EARTHQUAKE LOSS ESTIMATION OF INDIVIDUAL BUILDINGS BASED ON CONVEX SET MODEL

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ABSTRACT :
Probabilistic results drawn upon inadequate information, as usually happen, are suspicious. The uncertainties of spectrum displacement, damage state medians and loss ratio are considered with the bound envelope convex set model, and a bound loss estimation method is derived by integrating HAZUS-AEBM module with the convex set theory. The loss estimation results of a hotel in southern China shows that the loss by HAZUS-AEBM method locates in the lower half intervals of convex analysis results. The PEER's probabilistic loss estimation methodology is also applied to this hotel to demonstrate the benefits of the bound loss estimation method proposed in this study.

KEYWORDS:
uncertainty, convex set theory, earthquake loss estimation

1. INTRODUCTION

The Performance-base Earthquake Engineering demands that performance of buildings can be accurately predicted and evaluated. As a result, it is very essential to deal with the uncertainties in the process of performance evaluated, from seismic hazard analysis to the assessment of earthquake consequence. The probabilistic theory has been proven to be successful in dealing with uncertainty in engineering. However, when the data is insufficient to support a probabilistic assumption, the limitations and disadvantages of stochastic methods emerge in this situation, and thus decisions made from a pure stochastic approach may be questionable.

In this study, the non-probabilistic convex set theory is employed to deal with the uncertainties of spectrum displacement, damage state medians and loss ratio. A new bound earthquake loss estimation method for individual building is proposed in the framework of HAZUS procedure. Finally, the bound loss estimation method and the PEER's probabilistic loss estimation methodology are applied to a hotel in southern China.

2. LOSS ESTIMATION THEORY IN HAZUS-AEBM AND UNCERTAIN ANALYSIS

The Advanced Engineering Building Module (AEBM) is an extension of the HAZUS earthquake loss estimation methodology, and it is developed for building-specific damage and loss assessment.

2.1. Fragility Analysis Module

Buildings fragility curves are lognormal functions in HAZUS- AEBM that describe the probability of reaching, or exceeding, structural and nonstructural damage states, given median estimates of spectra response, for example spectral displacement (NIBS, 2002). The conditional probability of being in, or exceeding, a particular damage state, ds , given spectral displacement S_d , is defined by Eq.(2.1):

$$P\left[Ds \ge ds \middle| S_d\right] = \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d}{\overline{S}_{d,ds}}\right)\right] \quad (2.1)$$

Where $\overline{S}_{d,ds}$ is the median value of spectra displacement at which the building reaches the threshold of damage state ds ; β_{ds} is the standard deviation of the natural logarithm of spectral displacement for damage state ds ; Φ is the standard normal cumulative distribution function.

With the fragility functions, the probability that structure will be in a certain damage state ds_i can be computed as the arithmetic difference between fragility functions corresponding to two consecutive damage states, as follows

$$PSTR_{ds} = \begin{cases} 1 - P\left[Ds \ge ds_i \middle| S_d\right] & i = 0 \\ P\left[Ds \ge ds_i \middle| S_d\right] - P\left[Ds \ge ds_{i+1} \middle| S_d\right] & 1 \le i \le m \\ P\left[Ds \ge ds_i \middle| S_d\right] & i = m \end{cases} \quad (2.2)$$

Where $i = 0$ corresponds to the state of no damage in the component.

2.2 Uncertain Analysis of Spectra Displacement

The capacity-demand diagram method is used to derive spectra displacement as input of fragility analysis. The demand spectrum and capacity spectrum involves many uncertain factors that arise from the earthquake phenomenon, structural geometries, material properties as well as the approximations and assumptions used in developing the structural models for seismic analysis.

As a result, the spectra displacement S_d in Eq.(2.1) is a uncertain variable. Taking into account the uncertainty of demand spectrum arises from the uncertainties of the earthquake influence coefficient maximum $\alpha_{\max}$ and the predominant period T_g in this section. Moreover, the uncertainty of capacity spectrum by different lateral load patterns of pushover analysis is also considered (Jia and Duan, 2008).

In this study, the envelope bound convex model is used to model the uncertainty of spectra displacement. The bound spectra displacement is as input of fragility analysis instead of the median value.

The medians $\overline{S}_{d,ds}$ of spectra displacement in Eq.(2.1) is another factor that give most contribution to the fragility analysis. The pushover curves are used to predict damage-state medians in HAZUS- AEBM Manual. In this section, the uncertainties of pushover curves result from different lateral load patterns and the uncertainties of the earthquake influence coefficient maximum $\alpha_{\max}$ and the predominant period T_g in SRSS load pattern are modeled. Guidance is provided according to the broad descriptions of structural damage given in HAZUS-MH Technical Manual to quantify the damage-state medians by pushover curves in Table 2.1.

Table 2.1 General guidance for selection of damage state medians

Damage State	Criteria for selection of damage state medians
Slight	The first structural component yield
Moderate	50% of structural component cracks or 10% of structural component yield
Extensive	75% of structural component cracks or 50% of structural component yield
Complete	90% of structural component cracks or 75% of structural component yield

2.3 Loss Estimation Module

The direct economic loss of structural system in HAZUS- AEBM Manual is calculated by Eq.(2.3) as follows

$$EL = RV \times \sum_{ds=2}^{5}(PSTR_{ds} \times STRD_{ds}) \tag{2.3}$$

Where RV is the replacement value of structural system; $PSTR_{ds}$ is the discrete probability in a certain damage state; $STRD_{ds}$ is the loss ratio for different damage states, it can be derived as

$$STRD_{ds} = \frac{RC}{RV} \tag{2.4}$$

Where RC is the repair cost of different damage states.

2.4 Uncertain Analysis of Loss Ratio

The earthquake loss estimation is closely correlated with the loss ratio of different damage states. The uncertainty of loss ratio most arise from the uncertainties of repair cost of different damage sates by Eq.(2.4). In the following, the factors may lead to the uncertainties of repair cost will be discussed.

For a certain damage state, different company may provide different repair process. The uncertainties of repair method lead to the uncertainties of repair cost. The repair cost is calculated as Eq.(2.5) after the repair method is presented.

$$TC = DC + IC + PP + RC \tag{2.5}$$

Where TC is the total repair cost; DC is direct repair cost; IC is indirect repair cost; PP is plan profit; RC is tax cost. DC , IC and RC are derived as follows

$$DC = LC + MC + FC + ODC \tag{2.6}$$

$$IC = AC + OIC \tag{2.7}$$

$$RC = YR + CR + ER \tag{2.8}$$

where LC is labor cost; MC is material cost; FC is facility cost; ODC is others cost; AC is construction management cost; OIC is other indirect cost; YR is business tax; CR is city construction management tax; ER is education additional tax. The area difference and price fluctuation will cause the uncertainty of total repair cost TC . In addition, the correlation of different components, demand expand after earthquake, the adjusting of seismic design code and mental effects of the owner give contribution to the uncertainty of total repair cost.

The interval of loss ratio is provided in Table 2.2 in this study (Yin, 1996), and then describing the uncertainties of loss ration using convex set model.

Table 2.2 The range of loss ratio of different damage state

Damage State	Range of loss ratio
Slight	1%-10%
Moderate	10%~40%
Extensive	40%~80%
Complete	80%~100%

3. BOUND LOSS ESTIMATION OF INDIVIDUAL BUILDINGS BASED ON CONVEX SET MODEL

3.1 Bound Fragility Analysis

The spectra displacement S_d and the medians $\overline{S}_{d,ds}$ of spectra displacement are variables with uncertainty. In this paper, the envelope bound convex set model (Elishakoff and Ben-Haim, 1990) as described in Eq.(3.1) and

(3.2)is employed to model the uncertainties of S_d and $\overline{S}_{d,ds}$,

$$S_d^* = \left\{ S_d^l \le S_d \le S_d^u \middle| S_d^l,\ S_d^u \in \mathrm{R},\ S_d^l,\ S_d^u \ge 0 \right\} \tag{3.1}$$

$$\overline{S}_{d,ds}^* = \left\{ \overline{S}_{d,ds}^l \le \overline{S}_{d,ds} \le \overline{S}_{d,ds}^u \middle| \overline{S}_{d,ds}^l, \overline{S}_{d,ds}^u \in R, \overline{S}_{d,ds}^l, \overline{S}_{d,ds}^u \ge 0 \right\} \tag{3.2}$$

Where S_d^u and S_d^l are the bounds of the spectra displacement; and $\overline{S}_{d,ds}^u$ and $\overline{S}_{d,ds}^l$ are those of he medians of spectra displacement.

As S_d^u and S_d^l are described as convex set variables by Eq.(3.1) and (3.2), The conditional probability of being in, or exceeding, a particular damage state in Eq.(2.1) by Kelly-Weiss theorem (Elishakoff and Ben-Haim, 1990) and Eq.(2.1), Eq.(3.1) and (3.2) is in the range of the set P^* defined as

$$P^*\left[Ds \ge ds \middle| S_d\right] = \left[\Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d^l}{\overline{S}_{d,ds}^u}\right)\right], \Phi\left[\frac{1}{\beta_{ds}} \ln\left(\frac{S_d^u}{\overline{\overline{S}}_{d,ds}^l}\right)\right] \right] \tag{3.3}$$

Combination Eq.(2.2) and (3.3), the bound set of discrete probability of structure be in a certain damage state are derived as

$$PSTR_{ds}^* = \left[PSTR_{ds}^l, PSTR_{ds}^u \right] \tag{3.4}$$

Where $PSTR_{ds}^u$ and $PSTR_{ds}^l$ are the bounds of $PSTR_{ds}$. Figure 1 and Figure 2 present the process of the fragility analysis and the bound fragility analysis developed in this paper.

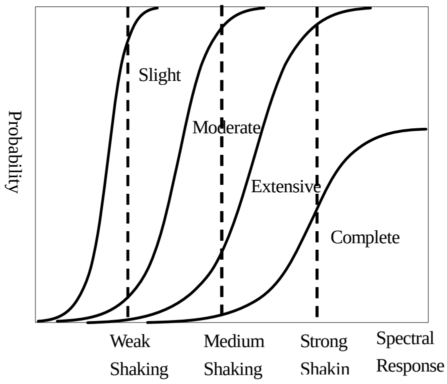

Fig 1. Fragility curves

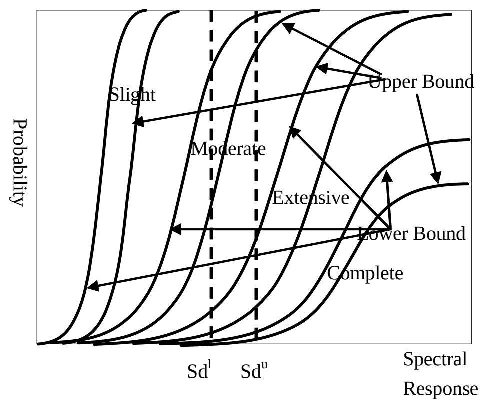

Fig2. Bound fragility curves

3.2 Bound Loss Analysis

The loss ratio varies in an interval as in Table 2.2, and the envelop bound convex set model is employed to model the uncertainty of loss ratio defined as

$$STRD_{ds}^* = \left\{ STRD_{ds}^l \le STRD_{ds} \le STRD_{ds}^u \middle| STRD_{ds}^l,\ STRD_{ds}^u \in \mathrm{R},\ STRD_{ds}^l,\ STRD_{ds}^u \ge 0 \right\} \tag{3.5}$$

Where $STRD_{ds}^l$ and $STRD_{ds}^u$ are the bounds of loss ratio.

According to Eq.(2.3), Eq.(3.4) and (3.5), the bound set of earthquake loss can be deduced as

$$EL^* = \left[RV \times \sum_{ds=2}^{5} (PSTR_{ds}^l \times STRD_{ds}^l),\ RV \times \sum_{ds=2}^{5} (PSTR_{ds}^u \times STRD_{ds}^u) \right] \tag{3.6}$$

In the following, earthquake loss estimation of an example is provided to demonstrate the benefits of the proposed method in this study.

4. EXAMPLE

In this example a hotel in southern China is analyzed (Figure 3 and 4). The column section is 400mm$\times$ 400mm, and the beam section is 250mm$\times$500mm. Column and beam concrete has nominal strength of $f_{cu} = 30\mathrm{N/m^2}$, slab concrete is nominally $25\mathrm{N/m^2}$. Column and beam reinforcement steel is scheduled as HRB335, and hoop reinforcement steel is scheduled as HPB235. The site class is Ⅱ, and the seismic fortification intensity is 8 degree according to GB50011-2001 (2001).

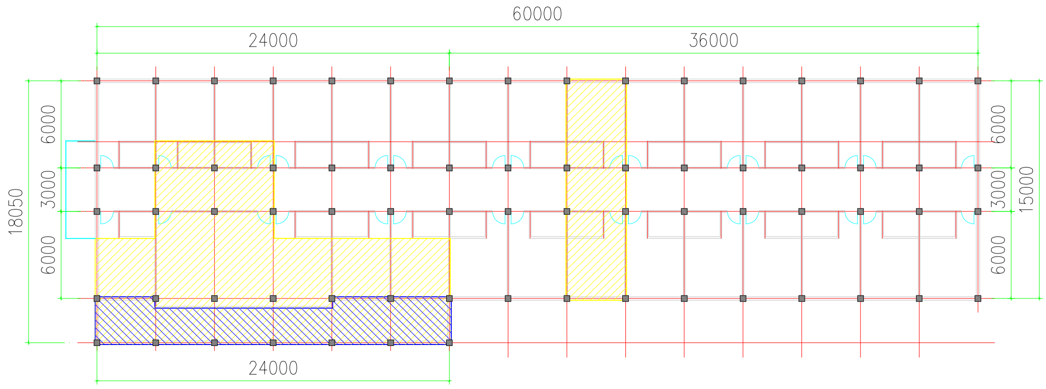

Fig3. Plane view of the hotel

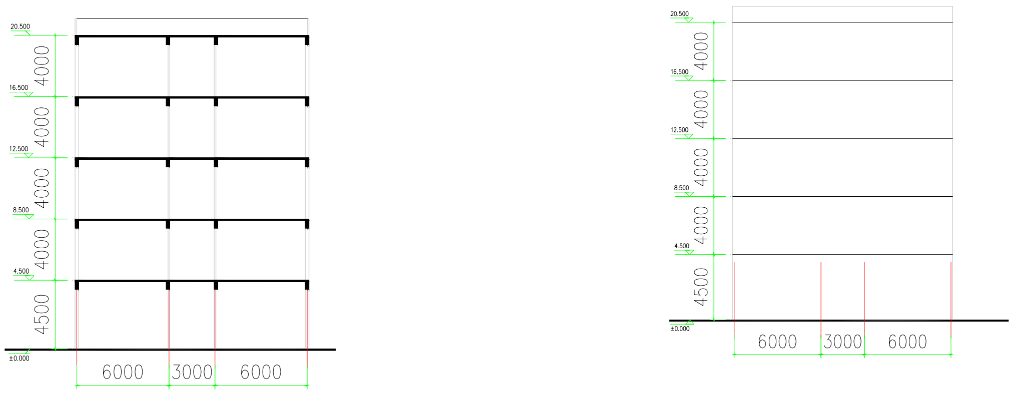

Fig 4. Section and elevation view of the hotel

4.1 Bound direct economic loss estimation

The interval of spectra displacement is 115mm~823mm after considering the uncertainties of demand and capacity spectrum, and more detailed results of spectra displacement solution are discussed in the companion paper by Jia and Duan (2008). Five load patterns including the inverse triangular loading distribution, the uniform loading distribution, the generalized power loading distribution, the modal adaptive distribution and the SRSS loading mode are employed to derive the pushover curves for predicted the medians of spectra displacement. The discrete probability of structure be in a certain damage state for the upper bound of spectra displacement, the lower bound and medians of its is described in Figure 5~7, respectively. Figure 8~10 shows the earthquake loss corresponding to the upper bound of damage probability, the lower bound and medians of its.

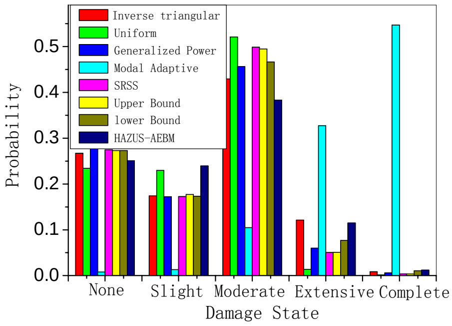

Fig5. Damage probability of spectra displacement lower bound

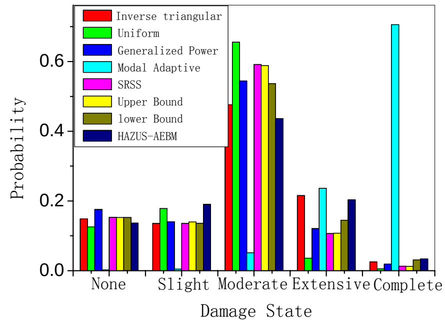

Fig6. Damage probability of spectra displacement medians

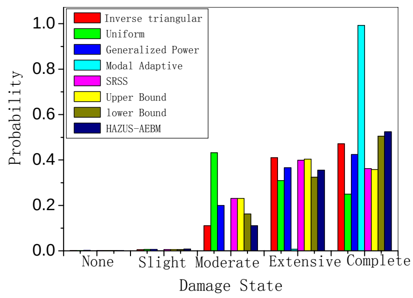

Fig7. Damage probability of spectra displacement upper bound

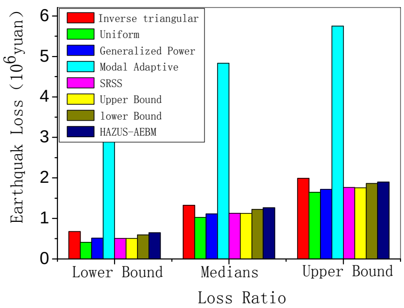

Fig8. Loss of damage probability lower bound

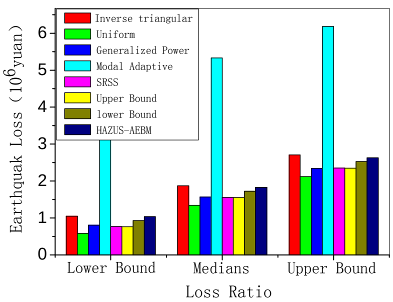

Fig9. Loss of deterministic damage probability

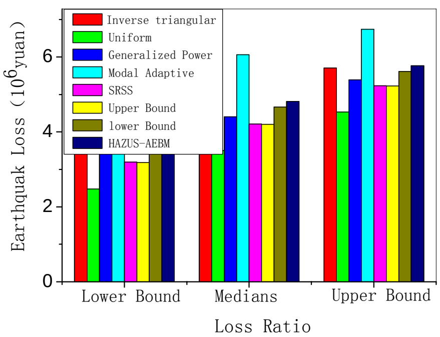

Fig10. Loss of damage probability upper bound

As described from Figure5~10, the uncertainties of spectra displacement, the medians of spectra displacement and loss ratio give most contribution to the uncertainty of earthquake loss estimation results. The earthquake loss of this hotel by convex analysis theory is 0.3915~6.7395million yuan, and is1.8727 million yuan by HAZUS-AEBM Manual methodology i.e. it locates in the lower half intervals of convex analysis results.

4.2 Direct economic loss estimation based on PEER'S probability methodology

The frame equation for performance assessment of PEER can be expressed as

$$\lambda(DV)=\iiint G(DV|DM)dG(DM|EDP)dG(EDP|IM)d\lambda(IM) \tag{4.1}$$

Where $\lambda(DV)$ is the mean annual frequency of exceedance of decision variable DV ; $G(DV|DM)$ is the probability of exceeding DV conditioned on damage measure DM ; $G(DM|EDP)$ is the probability of exceeding DM conditioned on engineering demand parameters EDP ; $\lambda(IM)$ is the mean annual frequency of exceedance of intensity measure IM .

In this section, the probability of losing a certain yuan amount in a given scenario $P(L_t \geq l_t | IM = im)$ is analyzed, and details are given Krawinkler (2005). The PGA of the seismic fortification intensity 8 degree is 0.4082g according to GB50011-2001(2001), and the probability of loss exceeding the bound value of convex analysis results is $P(L_t \geq 0.3915\text{M} | IM = 0.4082\text{g}) = 0.4131$, $P(L_t \geq 6.7395\text{M} | IM = 0.4082\text{g}) = 0.3272$.

5. CONCLUSIONS

The uncertainties of spectrum displacement, damage state medians and loss ratio are considered with the bound envelope convex set model, and a bound loss estimation method is derived by integrating HAZUS-AEBM module with the convex set theory. The loss estimation results of a hotel in southern China shows that the loss by HAZUS-AEBM method locates in the lower half intervals of convex analysis results. The probability of loss exceeding the bound value of convex analysis results is 0.4131and 0.3272, respectively.

The convex set theory based approach requires less information yet yields robust results comparing to the probabilistic approach. The simple presentation of results in the form of interval gives the convenience of easy understanding and decision making. It should be also noted that the convex set theory with less information is a little refined than probabilistic models, and the probabilistic model can give more information comparing with convex set theory.

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