

DAMAGES OF WOODEN HOUSES CAUSED BY 2011 GREAT EAST JAPAN EARTHQUAKE AND TSUNAMI

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ABSTRACT: Substantial earthquake damage of wooden buildings and structures, including collapse or other heavy damage to houses, occurred over a wide swath from Tohoku down to northern Kanto, although in only a fairly limited number of clusters. The type of damage is extremely diverse due to differences in site amplification of the ground motion characteristics.

The summary of damage is broadly divided by the cause of damage, either the damage due ground deformation or damage due to the vibration of the wooden building.

Key Words: wooden house, heavy timber structure, vibrational damage, liquefaction

INTRODUCTION

In Japan there are many types of wooden buildings. The first category, traditional wooden buildings, includes temple, shrines, folk house and town house. The second category includes single-family detached wooden houses. Japan has a stock of about 30 million units, and 600 thousand units are newly constructed every year. This category can be divided into four types according to the classification of construction method; conventional construction, two-by-four system, prefabricated houses and moment frame system. The third category is heavy timber structure, used example, to build schools, gymnasiums and museums. There are great varieties in the structural system of heavy timber structure. Moment-resisting frames and trusses are widely used.

Substantial earthquake damage of buildings and structures, including collapse or other heavy damage to houses, occurred over a wide swath from Tohoku down to northern Kanto (Fig.1), although in only a fairly limited number of clusters. The type of damage is extremely diverse due to differences in site amplification of the ground motion characteristics.

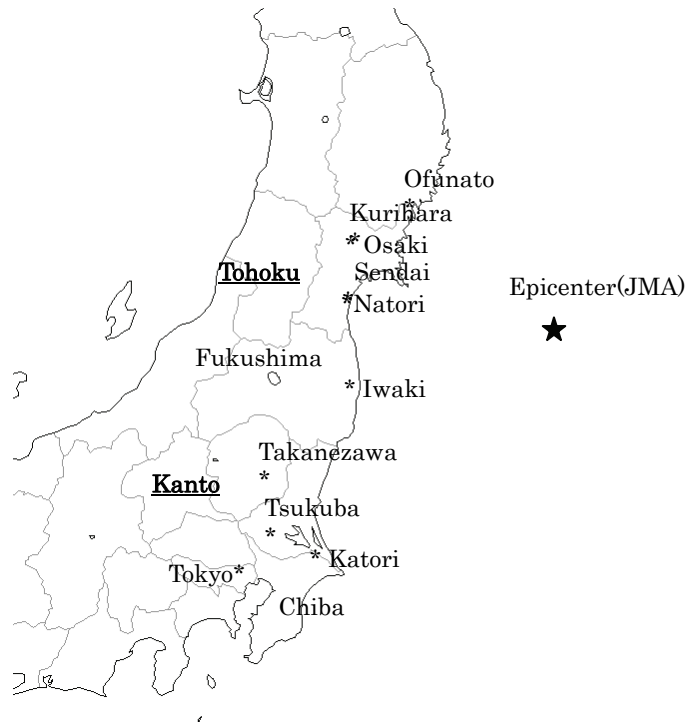


Fig.1 Damaged area

DAMAGE DUE TO GROUND MOTION

The summary of damage is broadly divided by the cause of damage, either the damage due to the vibration of the superstructure or damage due to ground deformation.

Among this division, the vibration of the superstructure is arranged as minor damage (damage to finishing materials), moderate damage (structural damage), and collapse. Buildings include houses, stores, apartments, barns, ware-houses, school buildings, public buildings, shrines, gymnasiums, and other large buildings. They vary in construction method, number of floors, size, and shape.

The earthquake caused extensive damage including housing collapses throughout northeastern Kanto to Tohoku in broad area. In areas such as river basins where the ground is soft, wooden structures are subjected to larger damage due to the longer natural periods. In addition to serious structural damage, roof tile damage and chipped wall finishes, although minor, were seen extensively throughout northern Kanto to the Tohoku area.

In addition to vibrational damage, a large amount of destruction occurred due to ground deformation. Wooden houses built on slopes collapsed or were heavily damaged due to landslides and the destruction of retaining walls. Prominent damage throughout the area was due to slope or land subsidence due to liquefaction of the upper structure of the sandy ground. The liquefaction often tilted the whole superstructure if it did not collapse. In addition, the areas where damage occurred were often on soft soil so the origin of the damage may not be clearly due to ground deformation or vibration.

In particular, the building members in Fig. 2 showed extensive termite damage. Numerous communities have reported serious damage to houses. This damage is reported in Ishinomaki, Osaki, Kurihara, Kesenuma, Sendai and Misato, in Miyagi Prefecture, Sukagawa in Fukushima Prefecture, Nasu Karasuyama, Nasu, Takanezawa and Haga in Tochigi Prefecture and Mito, Ibaraki, Sakuragawa, Naka, and Hitachiota in Ibaraki Prefecture. In addition, sporadic cases of deteriorated housing collapse have been reported in other cities such as Katori, Chiba Prefecture and Kounosu Saitama Prefecture. Fig. 2 – Fig. 5 illustrate some of this damage. Most of the extensive damage occurred in relatively old housing construction, often obsolete buildings, with decay and termite damage. In particular, the



Fig.2 Collapse of wooden house in Osaki



Fig.3 Partial collapse of wooden house in Kurihara



Fig.4 Collapse of wooden house with store attached in Misato



Fig.5 Severe damage of wooden house with store in Osaki

building members in Fig. 5 showed extensive termite damage.

The wooden houses typically have large openings facing the street, which is inadequate for earthquake resistance. Exterior walls often showed chipped mortar and glass as well as ants in the wood sheathing, which sometimes spread into the structural members. Therefore, the damage of most dwellings was amplified due to the termite damage.

In contrast, one distinct example of vibration damage is found in Fig. 6, which shows the partial collapse of the high stone foundation near the city of Nasu Karasuyama and the town of Ichigai in Tochigi Prefecture. This vibrational failure of the foundation was often found and would lead to the collapse of the wooden structure above.



Fig. 6 Collapse of wooden house with high stone foundation

Vibrational damage to storehouses, 'DOZO'

A wide array of damage to storehouse buildings was observed from Kanto to Tohoku, many of which have attached dwellings. Examples of storehouse damage are in Fig. 7 through Fig. 9

The primary type of damage was in the form of fallen roof tiles or chipped exterior wall coatings. Major damage, demonstrated in Fig. 7, was evident in the form of permanent inclination of the building. The group of store-houses in Osaki, as seen in Fig. 8, was over 200 years old and had obvious structural deficiencies. Although there is no deformation to the columns and other structural members, the termite decay is extensive within the members and would be difficult to repair. Fig. 9 shows a building on the same property as the warehouses. A retrofit was performed on the interior wooden bearing walls and reinforced concrete masonry foundation inside. The structural timbers were still intact but the roof collapsed.



Fig.7 Permanent inclination of a storehouse



Fig.8 Damage of older storehouses in Osaki



Fig.9 Retrofitted storehouse in Osaki



Fig.10 Damage of storehouse with heavy mud walls in Tsukuba



Fig.11 Damage of three storehouses with heavy mud walls

Fig. 10 and Fig. 11 show the damage of residential storehouses. Residual deformations were small and the damage was primarily in the form of cracks and spalling of the mud wall as well as falling roof tiles.

Vibrational damage to barns

In residential areas, many structures such as barns and small storage buildings collapsed. These structures did not have adequate seismic considerations. Examples of such damage are in Fig. 12 and Fig. 13.



Fig. 12 Collapse of shed in Kurihara



Fig.13 Collapse of shed in Kurihara

Vibrational damage to schools

School buildings were a mixture of old timber construction methods and new laminated timber structures. A schoolhouse using older timber construction was reported to have a partial second floor collapse and large deformations in Osaki city as well as traces of sand boiling in the schoolyard, caused by liquefaction of the sandy ground. Fig. 14 shows the markings indicating sand boiling. In Iwaki timber schoolhouses are heavily damaged as shown in Fig. 15.

School buildings using laminated wood construction, such as an elementary school gymnasium in Naka-city, only experienced minor damage to the concrete foundation and timber braces.



Fig.14 Damage of school building and markings of sand boiling in Osaki



Fig.15 Severe damage of school building in Iwaki

Vibrational damage to shrines

Damage to shrines are widely reported across the Northeast of Japan with a notable collapse of the main building of a temple in Takanezawa town, seen in Fig. 16.

In addition, Fig. 17 shows the severe damage of the gate to a shrine in Osaki-city. Marks around the site seem to indicate sand boiling caused by the liquefaction of the sandy ground. These shrines used traditional wooden construction methods and were located on soft soils.



Fig.16 Collapse of the main building of temple in Takanezawa



Fig.17 Severe damage to the gate of a shrine in Osaki

Vibrational damage of other wooden buildings

In addition to other building types discussed, a renovated theater in Kurihara-city experienced large residual deformation, evident in Figure 18.

Other examples of damaged timber buildings included houses that used logs assembly. Although this is a rare construction method, there are reports of damage at the intersection of the logs in houses in Nasushiobara-city.



Fig. 18 Severe damage of old cinema in Kurihara-city

Building damage due to landslides

This earthquake caused many landslides and destruction of retaining walls, leading to the destruction of many houses built on the slopes.

Areas of intense damage were found in Aoba-ku Sendai-city, Izumi-ku Sendai-city, Wakabayashi-ku Sendai-city, Fukushima-city, Kagamiishi town, Iwaki-city in Fukushima Prefecture,

and Nasu-karasuyama-city in Tochigi Prefecture. through Fig. 22.

Examples of such damage are found in Fig. 19



Fig. 19 Collapse of hotel due to landslide in Sendai-city

Fig. 20 Severe of a house due to landslide in Sendai-city



Fig. 21 Severe damage of a house due to landslide in Sendai-city

Fig. 22 Severe damage of a house due to landslide in Iwaki-city



Fig.23 Damage due to liquefaction in Katori-city

Damage due to liquefaction

Soil liquefaction occurred rapidly in a wide range of places due to the sandy soil. Ground subsidence lead to serious damage or a tilt of the superstructure.

This damage was evident in Kashima, Kamisu, Itako city, Inashiki, Kawachi-machi in Ibaraki Prefecture, Asahi city, Urayasu, Funabashi, Narashino, Chiba, Abiko, Katori (Fig. 23) in Chiba

Prefecture and Kuki city in Saitama Prefecture. The structural damage to the superstructure due to liquefaction was rather small if it used a reinforced concrete foundation. Damage was typically in the form of structural inclination and subsidence.

Ground deformation and other damage

In flat ground, even though liquefaction does not occur, the soft ground will result in land and soil cracks. Damage to the superstructure from differential settlement is reported in Sakura, and Narita in Chiba Prefecture. Similar damage may have happened in the other regions. This type of the damage occurred to old houses, so the origin of the damage may not be clearly due to ground deformation or vibration.

DAMAGE DUE TO THE TSUNAMI

Tsunami-affected area and study sites

The earthquake triggered a tsunami that flooded areas in the Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba Prefectures. The reconnaissance was conducted in two parts, as indicated in Table 1 due to limitations of time and human resources. A brief summary of the damage is contained within this re-port.

In addition, some results were calculated introducing the relationship between strength of wooden buildings and the horizontal distribution of the tsunami wave.

Table 1 Survey of the tsunami damage to wood buildings

Classification	Municipality	Study Dates
Lowland	Wakabayashi-ku, Sendai, Natori, Iwanuma, Watari, and Yamamoto in Miyagi Prefecture	April 6 th , 2011- April 8 th , 2011
Sloping land	Ootsuchi, Kamaishi, Ofunato, and Rikuzentakada, in Iwate Prefecture and Kesenuma Minamisanriku, Onagawa and Higashimatsushima in Miyagi Prefecture	May 25 th , 2011 – May 27 th , 2011

Damage to lowland areas

The lowlands, often with nothing blocking the force of tsunami, had extensive damage reaching locations far inland. The following provides an overview of this damage.

Wakabayashi-ku, Sendai-city, Miyagi Prefecture

With a few exceptions, most wood houses were completely washed away by the tsunami. Fig.24 shows one of the few wooden houses left standing, due to a location downstream of a reinforced concrete building. Inundation depth estimated from remaining reinforced concrete buildings reached 6 to 8 meters.

In an area approximately 1.5 km away from the shoreline in Arahama district, many low-rise buildings and dozens of hotels were washed away. In this area, some wooden houses situated in a line the direction of the water flow withstood damage, as shown in Fig. 25. Inundation depth in this area was estimated to be about 4 to 5 meters, with the remaining wooden houses being low-rise and non-residential. On the other hand, there were several cases identified that no buildings were left standing in the direction of the tsunami waves.

Fig. 26 shows one of the few wooden structures left standing, with damage limited to the walls in the direction of floodwater. The method of construction was relatively new, involving joints with more metal than traditional construction.



Fig. 24 Wood house remained downstream of RC building



Fig. 25 Wooden houses remained in a line



Fig. 26 Wooden building escaping complete devastation

Yuriage, Natori-city, Miyagi Prefecture

In general, this area experienced widespread catastrophic damage. Fig. 27 shows an aerial photo (from 3/13/2011) of the area surveyed, with the locations of the properties surveyed circled.

Initial investigation was conducted on the house in Fig. 28 at location (1) (Circled numbers in Fig.27 and so on), which had been carried away with the foundation attached. The junction of the foundation to the steel pile failed due to the force of the tsunami, leaving the steel pipe piles in the sand since in Fig. 29 at location (2). This would indicate that the tsunami wave was moving east to west-southwest.

In this same vicinity, the temple and steel building at locations (3) and (4) respectively, were severely damaged but remained in place. The wooden shop with dwelling at location (5) only received slight damage presumably due to being downstream to the temple and steel building. Fig. 30 shows a wooden house in location (10) that withstood the tsunami force without the protection from trees at location (7). This is probably due to the relatively new construction of the house, which was built in the last few years.



Fig. 27 Aerial photograph and the position of investigated buildings in Yuriage, Natori-City



Fig. 28 Wooden house that was carried away with foundation



Fig. 29 Steel pile left at the original position of Figure 28



Fig. 30 Wood house remaining without the protection of the forest (Location (10))

A few wooden houses remained around location (11), downstream of a factory building. Inundation depth is estimated at about 3.5 meters in this area. These buildings are pictured in Fig. 31 and Fig. 32 (Picture taken from location (12)).

Fig. 33 in location (14) shows a group of houses that remained down-stream of a large factory building. The buildings that survived were a mix of older and newly constructed wooden houses. In addition, the factory building in location (15) protected wooden houses for an even further distance. This is expected to be due to the relatively new construction of these houses that had superior structural specifications. These houses are seen in Fig. 34 taken from location (11). Another wooden house, at location (17), was spared from catastrophic damage presumably due to superior construction.



Fig.31 Japanese conventional post and beam wood house remaining (Location (11))



Fig. 32 One of few light frame construction wood houses remaining (Location (11))



Fig. 33 Group of wooden houses that escaped damage downstream of a RC structure (Location (14))



Fig. 34 Wooden houses which avoided being carried away downstream of the factory building (Location (11))

Araham, Watari-town, Miyagi Prefecture

The Araham, Watari-town area is surrounded by the Pacific Ocean on the west and a lake to the South, with a harbor off of the lake, as shown in Fig. 35. The tsunami washed away many of the wooden houses, leaving only the foundation.



Fig. 35 Aerial photograph in Arahama, Watari-machi

The extent of the severe damage was mostly on the eastern peninsular region. One wooden building, as pictured in Fig. 36, was previously “L” shaped in plan. The part of the house that had the largest amount of area exposed to the tsunami wave washed away while the shorter side remained. Judging from the connection in Fig. 37, the estimated date of construction was after 2000, revised building standard in Japan.

Fig. 38 shows a hybrid construction building that withstood the tsunami force. This building uses reinforced concrete stilts for the first floor and wooden construction on the second floor. Fig. 39 shows a one-story heavy timber structure with glulam frame in which the wooden structure remained intact, but the building was filled with wreckage and building materials.

North of the harbor, estimated to have been in 6 meters of floodwater, mostly consisted of detached wooden houses. Fig. 35 shows the impacted area, with very few houses remaining on the north side of the harbor. One of the few that remained, pictured in Fig. 40, was a three-story wooden house that had been design for superior seismic protection. This extra strength is probably responsible for the survival of the building. West of the harbor, estimated to have been in 4 meters of floodwater, had a number of buildings withstand the tsunami force. One of the wooden houses, pictured in Fig. 41, also withstood contact from a ship. This is probably due to relative young age of the house, which presumably has superior structural specification.



Fig. 36 A portion of a wood house that was washed away



Fig. 37 Fastener of joint in the house of Fig. 36



Fig. 38 Hybrid construction consisting of RC on the 1st floor and wooden construction on the second floor



Fig. 39 Heavy timber structure with Glulam frame remaining



Fig. 40 3-story wooden house remaining



Fig. 41 Wooden house remaining even after collision with ship

Summary of damage to the lowlands

The following conclusions were drawn about wooden building in the lowlands.

- Overall damage was quite severe
- If a building did withstand the tsunami, the wooden buildings downstream often stayed intact.
- The wooden buildings that stayed intact downstream of other buildings showed newer and superior structural construction.
- Even if there was no building blocking the force of the tsunami, there are a few examples of low-rise wooden buildings that remained intact due to newer construction specifications. However, the buildings that remained had severe damage to the lower level walls perpendicular to the tsunami direction.

Damage to wooden buildings on slopes

In this section, the damage survey results are only given for Akasaki-machi, Ofunato-city, a village on the east side of the bay of Ofunato situated on a gradual slope. Fig. 42 shows the aerial photograph of the district with the locations of the buildings surveyed.



Fig. 42 Aerial photograph in Ofunato-City

A house in location (1) (Fig. 43), according to residents, was almost completely submerged with inundation depth over 7 meters. The house had some damage but was largely spared overall. An adjacent work shed in location (2) was disconnected from the concrete foundation and moved. The two-story wooden house across the street in location (3) on the ocean side received very little damage (Fig. 44). The hill to the north of these buildings probably reduced the magnitude of the tsunami force.

Fig. 45 shows a traditional Japanese wood house in location (5) that survived the inundation depth of about 5-6 meters and it was located 1.5 meters above the road level. Although the walls were destroyed the structure was intact, and there seemed to be little residual deformation in the house. Fig. 46 in location (6) was about 2 meters above the road level. The house was spared despite floodwater levels reaching 6 meters, damaging parts of the roof as well as the house. A relatively new house to the northeast was washed away. This house was equipped with significant tie-down hardware and large partial corrosive pores were observed. This indicates that the tie-down hardware was not sufficient to fix the house to the foundation.

Along the prefecture road up the hill from these buildings, a lightweight steel frame house in location (9) withstood floodwaters up to 5 meters. Adjacent to this building in location (10), a small one-story building that had minor structural specifications survived, pictured in Fig. 47. The house

was con-firmed to have one brace with nailed joints and anchor bolts into the foundation. In addition, despite a 3.8-meter inundation depth, a dilapidated warehouse in location (11) remained standing (Fig. 48). Just to the East in location (12), old houses were rotated about 30 degrees clockwise (Fig. 49). The fact that some of these older buildings withstood these floodwaters suggests that the slope reduced the force of the tsunami in contrast to the lowlands.



Fig. 43 Wooden house intact with 7m wave depth



Fig. 44 Wood house without damage with over 7m wave depth



Fig. 45 Traditional wooden house that avoided being carried away under 5-6 m wave depth



Fig. 46 Wooden house that avoided being carried away even with flood damage up to the 1st floor roof



Fig. 47 House that survived with minor structural specifications



Fig. 48 Warehouse that survived with minor structural specifications



Fig. 49 Survived old house which was rotated

CONCLUSIONS

The summary of damage is broadly divided by the cause of damage, either the damage due ground deformation or damage due to the vibration of the wooden building.

Among this division, the vibration of the wooden building is arranged as minor damage (damage to finishing materials), moderate damage (structural damage), and collapse. Buildings include houses, stores, apartments, ware-houses, school buildings, public buildings, shrines, gymnasiums, and other large buildings. They vary in construction method, number of floors, size, and shape.

Collapse and other heavy damage affecting wooden houses, which tend to have long natural period and little seismic protection, were extensive in areas having soft ground (along river beds, etc.). Also reported was damage to earth wall storehouses, 'DOZO', not only in areas where houses in general suffered severe damage, but also in areas where they suffered little damage.

Slight damage, typically to roof tiles (especially fallen ridge tiles) and exterior wall coverings (peeling, etc.) was observed over a wide area extending from Tohoku to Kanto.

Particularly conspicuous in the aftermath of this earthquake are (1) collapse or other severe damage to houses and other structures as a result of landslides or failure of retaining wall on slopes, especially on land developed for residential use, and (2) tilting or sinking of entire structures as a result of the liquefaction of sandy soils. Furthermore, many of the areas that experienced significant vibrational stress are characterized by soft ground, and in several cases it is not entirely clear whether damage to structures there should be attributed to vibration or to ground deformation.

As for tsunami damage, many wooden houses were swept away within areas struck particularly hard. There were cases, however, of wooden houses that, because they were shielded from direct tsunami impacts by relatively large surviving structures, remained in place. There were also cases where wooden houses presumably having excellent structural specifications remained in place despite the lack of a shielding building, although some did suffer severe damage to their walls or frames. The use of hold-down connectors appeared not to be an important factor in determining whether a wooden house was swept away.

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