Analysis of Building Damage in Uki City due to the 2016 Kumamoto Earthquake

Kazuaki TORISAWA
College of Science and Engineering, Kanto Gakuin University, Yokohama, Japan.
E-mail: tori@kanto-gakuin.ac.jp

Kei HORIE
General Planning Department, MS&AD InterRisk Research & Consulting, Inc., Tokyo, Japan.

Masashi MATSUOKA
Department of Architecture and Building Engineering, Tokyo Institute of Technology, Yokohama, Japan.

Munenari INOGUCHI
Faculty of Sustainable Design, Toyama University, Toyama, Japan.

Fumio YAMAZAKI
National Research Institute for Earth Science and Disaster Resilience, Ibaraki, Japan.

This study investigates the building damage ratio based on damage survey data of the 2016 Kumamoto, Japan, earthquake. Most of building fragility curves in Japan were developed based on the actual damage data in the 1995 Kobe earthquake. However, already 24 years have passed after this event, and hence it is better to use recent earthquake data in Japan. In this study, the building damage in Uki City, Kumamoto prefecture, was analyzed based on the damage survey data by the local government. The damage ratios of buildings were investigated from the viewpoints of structural material and construction period. As the result, the damage ratio of wooden buildings was found to be larger than those of other structural materials (Reinforced Concrete (RC), Steel (S) and Light-gauge Steel (LS)), and it got higher as the construction period becomes older. The spatial distribution of damaged buildings was further investigated with their locations. The results were compared with the distribution of peak ground velocity values and the fragility curves of wooden buildings for four construction periods were developed.

Keywords: The 2016 Kumamoto earthquake, Building damage, Construction period, Peak ground velocity, Spatial analysis, 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 (Yamazaki and Murao 2000; Yamaguchi and Yamazaki 2000; Midorikawa et al. 2011; Cabinet Office of Japan 2013a). 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 matching 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 recent damaging earthquakes is considered to be 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 (National Institute for Land and Infrastructure Management 2016; Sugino et al. 2016; Yamada et al. 2017; Suto et al. 2018). Also, in other municipalities in Kumamoto prefecture many building damages occurred (Kumamoto Prefecture 2016), and the large amount of data obtained in the Kumamoto earthquake should be properly analyzed for estimating and mitigating damages due to future seismic events.

In this study, the result of damage survey provided by the Uki City government is used to analyze the characteristics of building damage due to the 2016 Kumamoto 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

Proceedings of the 29th European Safety and Reliability Conference.
Edited by Michael Beer and Enrico Zio

Published by Research Publishing, Singapore.
ISBN: 978-981-11-2724-3; doi:10.3850/978-981-11-2724-3_0772-cd

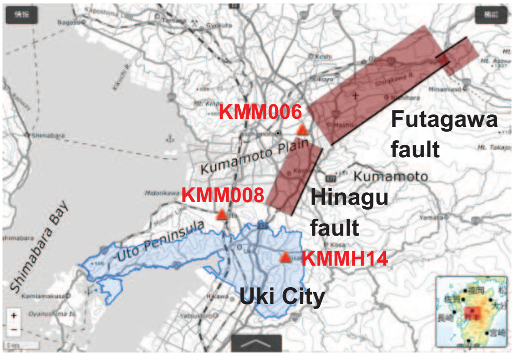


Fig. 1. Location of Uki City, K-NET and KiK-net stations near Uki City and causative faults of the 2016 Kumamoto earthquakes

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 "main-shock".

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

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

We estimated the earthquake ground motion distribution in the disaster area with high accuracy by collecting a total of 1,141 (K-NET and KiK-net: 698; Japan Meteorology Agency (JMA): 316; local governments: 111; Saibu Gas Co.: 16) strong motion records for the main-shock of the Kumamoto earthquake. The 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 adopted by QuiQuake (Matsuoka and Yamamoto 2012). Note that the resultant PGVs of the two horizontal components were used in the calculation.

Figure 3 shows the estimated PGV distribution in 250-m grid for Uki City. The estimated PGV is relatively larger in the central southern area than in the northeast area closer to the causative faults.

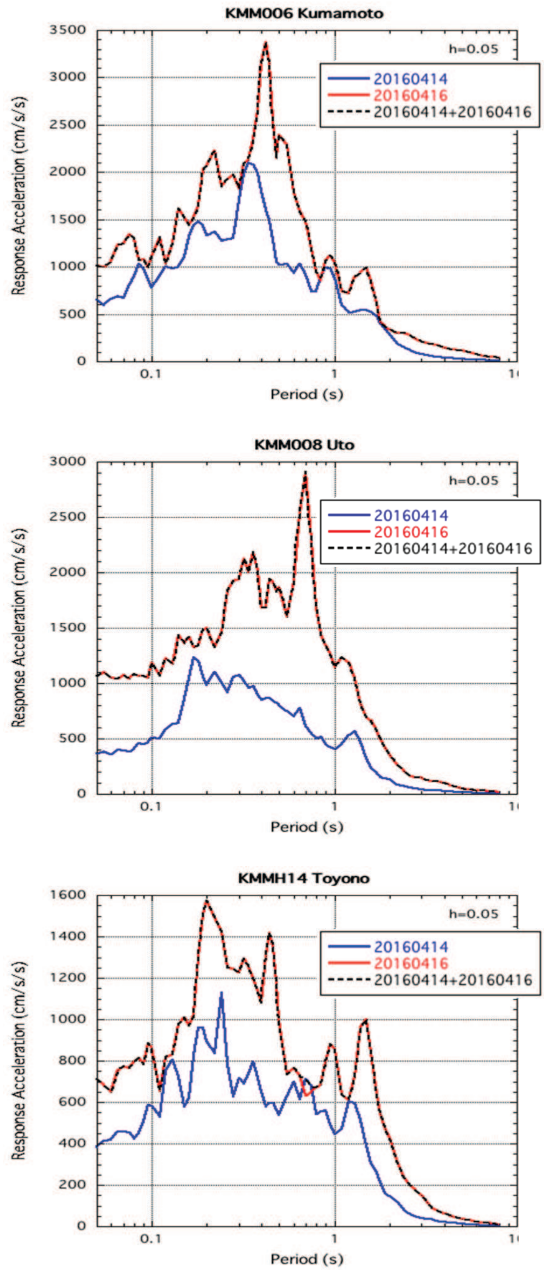


Fig. 2. Acceleration response spectra (the resultant of the two horizontal components, 5% damping ratio) for the records at K-NET Kumamoto (KMM006), K-NET Uto (KMM008) and KiK-net Toyono (KMMH14)

Figure 4 shows the PGV amplification factor used in the Kriging interpolation for the study area (National Research Institute for Earthquake Science and Disaster Resilience 2018). In the coastal area of this region, there are many reclaimed lands and deltas, and thus the

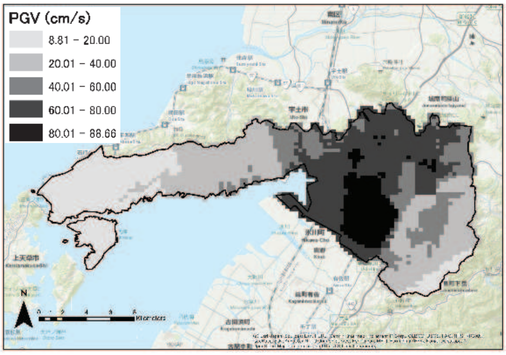


Fig. 3. Distribution of the estimated peak ground velocity (PGV) in 250-m grid cell units in Uki City

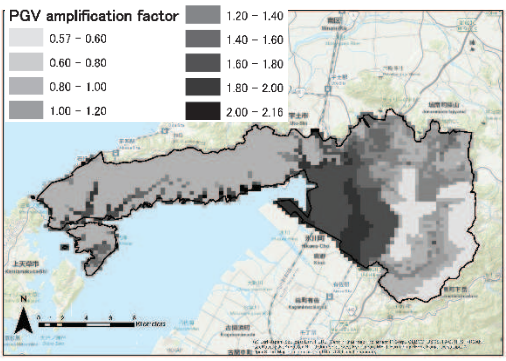


Fig. 4. Distribution of the PGV amplification factor in 250-m grid cell units in Uki City

distribution of the PGV amplification factor shows such tendency of the surface soil.

3. Analysis of Building Damage

Soon after the Kumamoto earthquake, the municipality governments carried out a 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 close to the source region, but Uki City was also seriously damaged, next to those areas (Kumamoto Prefecture 2016).

The damage extent of each building was classified into five classes by its monetary loss ratio, as current damage class shown in **Table 1**. Note that this classification was carried out following the unified loss evaluation method of Japan (Cabinet Office of Japan 2013b). In the table, an approximate correspondence with visual inspection methods is also shown (Grünthal ed. 1998; Okada and Takai 2000). 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,

Table 1. Earthquake loss evaluation class of buildings in Japan and schematics images of other damage classification methods

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	D3
Moderate -		$20\% \leq r < 40\%$	G2	D2
Minor	Minor	$0\% < r < 20\%$	G1	D1
No	No	$r = 0\%$	-	-

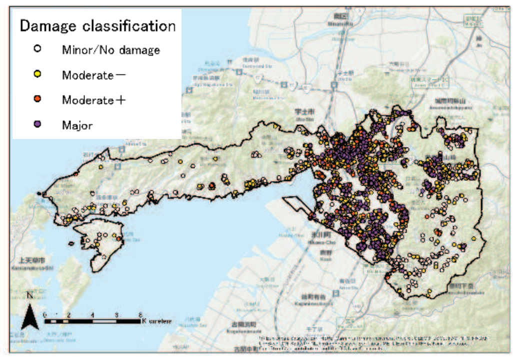


Fig. 5. Distribution of damaged buildings in Uki City based on city government's disaster-victim certificate data

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. Note that in the areas which were considered to be little damage, surveys were conducted only for the buildings requested by residents.

Finally, a total of 8,011 damage certificates were issued. However, these data also include data that are not suitable for analyzing building damage such as storage or warehouses. For this reason, we excluded the following data from the loss assessment data: the data of storage, warehouse, garage, etc. (79), previous records updated in the final assessment (111), those with the area less than 20 m^2 (255), those without ground floor (9) and those without location information (18). The remaining 7,539 data were used.

We also investigated the spatial distribution of damaged buildings in Uki City based on the disaster-victim certificate data as shown in **Fig. 5**. It is seen that buildings with major damage are distributed in the area where many buildings were located and the large PGV values were estimated. In the areas of peninsula and inland, the number of buildings was originally small and the PGV

Table 2. Number of buildings in Uki City with respect to the damage class and the construction period for each structural type

Structural type	Construction period	Major	Moderate+	Moderate-	Minor / No damage	Total
Wooden	-1951	177	85	282	283	827
	1952-61	45	27	104	102	278
	1962-71	61	40	209	283	593
	1972-81	78	78	455	920	1,531
	1982-90	36	31	317	848	1,232
	1991-2000	19	23	191	1,244	1,477
	2001-16	11	5	42	980	1,038
	Unknown	0	0	0	1	1
	Total	427	289	1,600	4,661	6,977
RC	-1981	0	0	2	12	14
	1982-90	0	0	0	8	8
	1991-2000	0	0	0	5	5
	2001-2016	0	0	0	21	21
	Unknown	0	0	0	0	0
	Total	0	0	2	46	48
S	-1981	1	4	16	31	52
	1982-90	1	2	8	16	27
	1991-2000	0	0	5	28	33
	2001-2016	0	1	0	20	21
	Unknown	0	0	0	0	0
	Total	2	7	29	95	133
LS	-1981	1	1	11	34	47
	1982-90	2	0	7	53	62
	1991-2000	1	0	4	134	139
	2001-2016	1	0	3	121	125
	Unknown	0	0	0	1	1
	Total	5	1	25	343	374
CB	Total	0	0	4	3	7
All	Total	434	297	1,660	5,148	7,539

was also relatively small, and hence few buildings with major damage were observed.

Table 2 shows the number of buildings in Uki City with respect to the damage class and the construction period for each structural type. With respect to the number of buildings by structural type, "Wooden" accounts for about 92%, "Light-gauge Steel (LS)" is about 5%, "Steel (S)" is about 2%, "Reinforced Concrete (RC)" is about 0.7%, and "Concrete Brick (CB) "is about 0.09%. There were no undamaged buildings in all construction types in Uki City.

The building damage data were analyzed based on the structural type and the construction period.

Figure 6 shows the damage classifications for a total of 7,539 buildings in Uki City due the 2016 Kumamoto earthquake. Major damages to buildings only occurred for the structural types (materials) wooden, S and LS. There was no major damage to RC and CB buildings. The major damage ratio for the all buildings is about 6%.

Figure 7 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 for more recent construction periods. The Japanese building standard law was significantly revised in 1981, and the seismic provision was tightened. Therefore, buildings built after 1981 are supposed to be more resistant to earthquakes than the pre-coded buildings. It is not easy to distinguish

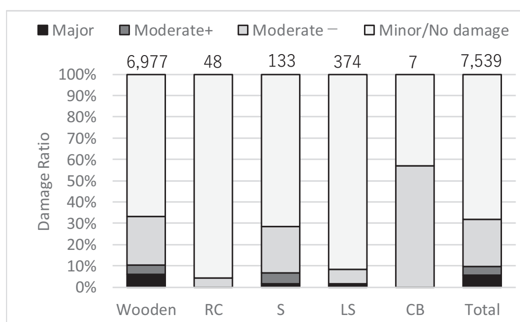


Fig. 6. Damage classification of buildings by the Uki City government with respect to the structural type

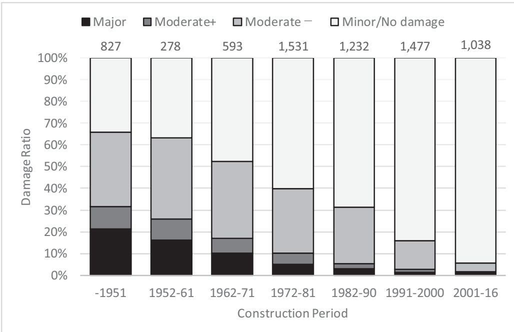


Fig. 7. Damage classification of wooden buildings by the Uki City government with respect to the construction period

because the ratio is small, the major damage ratio is decreased by half as the effect of the revision of seismic provision in 1981. Note that the seismic provision for wooden buildings was further upgraded in 2000.

Figure 8 shows the damage ratio of non-wooden buildings (RC, S and LS) in Uki City with respect to the construction period. Their major damage ratios also get smaller as the construction period becomes newer.

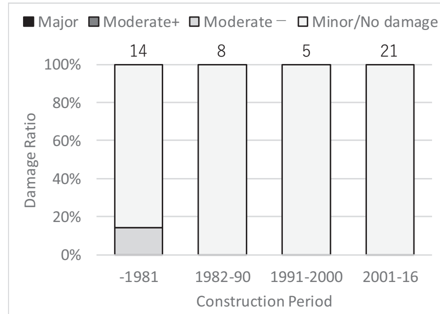
4. Development of Building Fragility Curves Based on Disaster-Victim Certificate Data

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 PGV for wooden buildings. For non-wooden buildings, fragility curves are not created because the number of data is insufficient.

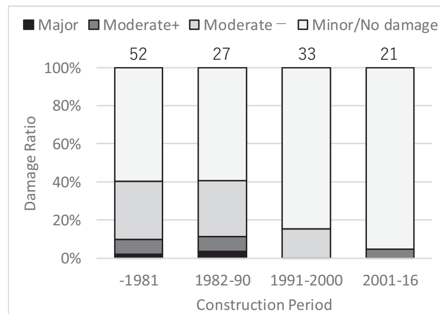
In order to analyze the relationship between a ground motion intensity and building damage, the building data and the estimated PGV at each building location were combined using a geographic information system (GIS). In constructing building fragility curves, after sorting based on the PGV value of each building, several buildings with a similar level of PGV values were classified as one block. The total number of blocks and the number of buildings per block for each construction period are shown in **Table 3**. The sizes of blocks could marginally differ for each block. Note that the PGV value for each block was calculated as the weighted mean of the PGVs of buildings in the block.

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 lognormal as follows:

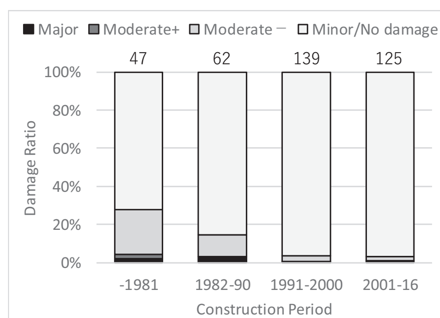
$$P_R(PGV) = \Phi\left((\ln PGV - \lambda) / \zeta\right) \qquad (1)$$



(a) Reinforced Concrete (RC)



(b) Steel (S)



(c) Light-gauge Steel (LS)

Fig. 8. Damage classification of non-wooden buildings by the Uki City government with respect to the construction period

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	6977	20	348 or 349
1962-71	593	10	59 or 60
1972-81	1531	10	153 or 154
1982-90	1232	10	123 or 124
1991-2000	1477	10	147 or 148
2001-16	1038	10	103 or 104

Table 4. Regression coefficients and correlation coefficient for fragility curves of wooden building with respect to the construction period

Construction period	Major			Moderate+			Moderate-		
	λ	ζ	*r*	λ	ζ	*r*	λ	ζ	*r*
All	6.01	1.11	0.78	6.17	1.48	0.72	5.37	2.51	0.45
1962-71	5.66	1.03	0.53	5.05	0.79	0.76	4.20	1.03	0.91
1972-81	5.51	0.73	0.86	5.20	0.70	0.83	4.66	1.48	0.48
1982-90	12.42	4.28	0.15	12.14	4.82	0.19	4.96	1.35	0.46
1991-2000	10.89	2.95	0.27	9.82	2.86	0.32	6.74	2.41	0.38
2001-16 *	—	—	—	—	—	—	—	—	—

* Note that the regression coefficient is not obtained because the slope becomes negative on the lognormal probability paper in the data of 2001-16.

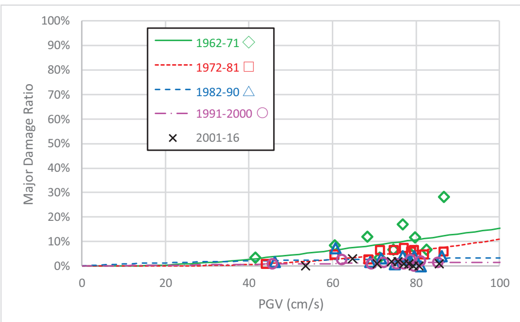


Fig. 9. Fragility curves of wooden building for major damage with respect to the construction period for Uki City

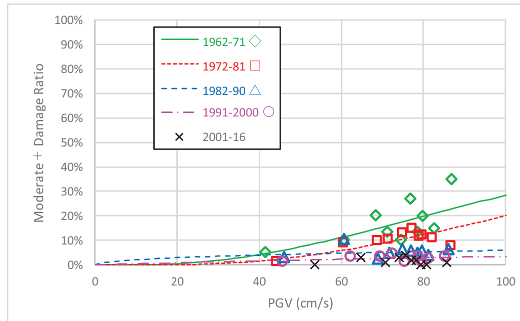


Fig. 10. Fragility curves of wooden building for moderate+ damage with respect to the construction period for Uki City

where Φ is the standard normal distribution and λ and ζ are the mean and the standard deviation of ln *PGV*. The two parameters, 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.

Figures 9, 10 and **11** show the fragility curves of wooden building for major damage, moderate+, and moderate- damage categories with respect to the construction period, respectively. Also shown in these figures are the data used to construct the fragility curves. It is observed that data is concentrated in the narrow range of PGV about 60 to 80 cm/s. In the case of the fragility curves for major and moderate+, there is a big difference between buildings constructed before 1981 and buildings constructed after 1982.

Yamazaki and Murao (2000) constructed the 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 and Yamazaki (2000) 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 the results for Nishinomiya City and Nada Ward due the 1995 Kobe earthquake.

Figure 12 shows the breakdown of the number of 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 construction period has changed significantly.

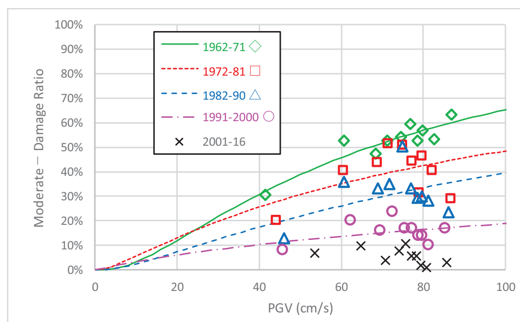


Fig. 11. Fragility curves of wooden building for moderate- damage with respect to the construction period for Uki City

Figures 13, 14 and **15** show 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. Note that the PGV in Uki City is in the range from 30 to 90 cm/s, and thus the range of the plot in **Figs 13-15** is a sort of extrapolation. It is seen in

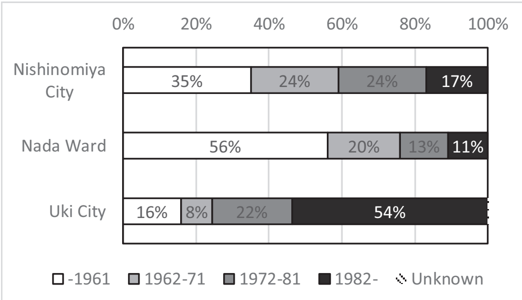


Fig. 12. Comparison of the breakdown of the number of wooden buildings with respect to the construction period for Uki City, Nishinomiya City and Nada Ward

the figure that Uki City's curve show lower damage probability than those for 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. As shown in **Fig. 12**, it is considered that the increase of the composition ratio of buildings built after 1981 makes a difference in the damage ratio.

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 (Yamaguchi and 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 Uki City may be more reliable.

5. Conclusion

In this study the characteristics of building damage due to the 2016 Kumamoto earthquake was analyzed based on the 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 close to the source region, but Uki City was also seriously damaged, next to those areas.

The damage ratios of buildings were investigated from the viewpoints of structural material and construction period. As a result, the damage ratio of wooden buildings was found to be larger than those of other structural materials and was higher for older construction periods. The major damage ratio is decreased as the effect of the revision of seismic provision in 1981.

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). In the fragility curves for major damage, there is a big difference between buildings constructed before 1981 and buildings constructed after 1982. Compared with the results of the previous studies for Nishinomiya City and Nada Ward due the 1995 Kobe

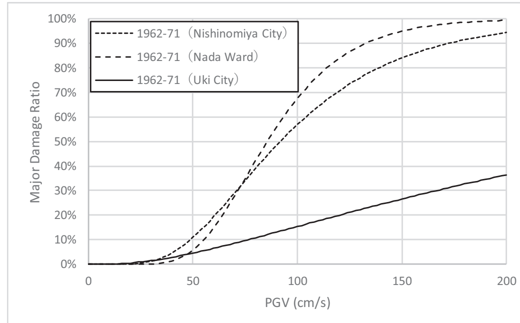


Fig. 13. Comparison of fragility curves of wooden building constructed from1962 to 1971 for Uki City, Nishinomiya City and Nada Ward

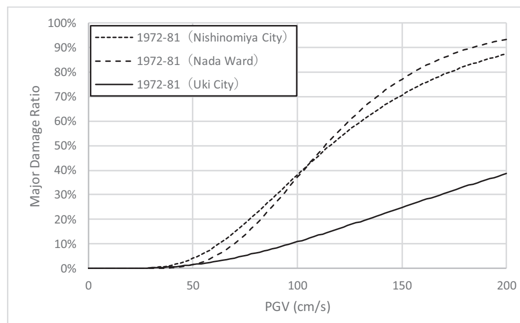


Fig. 14. Comparison of fragility curves of wooden building constructed from 1972 to 1981 for Uki City, Nishinomiya City and Nada Ward

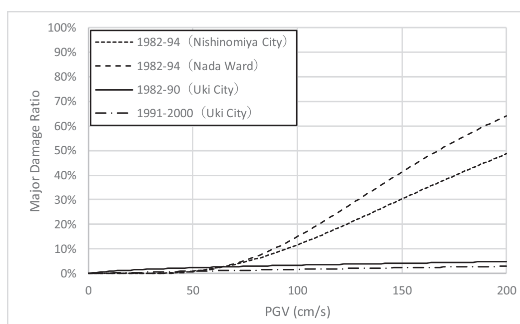


Fig. 15. Comparison of fragility curves of wooden buildings constructed after 1982 for Uki City, Nishinomiya City and Nada Ward

earthquake, the major damage ratios in Uki City showed lower levels in the same PGV.

Acknowledgement

This research was supported by "the Tokyo Metropolitan Resilience Project" of the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japanese Government, the National Research Institute for Earth Science and Disaster Resilience (NIED), and Niigata University.

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