INDOOR DAMAGE AND FLOOR RESPONSE OF HIGH-RISE RESIDENTIAL BUILDINGS DURING THE 2016 KUMAMOTO EARTHQUAKE BASED ON A QUESTIONNAIRE SURVEY

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ABSTRACT

The objective of this study is to estimate the peak floor responses of high-rise residential buildings during the 2016 Kumamoto earthquake in Japan. To determine the indoor damages, we used a questionnaire-based survey for residents. In Kumamoto City, more than 80% of the residents found it impossible or difficult to act during the mainshock. The Kumamoto City residents faced much more difficulty in performing actions than the Kanto area residents during the 2011 Tohoku earthquake. This trend can also be seen in the moving and/or the overturning of furniture and the scattering of small items on tables. Cracks in partitions and wallpapers were observed on all floors; however, there was no clear pattern in the height-wise distribution of these damages. A combination of various input ground motions and natural periods created differences in the height-wise variation of indoor damages in three buildings in Kumamoto City. The peak floor response was evaluated based on the results of the questionnaire survey and using two equations proposed in our previous study. We compared the peak floor responses of the buildings in Kumamoto City with those in the Kanto area during the 2011 Tohoku earthquake. Peak floor responses in the lower floors in Kumamoto City buildings were greater than those in the Kanto area during the 2011 Tohoku earthquake. This suggested that input ground motions for buildings in Kumamoto City were larger than those in the Kanto area.

Keywords: The 2016 Kumamoto earthquake; High-rise residential buildings; Questionnaire survey; Indoor damage; Peak floor response

1. INTRODUCTION

In Japan, more than 1,300 high-rise residential buildings having over 20 stories have been constructed, as shown in Figure 1. Many of these buildings are located in highly urbanized and densely populated areas of Kanto and Kansai. Lately, the construction of high-rise buildings has spread to middle-sized cities, such as the prefectural capitals in local prefectures. In Japan, a number of massive earthquakes have occurred. Various structural damages have resulted from the pulse-type ground motions of inland earthquakes such as the 1995 Kobe earthquake (Mw6.9) or ground motions with a long duration in massive subduction-zone earthquakes, such as the 2011 Tohoku earthquake (Mw9.0). In the latter case, ground motions of large amplitude and long duration were observed in the Kanto region, including the Tokyo Metropolitan area. A large number of high-rise residential buildings constructed in the Kanto region shook strongly during the earthquake. Quite a few buildings experienced a nonlinear behavior, which was observed in the strong motion records obtained from multiple floors (at least, the topmost and first floor), which were equipped with sensors (Nagano et al., 2012). At the same time, we clarified various types of indoor damages, such as the moving and/or overturning of furniture and the cracking

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of paper walls and concrete along with feelings of anxiety and difficulty in performing actions through questionnaire-based survey (Hida and Nagano, 2012).

A massive earthquake occurred in April 2016 in the Kumamoto Prefecture of Kyushu Island in the southern part of this Japanese archipelago. The Mw7.0 mainshock, which occurred at midnight on April 16, caused massive shaking in the densely populated area of Mashiki-Machi Town. This caused a devastating damage to a number of wooden houses because of the distinctive pulse-type large-amplitude ground motions (NILIM & BRI, 2016).

Kumamoto City, which lies adjacent to Mashiki-Machi Town, has three high-rise residential buildings. One of the buildings close to the epicenter zone suffered damage, which included diagonal cracks in the wing walls. Unlike the 2011 Tohoku earthquake case, these buildings were not equipped with strong motion observation systems. For the safety of the residents, it is important to grasp the structural responses along with the indoor damages caused by the violent ground shaking caused by the inland earthquake.

The objective of this study is to estimate the peak floor responses of high-rise residential buildings during the 2016 Kumamoto earthquake. We have used a questionnaire-based survey for residents to assess the indoor damages. In our previous studies, we proposed a relationship between indoor damage and floor response, which enabled us to assess the structural response without strong motion records and/or simulation analyses (Hida and Nagano, 2015; Nagano et al., 2016). In this study, we evaluated the peak floor response based on the results of the questionnaire survey, and the proposed formulations are compared with those of the Kanto area during the 2011 Tohoku earthquake.

2. OUTLINE OF THE QUESTIONNAIRE SURVEY

2.1 Target Buildings

The target buildings for the questionnaire survey are 10 high-rise residential buildings constructed in the Kyushu Island (see Figure 2); these include three buildings in Kumamoto City. The number of stories of these buildings varied from 19 to 36. Two of the buildings were seismically isolated; therefore, these were not considered in this study. Among the remaining eight buildings, most of them were moment-resisting reinforced concrete (RC) frame structures, except one building (named “EA”), which had steel-reinforced concrete (SRC) frame structure, as shown in Table 1.
Figure 2. Location of buildings for questionnaire survey in Kyushu Island.

Table 1. Target buildings in Kyushu Island.

<table>
<thead>
<tr>
<th>BLDG. code</th>
<th>Construction site</th>
<th>Main structure</th>
<th>Stories</th>
<th>Construction year</th>
<th>Num. of respondents</th>
</tr>
</thead>
<tbody>
<tr>
<td>EA</td>
<td>Kumamoto City</td>
<td>SRC</td>
<td>20</td>
<td>2003</td>
<td>56</td>
</tr>
<tr>
<td>EB</td>
<td>Kumamoto City</td>
<td>RC</td>
<td>25</td>
<td>2006</td>
<td>60</td>
</tr>
<tr>
<td>EC</td>
<td>Kumamoto City</td>
<td>RC*</td>
<td>36</td>
<td>2011</td>
<td>109</td>
</tr>
<tr>
<td>ED</td>
<td>Kurume City</td>
<td>RC</td>
<td>19</td>
<td>2012</td>
<td>63</td>
</tr>
<tr>
<td>EF</td>
<td>Fukuoka City</td>
<td>RC</td>
<td>20</td>
<td>1995</td>
<td>43</td>
</tr>
<tr>
<td>EG</td>
<td>Fukuoka City</td>
<td>RC</td>
<td>27</td>
<td>2004</td>
<td>86</td>
</tr>
<tr>
<td>EH</td>
<td>Fukuoka City</td>
<td>RC*</td>
<td>29</td>
<td>2010</td>
<td>33</td>
</tr>
<tr>
<td>EJ</td>
<td>Fukuoka City</td>
<td>RC*</td>
<td>29</td>
<td>2010</td>
<td>24</td>
</tr>
</tbody>
</table>

*Passive seismic control devices are installed.

The questionnaire survey was conducted in May 2016, approximately one month after the mainshock. The questionnaire was posted directly to the community mailboxes of all residents in the target buildings. We asked the residents to fill the questionnaires based on what they could recall and to reply via post using the provided stamped, self-addressed envelopes.

After the 2011 Tohoku earthquake, we conducted a questionnaire survey for the residents of the 16 high-rise residential buildings in the Kanto area (see Figure 3). Contents of the questionnaire were almost the same as those used in this study. The results were compiled by Hida and Nagano (2012), as discussed subsequently in Section 3. In addition, strong ground motions were recorded during the 2011 Tohoku earthquake in the eight high-rise residential buildings; this is indicated by the filled red squares in Figure 3. The relationship between the indoor damages and the actual floor responses during the 2011 Tohoku earthquake has also been discussed earlier (Hida and Nagano, 2012).
2.2 Outline of the Questionnaire

The questionnaire covered the following areas:
- Floor number of the residents (for the cross-tab data analysis)
- Location of the residents—whether they were in or out of their apartments
- Seismic intensity scale felt during the mainshock—which is different from the European Mercalli scale and not referred to in this paper.
- Difficulties faced by residents in performing actions (hereinafter “action difficulty”) during the massive shaking movement
- Development of insecurity as a psychological condition
- Movement and/or overturning of furniture (drawers, refrigerators, etc.)
- Scattering of small items on tables
- Cracks in interior materials, such as wallpaper.

Most of the survey items were five-level ranked questions. As examples, the answers for action difficulty, overturning of furniture, scattering of small items, and cracks in wallpaper are listed in Tables 2 and 3. Notice that type of answers from I to V is different from those used in the European Mercalli scale (EMS-98). The questionnaire also included some open-ended questions, such as special comments on floor shaking and indoor damages, the experience of anxiety about the future, and injuries (if any) during the massive shaking. In addition, we also asked questions on the conditions of utilities, such as elevators, water supply, electricity, and gas, and the need for an earthquake early warning system (which will not be referred to in this paper).

Table 2. Answers for “Action difficulty,” “Scattering of small items,” and “Cracks in wallpaper” and their corresponding scores.

<table>
<thead>
<tr>
<th>Type of answers</th>
<th>Action difficulty</th>
<th>Scattering of small items on tables</th>
<th>Cracks in wallpaper</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Impossible to act</td>
<td>Severely scattered</td>
<td>Severely cracked</td>
<td>4</td>
</tr>
<tr>
<td>IV</td>
<td>Intermediate level↓</td>
<td>Intermediate level↓</td>
<td>Intermediate level↓</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>Unstable but possible to act</td>
<td>Partially scattered</td>
<td>Partially cracked</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>Intermediate level↓</td>
<td>Intermediate level↓</td>
<td>Intermediate level↓</td>
<td>1</td>
</tr>
<tr>
<td>I</td>
<td>Possible to act</td>
<td>No scattering</td>
<td>No cracks</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3. Answers for “Moving and/or overturning of furniture” and the corresponding scores.

<table>
<thead>
<tr>
<th>Type of answers</th>
<th>Moving and/or overturning of furniture</th>
<th>Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>Severely moved and/or overturned</td>
<td>0.8</td>
</tr>
<tr>
<td>IV</td>
<td>Intermediate level</td>
<td>0.6</td>
</tr>
<tr>
<td>III</td>
<td>Partially moved and/or overturned</td>
<td>0.4</td>
</tr>
<tr>
<td>II</td>
<td>Intermediate level</td>
<td>0.2</td>
</tr>
<tr>
<td>I</td>
<td>No moving</td>
<td>0</td>
</tr>
</tbody>
</table>

The 2016 Kumamoto earthquake included two major events: the foreshock on April 14 (Mw6.2) and the mainshock on April 16 (Mw7.0). We asked residents to answer these questions exclusively for the mainshock, even though their answers may be less or more affected by the entire series of earthquakes including the foreshocks and aftershocks. The total number of valid responses in Table 1 and Figure 4 was more than 400. The reply rate reached approximately 50% in Kumamoto City, which was much more than 20% for the 2011 Tohoku earthquake. When the mainshock occurred, most of the residents were in their apartments; some were awake, and some who were sleeping had been awakened by the strong shaking.

3. RESULTS OF THE QUESTIONNAIRE SURVEY

3.1 Indoor Damages in Kyushu Island and Comparison with the 2011 Tohoku Earthquake

The aggregate for the questionnaire was compiled for three cities in Kyushu Island. All of the crosstab charts were made by dividing the floors into roughly three groups: “Upper floors,” “Middle floors,” and “Lower floors.”

The action difficulty faced by the residents (Takahashi et al., 2010) during the mainshock is illustrated in Figure 5. In Kumamoto City, more than 80% of residents found it impossible to act or faced considerable difficulty in acting during the massive shaking. As the floor level increased, the action difficulty became large. In Kurume and Fukuoka, which were far from the epicenter, action difficulties were small. The action difficulty in Kumamoto City was much larger than that in the Kanto area during the 2011 Tohoku earthquake; this suggested that floor shaking in Kumamoto City was much stronger than that in the Kanto area.

This trend can also be clearly seen in Figure 6. As the floor level increased, the moving and/or overturning of furniture became large. Approximately 30% of residents in Kumamoto City responded that their furniture had severely moved and/or was overturned, which was much more than that in the Kanto area. Figure 7 is the aggregate data on the scattering of small items on tables, which shows similar trends as the moving and/or overturning of furniture. Figure 8 is a height-wise distribution of cracks in the wallpaper during the mainshock. They were
observed on all floor levels, but we could not discern any clear pattern in this height-wise distribution. This is different from the distribution pattern observed for the 2011 Tohoku earthquake for which wallpaper cracks were generally concentrated in the lower floors. This was partly due to the difference in the input motion characteristics of the shallow inland 2016 Kumamoto earthquake, which generated distinctive pulse-type motions.

Figure 5. Action difficulty during the mainshock.

Figure 6. Moving and/or overturning of furniture.

Figure 7. Scattering of small items on tables.
3.2 Details of Indoor Damages in Three Buildings in Kumamoto City

In this section, we focus on the responses to the questionnaire survey obtained for the three buildings: EA, EB, and EC, in Kumamoto City (see Figure 2(b)), where there was maximum concentration of severe indoor damages. Figure 9 illustrates the height-wise distribution of action difficulty for the three buildings in Kumamoto City. In general, the action difficulty becomes large in the upper floor, except in EC. The moving and/or overturning of furniture for the three buildings in Kumamoto City is shown in Figure 10. The floor level is high in EA and EB; therefore, the moving and/or overturning of furniture was large. This trend is not clear in EC.

In Figure 11, we have compared the scattering of small items on the tables of the three buildings in Kumamoto City. The shape of the distribution is similar to the moving and/or overturning of furniture in Figure 10. Buildings EA and EB show severe damage to the higher floors. Figure 12 is the height-wise distribution of cracks in the wallpaper during the mainshock. The height-wise trend depends on buildings. In EB, the cracks were concentrated in the lower floors, as seen in the case of the 2011 Tohoku earthquake. In EA and EC, the middle and upper floors, respectively, also suffered from cracks in the wallpaper. The combination of input motion characteristics and dynamic characteristics, that is, the natural period, is supposed to produce different height-wise variations of indoor damages in the three buildings in Kumamoto City.

Figure 8. Cracks in wallpaper during the mainshock.

Figure 9. Action difficulty for the three buildings in Kumamoto City.
4. ESTIMATION OF PEAK FLOOR RESPONSES IN THREE BUILDINGS IN KUMAMOTO CITY

4.1 Relation between Indoor Damages and Floor Responses

For high-rise residential buildings with earthquake observation systems in the Kanto area, peak floor responses during the 2011 Tohoku earthquake were directly evaluated using recorded motions, even
though there were less than a dozen buildings with seismic observation systems. In Kumamoto City, there is no high-rise residential building equipped with accelerometers. We desired to estimate the peak floor responses because of the massive shaking that might occur as a result of a future inland earthquake. One approach is the numerical evaluation of earthquake response using the multi-degree-of-freedom (MDOF) nonlinear response analyses, as presented by Hinoura et al. (2018).

We proposed equations for the indoor damage and floor response, which enabled us to assess the structural response without strong motion records and/or simulation analyses (Hida and Nagano, 2015). The following equations express peak floor acceleration (PFA) and peak floor velocity (PFV) in terms of their weighted-average scores obtained from the questionnaire survey:

\[
PFA(\text{cm/s}^2) = 4.39R_D^{2.42} + 634.3R_O^{0.785} \tag{1a}
\]

\[
PFV(\text{cm/s}) = 2.74R_D^{2.43} + 111.9R_O, \tag{1b}
\]

where PFA and PFV are the absolute values for the floor responses, \(R_D\) is the average score for action difficulty during the mainshock, and \(R_O\) is the average score for moving and/or overturning of furniture. \(R_D\) and \(R_O\) can be calculated by a weighted average using the scores in Tables 2 and 3 from a group of respondents. Equations 1a and 1b are derived from the approximated formulation of PFA-\(R_D\), PFV-\(R_D\), PFA-\(R_O\), and PFV-\(R_O\) based on the Weibull distribution (Hida and Nagano, 2015). Figure 13 illustrates the contour maps of PFA and PFV for the scores of action difficulty and the overturning of furniture based on the results of the questionnaire survey for the 2011 Tohoku earthquake.

![Figure 13. Contours of PFA and PFV for scores of action difficulty and overturning of furniture (Source: Hida and Nagano, 2015).](image)

When a massive earthquake occurred at midnight, most residents were asleep. Therefore, the reliability of the evaluation of action difficulty at midnight was less than that for daytime events. We also proposed simple equations for PFA and PFV using only the scores for the scattering of small items on tables (Nagano et al., 2016). The average score for the scattering of small items on tables during the mainshock is defined by \(R_S\), which is calculated by a weighted average using the scores in Table 2. The \(R_S\) in the Kanto area for the 2011 Tohoku earthquake is presented in Figure 14. The approximated linear equations for PFA and PFV are as follows:

\[
R_S = 0.0063 \times \text{PFA}(\text{cm/s}^2) \tag{2a}
\]

\[
R_S = 0.0271 \times \text{PFV}(\text{cm/s}). \tag{2b}
\]

These equations can be useful when residents are out of their buildings or when earthquakes occur at
midnight. It must be noted that these equations can be applicable to peak floor response estimations with PFA and PFV values less than 500 cm/s$^2$ and 130 cm/s, respectively.

Figure 14. Relationship of PFA and PFV and the scores of scattering of small items on tables (Source: Nagano et al., 2016).

Figure 15. Estimated PFA and PFV of high-rise residential buildings compared with those in the Kanto area during the 2011 Tohoku earthquake from the recorded motions (Nagano et al., 2012).
4.2 Estimated Peak Floor Responses in Three Buildings in Kumamoto City

Using scores obtained from the questionnaire survey, we estimated the peak floor responses in three buildings in Kumamoto City. Figure 15 traces PFA and PFV of the high-rise residential buildings in Kumamoto City using Equations 1 and 2. The peak floor responses are compared with those of the eight high-rise residential buildings equipped with accelerometers in the Kanto area from the motions recorded during the 2011 Tohoku earthquake. Height-wise variations of the estimated PFA and PFV from equations 1 and 2 for the three buildings are consistent with one another, even though the approximation from Equation 2 has a very simple form. PFA and PFV in the lower floors in Kumamoto City are larger than those in the Kanto area during the 2011 Tohoku earthquake. This implies that input ground motions were stronger for buildings in Kumamoto City than for those in the Kanto area during the 2011 Tohoku earthquake. In general, the recorded motions show that the PFA and PFV in Kumamoto City were larger than those of the eight high-rise residential buildings in the Kanto area during the 2011 Tohoku earthquake. The structural response of EA was the largest among three buildings, partly because it was located closest to the epicenter, as seen in Figure 2(b). The peak floor responses of EA and EB increased in the upper floors. The floor responses of EC were almost flat for all levels. The amplification factors for the three buildings were small as compared with the 2011 Tohoku case. These trends are well reproduced and validated by the MDOF nonlinear response analyses (Hinoura et al., 2018).

5. CONCLUSIONS

This study investigates indoor damages and structural responses of high-rise residential buildings in the Kyushu Island during the 2016 Kumamoto earthquake using a questionnaire survey for residents. We estimated the peak floor responses for three buildings in Kumamoto City, where indoor damages were more serious than those for other cities. The conclusions of this study are summarized as follows:

1) In Kumamoto City, more than 80% of the residents found it impossible or difficult to act during the mainshock. The action difficulty encountered in the movements in Kumamoto City was much larger than that in the Kanto area during the 2011 Tohoku earthquake. This trend can also be seen in the moving and/or overturning of furniture and the scattering of small items on tables.

2) Cracks in partitions and wallpapers were observed in all floors, but we could not discern any height-wise trend in Kumamoto City. This is apparently different from the findings for the 2011 Tohoku earthquake, in which wallpaper cracks were generally concentrated on the lower floors. This is because of the difference in the input motion characteristics of the shallow inland 2016 Kumamoto earthquake, which generated pulse-type motions.

3) We estimated peak floor responses from two types of equations based on (a) action difficulty and overturning of furniture and (b) scattering of small items on tables. The PFA and PFV values of the two equations are consistent with each other for the three buildings. The PFA and PFV values in the lower floors of Kumamoto City were larger than those in the Kanto area during the 2011 Tohoku earthquake. This infers that input ground motions were stronger for buildings in Kumamoto City than for those in the Kanto area.

6. ACKNOWLEDGMENTS

We greatly appreciate the cooperation of the residents of the high-rise residential buildings for not only answering many questions but also sending useful comments on shaking and indoor damages. Some figures are created by the GMT (Wessel et al., 2013).
7. REFERENCES


