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Development of fragility curves of Japanese buildings based on the 2016 Kumamoto earthquake

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ABSTRACT

This study develops fragility curves of Japanese buildings based on damage survey data from the 2016 Kumamoto earthquake. The damage ratios of buildings in the event are investigated from the viewpoints of structural material and construction period. As a result, the damage ratio of wooden houses 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 houses. The reduction of damage ratio with construction period is also observed for RC and steel-frame 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 empirical fragility curves are developed on the lognormal probability paper. It is observed that the building damage ratios in the Kumamoto earthquake are in the similar levels with those in the 1995 Kobe earthquake for the same structural type and construction period.

1 INTRODUCTION

The damage patterns and damage levels of buildings 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 fragility curves (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; Okada & Takai 2000) or from aerial (Hasegawa et al. 2000) or satellite imagery and Lidar data (Moya et al. 2018), but the damage investigation including the internal damage situation is necessary to assess monetary losses for the owners 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 for 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 (Urakawa et al. 2010; Mashiki Town Government 2017). 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 the Mashiki Town government is used to analyze the characteristics of building damage due to the Kumamoto earthquake. 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 empirical fragility curves are developed on the lognormal probability paper. The obtained fragility curves are compared with those from the 1995 Kobe earthquake.

2 2016 KUMAMOTO EARTHQUAKE AND STRONG MOTION IN MASHIKI TOWN

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. The epicentre 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 just below or close to the centre 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-cause deaths were accounted by the earthquake sequence, due to the collapse of wooden houses in Mashiki Town and landslides in Minami-Aso Village etc. (Yamazaki & Liu 2016).

Figure 1 shows the location of these causative faults and Japanese national GNSS Earth Observation Network System (GEONET) stations in the source area operated by the Geospatial Information Authority of Japan (GSI). 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 airborne Lidar data acquired before and after the April 16 main-shock by Asia Air Survey Co., Ltd.

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, respectively. 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

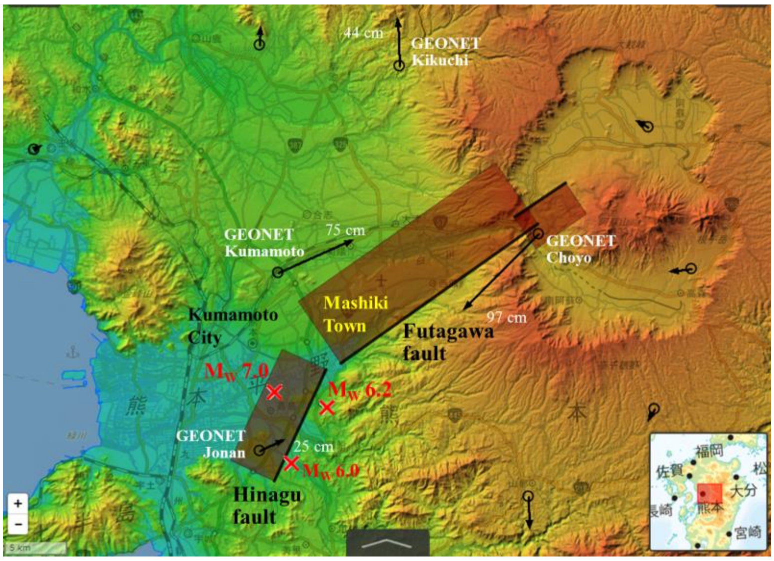


Figure 1: Location of causative faults and GNSS stations in the 2016 Kumamoto earthquake

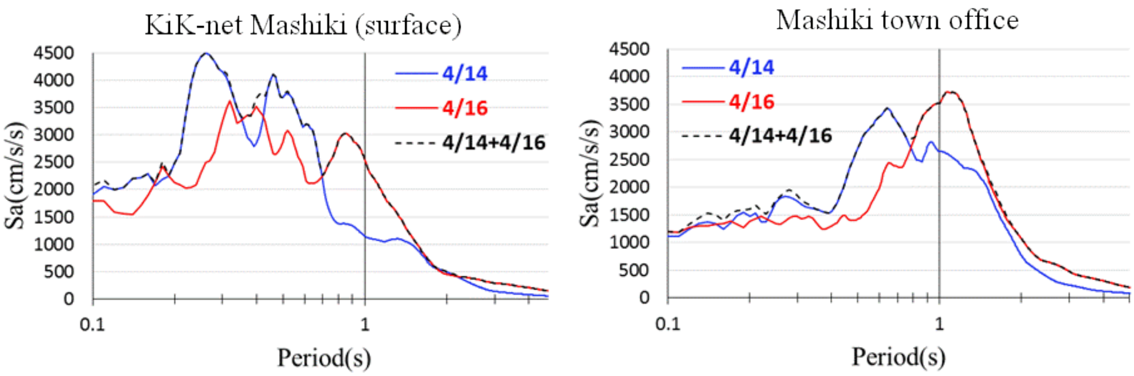


Figure 2: Acceleration response spectra (the resultant of the two horizontal component, 5% damping ratio) for the records at KiK-net Mashiki station and Mashiki Town office.

main-shock with PGA= 897 cm/s^2.

Figure 2 compares the acceleration response spectra (the resultant of the two horizontal component) 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 stations in the period longer than 0.7 s, which corresponds to the structural damage of wooden buildings in Japan.

The distribution of strong ground motion in the disaster area was estimated by collecting a total of 1,141 (K-NET and KiK-net: 698; JMA: 316; local governments: 111; Saibu Gas Co.: 16) strong motion records for the main-shock of the Kumamoto earthquake. Kriging interpolation was applied to these peak ground motion values considering the attenuation relationship from the causative fault plane of the main-shock and the soil amplification factor, following the method (Matsuoka & Yamamoto 2012). Figure 3a shows the estimated resultant PGV distribution in 250-m grid for Mashiki Town. The high PGV hit the centre of Mashiki Town,

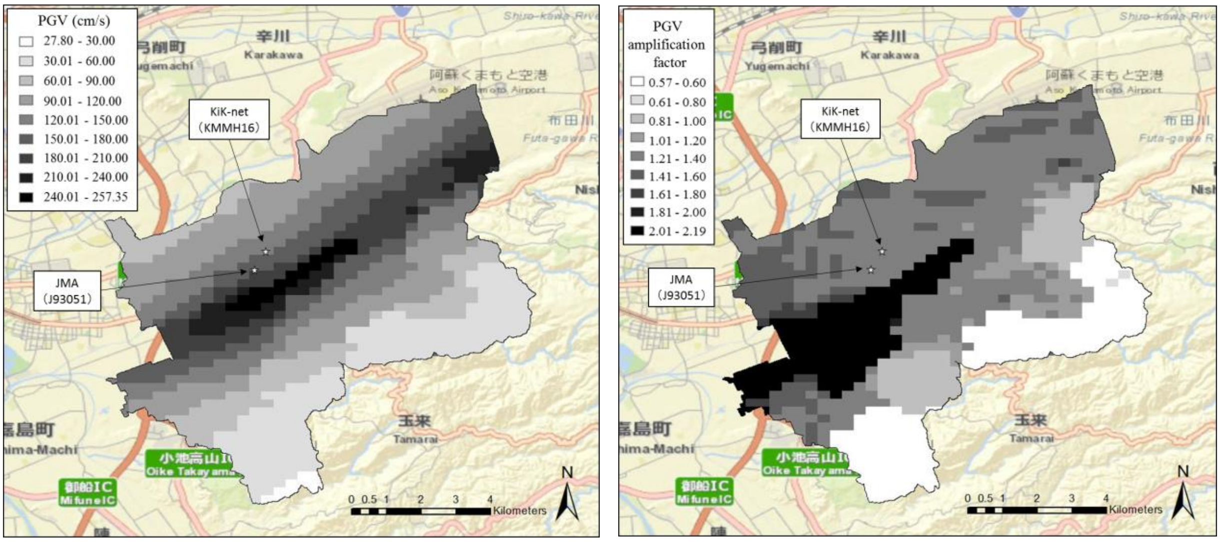


Figure 3: (a) Estimated peak ground velocity (PGV) distribution in a 250-m grid in Mashiki Town and (b) PGV amplification factor in 250-m grid used in Kriging interpolation.

where a lot of buildings were collapsed or damaged. Figure 3b shows the PGV amplification factor used in Kriging interpolation for the study area (NIED 2016). In the south of the central residential area, the amplification factor exceeding 2.0 is widely distributed. The small amplification ranges are distributed in the eastern and southern parts, which are mostly mountainous. Although the PGVs recorded at the KiK-net Mashiki station and Mashiki Town office show a big difference, the PGV amplification factor (sub-surface soil category) is the same for the two sites.

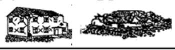
3 ANALYSIS OF BUILDING DAMAGE IN MASHIKI TOWN

Since the building damage in the Kumamoto earthquake sequence was most severe in Mashiki Town, a number of research groups conducted field investigations. 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 “total 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 fragility curves for Japanese buildings had been developed (Yamaguchi & Yamazaki 2000; Yamazaki & Murao 2000) and actually used in damage assessments for scenario future earthquakes in Japan, but that the damage (loss) evaluation methods were different depending on local governments at the time of the 1995 Kobe earthquake. After this 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 unified method.

Moshiki Town Government (2017) recently issued the summary report on the response/recovery activities for the Kumamoto earthquake. The building damage was classified in to five classes, following the unified loss evaluation method, shown in Table 1. In the table, an approximate correspondence with visual inspection methods (Grünthal ed. 1998; Okada & Takai 2000) is also shown. 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. A total of 13,718 damage certificates were issued by the government. However,

Table 1: Earthquake loss evaluation classes of buildings by local governments 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

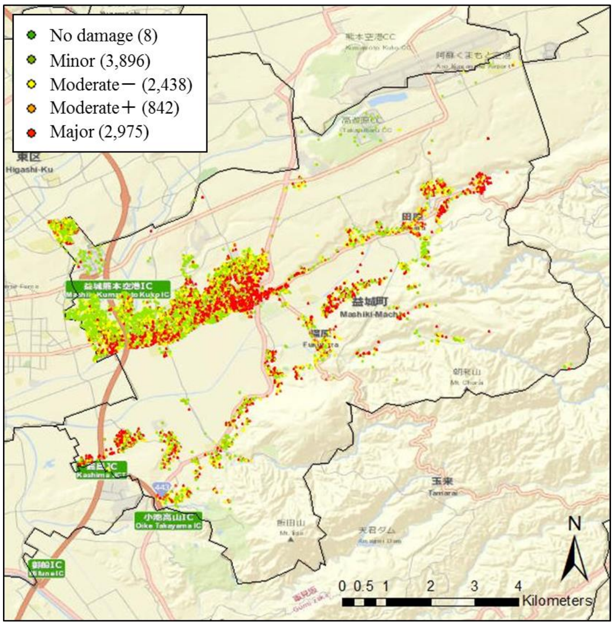
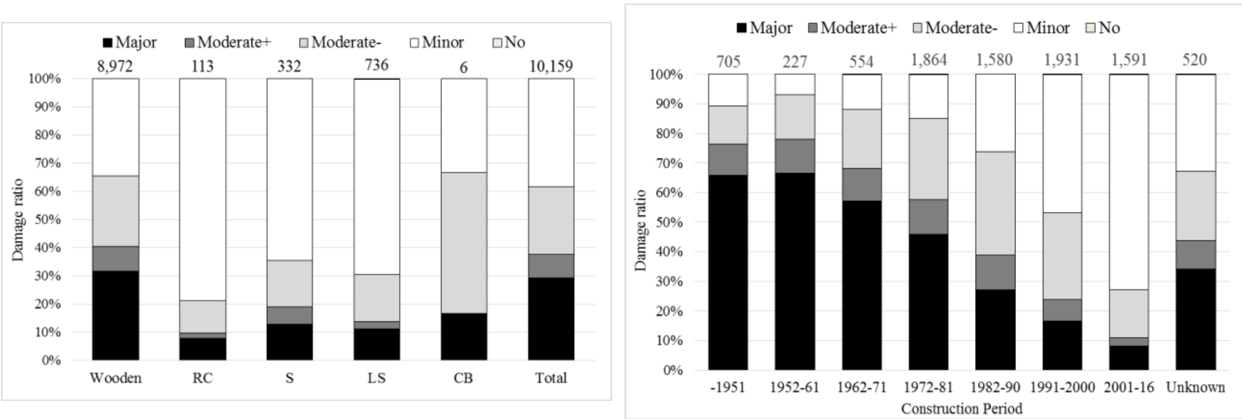


Figure 4: Distribution of damaged buildings in Mashiki Town based on the town government

these data also include ones that are not suitable for analyzing building damage. We excluded the following data from the loss assessment: storage, warehouse, garage, etc. (2,945), those other than the final assessment (461), those with the area less than 20 m^2 (142) and those without ground floor (11). The remaining 10,159 data were used.

The building data are plotted on GIS in Figure 4. 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.

Figure 5a shows the damage classifications for the 10,159 buildings in Mashiki Town. The ratio of major damage for each structural type (material) is in the order of "wooden", "Steel (S)", "Light Gauge Steel (LS)", and "Reinforced Concrete (RC)" for the dataset.



(a) Damage ratios for different structural types *(b) Damage ratio of wooden structures for construction period*

Figure 5: Damage ratios of buildings in Mashiki Town based on the town government survey data

Figure 5b shows the damage ratio of wooden buildings in Mashiki Town with respect to the construction period and damage grade. Except for the result prior to 1951, the damage ratio gets smaller as the construction period becomes newer. The major damage ratio is greatly declined after 1982 as the effect of the revision of seismic provision. Note that the seismic provision for wooden buildings was further upgraded in 2000. We also investigated the change of the damage ratio for each construction year, and it was found that the damage ratio gets larger gradually as the construction year become older (Yamazaki et al. 2018). The damage ratios of non-wooden buildings were also investigated with respect to the construction period (Suto et al. 2018). But the number of buildings for each category was not enough to obtain a solid conclusion.

4 DEVELOPMENT OF BUILDING FRAGILITY CURVES FOR MASHIKI DATA

The fragility curves were developed by combining the Mashiki Town's building damage data and the estimated PGV distribution on GIS. First, the fragility curves considering only the structural type were developed for wooden, S, and LS structures. The number of buildings was not enough for RC structures to develop such a curve. In constructing the fragility curves, after sorting damage data based on the PGV value of each building, several buildings with a similar level of PGV values were classified as one sub-group. For wooden buildings, the all data were divided into 20 sub-groups, while for S and LS buildings into 5 sub-groups because the data numbers were small. The average PGV value for each sub-group was calculated as the value to represent that the damage ratio of the sub-group of buildings.

A fragility curve of buildings was obtained by assuming the cumulative probability, $P_R(PGV)$, of the occurrence of damage equal to or higher than a rank R (such as "major") to be log-normal as follows:

$$P_R(PGV) = \Phi((\ln PGV - \lambda)/\zeta) \quad (1)$$

where Φ is the standard normal distribution and λ and ζ are the mean and standard deviation of *ln* PGV. The two parameters, λ and ζ, were determined by the least square method on a lognormal probability paper.

Figure 6 shows the fragility curve for the major damage ratio with respect to PGV for each structural type of all construction years. It is observed that one for wooden buildings show higher damage probability than those for S and LS buildings. The curves for S and LS are quite similar and compared with those, the damage ratio for wooden buildings starts to rise at a lower PGV level.

Yamazaki & Murao (2000) constructed a set of fragility curves due the 1995 Kobe earthquake with respect to PGV considering the structural type and construction period using the damage survey data for Nada Ward, conducted by Kobe City. Yamaguchi & Yamazaki (2000) also created the fragility curves using the damage data of Nishinomiya City due the Kobe earthquake. The fragility curve of S and LS structures for Mashiki Town are compared with those due to the 1995 Kobe earthquake in Figure 7.

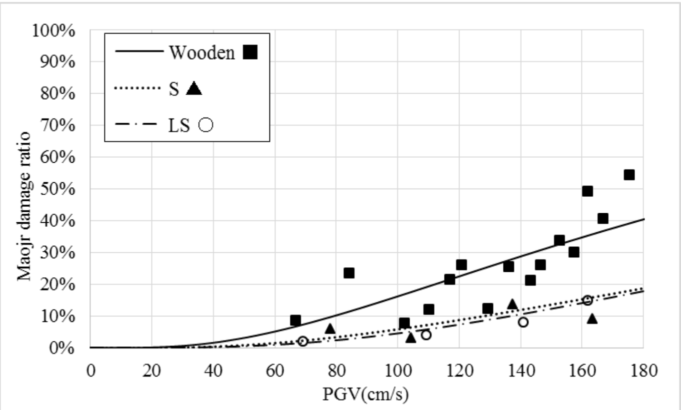


Figure 6: Fragility curves of Mashiki Town with respect to PGV for different structural types

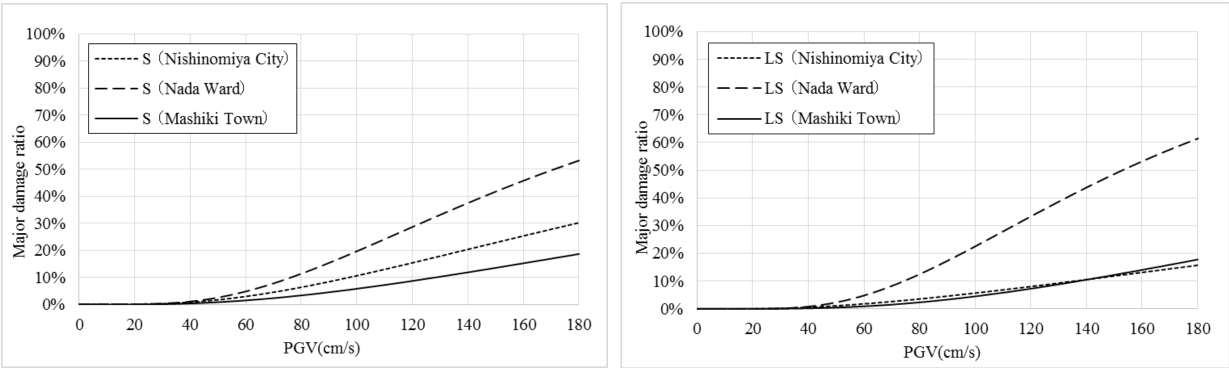
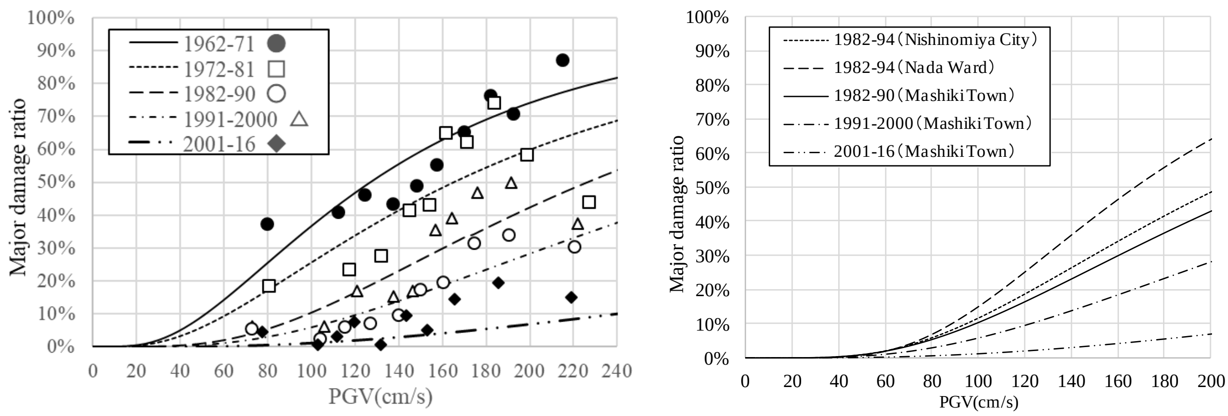


Figure 7: Comparison of fragility curves of S and LS for Mashiki Town, Nishinomiya City and Nada Ward for S (left) and LS (right) structures

The fragility curves for steel structures show some difference, but 21 years have passed between the two earthquakes and hence the composition ratio of newer structures got higher in Mashiki Town. Another possible reason is the difference in estimating the PGV distribution. The PGV in the Kobe event was estimated by analyzing the relationship between the strong motion records and the building damage data around the recording points (Yamaguchi & Yamazaki 2001). Actually, no effective strong motion site existed in Nishinomiya City and only one (Kobe University on a rock site) in Nada Ward at the time of the Kobe earthquake. In this sense, the estimated PGV in Mashiki may be more reliable. The fragility curves of LS for Nishinomiya City and Mashiki Town are quite similar. The closeness of the ratio of construction period (built after 1982) of these two data sets may be one of the possible reasons (Suto et al. 2018).

Finally, the fragility curves of wooden buildings were developed for Mashiki Town considering the construction period, as shown in Figure 8a. It is noticed from the figure that the developed curves for major damage class of wooden buildings are dependent on their construction period, as also had seen for the Kobe earthquake data. Even new coded buildings (built after 1982), the vulnerability gets lower for newer buildings. Several reasons are considered to explain this fact. One reason is another upgrade of the seismic code for wooden structures in 2000. The second is deterioration of wooden buildings in this period. Thirdly, the change of structural type for wooden buildings; the ratio of prefabricated (e.g. 2x4) lumber construction is increasing against traditional wood-framed structures. Lighter roof materials for newer construction are also one of the possible reasons. Figure 8b compares the fragility curves of wooden structures for new coded buildings in Mashiki Town, Nada Ward, and Nishinomiya City. The fragility curve of new-coded wooden buildings in Nishinomiya (1982-1994) is very close to one of the similar period in Mashiki (1982-1990). Thus the fragility curves developed for the Kobe earthquake are still valid, at least in the western Japan.



(a) Mashiki Town for different construction period *(b) Comparison for buildings built after 1982*

Figure 8: Fragility curves for wooden buildings based on the local government survey data

5 CONCLUSIONS

This study investigates the building damage in Mashiki Town based on damage survey data of the town government due to the 2016 Kumamoto, Japan, earthquake. The damage ratios of buildings were investigated from with respect to the structural material and construction period. Moreover, the "major damage" ratios of wooden buildings were compared with those from the 1995 Kobe earthquake. As the result, the damage ratio of wooden structures was found to be much larger than those of other structural materials, and it got higher as the construction period became older. The results were further compared with the estimated distributions of the peak ground velocity (PGV) and the fragility curves for different structural materials (wood, S, and LS) and those for wooden buildings for five construction periods were developed.

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