SEISMIC VULNERABILITY OF BUILDINGS UNDER CONSTRUCTION IN CHINA

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ABSTRACT :

Rapid economic growth in China over the past decade has resulted in an increasing number of new building construction projects. As a result, investors, contractors, and the insurance industry are calling for additional seismic risk assessments of buildings under construction. Unlike the risk of existing buildings, the vulnerability and replacement value of a building under construction vary over time, and its risk to the contractor diminishes upon the completion of construction. Relying on the vulnerability function and the total value at the finished state to provide an estimate of monetary damage may lead to inaccurate results. Drawing on examples of steel constructions in China, derivation of progressive vulnerability and statistics of their construction period and cost, this paper presents a framework designed to account for the time-dependent nature in managing this type of construction risk in the case of earthquakes. The proposed method can be used by insurance companies for both pricing and portfolio risk assessment, and it could also be easily extended for site-specific seismic risk assessment for buildings under construction.

KEYWORDS: Seismic, builder's risk, building vulnerability

1. INTRODUCTION

During the past decade rapid economic growth in China has resulted in an upsurge of new building construction averaging 15% growth annually. According to national statistics, by the end of 2008, the total floor areas of new construction are estimated around 1.8 trillion square meters. However, since China is an earthquake-prone country, many of those developments are under the threat of destructive earthquakes, as seen in the 1976 M7.8 Tangshan and 2008 M8.0 Wenchuan earthquakes. Thus, the demand for earthquake insurance coverage for these new buildings has increased, especially in regions where such coverage is mandatory. However, catastrophe risk poses challenges to insurers - who are developing strategies for pricing, underwriting, risk transfer and overall portfolio management since historical loss data is typically scarce. In the case of low probability catastrophes, insurers have to rely on a scientific assessment which requires an understanding of seismic hazard and the vulnerability function of general seismic risk assessment under construction.

In seismic risk analyses, the goal of the vulnerability function is to examine the relationship between ground motion and the buildings damage. That damage is usually expressed as a ratio of the repair cost to the building's replacement cost (cost to reconstruct the building). For a finished construction (refers to a conventional or existing building in this paper), its replacement cost and vulnerability are independent of time. However, for a building under construction, the vulnerability and damage both vary over the course of construction. An appropriate assessment of the seismic risk for buildings under construction is crucial.

To address the gap in assessing different construction risk types, a cost ramp function, the gradually-increasing relationship between the replacement cost and time, was developed. Illustrated by steel constructions in China, statistics of their construction period and cost were gathered to formulate the cost ramp function. Computational models of a 20-story SMRF (Steel Moment Resisting Frame) building at various stages of construction were created and the levels of damage in response to ground motions were evaluated analytically. The results were used to develop a vulnerability function that varies over time.

The objective of this paper is to illustrate a framework, including the development of the cost ramp and the time-dependent vulnerability functions, that enable risk modelers and managers to better assess construction risks for earthquakes.

2. CONSTRUCTION RISK ASSESSMENT METHODOLOGY

The proposed framework follows the methodology of standard probabilistic loss estimation. An expected loss $\overline{E}$ for a risk within the next year due to an earthquake can be expressed in a simple form in Eqn. (1), where $P[EQ]$ is the annual probability of occurrence of the earthquake, and $E[Loss|EQ]$ is the loss conditioned on ground motion intensity caused by the earthquake,

$$\overline{E} = E[Loss|EQ] \cdot P[EQ] \tag{1}$$

The conditional loss is a product of building replacement value and damage ratio estimated from a vulnerability function given the ground shaking severity. For a conventional building risk, and let DR_0 and V_0 represent its damage ratio and replacement value respectively, Eqn. (1) can be rewritten in the form of,

$$\overline{E}_0 = DR_0(GM)V_0 \cdot P[EQ] \tag{2}$$

As stated above, this estimate will not change no matter when the earthquake hits the finished building, and subscript *0* implies this independency. However, in case of a construction risk, the loss differs dramatically if the earthquake occurs at the beginning or the end of a construction. Eqn. (2) then can be generalized as,

$$\overline{E}(t) = DR(GM,t)V(t)\cdot P[EQ] \quad (0 \le t \le T) \tag{3}$$

where T is the total construction period, and $\overline{E}(t)$ is the expected loss within the next year if the earthquake occurs at time t during the construction. For a probabilistic risk analysis, an earthquake could happen at any time during construction, and an average, which assumes equal probability of various possible losses, is considered the best estimate. This is particularly true for a risk assessment of a large portfolio, where some projects may have just started, some are close to finishing while others are in the middle of the construction. A mathematical expression for the average is,

$$\overline{E} = \left(\int_0^T DR(GM,t)\ V(t)\ \mathrm{d}t \right) \cdot P[EQ] \quad (0 \le t \le T) \tag{4}$$

The integration over the construction time T reflects the insurer's effective coverage period, and $\overline{E}$ becomes an average loss over the project period. If the time-dependent functions *DR(GM, t)* and *V(t)* are normalized by their respective values at the finished states of $DR_0(GM)$ and V_0 ($t = T$), the above equation can be rephrased to,

$$\overline{E} = \left(\int_0^T dr(GM,t)\ v(t)\ \mathrm{d}t \right) \cdot DR_0(GM) \cdot V_0 \cdot P[EQ] \quad (0 \le t \le T) \tag{5}$$

where $dr(GM, t) = DR(GM, t)/DR_0(GM)$ and $v(t) = V(t)/V_0$ are the normalized damage ratio and replacement value functions, respectively. Theoretically, the *dr* is a function of ground motions as stated, and consequently a function of earthquakes as well. The implication is that the integration has to be repeated for every location and every earthquake although the building under construction is identical. It is found that, under the same set of ground motions, the variation of *dr* is much lower than that of DR_0. Thus an assumption that the normalized damage ratio function *dr* is independent of ground motions is introduced to simplify the above calculation. A mean value of the *dr(GM,t)* computed using the set of ground motions is used in the estimation of the average risk. Based on this assumption and referring to Eqn. (2), the above equation can be simplified as,

$$\overline{E} = \rho_{avg} \cdot \overline{E}_0 \tag{6a}$$

$$\rho_{avg} = \int_0^T dr(t) \cdot v(t)\,\mathrm{d}t \quad (0 \le t \le T) \tag{6b}$$

where *dr(t)* is the mean value of *dr(GM, t)*, and Eqn. (6a) suggests that the construction risk can be estimated as a fraction of its corresponding risk at finished state, and the adjustment factor can be pre-calculated since they are independent of earthquakes. This simplification provides great convenience for risk modelers and assessors when the assessment for a conventional building is already known.

3. DERIVATION OF NORMALIZED REPLACEMENT VALUE FUNCTION

In order to derive these time dependent functions, construction progress is divided into the following general five phases: foundation and substructure, superstructure and roofing, finishing (including installation of windows, doors, ceilings and etc.), mechanical and electrical installation, and final inspection. The building's seismic vulnerability is very low at the foundation and substructure phase, then increases rapidly during the superstructure phase, and reaches is finished state when approaching the finishing phase.

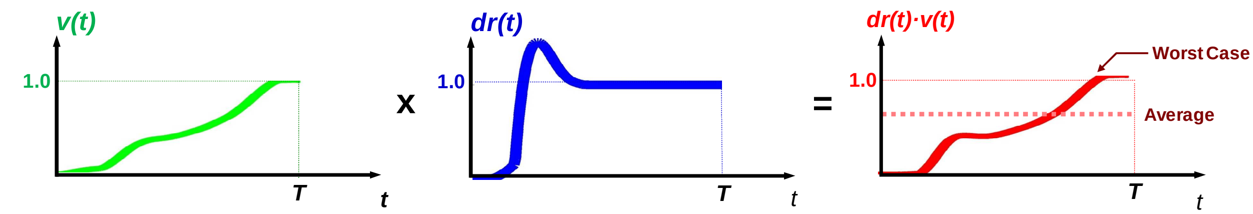

Figure 1: Graphical Illustration of Normalized Replacement Value *v(t)* and Damage Ratio *dr(t)* Functions, and the Computation of Adjustment Factor

Data of construction spending and period in China from various sources are collected to derive the normalized replacement value function. The sources include Huang and Zhang (2005), Yan (2004), various real estate web sites and personal communication with local engineers and contractors. For better classification, the spending and period are grouped by the construction types (RC or steel) and by the building height, which are categorized as low, mid, high and tall, representing buildings with 1 – 3, 4 – 9, 10 – 29, and 30+ stories, respectively. Table 1 summarizes the average construction durations and costs in percentage for steel constructions in each phase varied by heights.

Assuming a spending distribution over each phase, a normalized replacement value ramp function can be derived based the data set in Table 1, which is symbolically illustrated on the left-most plot of Figure 1.

Table 1: Duration and percentage cost of typical steel buildings in China classified by phases and heights

	Mean Duration, year				Mean Percentage Cost			
Construction Phase	**Low**	**Mid**	**High**	**Tall**	**Low**	**Mid**	**High**	**Tall**
Foundation & Substructure	0.08	0.17	0.38	0.42	6.5	4.9	4.2	3.6
Superstructure & Roofing	0.05	0.17	0.33	0.71	17.0	18.3	18.9	21.2
Finishing	0.13	0.25	0.42	0.58	35.3	34.2	34.0	32.5
Mechanical & Electrical	0.13	0.21	0.38	0.50	38.8	40.2	40.6	40.5
Final Inspection	0.04	0.07	0.13	0.13	2.3	2.3	2.3	2.1
Total	0.43	0.87	1.64	2.34	100.0	100.0	100.0	100.0

4. DERIVATION OF NORMALIZED DAMAGE RATIO FUNCTION

Derivation of the ground motion independent average *dr(t)* function is quite complicated. First of all, computational models of a typical building at different instances need to be created, and a suite of ground motion time histories, each representing a different level of hazard, is selected. Computational models are analyzed subjected to these ground motions to calculate their maximum inter story drift ratios, which are the basis for damage estimates. The damage then is normalized by its respective damage at the finished state to create a series of *dr(GM, t)*. Finally, the average of all *dr(GM, t)* leads to the ground motion independent function of *dr(t)*.

To elaborate this process, a 20-story steel moment-resisting frame (SMRF) new construction was selected for illustration. Since the vulnerability at the foundation and substructure phase is very low and the vulnerability from the finishing phase can be assumed to be close to that the building at its finished state, structural analyses are focused only on the superstructure and roofing phase. Thus computational models for this new construction are built at the instances of 2-, 5-, 8-, 11-, 14-, 17- and 20-story, respectively, as shown in Figure 2.

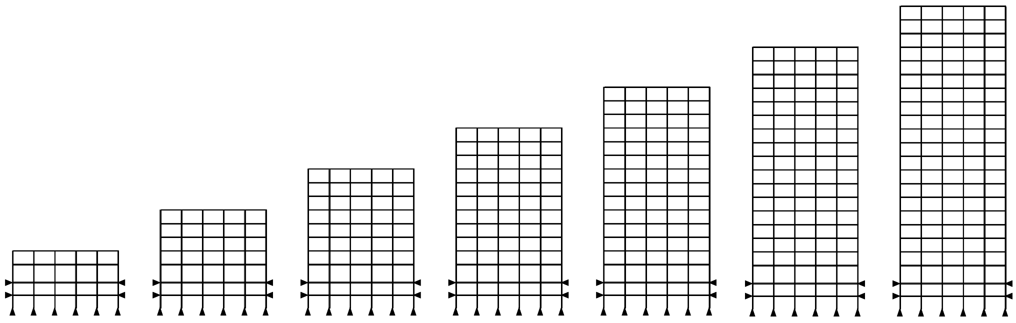

Figure 2. Computer Models to Represent Seven Construction Instances.

A suite of 60 ground motion records (SAC 1997) was selected for dynamic analyses. This suite is representative of earthquakes of various hazards with PGA ranging from 0.1*g* to 1.3*g*. Consequently, a total of 420 dynamic time history structural analyses are performed, and results are used to derive the ground motion independent and normalized damage ratio function. The central plot in Figure 1 is a symbolic function of this study. As highlighted in the graph, the vulnerability increases dramatically after the foundation and substructure phase, and goes beyond 1.0 (which means more vulnerable than its finished state), and falls back to 1.0 at the beginning of the finishing phase. For this particular case, the most vulnerable periods are during the substructure and roofing phase, where the building's fundamental periods are closer to the dominant frequency of earthquake shaking. For an RC construction, the vulnerability can even be higher because concrete has not reached its design strength during the construction.

The product of the two normalized functions is illustrated on the right-most plot of Figure 1. It clearly suggests that the worst-case scenario will be a situation when an earthquake strikes near the completion of a project. Although the vulnerability during the superstructure and roofing phase is very high, its risk is mitigated due to the relatively low replacement value in that period. For probabilistic risk assessment, the average is considered the best, where the risk is overestimated at early stage and underestimated at later stage.

5. APPLICATION TO INSURANCE INDUSTRY

One has to be cautious how Eqn. (6) is used for risk assessment. As stated before, Eqn. (6a) estimates an expected average loss during the entire project. It can be used for insurance pricing of policies that cover the entire construction period. However, when assessing risk of a portfolio for the next 12 months, especially a portfolio including conventional risks, the project wide expected loss, that spans over a one year period, it needs to be annualized for appropriate aggregation. The following two equations elaborate the difference for easy application.

$$\bar{E}_{APL} = \rho_{avg} \cdot \bar{E}_0 \qquad (7a)$$

$$\bar{E}_{AAL} = \frac{1}{T}\rho_{avg} \cdot \bar{E}_0 \quad (T \geq 1.0) \qquad (7b)$$

where the subscripts APL and AAL stand for Average Project Loss and Average Annual Loss, respectively. Table 2 tabulates the average adjustment factors derived by the authors.

Table 2: Average adjustment factor ρ_{avg} for steel construction in China

	Low (1-3)	**Mid (4-9)**	**High (10-29)**	**Tall (30+)**
Steel	0.25	0.38	0.61	0.92

6. SUMMARY

A framework, compatible with a full probabilistic risk analysis, is proposed for estimating the seismic risks of buildings under construction. The framework accounts for the time-dependency of vulnerability and replacement cost over the course of construction, and is further simplified for an easy application with the conventional risk assessment. Different formulas are given explicitly for the purposes of insurance pricing and portfolio risk assessment. Data on various construction spending and period in China are collected and analyzed. Average values of the spending and period of typical steel constructions is presented for various height classifications. A 20-story steel building is then used as an example to illustrate the development of time dependent vulnerability functions. Finally, a set of adjustment factors relative to the risk of conventional buildings is presented for an easy application. This framework could be extended to general seismic risk assessment under construction.

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