Damage ratio functions of buildings using damage data of the 1995 Hyogo-Ken Nanbu earthquake

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**ABSTRACT:** Vulnerability functions are developed using investigated data of building damage during the 1995 Hyogo-Ken Nanbu earthquake to evaluate seismic performance of building groups in an area of a city. Three types of vulnerability functions are obtained, according to different definitions of damage levels. By examining the difference in the definition and comparing the vulnerability functions, the seismic performance of buildings during the Hyogo-Ken Nanbu earthquake is discussed.

### 1 INTRODUCTION

The 1995 Hyogo-Ken Nanbu earthquake caused unprecedented building damage in Hanshin area. The existing disaster prevention plans of large cities needed to be reconsidered in the immediate aftermath. In particular, it is very important to evaluate the damage levels of building structures and their effects on social life during large earthquakes. To do this, it is significant to relate an index of building damage to an index of earthquake ground motion intensity. This relationship constitutes a vulnerability function, by which the seismic performance of building groups in an area of a city is evaluated.

The statistical data of the damaged buildings in the Hyogo-Ken Nanbu earthquake have been arranged by several groups (AIJ, 1996; BRI, 1996; Kinki branch of the AIJ, 1995). In this paper, we develop the vulnerability functions of building damage during the earthquake based on these results. Building damage is related to the evaluated distribution of peak ground velocities in Hanshin area (Hayashi et al., 1997). On the other hand, it has been seen that the definitions of damage levels are different respectively, because of the difference in the purpose of the reconnaissance. As a result, we obtained three types of vulnerability functions. By examining the difference in the definition of damage levels and comparing three vulnerability functions, we try to discuss the seismic performance of buildings during the Hyogo-Ken Nanbu earthquake.

### 2 DEVELOPMENT OF VULNERABILITY FUNCTION

A vulnerability function is a relation between an index of building damage and that of earthquake ground motion intensity. In this paper, vulnerability functions are made with regression analysis as shown Fig. 1. Each index is calculated for a "cho", or section of a ward.

The peak ground velocity (PGV), which has been evaluated by Hayashi et al. (1996), is used as an index of earthquake ground motion intensity, because PGV is considered to be related to structural damage. Their results were in agreement with the peak ground velocities of some observed records and those evaluated from the ratio of overturned tombstones. Therefore, the distribution of peak ground velocities shown in Fig. 2 is considered to be good approximation of that during the Hyogo-Ken Nanbu earthquake.

The damage ratio is used as an index of building damage. We calculate the damage ratio by using three statistical data on building damage during the Hyogo-Ken Nanbu earthquake, as shown in Table 1. The data are investigated according to different definitions of the damage criteria, the investigated regions and the classification of buildings. As shown in Table 1, the damage criteria of investigated data I (AIJ, 1996; Kinki branch of the AIJ, 1995), those of data II (BRI, 1996), and those of data III, are defined in relation to the structural damage of buildings, the repairability, and the loss of property value, respectively. Data II was obtained from data of Hanshin area including Kobe.
Figure 1. Procedure to develop vulnerability function.

- Tombstones
- Observation Point

Figure 2. Distribution of peak ground velocities calculated from damage ratios of residential houses.
city, and other data (I, III) were obtained from those of Kobe city only. Criteria for the classification are selected from four criteria. They are structural type, construction date, number of stories and building use. In data I, buildings are classified by structural type and construction date. In data II, on the other hand, they are classified by building use and number of stories. Buildings are classified by all the criteria for the classification but building use in data III.

3 SEISMIC PERFORMANCE OF BUILDINGS

3.1 Vulnerability functions based on damage data III

By using data III, we calculate the ratios of severe damage ($P_S$), and those of severe or moderate damage ($P_{S+M}$), of every cho for each structural type and construction date. A severely-damaged building is defined as a building which suffers a decrease in property value of 50% or more. A moderately-damaged building is defined as a building which suffers a decrease in property value of 20% or more. The peak ground velocities of individual cho are evaluated. However, the correlation of the damage ratio to PGV is not very good, because the total number of buildings is not enough to calculate the damage ratios. Therefore, we calculate average values of damage ratios and those of peak ground velocities according to the range of PGV. Vulnerability functions are developed using regression analysis. The procedure is shown in the following.

(i) Every cho is classified by the range of PGV.

(ii) Numbers of severely-damaged buildings and those of moderately-damaged buildings are totaled at each range of PGV, and then $P_S$ and $P_{S+M}$ are calculated at each range of PGV. The peak ground velocity of each range is calculated from the average

Table 1. Comparison between three investigated data of building damage.

<table>
<thead>
<tr>
<th>Investigated Data</th>
<th>Purpose of Investigation</th>
<th>Criteria for Classification</th>
<th>Investigated Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>structural damage</td>
<td>Structural Type, Construction Date, Number of Stories</td>
<td>Kobe city</td>
</tr>
<tr>
<td>II</td>
<td>repairability</td>
<td>Building Use</td>
<td>Hanshin area (including Kobe city)</td>
</tr>
<tr>
<td>III</td>
<td>loss of property value</td>
<td></td>
<td>Kobe city</td>
</tr>
</tbody>
</table>

$\Box$ : It is possible that buildings are classified by the criterion.

Table 2. Parameters to characterize vulnerability functions based on investigated data III.

<table>
<thead>
<tr>
<th>Structural Type</th>
<th>Construction Date</th>
<th>Severe Damage ($P_S$)</th>
<th>Severe or Moderate Damage ($P_{S+M}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>average</td>
<td>4.42 0.538 0.998</td>
<td>3.81 0.721 0.984</td>
</tr>
<tr>
<td></td>
<td>- 1950</td>
<td>4.22 0.558 0.994</td>
<td>3.26 0.945 0.983</td>
</tr>
<tr>
<td></td>
<td>1951 - 1960</td>
<td>4.38 0.445 0.92</td>
<td>3.77 0.674 0.978</td>
</tr>
<tr>
<td></td>
<td>1961 - 1970</td>
<td>4.32 0.467 0.990</td>
<td>3.72 0.614 0.965</td>
</tr>
<tr>
<td></td>
<td>1971 - 1980</td>
<td>4.67 0.462 0.984</td>
<td>4.08 0.551 0.983</td>
</tr>
<tr>
<td></td>
<td>1981 -</td>
<td>5.12 0.552 0.966</td>
<td>4.56 0.624 0.950</td>
</tr>
<tr>
<td>Reinforced Concrete</td>
<td>averaging</td>
<td>5.58 0.863 0.982</td>
<td>5.04 1.077 0.935</td>
</tr>
<tr>
<td></td>
<td>- 1971</td>
<td>5.16 0.849 0.961</td>
<td>4.58 1.015 0.908</td>
</tr>
<tr>
<td></td>
<td>1972 - 1981</td>
<td>5.40 0.710 0.980</td>
<td>4.93 1.120 0.978</td>
</tr>
<tr>
<td></td>
<td>1982 -</td>
<td>5.58 0.551 0.983</td>
<td>5.36 0.897 0.924</td>
</tr>
<tr>
<td>Steel</td>
<td>averaging</td>
<td>5.14 0.695 0.981</td>
<td>4.58 0.937 0.973</td>
</tr>
<tr>
<td></td>
<td>- 1981</td>
<td>4.80 0.644 0.982</td>
<td>4.12 0.916 0.980</td>
</tr>
<tr>
<td></td>
<td>1982 -</td>
<td>5.44 0.576 0.947</td>
<td>5.00 0.923 0.885</td>
</tr>
<tr>
<td>Light-gauge Steel</td>
<td>averaging</td>
<td>5.06 0.622 0.971</td>
<td>4.73 0.699 0.962</td>
</tr>
</tbody>
</table>

R : correlation coefficient
(iii) The expression of regression to the damage ratio of buildings on PGV is calculated by using the method of least squares with probability paper, and it is denoted by the standard normal distribution function $\Phi$ in the following equation (Ang and Tang, 1975).

$$ P(\text{PGV}) = \Phi\left(\frac{\ln \text{PGV} - \lambda}{\zeta}\right) $$

where $\lambda$ and $\zeta$ are parameters to characterize the function $\Phi$, and they are the average and the standard deviation of the logarithm of PGV, respectively. The expression is weighted by total numbers of buildings at each range of PGV. The available range of PGV of the vulnerability function calculated by Eq. (1) is that from 50 to 150 cm/sec, because of the correspondence with the range of evaluated PGV.

Table 2 shows the parameters of Eq. (1) for all the cases examined in this paper. Vulnerability functions are constructed easily using these parameters.

Effects of structural type on $P_S$ and $P_{S+M}$ are shown in Fig. 3. The damage ratios ($P_S$ and $P_{S+M}$) of wooden buildings is the largest in the four structural types. The damage ratios of reinforced concrete buildings is smaller than those of steel buildings. $P_S$ of light-gauge steel buildings corresponds with that of steel buildings. $P_{S+M}$ of light-gauge steel buildings is larger than that of reinforced concrete buildings, and is smaller than that of steel buildings. A peak ground velocity of 100 cm/sec causes moderate damage to 87% of wooden buildings, and to 34% of reinforced concrete buildings; however, in both cases the property value is decreased by at least 20%.

Fig. 4 shows effects of construction date on $P_{S+M}$ of reinforced concrete buildings. $P_{S+M}$ decreases as the construction date becomes more recent. At a peak ground velocity of 100 cm/sec, 51% of the buildings constructed before 1971 experience a minimum 20% drop in property value, while only 20% of those buildings constructed after 1982 experience the same drop in value.

These results indicate that the damage ratios are influenced not only by structural type but also by construction date.

3.2 Comparison between damage levels of three data

We investigate the variation in vulnerability functions with the definition of the damage level. To compare the vulnerability functions based on data III, we develop the functions based on data I and data II. As concerns data I, we calculate $P_{S+M}$ of reinforced concrete buildings and $P_d$ of wooden buildings, and...
then vulnerability functions of damage ratios are evaluated using the method in the preceding section. 

\[ P_d = P_s + \frac{P_m}{2} \]

\( P_d \) is the ratio of severe damage plus half of the ratio of moderate damage. Similarly, vulnerability functions based on data II were developed according to building use and number of stories by Miyakoshi (1997). In this paper, we regard the vulnerability function of low-rise houses and that of mid-to-high-rise apartment buildings as that of wooden buildings and that of reinforced concrete buildings, respectively.

Before we compare the vulnerability functions, we describe the definition of the damage level. Table 3 shows the definitions of the moderate damage level according to wooden buildings and reinforced concrete buildings. For wooden buildings, the level of the structural damage almost corresponds to that of the dwelling possibility, however the loss of property value is much more serious than the structural damage. When the majority of exterior walls of a building is cracked, the damage level of the building is judged to be moderate from the viewpoint of the structural damage. From the viewpoint of the loss of property value, however, the damage level is judged to be severe, that is, a building loses at least 50% of its original property value. On the other hand, the damage level of reinforced concrete buildings is probably judged to be severe, according to the loss of property value, when the external facing and the interior finishing are damaged heavily, even if we cannot find any structural damage. When columns have shear cracks, the damage

![Figure 5. Vulnerability functions of wooden buildings with respect to investigated data.](image)

![Figure 6. Vulnerability functions of reinforced concrete buildings with respect to investigated data.](image)
level of the building is judged to be moderate, according to the structural damage, but the damage level is judged to be severe, according to the repairability. In addition, the manner in which definitions apply to an exterior wall aren’t the same between different data. The destruction of exterior walls is structurally moderate damage, but hard to repair.

The effect of investigated data on $P_d$ of wooden buildings is shown in Fig. 5. The vulnerability function based on data I almost corresponds with that based on data II, but $P_d$ based on data III is considerably larger than that based on other data. For example, at a peak ground velocity of 100 cm/sec, 31% of the buildings experience such medium damage that the majority of the building requires repairs; however, 75% of the buildings lose at least 20% of their original property value. This result indicates that the loss of property value is much more serious than the structural damage as shown Table 3.

Fig. 6 shows vulnerability functions of reinforced concrete buildings. It is the same tendency as wooden buildings that $P_{SM}$ based on data III is obviously larger than the others. On the other hand, $P_{SM}$ based on data I is considerably smaller than that based on data II, which differs from the case of wooden buildings. One of the reasons for this is that the levels of moderate damage are differently defined according to investigated data as shown Table 3. At a peak ground velocity of 100 cm/sec, 3% of the buildings sustain moderate structural damage, and 15% of the buildings sustain such medium damage that the majority of the building requires repairs. Only 34% of the buildings suffer a decrease in property value of 20% or more.

4 CONCLUSIONS

Vulnerability functions to evaluate the seismic performance of building groups in an area of a city are developed using investigated data of building damage during the Hyogo-Ken Nanbu earthquake. It is proved that the ratio of building damage is influenced not only by structural type but also by construction date.

The definitions of damage levels are different according to the purpose of investigated data. Three types of vulnerability functions based on their data are obtained. By comparing their functions, it is proved that the building damage from the loss of property value is much more serious than that from structural damage.

ACKNOWLEDGMENT

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REFERENCES