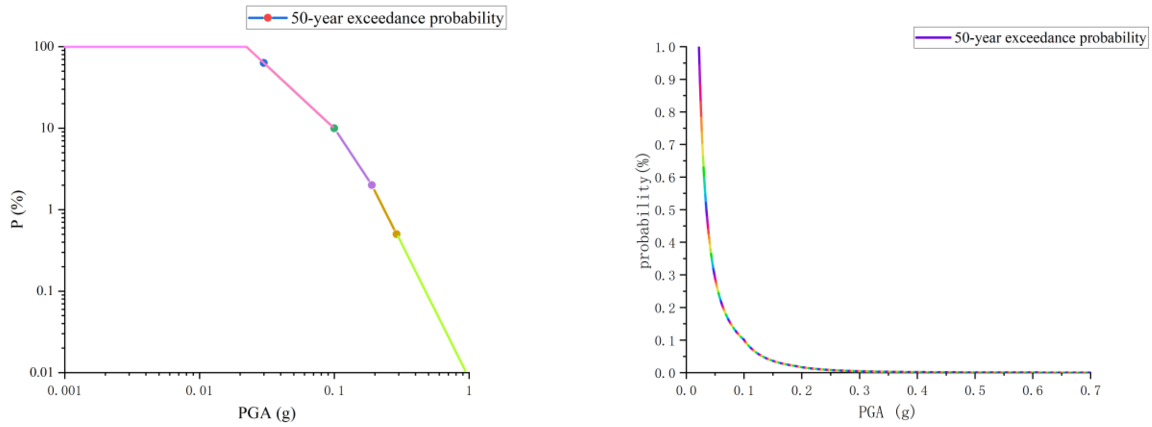
In order to simplify the calculation, the seismic hazard curve was approximated as a segmented straight line when plotted in a double logarithmic coordinate system in this paper.

It is known that the peak acceleration of basic ground shaking in Xuanwu district is 0.1 g, a Class II site. To analyze the seismic hazard in the area with a peak acceleration of 0.1 g, we first consulted the ground shaking parameter zoning map of China and obtained the following Figure 6 of the 50-year exceeding probability of the peak ground shaking acceleration PGA in the area (first segment: k1 = 0.00305, k2 = −1.52; second segment: k1 = 0.000311, k2 = −2.51; third segment: k1 = 0.0000856, k2 = −3.28).

From the relationship between PGA and earthquake intensity delineated in the Chinese Seismic Intensity Table, the houses are almost intact when the earthquake intensity is IV and below, so they are considered starting from V intensity. To simplify the calculation, in this paper, the fragility curve was discretized into a matrix of five columns from five degrees to nine degrees as shown in Table 3:

Table 3. Correspondence table between seismic intensity and PGA.

Seismic Intensity	The Performance of Housing Damage	Range of PGA (g)	Typical PGA Values (g)
V	Small cracks at plastering and plastering	0.022~0.044	0.031
VI	Small cracks appear in the wall	0.045~0.089	0.063
VII	Cracking of the wall occurs	0.090~0.177	0.125
VIII	Moderate structural damage occurs	0.178~0.353	0.250
IX	Severe structural damage or even collapse	0.354~0.707	0.500



(a) (b)

Figure 6. (**a**) Seismic hazard curve of the zone (logarithmic coordinates); (**b**) Seismic hazard curve of the zone (general coordinates).

In order to simplify the calculation, we used the probability of different damage states in the state of "Typical PGA values"; therefore, the probability of different damage states at 0.031 g represents the probability of different damage states at an earthquake intensity of V, and so on. Therefore, the probability of buildings being in different states under different intensities of earthquakes is shown in Table 4.

Table 4. Damage probability matrix for different earthquake intensities.

Seismic Intensity	V	VI	VII	VIII	IX
Intact	0.962690	0.812103	0.350824	0.128737	0.109069
Slightly damaged	0.034891	0.157257	0.388316	0.206029	0.023837
Moderately damaged	0.002416	0.030441	0.250714	0.543084	0.363558
extensively damaged	0.000003	0.000199	0.009996	0.114639	0.390727
Collapse	0.000000	0.000001	0.000151	0.007510	0.112809

Based on the 50-year earthquake hazard curve, we can calculate the probability of occurrence of earthquakes of different intensities at the site, as shown in Table 5.

Table 5. Probability of occurrence of earthquakes of different intensities.

Seismic Intensity	V	VI	VII	VIII	IX
Probability of occurrence	0.660315	0.221415	0.094866	0.021089	0.002315

Now, we multiply Table 4 with Table 5, and we can calculate the probability of occurrence of different levels of damage to the building, as shown in Table 6.

Table 6. Probability of occurrence of different levels of damage to the building.

Structure Status	Probability of Occurrence
Intact	0.851739
Slightly damaged	0.099096
Moderately damaged	0.044415
Extensively damaged	0.004316
Collapse	0.000434

Reference indexes for the investment estimation of an assembled concrete residential project in China can be accessed in the Consumption Quotas for Assembly Building

Projects [46], and the PC rate of 40% is taken for assembled concrete, high-rise buildings in the reference quotas in this paper, as shown in the Table 7.

Table 7. Reference index for investment estimation of an assembled concrete high-rise building with 40% PC rate.

Project Name	Unit	Cost	Percentage
Estimated reference indicators	Yuan/m^2	2396.00	100.00%
Construction and safety costs	Yuan/m^2	2037.00	85%
Other costs of construction	Yuan/m^2	240.00	10%
Preliminary costs	Yuan/m^2	120.00	5%

The estimated cost (physical depreciation) is about 11,374.16 m^2 $\times$ 2396 yuan/m^2 = 27,252,487.36 yuan, and the average annual loss is 17,203.07814 yuan.

The case assembly building is a steel-composite structure, and a review of the information showed that the residual value of this structure is generally taken as 0%, and the fund interest rate is taken as 5%. Thus the value of the building over its life cycle is shown in Figure 7.

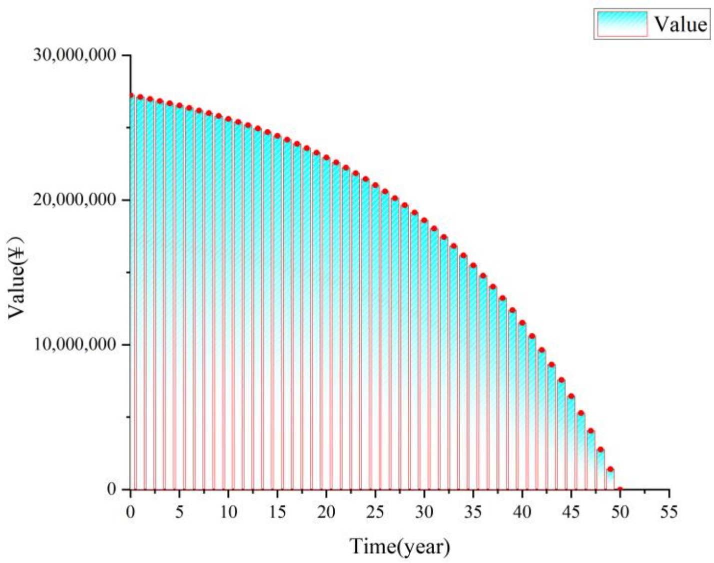


Figure 7. Depreciation over the useful life of the building.

Therefore, the total risk value (expected loss) of the building during its 50-year service life is ¥589,735.3013, and the average annual risk value is ¥11,794.70603. The proportion of total expected loss to the estimated cost of investment in this building is about ω = 589,735.3013/27,252,487.36 $\approx$ 2.16%.

This paper refers to the concept of risk allowance, sets the risk indicator as the total expected loss over the design life of the structure divided by the original estimated investment cost, roughly considers about 10% of expected loss as a medium risk, and classifies the risk level as shown in Table 8:

Table 8. Risk level and risk indicators.

Expected loss/Estimated Cost of Investment	Risk Level	Risk Color
Less than 1%	Negligible risk	
1~5%	Low risk	
5~15%	Medium risk	
15~40%	High risk	
More than 40%	Catastrophic risk	

For the risk of structural failure of prefabricated buildings, negligible or low risk levels are generally acceptable risks; for low and medium risks, consideration can be given to purchasing catastrophic insurance, earthquake insurance, etc., to transfer the risk, or strengthening the seismic design of the building in the design and imposing seismic devices on the structure to mitigate or prevent the risk; for high or catastrophic risks, risk avoidance can be considered, such as abandoning the original structural design and redesigning the structure.

4. Conclusions

In this paper, based on the study of previous work on fragility analysis, seismic hazard analysis and risk theory, the general methods of fragility analysis and hazard analysis were summarized and combined with the economic depreciation model, and an evaluation method of structural failure risk of the prefabricated buildings was proposed and successfully applied to the case.

(1) The vulnerability curve of a prefabricated building was established based on the IDA method. The data corresponding to the maximum inter-story displacement angle and PGA were fitted by using Origin2021b software analysis, the log-linear relationship between the maximum inter-story displacement angle and PGA was determined, and the probability curve of the vulnerability of prefabricated building was obtained by combining with the principles of statistics.
(2) The seismic hazard curve of the prefabricated building site was established under the double logarithmic coordinate system based on Cornell's calculation model, the parameters of seismic intensity zoning, and the case project profile.
(3) The cost of the prefabricated building was estimated by consulting the fixed rate as well as the floor area calculation code, and the risk was calculated by combining the three. Finally, the risk calculation was placed in the framework of the economic depreciation model, the risk of structural failure of the prefabricated building under earthquake action was calculated considering the depreciation condition, and the total seismic risk value of its prefabricated building in 50 years was evaluated in the case as ¥589,735.3013, with a total loss ratio of 2.16% and a low risk level, which verified the risk evaluation method for the structural failure of the prefabricated building. The feasibility and effectiveness of the risk evaluation method for structural failure of prefabricated buildings were verified.

In this paper, a preliminary study on a set of structural failure risk evaluation methods applicable to prefabricated buildings under the action of earthquakes was conducted, and tangible and intangible losses were integrated. The methodology in this paper helps to provide some reference for the seismic risk assessment of the design solutions of prefabricated buildings. The main weakness of the study is the failure to use new methods in the field of vulnerability analysis and hazard analysis that have been researched in academia, and this paper only considers the economic loss of the building itself. A building seismic risk assessment requires a combination of vulnerability analysis, seismic hazard analysis and damage assessment. The reliability of a seismic risk assessment is determined by the scientific basis and applicability of these methodologies. Therefore, in the future, we will try to adopt more cutting-edge methods to comprehensively assess the seismic risk of this type of building as an assembled building. In future research, the losses caused by downtime can be subsequently considered in the earthquake loss estimation, and the method helps to assist managers in decision making and achieve the purpose of disaster prevention and mitigation.

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