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STUDY ON DAMAGE AND SEISMIC PERFORMANCE OF TIMBER BUILDINGS DAMAGED DURING THE RECENT LARGE EARTHQUAKES IN JAPAN

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Abstract

It is said that Japan has come to the term of seismic activity. Once, the damage of 1948 Fukui Earthquake triggered the establishment of Building Standard Law of Japan including the seismic regulation. The regulation for timber building adopted the way to set up enough shear wall by using the brace. After that, the regulations were reformed and revised several times at every damage due to earthquake. The required shear wall length increased at every revision of regulation.

Timber buildings in Japan were damaged due to large earthquake since 2000, for example, 2000 West of Tottori Pref., 2004 Chuetsu, 2005 Fukuoka west off the coast, 2007 Noto Peninsula, 2007 offshore of Chuetsu, 2011 off the Pacific coast of Tohoku earthquake and 2014 Nagano Kamishiro Fault.

The damage to timber buildings due to every earthquake was surveyed on site. Several wood houses were picked up and investigated in detail, for example, floor plans, shear wall length, damage states and structural specification. The reason and the characteristic of damage were discussed.

The results of these surveys and studies were summarized as follows;

- The 14 major earthquake suffering heavy damage to wood houses has occurred after the year of 2000.
- The severe damage was concentrated in the old post and beam construction with the mud walls and the heavy roof tiles. On the other hand, the relatively new wood houses were rarely damaged except for due to the damage of land. However, the several new houses built after 2000 collapsed and many new houses suffered the damage under 2016 Kumamoto Earthquake.
- The ratio of wood houses with heavy damage was not higher in the area where the higher seismic intensity or acceleration was recorded. However, the ratio was higher in the area with higher velocity.
- The shear wall length in the surveyed wood house didn't have significant difference among the disaster area within our field works.
- It was rare that the shear wall length of wood house had a significant correlation with the damage states and the residual story drifts. However, when the shear wall length satisfied with the requirement of BSL, the story drifts were extremely little.
- Some wood houses which bio deterioration or termite attacks were found suffered severe damage by all means. So, it couldn't be concluded that the bio deterioration or termite attacks caused the seismic damage.

Keywords: Damage due to earthquake, Wood houses, Shear wall length, Residual story drifts, Bio-deterioration

1. Introduction

It is said that Japan has come to the term of seismic activity after Hyogo-Nambu Earthquake in 1995. Once, the damage of 1948 Fukui Earthquake triggered the establishment of Building Standard Law of Japan including the seismic regulation. The regulation for timber building adopted the way to set up enough shear wall by using the brace. After that, the regulations were reformed and revised several times at every damage due to earthquake. The required shear wall length increased at every revision of the regulation.

Timber buildings in Japan were damaged by the large earthquake even since 2000, for example, 2000 West of Tottori Pref., 2004 Chuetsu, 2005 Fukuoka southwest off the coast, 2007 Noto Peninsula, 2007 offshore of Chuetsu, 2011 off the Pacific coast of Tohoku earthquake and 2014 Nagano Kamishiro Fault. In addition to them, 2016 Kumamoto Earthquake occurred last April.

In this paper, the feature of the damage due to each earthquake and seismic performance of timber buildings in Japan would be reported.

2. Perspective of Recent Earthquake

The major earthquake suffering heavy damage to wood houses since 2000 has occurred 14 times and were shown in Table 1. I made field surveys of the damage to the timber construction due to 10 or more of these major earthquake. The magnitude is the value presented by the Japan Meteorological Agency. The numbers of damage to people and buildings were presented by the National Police Agency and the Fire and Disaster Management Agency of Ministry of Internal Affairs and Communications, respectively. The numbers of damage to buildings include the other type of construction, but are almost the number of the damaged timber buildings.

The completely destroyed was defined as the building whose more than 70 % of floor area collapsed, was burned or washed away, or which the repair and recover couldn't make the survival part of the building reusable, if the collapsed, burned down or washed away floor area were less than 70 %. And, the half destroyed was defined as the building whose damaged floor area was more than 20 % and less than 70 % and the repair and recover could make the damaged part reusable. The partially damaged was other than the completely destroyed and the half destroyed.

The maximum seismic intensity is the largest value of the seismic intensity calculated from the measured seismic wave at the earthquake. The seismic intensity is defined as a scale of ground motion by Japan Meteorological Agency. The intensity is expressed by the value of 0 to 4 and 5-, 5+, 6-, 6+ and 7. The value of 7 is the maximum value and includes the infinitely large earthquake beyond the intensity of 6+.

3. Typical Damage Due to Strong Ground Motion

3.1 Collapse of the whole 1st story

One of the most severe damage is the collapse of the whole 1st story which was observed in most major earthquake, as shown in Photo 1. There are several reasons, and the main cause is because the wall length is not enough for the seismic force. Under the many of the seismic disaster, the collapse occurred selectively in the relatively old house. The typical old houses have the heavy mud wall and roof tiles and are also built under the old seismic regulation. Most of the detached wood houses assured the seismic performance by the shear wall length in Japan. The seismic regulation providing the required wall length were revised by the repeated seismic disaster. It was the reason why the old houses suffered heavy damage selectively. However, the several new houses built after 2000 collapsed and many new houses suffered the damage under 2016 Kumamoto Earthquake. Now, the reason is under discussion, and it was one of the reason for the ground motion of 2016 to be stronger than the other earthquake.

3.2 Partial collapse

As the second significant damage, there is the partial collapse, as shown in Photo 2. It is considered that a part of the house doesn't have enough wall length for the input seismic force and the other part has enough wall without enough strength of the horizontal diaphragm the joints between both parts. As a result, the partial collapse has occurred.

Table 1 –. Major earthquakes suffering heavy damage on wood houses since 2000

Name	Date	Magnitude	Damage to people	Damage to buildings	Max. Seismic intensity
2000 West Tottori Earthquake	Oct. 6	7.3	182 injured	435 completely destroyed and 3,101 half destroyed	6+
2001 Geiyo Earthquake	Mar. 24	6.7	2 victims and 288 injured	70 completely destroyed and 774 half destroyed	6-
2003 Off-Miyagi Earthquake	May 26	7.1	174 injured	2 completely destroyed and 21 half destroyed	6-
2003 North Miyagi Earthquake	July 26	6.4	677 injured	1,276 completely destroyed and 3,809 half destroyed	6+
2003 Off-Tokachi Earthquake	Sep. 26, 2003	8.0	1 victim, 1 missing and 849 injured	116 completely destroyed and 368 half destroyed	6-
2004 Chūetsu Earthquake	Oct. 23	6.8	59 victims and 4,805 injured	3,175 completely destroyed and 13,772 half destroyed	7
2005 Fukuoka Earthquake	Mar. 20	7.0	1 victim and 1,087 injured	133 completely destroyed and 244 half destroyed	6-
2005 Off-Miyagi Earthquake	Aug. 16	7.2	100 injured	1 completely destroyed and 984 partially damaged	6-
2007 Noto Peninsula Earthquake	Mar. 25	6.9	1 victim and 356 injured	688 completely destroyed and 1,740 half destroyed	6+
2007 Chūetsu Offshore Earthquake	July 16	6.8	15 victims and 2,346 injured	1,331 completely destroyed, 5,710 half destroyed and 37,633 partially damaged	6+
2008 Iwate–Miyagi Inland Earthquake	June 14	7.2	17 victims, 6 missing and 2,346 injured	30 completely destroyed and 146 half destroyed	6+
2011 Great East Japan Earthquake	Mar. 11	9.0	19,418 victims, 2,592 missing and 6,220 injured*	121,809 completely destroyed, 278,496 half destroyed and 744,190 partially damaged*	7
2014 Nagano Kamishiro Fault	Nov. 22	6.7	46 injured	77 completely destroyed, 137 half destroyed and 1,626 partially damaged	6-
2016 Kumamoto Earthquake	Apr. 16	7.3	50 victims and 1,496 injured	7,363 completely destroyed, 21,981 half destroyed and 107,204 partially damaged**	7

Notes: *: as of April 28, 2016, **: as of June 9, 2016.

(a) 2004 Chuetsu Earthquake (b) 2014 Kamishiro Fault Earthquake (c) 2016 Kumamoto Earthquake

Photo 1 – Collapsed wood houses

(a) 2004 Chuetsu Earthquake (b) 2016 Kumamoto Earthquake

Photo 2 – Partial Collapse of wood houses

3.3 Large residual story deformation

As the more type of damage, the large story drift has left for the wood house, as shown in Photo 3. It is considered that the wall length was not enough for the seismic, but was enough for the house not to collapse. About 1/30 rad story drift are visible and defined as safety limit in Japan. But the limit of collapse is considered to be over 1/5 rad due to the past field surveys of the seismic damage and the several static load tests [1] to collapse.

(a) 2007 Noto Peninsula quake (b) 2007 Chūetsu Offshore quake (c) 2011 Great East Japan Earthquake

Photo 3 – Wood houses with large residual story deformation

3.4 Partial or light damage

The damage which has never extended to the whole building is called as the partial or light damage and shown in Photo 4. The partial or light damage is various and includes the damage on the openings, the exterior finishing materials or the foundation. Many of the partial or light damage is repairable within relatively low cost.

(a) 2007 Noto Peninsula Earthquake (b) 2011 Great East Japan Eq. (c) 2016 Kumamoto Earthquake

Photo 4 – Wood houses with partial or light damage

3.5 Damage on the only 2nd floor

The damage on the 2nd floor was almost less than that on 1st floor. But the only 2nd floor suffered severe damage exceptionally, as shown in Photo 5. The reason of the damage of (a) was considered that the brace whose number was very few due to small area of 2nd floor wasn't jointed effectively to the column and beam and missed its bottom from the beam due to the initial seismic input, and that the seismic performance were reduced significantly. It is the reason of (b) why the roof system of the house was damaged by the termite which could attack not only the wet wood but also dry wood. The reason of (c) has never been clarified and the damage like (c) was often seen in 2016 Kumamoto Earthquake.

(a) 2004 Chuetsu Earthquake (b) 2005 Fukuoka Earthquake (c) 2016 Kumamoto Earthquake

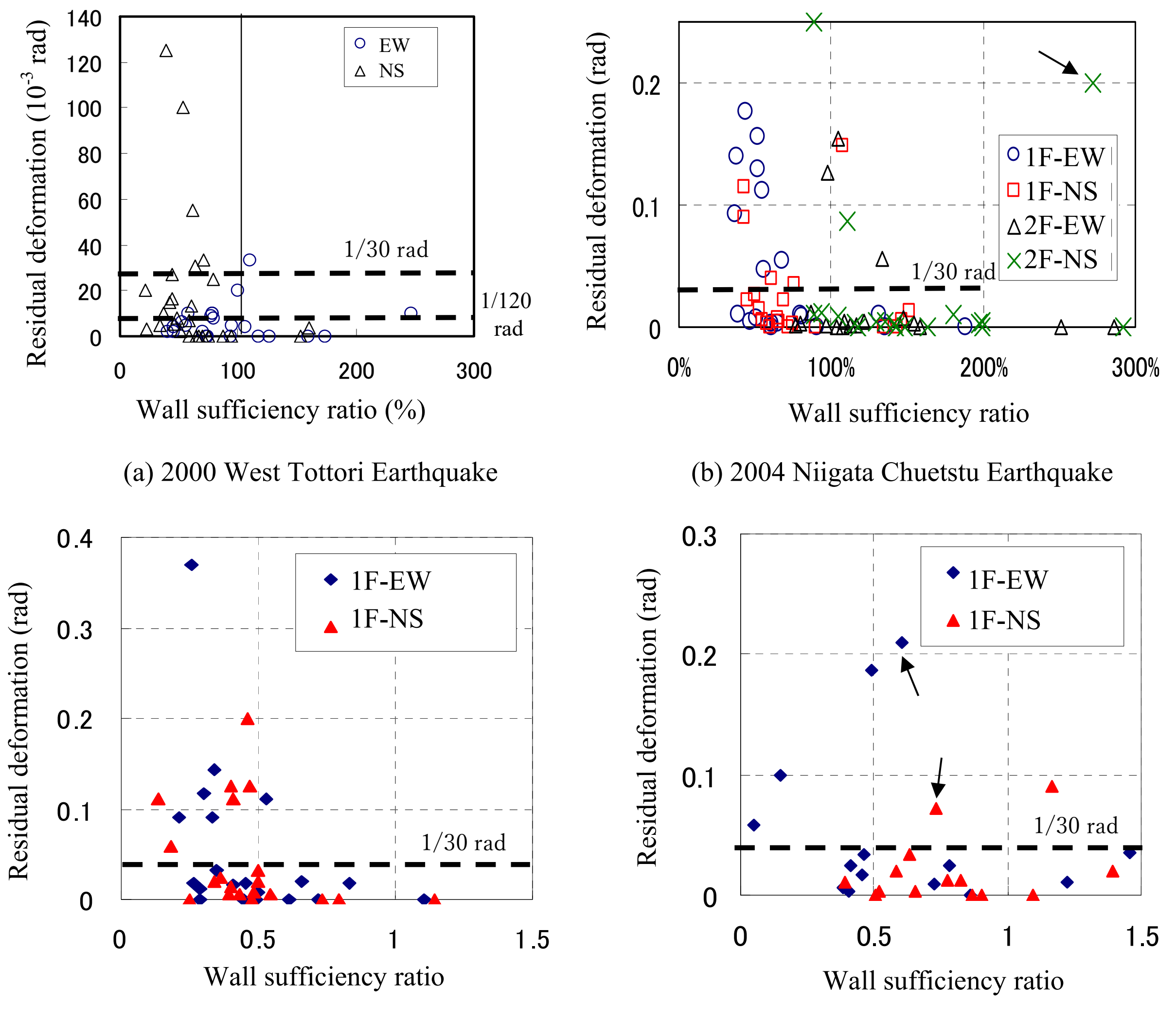
Photo 5 – Wood houses with partial or light damage

4. Relationships between shear wall length and residual story deformation

Several wood houses with the large residual story deformation and the partial or light damage were selected in order to investigate the floor plan and shear wall layouts. The wall without opening was regarded to possess the shear capacity of 1.96 kN/m, because the specifications of wall could be unknown. Then, the sufficiency ratios of the shear capacity of each wood house to the requirement of Japanese building code which corresponded to the base shear of 0.2 were calculated. The relationships between the sufficiency ratios and the residual story deformation were shown in Fig. 1 (a)-(d).

In 2000 West Tottori Earthquake (a), the wood house with wall sufficiency ratio of about 100 % or more has never suffered the damage with residual deformation of about 1/120 rad or more. Here, the sear deformation of 1/120 rad is the allowable story deformation of Japanese building code for timber constructions. In Noto Peninsula Earthquake (c) and Chuetsu Offshore Earthquake, these are in the same tendency except for a few plots. The arrowed plots in (d) is the timber construction shown in Photo 3 (b) and has the reason why many books make the seismic force unexpectedly large because of the change of usage from hospital to library.

On the other hand, in 2004 Niigata Chuetstu Earthquake (b), several wood houses with the wall sufficiency ratio of about 100 % or more suffered the damage with the residual deformation of about 1/10 rad or more. It is the reason why the seismic intensity of 2004 Niigata Chuetstu Earthquake was 7 and stronger than the other three earthquakes. However, the arrowed plots in (b) is the wood house shown in Photo 5 (a) and has the reason as mentioned in the section of 3.5.



(a) 2000 West Tottori Earthquake (b) 2004 Niigata Chuetstu Earthquake

(c) 2007 Noto Peninsula Earthquake (d) 2007 Chuetstu Offshore Earthquake

Fig. 1 – Relationships between shear wall sufficiency ratio and residual story deformation

5. Study on parameter of seismic wave making wood houses suffer the damage

5.1 Post-earthquake temporary risk evaluation of damaged buildings

After the major earthquake with the damage to buildings, the Post-Earthquake Temporary Risk Evalution of Damaged Buildings (PERED) was conducted immediately. In order to offer the information about the risk that faced the use of the damaged building and to prevent a second disaster about human life, PERED make a judgement for the collapse of the damaged building and the falling objects caused by the aftershocks. The specialist who have taken the class of PERED inspects the damage degree of the building due to ground motion or ground deformation, the risk by the next building, the collapse of sites ground, the falling object from the next building, and so on. The results of inspection were indicated by the poster, as shown in Fig. 2 of 3 levels which were "Unsafe", "Limited Entry" and "Inspected".

The results of PERED due to 2004 Niigata Chuetsu Earthquake for over 30,000 buildings were obtained and analyzed. The only informations of the structural damage were picked up form the results. And, the structural damage levels were defined as shown in Table 2. The results of PERED and the classified strucral damage level were compared and shown in Fig. 3. It is considered that the "Unsafe" of PERED were classified to the structural level 5-2.

Fig. 2 – Posters indicating the result of Post-Earthquake Temporary Risk Evaluation of Damaged Buildings (PERED)

Table 2 –. Structural damage levels based on Post-Earthquake Temporary Risk Evaluation of Damaged Buildings (PERED)

Damage Level	Definition of damage level
5	Collapse of whole or a part of building and dangerous at a glance
4	Significant residual story deformation of whole or a part of building except for the damage level of 4
3	Unsafe based only on the structural damage except for the case corresponding to the damage level of 4 and 5.
2	Limited entry based only on the structural damage
1	Inspected based only on the structural damage

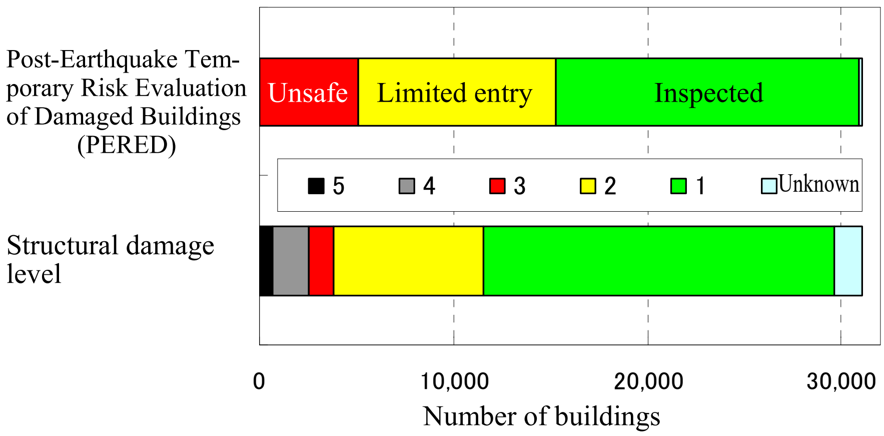
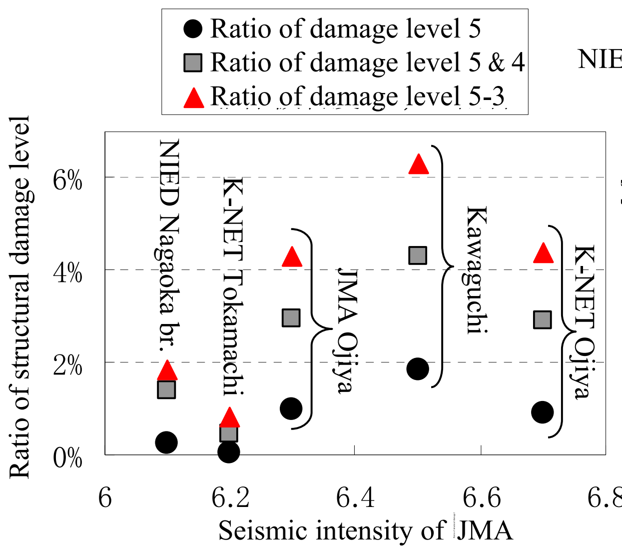


Fig. 3 – Results of post-earthquake temporary risk evaluation of damaged buildings and structural damage level

5.2 Parameter of seismic wave and the structural damage level

Next, the datum within 1 km from the point of the strong-motion seismograph were picked up and analyzed. The structural damage level and the several parameters of the recorded seismic wave were compared togeter. At first, the ratios of the damage level to all datum within 1 km were compared with the seismic intensity calculated from the recorded wave, as shown in Fig. 4. However, the ratio and the seismic intensity didn't have significant corelarion. Second, the ratios were compared with the maximum acceleration recorded in the seismic wave, as shown in Fig. 5. The ratio didn't always become larger with the rising of the acceleration. Finally, the ratios were compared with the maximum velocity recorded in the seismic wave, as shown in Fig. 6. The ratio became larger with the rising up of the velocity. In other words, as the earthquake that the large velocity was observed or as the area where the large velocity was observed, the seismic damage to wood houses became heavy.



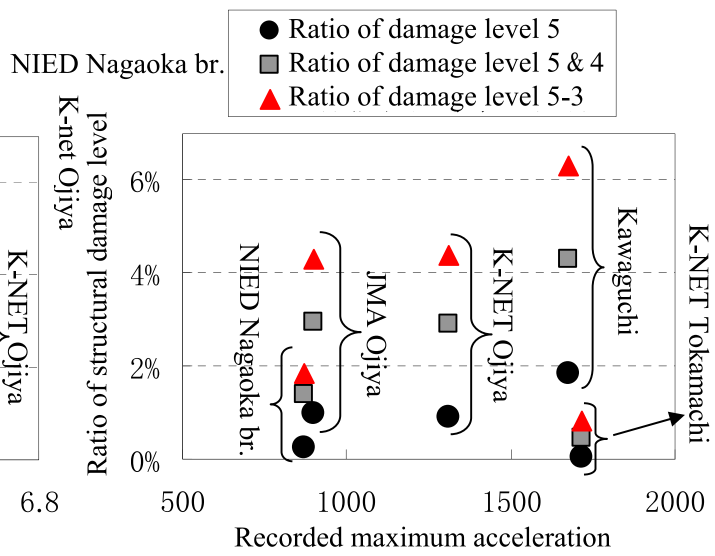


Fig. 4 – Relationships between the seismic intensity and the ratios of the structural damage.

Fig. 5 – Relationships between the recoeded maxmum acceleration and the ratios of the structural damage.

Notes: JMA: Japan Meteorological Agency, NIED: The National Research Institute for Earth Science and Disaster Resilience, K-NET: Nation-wide strong-motion seismograph network, which consists of more than 1,000 observation stations distributed every 20 km uniformly covering Japan and has been operated by NIED, and Ojiya, Nagaoka, Kawaguchi and Tokamachi: The name of city or town.

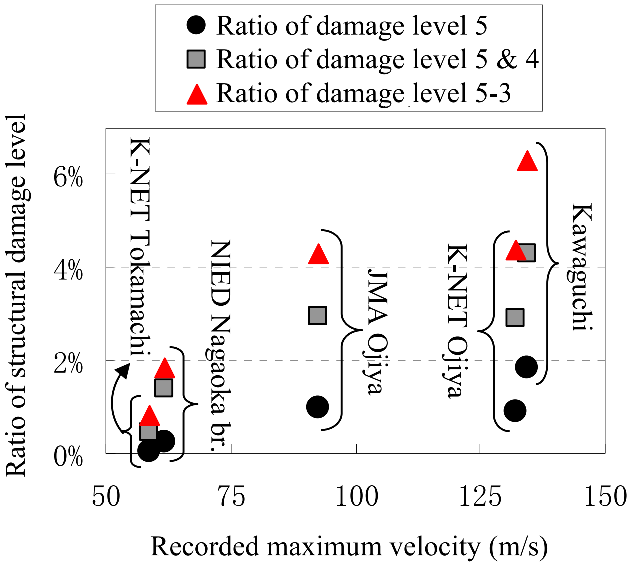


Fig. 6 – Relationships between the recoeded maxmum velocity and the ratios of the structural damage.

6. Conclusion

The results of these surveys and studies in this paper were summarized as follows;

- The 14 major earthquake suffering heavy damage to wood houses has occurred after the year of 2000.
- The severe damage including the collapse was concentrated in the old post and beam house construction with the mud walls and the heavy roof tiles. On the other hand, the relatively new wood houses were rarely damaged except for due to the damage of land. However, the several new houses built after 2000 collapsed and many new houses suffered the damage under 2016 Kumamoto Earthquake.
- The shear wall length in the surveyed wood house didn't have significant difference among the disaster area within our field works.
- It was rare that the shear wall length of wood house had a significant correlation with the damage states and the residual story drifts. However, when the shear wall length satisfied with the requirement of BSL, the story drifts were extremely little.
- Some wood houses which bio-deterioration or termite attacks were found suffered severe damage by all means. So, it couldn't be concluded that the bio deterioration or termite attacks caused the seismic damage.
- The structural damage ratio of wood houses was not higher in the area where the higher seismic intensity or acceleration was recorded. However, the ratio was higher in the area where the higher velocity was recorded. as the earthquake that the large velocity was observed or as the area where the large velocity was observed, the seismic damage to wood houses became heavy.

6. Acknowledgements

The floor plans and the wall layouts of the damaged couldn't be obtained without the cooperation of the people living in the house or in the area. And, the officer of Ministry of Land, Infrastructure, Transport and Tourism in charge helped and supported our field survey. The regional branch of MLIT and the local government provided the useful and accurate information on site. We appreciate for all people's help, support and contribution to this paper.

5. References

[1] Tsuchimoto T, Koshihara M, Matsuda M, Suzuki K, Sugimoto K, Sakamoto I(2006): Effect of deterioration and degradation of structural members on the static collapsing behavior and limit deformation to collapse. *9th World Conference on Timber Engineering*, Portland, OR, USA.