Damage ratio functions of steel buildings in 1995 Hyogo-ken Nanbu earthquake

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ABSTRACT: Seismic performance of 3 to 6 story steel buildings are investigated based on the damage survey and PGV estimation during the 1995 Hyogo-ken Nanbu earthquake. Major findings are as follows. First, damage levels of exterior walls such as mortar walls and ALC panel walls are classified schematically and their correspondence to structural damage is investigated. The damage ratio functions, which indicate relationships between PGVs and damage ratios for damage levels of structure or exterior walls. From the comparison of damage ratio functions, the moderate structural damage is comparable to the complete loss of property value and the damage level of ALC panel walls is reduced by the improvement in seismic performance of steel structures by the amendment of the Building Standard Law in 1981.

1 INTRODUCTION

Investigation and record of buildings’ damage data in the earthquakes is important for amending seismic resistant design criteria to reduce and avoid the same damage in the future. After the 1995 Hyogo-ken Nanbu earthquake occurred, many organizations made their best effort to investigate the damaged buildings.

As to the damage survey of steel buildings, the results of Kinki Branch of the Architectural Institute of Japan (AIJ) and the Building Research Institute (BRI) are different from those of the municipal government. The survey held by the last one is for the purpose of issuing disaster victim evidence; survey purpose of the former two is to conduct judgment of structural damage level, by professionals of building structures. However, in contrast to the entire investigation held by BRI, Kinki Branch of AIJ surveyed only the damaged ones, such that damage ratios of different level or the relationship with construction years are not available. Furthermore, the seismic intensity in the investigation area is not clear in any one of the investigations mentioned above. Therefore, in contrast to the constructed damage ratio functions of reinforced concrete or wooden buildings, it’s emergent and meaningful to construct damage ratio functions of steel buildings.

In 2000, the Performance-based design method is adopted in the Building Standard Law in Japan. As to the requirement of seismic resistant performance, from the viewpoint of property insurance and function maintain, it should include not only structural components but also nonstructural ones. However, only few researches were conducted on nonstructural components, such as exterior walls or finishes for the 1995 Hyogo-ken Nanbu earthquake. In addition, when setting the required seismic performance target by considering the occurrence frequency of earthquakes, it’s important to let clients easily understand the risk of set seismic performance target. Such that researches on the following two points are necessary based on the lessons learned from the great earthquake.

(a) Clarify damage level, including nonstructural components
(b) Construct damage ratio functions, including nonstructural components

Under the background described above, to clarify the seismic performance of steel buildings based on the damage data of 1995 Hyogo-ken Nanbu earthquake, at first, we classify schematically damage level for ALC panel walls and mortar walls, which are used most commonly in steel buildings. Secondly, we construct damage ratio functions, which indicate relationships between PGVs and damage ratios for damage levels, of steel structure and exterior walls. However, because the data of Kinki Branch of AIJ involve only damaged buildings, to derive damage ratio functions, the number of all buildings...
2 DAMAGE DATA OF STEEL BUILDINGS

2.1 Data form Kinki Branch of AIJ

Kinki Branch of AIJ conducted the investigation for approximately one month, from the middle of February 1995. The area of investigation covered the disaster area, west from Nagata ward and east to Ashiya city. All the damaged steel buildings except the ones built with light-gauged columns and beams, in this area were surveyed, and the total number of surveyed buildings was 988. The damage level was mainly judged by observing from outside the building. The judgment guidelines of structural damage level are as follows.

(a) Minor: No damage to major vertical force supporting members like columns and beams. Minor cracking and spalling of exterior finishes and/or buckling of rod or flat bar braces. No or nearly no permanent lateral deformations.
(b) Moderate: Buckling and rupture of bracing members and yielding of columns and beams. Small residual lateral deformation, approximately smaller than 1/100, is observed. Any damage not categorized as minor, major or collapse.
(c) Major: Serious damage to columns, beams, and connections to an extent considered difficult to repair. Significant residual deformation more than 1/100 is observed.
(d) Collapse: Collapse of the entire building or a story of the building.

2.2 Data from BRI

The investigation was conducted from 20~23 February 1995; all the steel buildings with more than 3 stories were surveyed. The area of investigation was in the major disaster area and involved part of Chuoh ward, Hyogo ward, and Higashinada ward in Kobe city. The damage was mainly judged by observing from outside of the building, and the judgment guidelines of structural damage level are similar to those of Kinki Branch of AIJ. In addition, the principal feature of this investigation is confirming construction years and structural types of all the surveyed building, excluding those were removed or torn down, after the survey finished.

2.3 Data from municipal government

We also used the data obtained by Nada ward, Kobe city. The data are for the purpose of issuing disaster victim evidence, and are arranged for each district area by construction type, construction years, number of stories, and number of complete, half and part damage level.

3 ANALYSIS OF THE EXTERIOR WALL DAMAGE

3.1 Data of subject buildings

In the data of Kinki Branch of AIJ, we took 451 buildings located in Nada ward and Higashinada ward as the subject data. After excluding 96 cases whose exterior walls cannot be identified due to collapse or fire, the types of exterior walls in the left 355 cases are shown in Fig. 1(a). The number of cases with ALC panel walls and mortar walls are as many as 146(41%) and 164(46%) respectively. The rest 45(13%) cases of other types of exterior walls will not be used due to few samples or hard to investigate relationship with structural damage. Thus only the 310 buildings with ALC panel walls and mortar will be analyzed in this study.

Comparing Fig. 1(b) and (c), in contrast to 67 (46%) buildings with ALC panel walls suffered minor structural damage, among the buildings with mortar walls, 69 (42%) suffered major structural damage. Therefore, relatively, more buildings with ALC panel walls suffer structural damage of lower level in general.

3.2 Classification of exterior walls’ damage levels

In the data of Kinki Branch of AIJ, a few photos of notable damage were taken for each surveyed building. Thus, based on the photos, we classify schematically damage of exterior walls into 6 levels,

![Figure 1](image-url)
from 0 to 5, as shown in Fig. 2 and Fig. 3. Either in the classification of ALC panel walls or mortar walls, the damage over level 3 means increasing risk to life safety.

From the number of buildings by exterior walls’ damage level (see Fig.4), damage level of the largest ratios for ALC panel and mortar walls are level 2 (33%) and level 3 (38%) respectively. In addition, the number of cases of damage level 2 in ALC panel walls is quite small. That’s to say, damage level 2, shear cracks or out-of-plane movement of panels (see Fig.5), extend easily to damage more than level 3, falling of panels.

3.3 Relationship of structural damage and exterior walls’ damage

Fig. 6(a), (b) show the distribution ratios of structural damage, minor, moderate, and major, in different exterior walls’ damage level. Major findings are as follows.

(a) As damage level of exterior walls increases, the ratios of major structural damage also increase; conversely, the ratios of minor structural damage decreases. Apparent correspondence exists between structural damage and exterior walls’ damage.

(b) In the buildings with exterior walls of damage level 1–4, the structural damage involve minor, moderate, and major. That’s to say, buildings with exterior walls of lower damage level are not necessarily with structural damage of lower level. Conversely, the buildings with structural damage of lower level are not necessarily with exterior walls of lower damage level either.
From the description of (b), it means that the deformation capacity of steel structure isn’t necessary corresponding to that of exterior walls, due to the installation method or accuracy of exterior walls.

Furthermore, we analyze cumulative ratios of exterior walls’ damage for each structural damage level, involving minor, moderate, and major (see Fig. 7(a), (b)). Let $P_{SiEj}$ represent ratios of exterior walls of $j$-th level damage in the buildings with $i$-th level structural damage. Then for the buildings of $i$-th level structural damage, the cumulative ratio, $P_{SiEj}$, of exterior walls’ damage under $j$-th level is calculated by Eq. (1).

$$P_{SiEj} = \sum_{k=i}^{S} P_{SiEk}$$

(1)

Major findings from Fig. 7(a), (b) are as follows. (a) Even in the buildings of major structural damage, either the ratios of ALC panel walls’ damage more than level 4 or that of mortar walls’ damage of level 5 are still quite small. (b) In the buildings of minor structural damage, 70% of ALC panel walls’ damage is under level 1; 40% and 70% of mortar walls’ damage is under level 1 and 2 respectively. Furthermore, in the buildings of major structural damage, the ratios of ALC panel walls with damage over level 3 are under 10%; in contrast, about 40% mortar walls are with damage over level 3. That’s to say damage of mortar walls is more serious.

4 CONSTRUCTION OF THE STRUCTURAL DAMAGE RATIO FUNCTIONS

4.1 Method of constructing the damage ratio functions

There are two types of damage ratio functions in this study. One is for structural damage level, and the other one is for exterior walls’ damage level.

The method of constructing damage ratio functions includes the following steps.

1. Correspond the investigated buildings to the estimated PGV of that district where the buildings located. However, in the area southern than highway No.43, PGV may be under estimated due to high possibility of liquefaction, the buildings in this area are excluded.

2. Classify estimated PGV by the interval of 0.2 m/s.

3. Damage ratio is by calculating the percentage of damaged buildings in the same estimated PGV interval.

4. To avoid regression curve’s precision being affected by damage ratios that was calculated from few buildings, weight factors by considering number of buildings are adopted in the regression of log-normal distribution function (Eq. 2).

$$P_{Si}(V) \cdot \Phi(\ln(V) - \frac{\mu_i}{\sigma_i})$$

(2)

Here, $P_{Si}(V)$ represents ratios of buildings with structural damage more than $i$-th level; $i=0$–5 corre-
sponds to damage level of none, slight, minor, moderate, major, and collapse respectively. \( \Phi \) is standard normal distribution function; \( \lambda \) and \( \zeta \) are mean and standard deviation of \( \ln(V) \).

However, it’s difficult to construct damage ratio functions directly based on the data of Kinki Branch AIJ. Because number of the all buildings, including those unable to confirm their damage, is unclear, and many buildings’ construction years are not available either. Therefore, based on the data, obtained by municipal government, arranged by number of stories, we calculate the buildings of 3–6 stories over the investigated districts to gain number of all the subject buildings.

In addition, we estimate construction years based on analysis results from the data of BRI. Fig. 8(a), (b) show the relationship between construction years and type of cladding and column in the data of BRI. Most of the types of mortar or folded plate are used in old buildings, built before 1981; curtain wall is used in new buildings, built after 1982. Thus for buildings with mortar walls or folded plate walls, construction years is corresponding to the type of cladding. In contrast, we cannot judge construction years when buildings are with ACL panel walls. Because both old and new buildings use that type of cladding (see Fig. 8 (a)).

In addition, most buildings with columns of wide-flange column or wide-flange column with stiffening plate are built before 1981. And among the buildings with columns of square shape section, the number of new buildings is larger than that of old ones. However, because the section of column cannot be identified if damage of buildings didn’t proceed over a certain level, number of buildings with unidentified types of column is large (see Fig. 8 (b)).

Based on the relationship between construction years and type of cladding and column described above, we adopt several rules as follows to judge construction years, before or after the year Building Standard Law was revised, of the data obtained by Kinki Branch of AIJ. These rules are applicable in order.

(a) Adopt the information about building’s construction years or time of design, if it’s available.
(b) Buildings with mortar walls are judged as being built before 1981.
(c) Buildings with columns of wide-flange column or wide-flange column with stiffening plate are judged as being built before 1981.
(d) Buildings with columns of square shape sections are judged as being built after 1982, because that type becomes main construction method for steel buildings after 1982.
(e) If it’s possible to estimate form the relationship with the data of disaster victim evidence, arranged by construction years, number of stories, and damage level, adopt the estimated construction years.

Figure 8 Relation between exterior wall and construction years (from BRI)

Figure 9 Relationship between exterior walls and column section (Data from Kinki branch of AIJ)
After applying these rules, there are still 2 cases unable to be identified. We exclude the 2 cases from damaged building data because the influence is little. For reference, based on the data of Kinki Branch of AIJ, Fig. 9 (a), (b) show number of buildings with different type column section in the cases with ALC panel and mortar walls respectively. In the buildings with mortar walls, about 2/3, i.e. 108 cases, are of wide-flange column; if count the cases of wide-flange column with stiffening plate, the ratio becomes 3/4, which means the ratio of old buildings built before 1981 according to the rules above. On the other hand, in the buildings with ALC panel walls, the ratio of cases of wide-flange column or wide-flange column with stiffening column is also over 1/4. It means that also many old steel buildings use the ALC panel walls.

4.2 Structural damage ratio functions

Damage ratio functions based on the confirmed data obtained from BRI and those of Kinki Branch of AIJ are shown in Fig. 10(a), (b). In addition, regardless of construction years, the comparison of damage ratio functions based on Kinki Branch of AIJ and municipal government is shown in Fig. 10(c). Major findings from these figures are as follows.

(a) Damage ratios based on the data of BRI differ apparently by construction years (see Fig. 10(a)). In PGV of 1.0~1.5 m/s, corresponding to seismic intensity 7 by the Japan Meteorological Agency, ratios of moderate structural damage of buildings built before 1981 range from 25~50%; in contrast, those of buildings built after 1982 range from 5~20%. The difference of damage ratios due to construction years is particularly large.

(b) By comparing damage ratio functions based on the data of Kinki Branch of AIJ and BRI (see Fig. 10(a), (b)), damage ratios based on the data of Kinki Branch of AIJ are smaller generally. This is because we calculate number of steel buildings of 3~6 stories based on the data of municipal government; but some removed or torn down cases also exist in the data, such that the calculated number may be larger than the actual number of buildings able to be observed in the investigation. Furthermore, the difference varies by damage level. In contrast to less difference in ratios of major structural damage regressed from the data of BRI and Kinki Branch of AIJ, the ratios of moderate structural damage regressed from the data of Kinki Branch of AIJ are apparently smaller. The difference in damage ratio functions is also due to the different investigation method and judgment of damage level. In addition, it’s also influenced by the estimated construction years in the data of Kinki Branch of AIJ.

(c) By comparing damage ratio functions based on the data of BRI and municipal government (see Fig. 10(c)), it’s found that moderate structural damage is comparable to complete loss of property value. If take the correspondence between the data of BRI and Kinki Branch AIJ into consideration also, many buildings were judged as complete loss of property, even though they didn’t suffer major structural damage or collapse. This experience is important for setting up the required seismic performance in the future.

5 EXTERIOR WALLS’ DAMAGE RATIO FUNCTIONS

Let $P_{S_i}(V)$ represent the ratio of buildings with structural damage more than $i$-th level, thus the ratio of $i$-th structural damage buildings is $(P_{S_i}(V) - P_{S_{i+1}}(V))$. Under the condition of $i$-th level structural damage, the ratio of exterior walls of $j$-th level damage is represented by $p_{SEMj}$. Then $P_{E_j}$, the ratio of buildings with exterior walls’ damage more than $j$-th level, is calculated by Eq. (3).

$$
P_{E_j} = \sum_{i=1}^{j} \left( p_{S_{i+1}}(V_1) - p_{S_{i+1}}(V_2) \right) + p_{S_{i+1}}(V_3) - p_{S_{i+1}}(V_4) + p_{S_{i+1}}(V_5)$$

(3)
However, only three structural damage levels, minor, moderate, and major/collapse, are considered in Eq. (3), i.e. $P_{55}(p_{S55}^{}-p_{S45}^{})$ is assumed to be nearly equal to zero. This is because that for the buildings built before 1981, the ratio of structural damage of collapse level, $P_{55}^{}$, is 0.03–0.07 even in the PGV range of 1.0–1.5 m/s. Therefore, it’s neglected when calculating the damage ratio of exterior walls.

Figure 11 shows the calculated damage ratio functions of exterior walls. From damage ratio functions of mortar walls, and ALC panels of construction years before 1981 and after 1982, major findings are as follows.

(a) For mortar walls and ALC panel walls of construction years before 1981, the ratios of the damage more than level 3, which means higher risk to life safety, are similar, say 10–25% in the PGV range of 1.0–1.5 m/s. In contrast, for ALC panel walls of construction years after 1981, the damage ratios are as small as 3% in the same PGV range.

(b) Damage ratio functions of ALC panel walls differ apparently by construction years. Because the installation method is assumed to be the same, the decreased damage ratio is considered due to improvement seismic performance of the building structure.

6 CONCLUSIONS

Based on the damage survey and PGV estimation during the 1995 Hyogo-ken Nanbu earthquake, we constructed damage ratio functions of structural damage and exterior wall’s damage for 3-6 steel buildings. The conclusions are as follows.

(1) From damage ratio functions of structural damage of steel buildings, it’s found that moderate structural damage is comparable to complete loss of property value.

(2) Damage levels of exterior walls, including mortar walls and ALC panel walls, are classified schematically, and their correspondence to structural damage is analyzed quantitatively.

(3) Damage ratios of ALC panel walls are reduced remarkably by improvement in seismic performance of steel structures by the amendment of the Building Standard Law in 1981.

(4) Comparing exterior walls of highest-level damage in steel buildings built before the amendment of the Building Standard Law in 1981, the damage ratio of spalling of most mortar walls is much higher than that of falling of most panels.

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REFERENCES


