ANALYTICAL STUDY ON REINFORCED CONCRETE SCHOOL BUILDINGS DAMAGED BY KUMAMOTO EARTHQUAKE

S. Tajiri¹, M. Saito² and C.W. Sung²

ABSTRACT

On April 16, 2016, a Mw7.0 earthquake struck Kumamoto in Japan following a Mw6.2 earthquake on April 14. It heavily damaged not only many wooden houses but also some reinforced concrete (RC) buildings such as residential buildings, commercial buildings, and school buildings. This paper presented damage to five RC buildings of a school in Mashiki town, the most affected area. A three-story school building seismically retrofitted with steel braces was minor damaged. A two-story school building evaluated to be seismically safe in a seismic assessment was slightly damaged. A single-story school building designed with a current seismic code was not damaged. Two 2-story connecting corridors standing between the school buildings evaluated to be safe in a seismic assessment almost collapsed because of flexural failures at both ends of all the columns in the first floor. Two RC connecting corridors collapsed and the other three RC school buildings damaged slightly. This paper also showed their earthquake responses estimated with analytical studies. Responses to ground motions of a foreshock and a main shock recorded at the nearest seismic station were so large that they overestimated observed damage except for the connecting corridor's response to the main shock. Considering 30% observed ground motions, estimated damage to the school buildings got close to their observed damage. However, the corridor's estimated deformation got too small to meet its damage. Assuming sliding of superstructures on the ground occurred under the condition that their friction factor was 0.5, their estimated responses met the actual damages except for the response of the connecting corridors to the foreshock.

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On April 16, 2016, a Mw7.0 earthquake struck Kumamoto in Japan following a Mw6.2 earthquake on April 14. It heavily damaged not only many wooden houses but also some reinforced concrete (RC) buildings such as residential buildings, commercial buildings, and school buildings. This paper presented damage to five RC buildings of a school in Mashiki town, the most affected area. A three-story school building seismically retrofitted with steel braces was minor damaged. A two-story school building evaluated to be seismically safe in a seismic assessment was slightly damaged. A single-story school building designed with a current seismic code was not damaged. Two 2-story connecting corridors standing between the school buildings evaluated to be safe in a seismic assessment almost collapsed because of flexural failures at both ends of all the columns in the first floor. Two RC connecting corridors collapsed and the other three RC school buildings damaged slightly. This paper also showed their earthquake responses estimated with analytical studies. Responses to ground motions of a foreshock and a main shock recorded at the nearest seismic station were so large that they overestimated observed damage except for the connecting corridor's response to the main shock. Considering 30% observed ground motions, estimated damage to the school buildings got close to their observed damage. However, the corridor's estimated deformation got too small to meet its damage. Assuming sliding of superstructures on the ground occurred under the condition that their friction factor was 0.5, their estimated responses met the actual damages except for the response of the connecting corridors to the foreshock.

Introduction

On April 16, 2016, a Mw7.0 earthquake (main shock) struck Kumamoto in Japan following a Mw6.2 earthquake (foreshock) on April 14 (Fig. 1). It heavily damaged not only many wooden houses but also some reinforced concrete (RC) buildings such as residential buildings, commercial buildings, and school buildings. This paper presents seismic damage to five RC buildings of a junior high school in Mashiki town, where the severest seismic damage was observed. This paper also shows structural properties and estimated earthquake responses of the buildings to discuss what affected a damage difference between these buildings.

Investigated School

The investigated school is a junior high school, which is about 6 km northeast from an epicenter

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of the foreshock and about 8 km east-northeast from an epicenter of the main shock (Fig. 1). This school has three RC school buildings A, B and C as well as two RC connecting corridors as shown in Fig. 2. Gaps between these buildings structurally separate each other.

**Earthquake**

One of the nearest seismic station, KMMH16, is 1.4 km northwest from the investigated school. Fig. 3 shows ground acceleration records of the foreshock and the main shock observed at KMMH16 [1]. Fig. 4 shows their elastic acceleration response spectra with 5% damping and a design spectrum in the Japanese seismic code. This figure shows that acceleration responses to the earthquakes were about 2-3 times larger than the design spectrum in the range of short period.

![Figure 1. Locations of the investigated school and epicenters of earthquakes.](image)

![Figure 2. Layout of RC buildings in the investigated school.](image)

![Figure 3. Ground motions of the foreshock and the main shock recorded at KMMH16.](image)
Damage Classification

Seismic damage to the five RC buildings were investigated and classified with a Japanese seismic damage classification standard [2]. Table 1 shows how to judge damage level of RC column and wall according to the standard. Using these damage level at the heaviest damaged floor and direction, residual seismic performance of a building $R$ is calculated with Eq. 1.

$$R = \frac{\sum k_i \eta_i}{\sum k_i} \times 100\%$$  \hspace{1cm} (1)

where $k_i$ is 1 (for a column and a rectangular wall), 2 (for a column with wing wall), or 6 (for a wall with both end columns), and $\eta_i$ is a strength reduction factor as shown in Table 2.

Table 1. Damage level of RC columns and walls.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Flexure</th>
<th>Shear</th>
<th>Shear and flexure</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No damage</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>I</td>
<td>A 0.2 mm wide flexural crack occurred.</td>
<td>A 0.2 mm wide shear crack occurred.</td>
<td>1.0</td>
</tr>
<tr>
<td>II</td>
<td>A 0.2 - 1.0 mm wide flexural crack occurred.</td>
<td>A 0.2 - 1.0 mm wide shear crack occurred.</td>
<td>0.95</td>
</tr>
<tr>
<td>III</td>
<td>A 1.0 - 2.0 mm wide flexural crack occurred.</td>
<td>A 1.0 - 2.0 mm wide shear crack occurred.</td>
<td>0.6</td>
</tr>
<tr>
<td>IV</td>
<td>A &gt;2.0 mm wide flexural crack occurred. / Cover concrete spalled.</td>
<td>A &gt;2.0 mm wide shear crack occurred. / Shear strength deteriorated.</td>
<td>0.3</td>
</tr>
<tr>
<td>V</td>
<td>Axial shrinkage occurred.</td>
<td>0.1</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 2. Strength reduction factor $\eta_i$.

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Column</th>
<th>Wall</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shear</td>
<td>Shear</td>
</tr>
<tr>
<td>0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>I</td>
<td>0.95</td>
<td>0.95</td>
</tr>
<tr>
<td>II</td>
<td>0.6</td>
<td>0.7</td>
</tr>
<tr>
<td>III</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>IV</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>V</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
School buildings

Building A is a 3-story RC building which was built in 1981 and seismically retrofitted with steel braces in 2013. Figs. 5 and 6 show its first-floor plan and framing elevation. Table 3 shows sections of columns and walls of this building. Fig. 5 also shows damage to each column and wall in the east-west direction. R value is 80% which corresponds to minor damage.

Building B is a 2-story RC building which was built in 1981 and seismically evaluated to be safe. Figs. 7 and 8 show its first-floor plan and framing elevation. Table 3 shows sections of columns and walls of this building. Fig. 7 also shows damage to each column and wall in the east-west direction. R value is 98% which corresponds to slight damage.

Building C is a single-story RC building which was built in 1992 and designed with a current seismic code. Almost no damage occurred in this building.

Figure 5. First floor plan of the building A.

Figure 6. Framing elevation of the building A.
Table 3.  Section list of the investigated buildings.

<table>
<thead>
<tr>
<th>Connecting bar</th>
<th>Building A</th>
<th>Connecting bar</th>
<th>Building B</th>
<th>Connecting bar</th>
<th>Building B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoop</td>
<td>C1</td>
<td>C3</td>
<td>C5</td>
<td>C7</td>
<td>C9</td>
</tr>
<tr>
<td>3F</td>
<td>18-D22</td>
<td>10-D22</td>
<td>8-D22</td>
<td>10-D22</td>
<td>D3-D19</td>
</tr>
<tr>
<td>Hoop</td>
<td>D10@100</td>
<td>D12@100</td>
<td>D10@100</td>
<td>D10@100</td>
<td>D10@100</td>
</tr>
<tr>
<td>2F</td>
<td>12-D22</td>
<td>12-D22</td>
<td>12-D22</td>
<td>12-D22</td>
<td>14-D22</td>
</tr>
<tr>
<td>Hoop</td>
<td>D12@100</td>
<td>D12@100</td>
<td>D12@100</td>
<td>D12@100</td>
<td>D12@100</td>
</tr>
<tr>
<td>1F</td>
<td>14-D22</td>
<td>16-D22</td>
<td>18-D22</td>
<td>14-D22</td>
<td>14-D22</td>
</tr>
<tr>
<td>Hoop</td>
<td>D15@100</td>
<td>D15@100</td>
<td>D15@100</td>
<td>D15@100</td>
<td>D15@100</td>
</tr>
</tbody>
</table>

Figure 7. First floor plan of the building B.

Figure 8. Framing elevation of the building B.
Connecting corridors

East and west connecting corridors are the same structures. These are 2-story RC buildings which were built in 1981 and seismically evaluated to be safe. Fig. 9 shows their first-floor plan and framing elevation. As shown in Fig. 10, the east connecting corridor failed in flexural at both ends of all the columns in the first story and inclined about 20% in the first story. The west connecting corridor failed as same as the east corridor and inclined about 6% in the first story. $R$ values of both corridors are 0% which corresponds to collapse. According to a principal of the school, main shock caused such severe damage to the corridors.

![First floor plan and framing elevation of the connecting corridors](image)

Figure 9. First floor plan and framing elevation of the connecting corridors

![Appearance of the east connecting corridor.](image)

Figure 10. Appearance of the east connecting corridor.

Analytical Study

Earthquake responses of school buildings A, B and connecting corridors to the foreshock and the main shock were estimated with a capacity spectrum method in the Japanese seismic code [3]. Fig. 11 shows shear force-story drift of columns and walls used for the simulation, which were the same assumed in the Japanese seismic evaluation standard [4]. Fig. 12 shows story shear-drift of the buildings.
Figure 11. Force-deformation and corresponding damage level of columns and walls assumed for analytical studies.

Figure 12. Story shear-drift of the buildings.

Capacity spectrum for each building was calculated with Eqs. (2) and (3).

\[ S_{d,c} = \frac{\sum_i m_i d_i^2}{\sum_i m_i d_i} \]  

(2)

\[ S_{a,c} = Q_s \frac{\sum_i m_i d_i^2}{\left( \sum_i m_i d_i \right)^2} \]  

(3)

where \( S_{d,c} \) is a spectral displacement, \( S_{a,c} \) is a spectral acceleration, \( m_i \) is a mass of \( i \)-th story, \( d_i \) is
is a drift at $i$-th story, and $Q_i$ is a story shear at $i$-th story.

Demand spectrum was calculated as a response spectrum of an equivalent SDOF system, whose period $T_{eq}$ and damping factor $h_{eq}$ were calculated with Eqs. (4) and (5).

$$T_{eq} = 2\pi \sqrt{\frac{S_{d,c}}{S_{a,c}}}$$

$$h_{eq} = 0.25\left(1 - \frac{1}{\sqrt{\frac{S_{d,c}}{S_{dy,c}}}}\right) + 0.05$$

where $S_{dy,c}$ is a spectral displacement of a capacity spectrum at a yielding point.

As shown in Fig. 13, an intersection point of a capacity spectrum and a demand spectrum shows an earthquake response. This figure also shows each story drift response. The simulated responses of the Buildings A and B are much larger than responses assumed according to their investigated damage. The simulated response of the connecting corridors to the main shock is not so much different from their actual response although their response to the foreshock is much larger than the actual response.

![Figure 13](image)

**Figure 13.** Capacity spectrum, demand spectrum and estimated response of the buildings.

As the simulated responses of the building A and B is much larger than the actual response, ground motions at this school might be smaller than the recorded ground motions at KMMH16 station. So additional analyses were conducted with decreasing ground motions by 10% until the simulated response almost met their actual damage. As the results, simulated responses of the buildings A and B to 30% ground motions almost meet their investigated damage level as shown in Fig. 14. However, the response of the connecting corridors to the 30% main shock is 2.62% in the first story, which is too small to meet their actual response. Additionally, 30% of ground
motions look too small as the school is not so far from the seismic station.

Recently in Japan, damage to piles was often found caused by a large ground motion although the damage to superstructure was slight. The investigated buildings, which have individual footings and no piles, might slide on the ground. Although any apparent trace due to sliding was not found in site, it is not easy to find such trace. Then, additional analyses were conducted with reducing demand spectral acceleration to 0.5g to estimate response considering sliding under the condition that the friction factor is 0.5. As the results, responses of the buildings A and B meet their actual damage as well as the response of the connecting corridors to the main shock meets their actual damage as shown in Fig. 15. However, the response of the connecting corridors to the foreshock overestimated their actual damage.

**Conclusions**

In a junior high school in Mashiki town, two RC connecting corridors collapsed due to the main shock although the other RC school buildings in the school damaged slightly.

Estimated responses of the investigated buildings to the observed earthquakes are so large that they overestimate observed damage except for the connecting corridor's response to the main shock.

Considering 30% observed ground motions, estimated damage to the school buildings A and B gets close to their observed damage. However, the corridor's estimated deformation gets too small to meet its damage.

Assuming sliding of superstructures on the ground occurs under the condition that their
friction factor is 0.5, their estimated responses meet the actual damages except for the response of the connecting corridors to the foreshock.

Figure 15. Estimated response of the buildings considering sliding.

Acknowledgments

The authors are grateful to an officer of Mashiki town for providing us information of the school buildings investigated in this paper. We also thank the National Institute for Earth Science and Disaster Resilience for providing the Kik-net strong motion data.

References


