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FRAGILITY CURVES OF WOODEN BUILDINGS BASED ON DAMAGE DATA FROM THE 2016 KUMAMOTO EARTHQUAKE IN UKI CITY

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Abstract

Building fragility curves (vulnerability functions) have been used for damage assessment studies by the national and local governments in Japan to plan appropriate and efficient countermeasures against future earthquakes. Building fragility curves have been created by comparing the ground motion distribution and building damage survey data by local governments. Most of the present damage assessment studies use empirical fragility curves from the 1995 Kobe earthquake because there were no other earthquakes with abundant damage data. For this reason, the reconstruction of fragility curves based on damage data in the recent damaging earthquakes is considered an important issue.

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. Many building damages occurred especially in Mashiki Town. Also, in other municipalities in Kumamoto prefecture many building damages occurred, and the large amount of data obtained in the 2016 Kumamoto earthquake should be properly analyzed for estimating and mitigating damages due to future seismic events.

In this study the characteristics of wooden building damage due to the 2016 Kumamoto earthquake was analyzed using the building damage survey data provided by the Uki City government. Building damage caused by the 2016 Kumamoto earthquake was serious especially in Mashiki Town and Minami-Aso Village, which are located close to the source region, but Uki City was also heavily damaged, next to those areas. The damage ratios of wooden buildings were investigated from the viewpoint of the construction period and its effects were found to be dominant. The damage ratio gets smaller as the construction period becomes newer. The fragility curves of wooden buildings with respect to the construction period were developed using the damage survey data and the estimated peak ground velocity (PGV). Compared with the results of the previous studies for Nishinomiya City and Nada Ward due the 1995 Kobe earthquake, the major damage ratios in Uki City were shown in much lower levels for the same PGV.

Keywords: The 2016 Kumamoto earthquake; Building damage; Peak ground velocity; Fragility curve

1. Introduction

Building fragility curves (vulnerability functions) have been used for damage assessment studies by the national and local governments in Japan to plan appropriate and efficient countermeasures against future earthquakes [1-4]. Among various types of damage due to strong shaking, building damage is one of the most significant effects of earthquakes, especially for inland (crustal) earthquakes. Building fragility curves have been created by comparing the ground motion distribution and building damage survey data by local governments. Most of the present damage assessment studies use empirical fragility curves from the 1995 Kobe earthquake because there were no other earthquakes with abundant damage data. For this reason, the reconstruction of fragility curves based on damage data in the recent damaging earthquakes is considered an important issue.

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. Many building damages occurred especially in Mashiki Town, and some analysis results of these data have already been reported by a lot of engineers and researchers for various organizations including the present authors [5-8]. Also, in other municipalities in Kumamoto prefecture many building damages occurred [9], and the large amount of data obtained in the 2016 Kumamoto earthquake should be properly analyzed for estimating and mitigating damages due to future seismic events.

In this study, the characteristics of wooden building damage due to the 2016 Kumamoto earthquake was analyzed using the building damage survey data provided by the Uki City government. The fragility curves of wooden buildings with respect to the construction period were developed using the damage survey data and the estimated peak ground velocity (PGV), and the results were compared with those of the previous studies for Nishinomiya City and Nada Ward due the 1995 Kobe earthquake.

2. Estimation of Ground Motion Distribution

A Mw 6.2 earthquake hit Kumamoto prefecture on April 14, 2016 at 21:26 (JST). 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 Mw 7.0 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 "mainshock".

Figure 1 shows the location of Uki City and these causative faults of the 2016 Kumamoto earthquake. Uki City is located in the southwest direction of the causative faults. Also shown in the figure are the K-NET and KiK-net stations near Uki City.

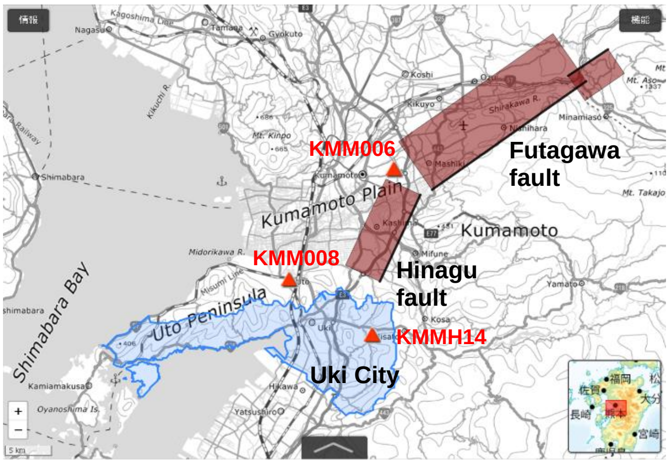

Fig. 1 – Location of Uki City, K-NET and KiK-net stations near Uki City and the causative faults of the 2016 Kumamoto earthquake

Figure 2 compares the acceleration response spectra (the resultant of the two horizontal components, 5% damping ratio) of the recorded motions at the three seismic stations shown in Fig. 1 for the foreshock (April 14) and the mainshock (April 16). In the figure, the result for the connected time histories (April 14 and April 16 in 2 minutes interval) is also plotted. It is seen for each station that the April 16 event has a dominant influence in the all period range.

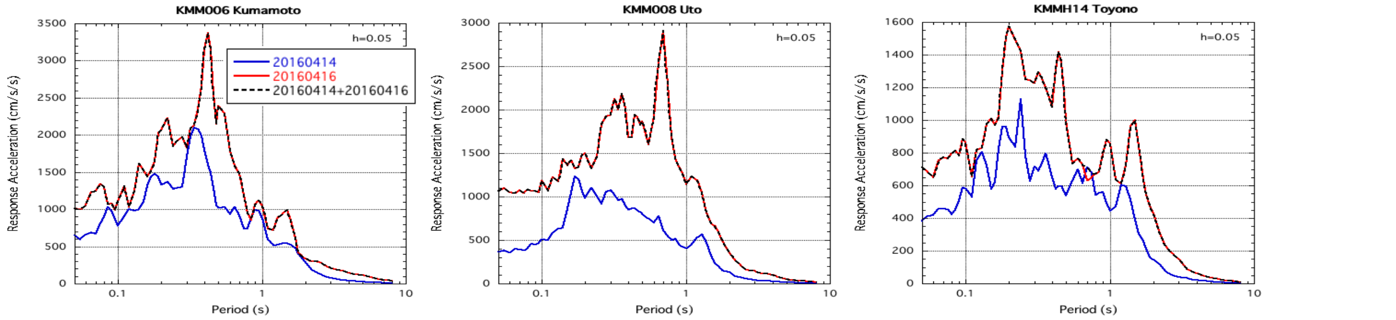

Fig. 2 – Acceleration response spectra (the resultant of the two horizontal components, 5% damping ratio) of the recorded motions at K-NET Kumamoto, K-NET Uto and KiK-net Toyono

We estimated the seismic ground motion distribution in the disaster area with high accuracy 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 mainshock of the 2016 Kumamoto earthquake. The Kriging interpolation was applied to these peak ground motion values considering the attenuation relationship from the causative fault plane of the mainshock and soil amplification factors, following the method adopted by QuiQuake [10]. Note that the resultant PGVs of the two horizontal components were used in the calculation.

Figure 3 shows the estimated PGV distribution in the 250-m grid cell units and the PGV amplification factor [11] used in the Kriging interpolation for the study area. The estimated PGV is relatively larger in the central southern area than in the northeast area closer to the causative faults. In the coastal area of this region, there are many reclaimed lands and deltas, and thus the distribution of the PGV amplification factor shows such tendency of the surface soil.

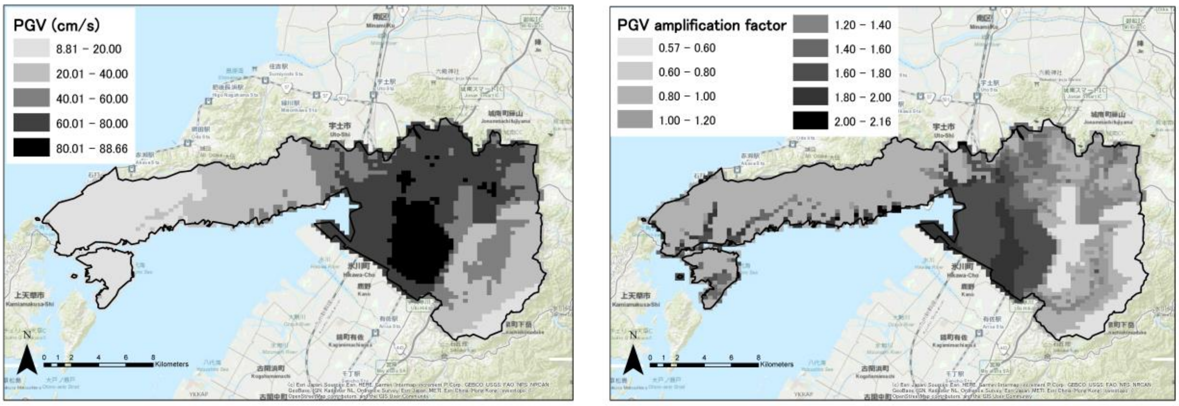

Fig. 3 – Distribution of the estimated peak ground velocity (PGV) in the 250-m grid cell units and the PGV amplification factor in Uki City

3. Analysis of Building Damage

Soon after the 2016 Kumamoto earthquake, the municipality governments carried out building damage survey in order to issue disaster-victim certificates. Building damage caused by the 2016 Kumamoto earthquake was serious in Mashiki Town and Minami-Aso Village, which are located close to the source region, but Uki City was also heavily damaged, next to those areas [9].

The damage extent of each building was classified into five classes by its damage level (or monetary loss), as current damage class shown in Table 1. Note that this classification was carried out following the unified loss evaluation method of Japan [12]. In the table, an approximate correspondence with visual inspection methods is also shown [13]. Note that the result of loss assessment by local governments is important for affected people to receive financial support and property tax reduction. In Uki City, the first stage assessment, viewing from outside, was conducted for the all 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 schematics images of other damage classification methods [8]

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

Finally, a total of 8,560 damage certificates were issued. However, Uki City's damage certificate issuance data do not include undamaged buildings. Therefore, a building database was constructed by matching the taxation building data with the damage certificate issuance data, and a building without a damage certificate was regarded as no damage. These data also include ones that are not suitable for analyzing building damage, such as storages. For this reason, we excluded the following data from the loss assessment data: the data on storage, warehouse, garage, etc., those other than the final assessment records, those with the area less than 20 m^2, those without ground floor and those without location information. Among the remaining 28,486 data, in this study, we used 23,968 wooden building data below.

We also investigated the spatial distribution of damaged buildings in Uki City based on the city government's disaster-victim certificate data as shown in Fig. 4. It is seen that the major damage buildings are distributed in the area where many buildings were located and the large PGV values were estimated. In the areas of peninsula (west) and inland (east), the number of buildings was small and the PGV was also relatively small, and hence few major damage buildings were observed.

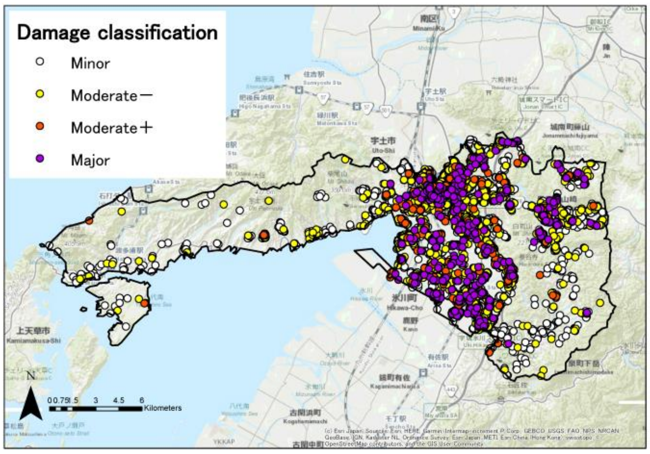

Fig. 4 – Distribution of damaged buildings in Uki City based on the city government's disaster-victim certificate data

Table 2 shows the number of wooden buildings in Uki City with respect to the damage class and the construction period. The building damage data were analyzed based on the construction period, the roof type and the number of floors for wooden buildings, but in this paper only the result for the construction period, the most significant factor, is shown.

Table 2 – Number of wooden buildings in Uki City with respect to the damage class and the construction period

Construction period	Major	Moderate+	Moderate-	Minor	No damage	Total
-1951	167	83	293	283	2,758	3,584
1952-61	39	26	103	103	673	944
1962-71	60	33	201	275	2,127	2,696
1972-81	75	78	453	902	3,824	5,332
1982-90	33	28	312	841	2,600	3,814
1991-2000	18	23	192	1,227	2,629	4,089
2001-16	13	5	43	973	2,475	3,509
Total	**405**	**276**	**1,597**	**4,604**	**17,086**	**23,968**

Figure 5 shows the damage ratio of wooden buildings in Uki City with respect to the construction period. The damage ratios of major, moderate+, and moderate- get smaller as the construction period becomes newer.

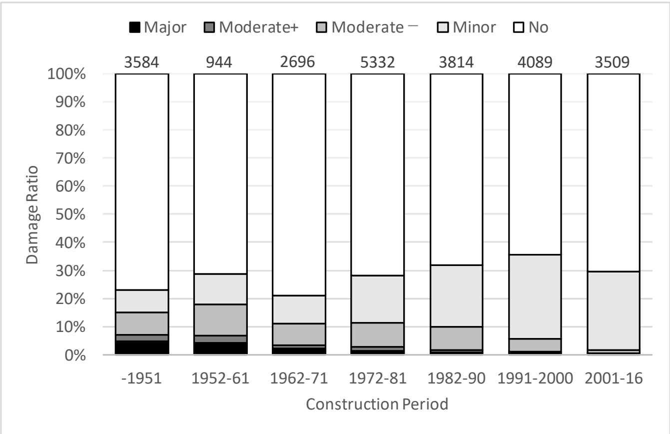

Fig. 5 – Damage classification of wooden buildings by the Uki City government with respect to the construction period

4. Development of Building Fragility Curves Based on Damage Survey Data by the City Government

We developed the fragility curves based on Uki City's disaster-victim certificate data due the 2016 Kumamoto earthquake. We proposed the building fragility curve with respect to the PGV for buildings.

In order to analyze the relationship between the seismic ground motion and building damage, the building data and the estimated PGV at each building location were combined using GIS. Note that we used the residential district ("O-Aza") level value for the seismic ground motion (PGV) because the taxation building data have only this district-level location information and it was difficult to convert it to the precise location (latitude and longitude).

In constructing building fragility curves, after sorting based on the PGV value of each building, several buildings with a similar level of PGV values were classified as one data group (block). The total number of blocks and the number of buildings per block for each construction period are shown in Table 3. Note that the PGV value for each block was calculated as the weighted mean of the PGVs of buildings in the block.

Table 3 – Number of blocks and number of buildings per block for each construction period

Construction period	Number of buildings	Number of blocks	Number of buildings per block
All	23,968	20	1,198 or 1,199
-1951	3,584	10	358 or 359
1952-61	944	10	94 or 95
1962-71	2,696	10	269 or 270
1972-81	5,332	10	533 or 534
1982-90	3,814	10	381 or 382
1991-2000	4,089	10	408 or 409
2001-16	3,509	10	350 or 351

For a ground motion index x (PGV), the cumulative probability $P_R(x)$ of the occurrence of damage equal to or higher than a rank R (such as "major") is assumed to be lognormal as follows:

$$P_R(x) = \Phi\left((\ln x - \lambda) / \zeta\right) \tag{1}$$

in which Φ is the standard normal distribution and λ and ζ are the mean and the standard deviation of ln x. The two parameters of the distributions, λ and ζ, were determined by the least square method on a lognormal probability paper. Table 4 summarizes the results of the regression analysis for each damage class.

Table 4 – Regression coefficients (λ, ζ) and correlation coefficient (r) for fragility curves of wooden buildings with respect to the construction period

Construction period	Major			Moderate+			Moderate-		
	λ	ζ	r	λ	ζ	r	λ	ζ	r
All	6.62	1.16	0.86	6.29	1.12	0.95	5.58	1.13	0.97
-1951	5.15	0.66	0.90	5.39	0.91	0.91	4.83	0.89	0.96
1952-61	5.87	1.02	0.86	5.55	0.98	0.85	4.80	0.84	0.99
1962-71	5.72	0.79	0.96	5.72	0.88	0.96	5.20	0.95	0.99
1972-81	7.33	1.44	0.66	6.31	1.14	0.82	5.33	1.01	0.97
1982-90	7.80	1.52	0.71	8.02	1.81	0.65	5.63	1.17	0.93
1991-2000	15.15	4.31	0.43	9.13	2.14	0.64	6.66	1.57	0.88
2001-16 *	—	—	—	—	—	—	—	—	—

* Note that the regression coefficients were omitted because the result could not be obtained with a certain precision.

Figure 6 shows the fragility curves of wooden buildings for each damage class with respect to the PGV. Also shown in the figure are the data used to construct the fragility curves.

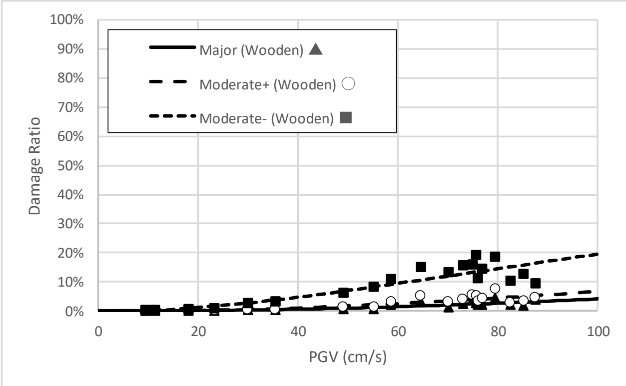

Fig. 6 – Fragility curves of wooden buildings for each damage class with respect to the PGV for Uki City

Yamazaki and Murao [1] constructed the fragility curves due the 1995 Kobe earthquake with respect to the PGV considering the structural type and construction period using the damage survey data for Nada Ward, conducted by Kobe City. Yamaguchi and Yamazaki [2] also created the fragility curves using the damage survey data of Nishinomiya City due the 1995 Kobe earthquake. The fragility curves for Uki City are compared with those for Nishinomiya City and Nada Ward in Fig. 7. It is seen in the figure that the Uki City's curve show a much lower damage probability than those for Nishinomiya City and Nada Ward.

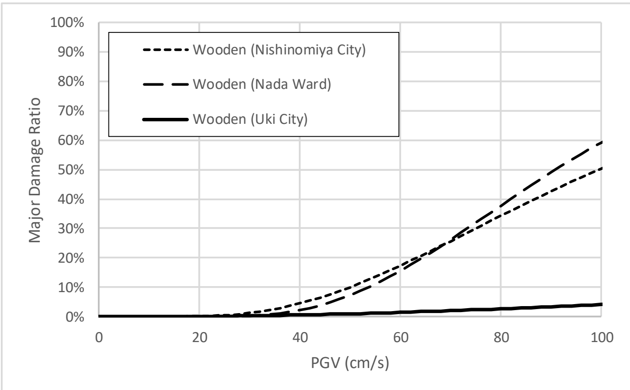

Fig. 7 – Comparison of fragility curves of wooden buildings for Uki City, Nishinomiya City and Nada Ward

A few reasons are considered to explain the difference of the fragility curves. First, the change of data used to construct the fragility curves may affect the result. Figure 8 shows the breakdown of the number of wooden buildings with respect to the construction period, which were used to construct fragility curves. As there is a 21-year time difference between the Kobe and Kumamoto earthquakes, the composition ratio of data with respect to the construction period has changed significantly.

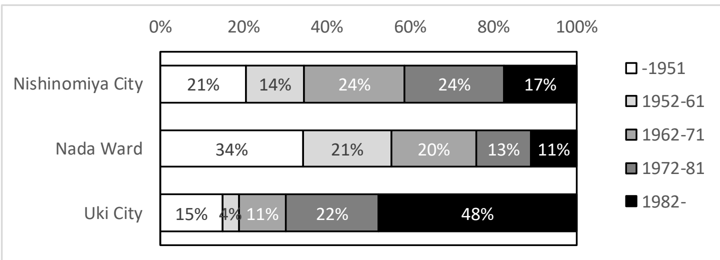

Fig. 8 – Comparison of the breakdown of the number of wooden buildings with respect to the construction period for Uki City, Nishinomiya City and Nada Ward

The difference in the damage classification of the surveys may be the second possible reason of the difference of the fragility curves. It is pointed out that "Major damage" was more easily issued in the Kobe earthquake than in the Kumamoto earthquake.

Another possible reason is the difference in the estimation methods of PGV. The PGV in the Kobe event was estimated by analyzing the relationship between the strong motion records and the building damage data around the seismic recording points [14]. 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 Uki City may be more reliable.

It is also considered that the range of estimated PGV is smaller in Uki City, thus the regression results reflect the trend in the smaller PGV range. The combined use of Mashiki Town data [8] in lager PGV and Uki City data in smaller PGV may be necessary in a future study.

Figure 9 shows the fragility curves of wooden building for major damage, moderate+ damage and moderate- damage with respect to the construction period, respectively. Also shown in these figures are the data used to construct the fragility curves. In the same PGV, the damage ratio is higher as the construction period gets older.

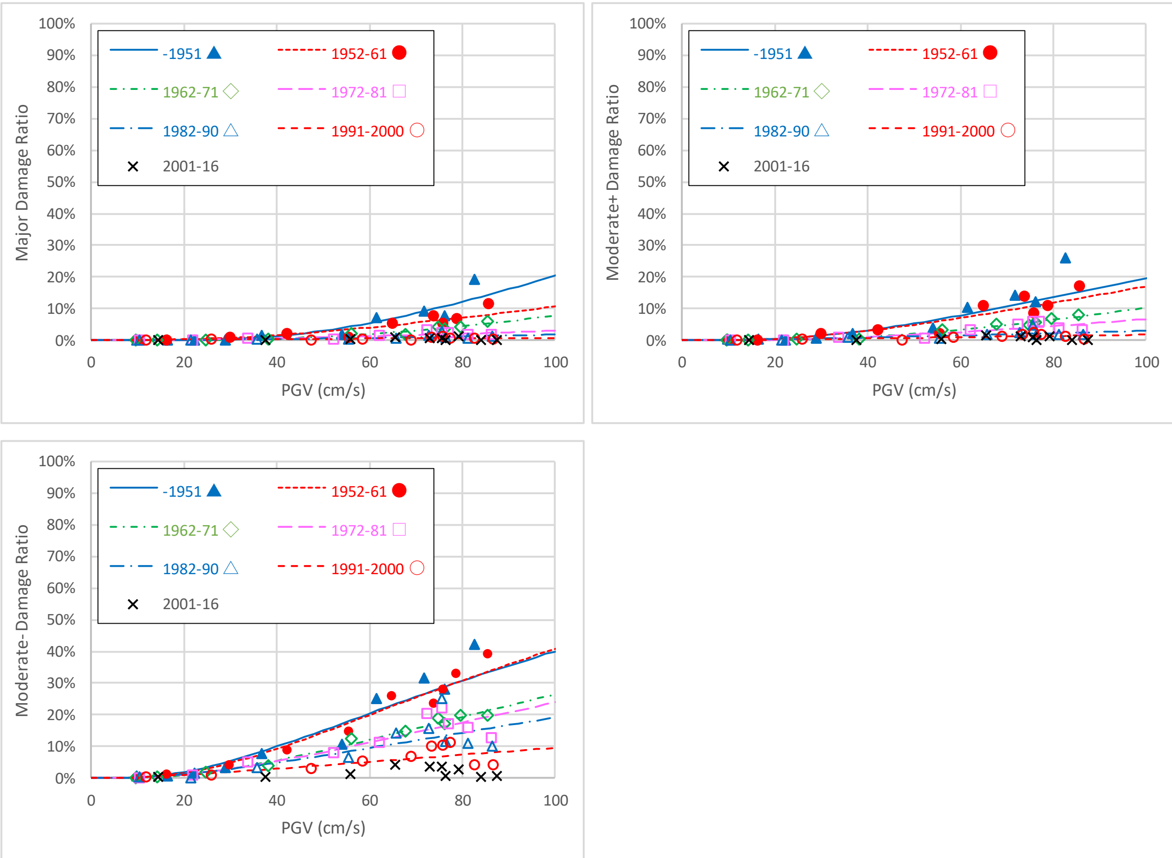

Fig. 9 – Fragility curves of wooden buildings with respect to the construction period for Uki City

Figure 10 shows the comparison of fragility curves with respect to the construction period for Uki City, Nishinomiya City and Nada Ward. As in the comparison of all construction period described above, it is seen in the figure that Uki City's curves show lower damage probability than those for Nishinomiya City and Nada Ward.

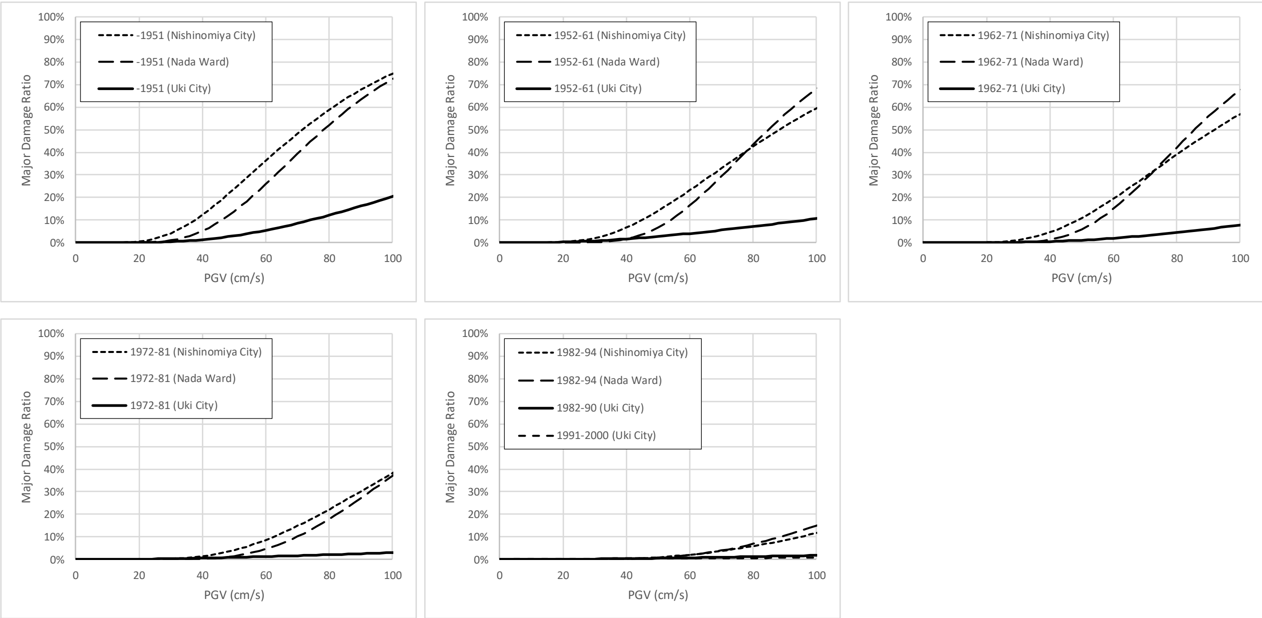

Fig. 10 – Comparison of fragility curves of wooden buildings with respect to the construction period for Uki City, Nishinomiya City and Nada Ward

5. Conclusions

In this study the characteristics of wooden building damage due to the 2016 Kumamoto earthquake was analyzed using the building damage survey data provided by the Uki City government. Building damage caused by the 2016 Kumamoto earthquake was serious especially in Mashiki Town and Minami-Aso Village, which are located close to the source region, but Uki City was also heavily damaged, next to those areas. The damage ratios of wooden buildings were investigated from the viewpoint of the construction period. As a result, the damage ratio gets smaller as the construction period becomes newer. The fragility curves of wooden buildings with respect to the construction period were developed using the damage survey data and the estimated peak ground velocity (PGV). Compared with the results of the previous studies for Nishinomiya City and Nada Ward due the 1995 Kobe earthquake, the major damage ratios for Uki City showed much lower levels than the Kobe studies in the same PGV.

6. Acknowledgements

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