STATISTICAL ANALYSIS OF BUILDING DAMAGE IN JAPAN BASED ON THE 2016 KUMAMOTO EARTHQUAKE

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Abstract

This study investigates the building damage in Mashiki Town, Kumamoto Prefecture, due to the 2016 Kumamoto, Japan, earthquake. Most building fragility curves, used for damage estimation for scenario earthquakes in Japan, were developed based on the damage data in the 1995 Kobe earthquake. However, already 23 years have passed after this event, and hence it is better to use recent earthquake data. In this study, the damage ratios of buildings are investigated from the viewpoints of structural material and construction period. As a result, the damage ratio of wooden buildings gets higher as the construction period becomes older. It is clearly observed that within the construction period of 1982-2016, corresponding to the new seismic code in Japan, the damage ratio becomes smaller for newer wooden buildings. The reduction of damage ratio with construction period is also observed for RC and steel buildings. The spatial distribution of damaged buildings is further investigated with their locations on GIS. The results are compared with the distribution of peak ground velocity (PGV) values and the statistical fragility curves are developed on a log-normal probability paper. The developed fragility curves for wooden buildings show a slightly lower level of damage than those from the Kobe earthquake.

Introduction

The damage patterns and damage levels of buildings due to strong earthquake motion are highly dependent on the structural materials, building laws and regulations, and local construction practice, and hence the investigation on actual earthquake damage situations is quite important and is useful to develop vulnerability functions of buildings. In this regard, the definition of damage levels and the classification of building types are crucial issues. The damage status of buildings can be judged by visual inspection in the field (Grünthal ed. 1998; Building Research Institute 1996; Okada & Takai 2000) or from aerial (Hasegawa et al. 2000) or satellite imagery (Yamazaki et al. 2005) and Lidar data (Moya et al. 2018), but the damage investigation including the internal damage situation is necessary to assess monetary losses and is often conducted by local governments in Japan for the purpose of property-tax exemption and financial support (Yamazaki & Murao 2000; Yamaguchi & Yamazaki 2000).

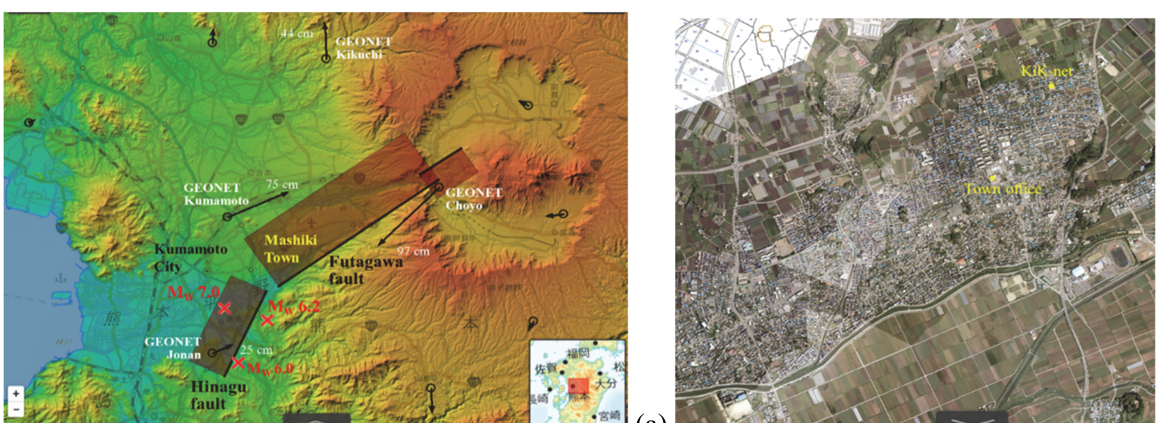
A series of earthquakes hit Kumamoto Prefecture in Kyushu Island, Japan, on April 14 and 16, 2016. A large number of buildings, mostly wooden houses, were damaged and some of them were totally collapsed. A number of engineers and researchers from various organizations conducted damage investigation of buildings in Mashiki Town, where the building damage was most severe in the earthquake. Among them, the local governments in Kumamoto Prefecture carried out field investigation in order to issue disaster-victim certificates. The people who have had their houses damaged by a natural disaster require this certificate to be eligible to receive various aids. In this paper, the result of damage assessment provided by Mashiki Town government is used to analyze the characteristics of building damage due to the Kumamoto earthquake. The result of the analysis is compared with those by other damaging earthquakes in Japan.

The 2016 Kumamoto Earthquake

A Mw6.2 earthquake hit Kumamoto Prefecture on April 14, 2016 at 21:26 (JST). A considerable amount of structural damages and human casualties had been reported due to this event, including 9 deaths (Cabinet Office of Japan 2016). The epicenter was located in the Hinagu fault with a shallow depth. On April 16, 2016 at 01:25 (JST), about 28 hours after the first event, another earthquake of Mw7.0 occurred in the Futagawa fault, closely located with the Hinagu fault. Thus, the first event was called as the "foreshock" and the second one as the "main-shock". The focal planes of the both events were located close to the center of Mashiki Town (about 33-thousand population), which is to the east of Kumamoto City (about 735-thousand population). A total of fifty (50) direct-causes deaths were accounted by the earthquake sequence, mostly due to the collapse of wooden houses in Mashiki Town and landslides in Minami-Aso Village (Cabinet Office of Japan 2016; Yamazaki & Liu 2016). The total number of aftershocks (larger than magnitude 3.5) reached 340 times as of April 30, 2017, one year after the first event. This number is the largest among recent inland earthquakes in Japan (Japan Meteorological Agency 2017).

Figure 1(a) shows the location of the causative faults and Japanese national GNSS Earth Observation Network System (GEONET) stations in the source area (Geospatial Information Authority of Japan (GSI) 2016). Note that the GEONET system has about 1,300 stations covering Japan's territory uniformly. The displacement of 75 cm to the east-northeast (ENE) was observed at the Kumamoto station while that of 97 cm to the southwest (SE) was recorded at the Choyo station during the main-shock. These observations validated the right-lateral strike-slip mechanism of the Futagawa fault. A detailed distribution of coseismic displacements in Mashiki Town was estimated by the present authors (Moya et al. 2017) using the Lidar data acquired before and after the April 16 main-shock (Asia Air Survey 2016).

The peak ground acceleration (PGA) and the peak ground velocity (PGV) recorded at the KiK-net Mashiki station (KMMH16) were 925 cm/s^2 and 92 cm/s in the foreshock while those were 1,313 cm/s^2 and 132 cm/s in the main-shock (Suzuki et al. 2016). These values are quite large in the recent earthquake records in Japan. Even a larger PGV value, 183 cm/s, was recorded on the ground floor of Mashiki Town office building in the main-shock with PGA= 897 cm/s^2. The location of these two seismic stations are plotted in Figure 1(b) on a mosaiced orthorectified aerial image acquired by GSI (2016) on April 29, 2016. In general, building damage was most severe in the south of the town-office building while the damage situation was much smaller around the KiK-net station (Yamada et al. 2017).



(b)

Figure 1. Location of causative faults and GNSS stations in the 2016 Kumamoto earthquake (a) and a mosaiced orthorectified aerial image by GSI and location of seismic stations in Mashiki Town (b)

Building Damage Assessment in Mashiki Town

Since the building damage in the Kumamoto earthquake was most severe in Mashiki Town, a number of research groups conducted field investigations (NILIM 2016; Sugino et al. 2016; Yamada et al. 2017) and the results were used to explain the heavy damage situation of buildings, compared with the seismic records. But these damage surveys were mostly visual inspection from the road side or some used aerial photographs, they are applicable only to significant damage levels, such as “collapse” or “partial collapse”. Another drawback of these kinds of voluntary investigations is the difficulty to obtain detailed building information, such as the structural-material and construction-year. In this regard, only the damage investigation by local governments can link the damage classification result with the detailed building information.

Several vulnerability functions (fragility curves) for Japanese buildings had been developed (Yamaguchi & Yamazaki 2000; Yamazaki & Murao 2000; Midorikawa et al. 2011) and actually used in damage assessments for scenario earthquakes, but that the damage (loss) evaluation methods were different depending on local governments at the time of the 1995 Kobe earthquake (Murao & Yamazaki 1999). After the Kobe event, the central government issued the unified loss evaluation method (Cabinet Office of Japan 2013) and the workflow and training procedure were proposed (Urakawa et al. 2010; Tanaka & Shigekawa 2014). The affected local jurisdictions in Kumamoto Prefecture followed this method and hence the results of the loss evaluations can be considered as the data of same category.

Moshiki Town (2017) recently issued the summary report on the response/recovery activities for the Kumamoto earthquake. In the report, a total of 10,742 buildings were classified in to five classes by their damage (or monetary loss) classes, shown in Table 1. Note that this classification was carried out following the unified loss evaluation method (Cabinet Office of Japan 2013). In the table, an approximate correspondence with visual inspection methods (Grünthal ed. 1998; Okada & Takai 2000) is also shown. The result of loss assessment by local government is important for affected people to receive financial support and property tax reduction. In Mashiki Town, the first stage assessment, viewing from outside, was conducted for all the buildings. This result was shown to the residents and in case, they did not accept it, the second stage assessment, viewing the damage status of inside a building, was carried out.

Table 1. Earthquake Loss Evaluation Class of Buildings in Japan and Schematic Images of Other Damage Classification Methods

Current Damage (Loss) Class	Former Damage (Loss) Class	Loss Ratio (r), Damage Index	EMS-98	Okada & Takai (2000)
Major	Major	$r \geq 60\%$	G4 G5 	D4 D5 
		$50\% \leq r < 60\%$	G3 	D3 
Moderate +	Moderate	$40\% \leq r < 50\%$		
Moderate −		$20\% \leq r < 40\%$	G2 	D2 
Minor	Minor	$0\% < r < 20\%$	G1 	D1 
No	No	$r = 0\%$	(G0)	D0

The final result of the property loss evaluation is shown in Figure 2 (Mashiki Town 2017). It is observed from the figure that the major damage buildings are distributed widely, especially along the Futagawa fault line. The overall damage grade gets smaller in the northern and eastern areas. In the central part of Mashiki Town, major damaged buildings exist more around the Town office building than around the KiK-net station, which is consistent with field observations.

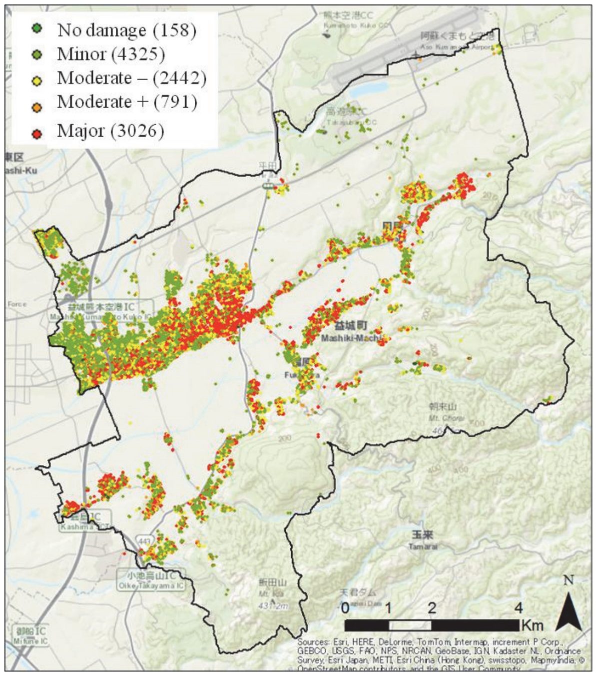


Figure 2. Result of damage (loss) assessment by Mashiki Town government (2017)

Figure 3 compares the acceleration response spectra (the resultant of the two horizontal components, 5% damping ratio) for the recorded motions at the two seismic stations for the foreshock (April 14) and the main-shock (April 16). In the figure, the result for the connected time histories (April 14 and April 16 in 5-s interval) is also plotted. It is seen for the KiK-net station that in a short period range less than 0.7 s (0.8 s for the Town office station), the April-14 event exhibits higher response values than those of the April 16 event. But in the longer period range, the April 16 event shows higher response values. It is also noticeable, especially for the April 16 event, that the Mashiki town office record shows much higher values than those of the KiK-net station in the period longer than 0.7 s, which is considered to be responsible for the structural damage of wooden buildings in Japan.

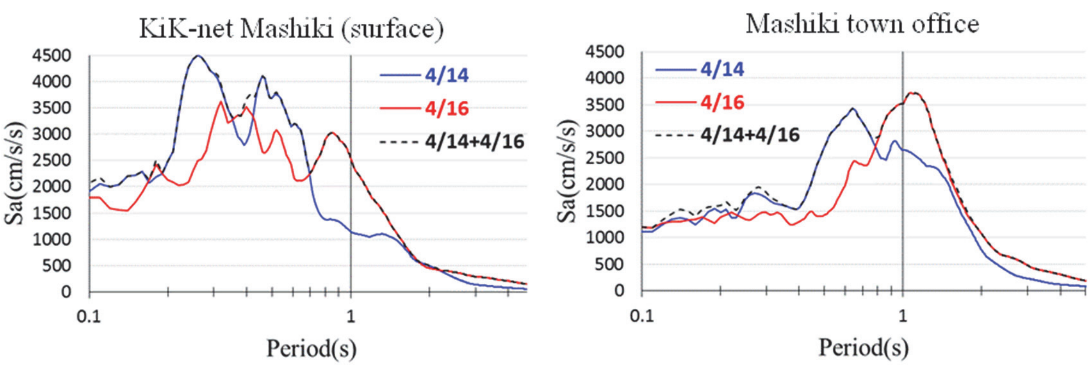
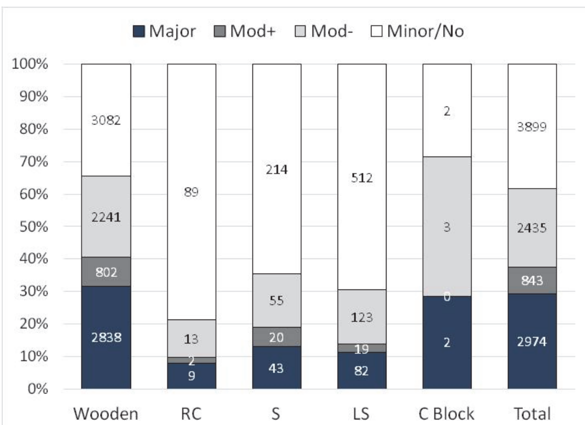


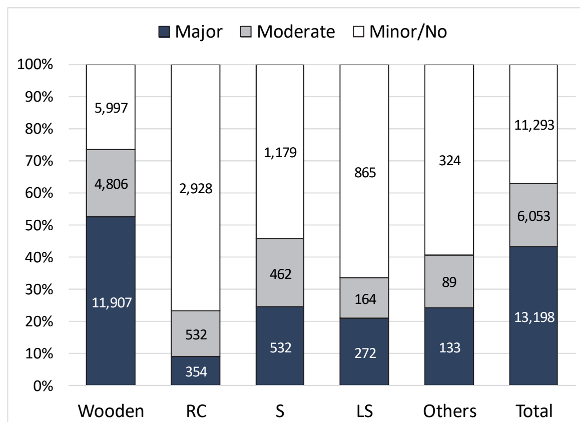
Figure 3. Acceleration response spectra (the resultant of the two horizontal components, 5% damping ratio) for the records at KiK-net Mashiki station and Mashiki Town office.

Analysis of Building Damage in Mashiki Town

The building damage data shown in Figure 2 were analyzed based on the structural material and construction period. From all the loss assessment data, non-residential or non office-use buildings, such as a storage barn, were excluded. Figure 4 shows the damage classifications for a total of 10,151 buildings in Mashiki Town due the 2016 Kumamoto earthquake and that for 30,544 buildings in Nada Ward due the 1995 Kobe earthquake (Yamazaki & Murao 2000). The ratio of major damage for each structural material is in the order of "wooden", "Steel (S)", "Light-gauge Steel (LS)", and "Reinforced Concrete (RC)" buildings for the both datasets. Although there is a 21-year time difference, the vulnerability of buildings with respect to the structural type is quite similar. Note that at the time of the Kobe earthquake, the damage class "Moderate" correspondeds to the monetary loss ratio of 20%≤ r <50%, which is the summation of "Moderate+" and "Moderate-" in the Mashiki data.



(a) Mashiki Town in 2016 Kumamoto EQ



(b) Nada Ward in 1995 Kobe EQ

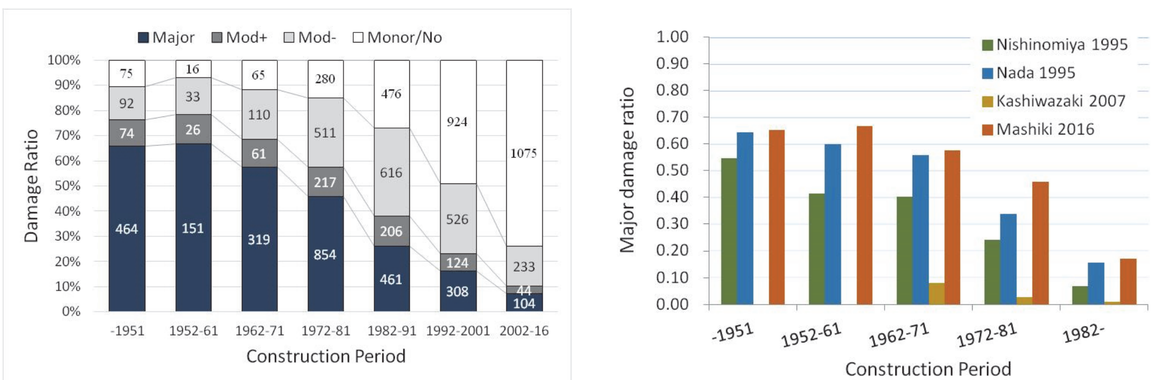
Figure 4. Damage classification of buildings by local governments with respect to the structural type.

The effect of construction period, which corresponds to the change of seismic code in Japan, was then investigated only for wooden buildings since the number of buildings for other structural types was not large enough. Figure 5(a) shows the damage ratio of wooden buildings in Mashiki Town with respect to the construction period and damage (loss) category. It is clearly observed that within the construction period of 1982-2016, that corresponds to the new seismic code in Japan, the damage ratio becomes smaller for newer wooden buildings. Note that the seismic provision for wooden buildings was upgraded in 2000.

In the damage category, "Major", which represents the monetary loss over 50%, is most important since the demolition of the building is a normal situation for this class. Figure 5(b) compares the ratio of major damage class for wooden buildings with respect to the construction period for Nada Ward in Kobe City (Yamazaki & Murao 2000) and Nishinomitya City (Yamaguchi & Yamazaki 2000) due to the 1995 Kobe earthquake, and Kashiwazaki City (Nagao et al. 2011) due to the 2007 Niigata-Chuetsu-Oki earthquake, and the Mashiki Town data in this study. For the same construction period, the major damage ratio of the Mashiki Town is almost the same level as that of Nada Ward. The damage ratio of Nishinomiya City is slightly small than that of Nada Ward since the city includes the area of lower seismic motion in the northern part.

The major damage ratio of Kashiwazaki City was much lower than the other three locations although the strong motion records are in the comparable level. Similarly, the major damage ratios for recent earthquakes in Japan were much smaller than that in the Kobe earthquake for the same ground motion level. A few reasons are considered to explain this discrepancy. First, the damage assessment method was not unified and the local governments issued higher damage grades following citizens' requests. The regional difference in construction practice for wooden buildings may be the second reason. In the western Japan, like Kobe and Kumamoto, wooden houses are considered to be more vulnerable than those in the eastern (northern) Japan since typhoons are a more frequent natural hazard than earthquakes, and thus heavy roofs were dominant for older wooden houses in the western Japan. The luck of seismometers at the time of the Kobe earthquake gave uncertainty in estimating the strong motion distribution.

Based on the building damage data and estimated strong motion distribution due the 2016 Kumamoto earthquake, the present authors will try to develop new empirical vulnerability functions for Japanese buildings in the near future. To do this task, the damage assessment data and inventory data of buildings in other municipalities in Kumamoto Prefecture should be included in order to increase the data from smaller shaking level regions.



(a) (b)

Figure 5. Damage classification of wooden buildings with respect to construction period in Mashiki Town (a) and comparison of the major damage ratio class for wooden buildings for four different datasets in Japan.

Conclusions

Building damage in Mashiki Town, Kumamoto Prefecture, Japan, due to the 2016 Kumamoto earthquake was investigate based on the result of damage investigation by the local government. The structural material was seen to be the primary factor to determine damage grades of buildings as well as the strong motion intensity. The major damage ratio of wooden buildings gets higher as the construction period becomes older. It is clearly observed that within the construction period of 1982-2016, that corresponds to the new seismic code in Japan, the damage ratio becomes smaller for newer wooden buildings. A similar trend of damage was also observed for other structural materials, RC and steel, but the ratios are much smaller than those for wooden houses. A preliminary study on the spatial distribution of damaged buildings was also conducted on a GIS.

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