Abstract

There are about 10 million existing non-conforming wooden houses today in Japan, and upgrading the seismic performance of such houses is essential for disaster mitigation. However, most of them remain untouched because of large expenditure for upgrading for both the owners and society. The owners have to spend about $8,000 on average to satisfy the current design code. In Aichi prefecture alone, it would cost about $7.5 billion, which is more than 1/3 of the annual budget, to upgrade all of them. In order to implement the upgrading of existing non-conforming wooden houses more efficiently, this paper investigates the alternative strategies for upgrading. The seismic risks of wooden houses as a whole in Aichi prefecture is estimated and then the effective target level for upgrading is discussed from the viewpoint of both economic loss and the number of fatalities.

1. Introduction

More than 6400 people lost their lives during Kobe Earthquake in 1995; about 84% of them became victims of structural collapse of wooden houses and wooden apartment buildings. Most of such houses do not meet the current seismic code enacted in 1981. There are about 10 million existing non-conforming wooden houses today in Japan, and upgrading of their seismic performance is essential for disaster mitigation.

Many of the local governments are trying to educate people to be aware of the seismic risk. They also offer financial support for the upgrading provided that the upgraded performance satisfies the current design code. For example, Aichi prefecture, where a huge inter-plate earthquake would hit with probability of 50% within the next 30 years, offers a half of the cost and up to $5,000. However, despite such efforts, most of the existing non-conforming wooden houses remain
untouched because of the large expenditure for upgrading for both the owners and society. The owners still have to spend about $8,000 on average even after the financial support. Upgrading houses with very poor structural performance costs much more. Such houses would remain as they are, although they should have been upgraded first from the viewpoint of saving human lives.

In Aichi prefecture alone, there are 550,000 existing non-conforming wooden houses and it would cost about $7.5 billion to upgrade all of them to meet current design code. Do we, society as a whole agree to spend such amount of money for upgrading? Considering the facts the annual total budget of the prefecture ($23 billion) and that the annual budget for the financial supports ($5 million), it would take hundreds of years to complete the upgrading. It seems the strategy of upgrading all the houses to satisfy the current design code is infeasible.

In order to implement the upgrading of existing non-conforming wooden houses much more efficiently, this paper investigate the alternative strategies for upgrading. The seismic risks of wooden houses as a whole in each city and town of Aichi prefecture is evaluated, and then the effective target level for upgrading from the viewpoint of both economy and fatalities is discussed.

2. Risk analysis

2.1 Analytical Model

Structural performance level of existing wooden houses is often measured by the index of seismic diagnosis, in which a seismic index, $I_S$, being equal to 1.0 is considered to satisfy the current design code. The following analytical models are considered in this study.

1. Seismic hazard

The Headquarters for Earthquake Research Promotion has recently developed a seismic hazard map of Japan presented in 1 km mesh (2005, see Fig.1). It provides the maximum peak ground velocity corresponding to the exceedence probability of 3% and 6% during the next 30 years. Based on the results, it is assumed here that 30 year maximum velocity is lognormally distributed with parameters corresponding to these exceedence probabilities for each site. For the preliminary estimation of seismic risks, the seismic hazard for each city and town is represented by the hazard at the respective city hall and town hall. Since seismic hazard is sensitive to the soil type at a site, local hazard should be considered for more detailed risk estimation.

2. Probability model of structural performance level of existing wooden houses

Considering the modification of seismic design code in 1971 and 1981, wooden houses are classified into three groups depending on their construction periods as shown in Table 1. It is assumed that the seismic performance level of the houses is lognormally distributed with parameters shown in Table 1. The parameters for Periods I and II are based on the results of field investigation of $I_S$’s conducted by Japan Upgrading Wooden Housings Business Co-operation (2005). For Period III, the parameters are determined so that the coefficient of variation is 0.24 and that the probability of $I_S$ lower than 1.0 is about 0.15.

3. Fragility curve for damage level

Damage level is quantified by a damage index shown in Fig.2 (Okada and Takai, 2004). It is assumed that the damage index, $w$, of a wooden house with $I_S = x$ subjected to a ground motion with maximum peak velocity, $v$ (cm/sec.), is estimated by the Weibull distribution (Okada and Takai, 2004) expressed as,
\[ w = g_1(x; v) = 1 - \exp\left(-\left(\frac{v}{241 \cdot x^{1.16}}\right)^{1.16}\right) \]  

(1)

The damage indices of a house with \( IS = x \) subjected to a ground motion with maximum velocity, 20, 40, 60, 80, 100, or 120 (cm/sec.) are shown in Fig.3.

(4) Economic loss function

Based on the discrete model by Minagawa et al (2003), the economic loss for each unit floor area, \( z \) ($1,000/m^2), of a house damaged measured by damage index, \( w \), is modelled as,

\[ w = g_2(z) = 3.11 \cdot z^3 - 5.37 \cdot z^3 + 3.24 \cdot z \]  

(2)

Here it is assumed that the construction cost of a house is $1,000/m^2. It is also assumed that total of $40,000 are required for collapsed houses for demolishing them and for the temporal houses for the people who are forced to evacuate from their houses.

(5) Fatalities

It is assumed that the probability of loosing their lives, \( d \), of the people staying in a house due to the structural damage with damage index, \( w \), is evaluated by (Tabata and Okada, 2005)

\[ d = g_3(w) = 0.0001 \cdot \exp(6.98 \cdot w) \]  

(3)

Although there exist uncertainties in Eqs.(1) - (3), they are not considered here for the purpose of preliminary estimation.

(6) Cost for upgrading

Based on Araki and Idota (2004), it is assumed that it costs $13.3/m^2 to increase \( IS \) 0.1 (eg. from 0.2 to 0.3). It is assumed further that it cost $83/m^2 more to increase \( IS \) more than 0.6 (eg. from 0.2 to 0.8), considering possible upgrading of not only structure itself but also the foundation.

2.2 Estimation of seismic risk

Risk curves can be evaluated taking the following steps.

The conditional probability distribution function (cdf) of damage index, \( W \), of a house constructed in Period \( j \) given that the house is subjected to a ground motion with intensity, \( v \) (cm/sec.), is expressed as,

\[ F_{W|v} (w | v; j) = F_{IS} \left(g_j^{-1}(w; v); j \right) \]  

(4)

in which \( F_{IS}(i|j) \) is the cdf of \( IS \) of a house constructed in Period \( j \), and \( g_j^{-1}(w; v) \) is the inverse of \( g(w; v) \) in Eq.(1). The conditional cdf of \( W \) given \( v = 20, 40, 60, 80, 100, \) or 120 (cm/sec.) are shown in Fig.4.

The conditional cdf of economic loss, \( Z \), of a house constructed in Period \( j \) given that the house is subjected to a ground motion with intensity, \( v \) (cm/sec.), can be evaluated from Eqs.(2) and (3) as,
The conditional cdf of $Z$ given $v = 20, 40, 60, 80, 100, \text{ or } 120$ (cm/sec.) are shown in Fig.5.

Similarly, the conditional cdf of fatalities, $D$, of a person in a house constructed in Period $j$ given that the house is subjected to a ground motion with intensity, $v$ (cm/sec.), can be evaluated from Eqs.(2) and (4) as,

$$F_{D|v}(d | v; j) = F_{W|g^{-1}(d) | v, j}$$

(6)

Applying the theorem of total probability, the risk curve of economic loss, $R_m(z)$ and that of fatalities, $R_d(d)$, can be evaluated by

$$R_m(z) = \sum_{j=1}^{n} A_j \cdot \int_0^\infty \{1 - F_{Z|v}(z | v, j)\} \cdot f_v(v) dv$$

(7)

$$R_d(d) = \sum_{j=1}^{n} M_j \cdot \int_0^\infty \{1 - F_{D|v}(d | v, j)\} \cdot f_v(v) dv \cdot m_p$$

(8)

in which $f_v(v)$ is the probability density function of the maximum velocity of a city or a town during the next 30 years, $A_j$ is the grand total floor area of the wooden houses constructed during Period $j$ in the city or the town, $M_j$ is the number of the people living in the houses, and $m_p$ is the probability that a person living in one of the houses is staying at the event of strong ground motion. In the numerical example in the next section, it is assumed that $m_p = 0.64$ assuming that an event occurs around 6 p.m.

3. Seismic risk and upgrading strategies

Fig.6 illustrates risk curves of economic loss and fatalities in one of the cities in Aichi prefecture during the next 30 years associated with one of five strategies. The strategies are no upgrading, and upgrading all of the houses with seismic index lower than a target level to the target level of $IS = 0.4, 0.6, 0.8, \text{ or } 1.0$. For the comparison among the strategies, the cost of upgrading associated with each strategy is included in the risk curve of economic loss.

Fig.7 illustrates total expected economic loss as the sum of the expected economic loss and cost associated with the upgrading for each strategy at the same city presented in Fig.6. It is interesting to note that the total expected economic loss is minimised not by the strategy with the target $IS = 1.0$ but 0.6. The same risk analysis is carried out for all the cities and towns in Aichi prefecture, and the optimum target $IS$ for each city and town is identified as shown in Fig.8.

Fig.9 shows the sum of (a) the total expected economy losses and (b) the expected fatalities of all the cities and towns in Aichi prefecture for each strategy. The combination of $(IS = ) 0.6 \text{ and } 0.8$ refers to the case that the optimum strategies for each city and town shown in Fig.8 are adopted. The cost for upgrading for each strategy is also presented in the figure. Similar to Fig.7, the expected losses decrease as the target level of upgrading increases; yet, the rate comes to be milder. From the viewpoint of the expected economic loss, the strategy of upgrading to $IS = 1.0$ is not as cost effective as the strategies of upgrading to $IS = 0.6 \text{ or } 0.8$. 
The expected fatalities decreases more than 60% from the case without upgrading when all the houses are upgraded to $IS = 0.6$, about 80% when upgraded to $IS = 0.8$, and about 90% when upgraded to $IS = 1.0$. Of course the strategy with target $IS = 1.0$ lowers the expected fatalities among the strategies considered here. Yet, it is doubtful whether it is plausible to upgrade all the wooden houses in the prefecture spending $7.4$ billion.

Similar to Fig.9, Fig.10 also shows the sum of the expected loss, but different strategies are considered. Here it is assumed that only arbitrarily selected houses are upgraded to $IS = 1.0$ spending the same amount of money to the strategies considered in Fig.9. The strategy upgrading all the houses to $IS = 0.4$ costs $0.17$ billion; with this budget only 3% of the houses in the prefecture can be upgraded to $IS = 1.0$. Similarly, the strategies with target $IS = 0.6$, combination of $IS = 0.6$ and 0.8, 0.8, and $IS = 1.0$ cost $1.25$ billion, $2.9$ billion, $3.9$ billion, and $7.4$ billion, respectively. With these budgets, 18%, 38%, 47%, and of course 100% of the houses in the prefecture can be upgraded. It is interesting to note that the expected losses, both economic loss and fatalities, do not decrease drastically except for the case when all the houses are upgraded. Even if $3.9$ billion is spent, the expected loss decreases only 50 - 55%. With the same expenditure all the houses can be upgraded to $IS = 0.8$, and fatalities decreases 80%.

Unless it is truly intended to upgrade all the houses to $IS = 1.0$, it is more reasonable to consider other strategies lowering the target level of upgrading. If such a strategy is combined with financial support, a large number of houses would be upgraded with less expense. Authors have received positive reactions on this results and high expectation for the future work from some people of the local government.

**Conclusions**

In order to implement the upgrading of existing non-conforming wooden houses much more efficiently, the seismic risks of wooden houses as a whole in Aichi prefecture are evaluated considering several strategies for upgrading. It is presented that the current strategy and financial support system, that is supporting only those upgraded houses which meet the current design code, is not neither quite efficient nor plausible. Far from that, target $IS = 1.0$ is much less effective than the strategy with lower target level. It is desirable to estimate first the total budget for upgrading that the society can spend.

Upgrading with lower target level decreases the risk of lives but not contributes much on the other aspect of disaster. For example, there would still be a large number of injuries and refugees in case of a huge earthquake. Local governments also have to consider upgrading hospitals and also public buildings that could be used as refuges. Research on an efficient strategy from a viewpoint of urban system is expected considering networks, cost effectiveness of upgrading houses as well as spatial correlation on the seismic intensity among various points.

**Acknowledgements**

The first author is grateful for the support receive d of the Grant-in-Aid for Scientific Research (A) (No.17201034) from the Ministry of Education, Science, Sports, and Culture and Japan Society for the Promotion of Science.

**References**


Table 1: Probabilistic model of seismic index of existing wooden houses

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<tr>
<td>Mean</td>
<td>0.61</td>
<td>0.74</td>
<td>1.31</td>
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<td>c.o.v</td>
<td>0.29</td>
<td>0.36</td>
<td>0.24</td>
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Figure 1: Hazard map
Figure 2: Damage level and damage index

<table>
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<tr>
<th>Stat. of local gov.</th>
<th>Partial damage</th>
<th>Partial collapse</th>
<th>Total collapse</th>
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<tbody>
<tr>
<td>Uraga-oki Eqk</td>
<td>Light</td>
<td>Minor</td>
<td>Severe</td>
</tr>
<tr>
<td>Damage index (w)</td>
<td>0.0</td>
<td>0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0</td>
<td>0.0 0.2 0.4 0.6 0.8 1.0</td>
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Figure 3: Fragility curves

Figure 4: Probabilistic model of damage index for each construction period

(a) Period I

(b) Period II

(c) Period III
Figure 5: Probabilistic model of economic loss for each construction period

Figure 6: Risk curves

Figure 7:
Figure 8: “Optimum” target seismic index

Figure 9: Sum of the expected loss when all the houses are upgraded to the target level

Figure 10: Sum of the expected loss when arbitrarily selected houses are upgraded to 1.0