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SEISMIC PERFORMANCE OF A TRADITIONAL WOODEN HOUSE IN OKINAWA

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Abstract

During the Second World War, many buildings in the Okinawan archipelago were destroyed, however, some traditional wooden houses constructed even more than 100 years ago still remain. These traditional houses are important cultural assets that can give an idea of life in Okinawa during that era.

According to historical records, the Okinawa area has experienced several strong earthquakes. One of the strongest was the Meiwa earthquake with an estimated magnitude of 7.3 (Richter scale) in the year 1771, which was followed by a tsunami of 80 meters. More recently, in the 1900's, six major earthquakes of magnitude above 7.0 were also recorded. As an example, an earthquake with a local magnitude of 7.2 occurred on the east side of Okinawa's main island in 2010. This earthquake caused some structural damage, including the partial collapse of the retaining walls of Katsuren Castle and some other important cultural properties.

In the year 2017 according to the Japan Meteorological Agency, more than 15000 earthquakes occurred around the Okinawan islands, which represent 10% of the total number of earthquakes that occurred that year in Japan. This indicates that the Okinawa archipelago is very much seismic active and precautions should be taken to protect the structures such as historical buildings.

This study aims to evaluate the actual mechanical properties of structural wood elements and the seismic capacity of the structure of Okinawan traditional houses. Especially those which are designed as a cultural asset. Mekaru house which was constructed in 1906 was selected as a model in this study. This house is located on a remote island so-called Izena, which is located north from Okinawa mainland.

Most of the Okinawan traditional wooden houses were built using unique materials that were rarely used in other prefectures in Japan such as Inumaki (*Podocarps macrophyllus*) and Iju (*Schima wallichii*) as a structural material. For this reason, their standard mechanical properties have not been precisely determined yet.

Firstly, non-destructive stress wave velocity tests were used to measure the mechanical properties of wood materials such as the Young's modulus. Secondly, the current seismic capacity calculation was carried out by the response and limit strength method, using the mechanical properties of wood, obtained by non-destructive stress wave velocity tests in the previous steps. The seismic force was calculated for a mid-range type earthquake (case e-1) and a large range type earthquake (case e-2).

The results indicate that Young's modulus value of old Inumaki which used as structural elements in Mekaru house was 6.7 kN/mm^2. This value is comparable with Young's modulus obtained for new wood materials, therefore, the wood elements of the target building were not confirmed to have the effects of time deterioration.

According to the calculations for a mid-range type earthquake, the seismic capacity was 38% higher value in the X direction than the required value, however, in the Y direction, the seismic capacity was 43% lower than the required value. This value was calculated for a lateral drift angle of 1/120 radians. For a large-range type earthquake, the seismic capacity was 3.3% lower value in the X direction and, 20% lower value in the Y direction than the required value. This value was calculated for a lateral drift angle of 1/30 radians. Hence, when if a large-range type earthquake occurs, it was confirmed that there is a risk that this house will collapse

Keywords: cultural assets, traditional wooden houses, Okinawa, seismic capacity, limit proof stress calculation

1.Introduction

During World War II, fierce ground battles took place in Okinawa between March and June 1945. It is said that 90% of the houses in Naha city that is the main city of Okinawa were destroyed by the war. But fortunately, some of Okinawa's historic houses had suffered less damage from the war.

According to previous studies [1], about 100 traditional wooden houses built more than 60 years ago have been identified by a local government survey where the oldest one was constructed in 1780. These traditional wooden houses are important cultural assets that suggest the lifestyle in Okinawa during that era. Thus, they have a very high cultural value and needs to be preserved for posterity.

According to historical records, the Okinawa area has experienced several strong earthquakes. One of the strongest was the Meiwa earthquake with an estimated magnitude of 7.3 (Richter scale) in the year 1771, which was followed by a tsunami of 80 meters. This event caused 9000 deaths on Ishigaki island, which was half of its population, and another 2000 deaths on Miyako island.

More recently, in the 1900's, six major earthquakes of magnitude above 7.0 were also recorded. As an example, an earthquake with a local magnitude of 7.2 occurred on the east side of Okinawa's main island in 2010. This earthquake caused some structural damage, including the partial collapse of the retaining walls of Katsuren Castle and some other important cultural properties.

In the year 2017 according to the Japan Meteorological Agency, more than 15000 earthquakes occurred around the Okinawan islands, which represent 10% of the total number of earthquakes that occurred that year in Japan[2]. This indicates that the Okinawa archipelago is very much seismic active and precautions should be taken to protect the structures such as historical buildings. Therefore, it is necessary to evaluate the seismic structural performance of these historical traditional houses to protect them as cultural assets.

Most of the Okinawan traditional wooden houses were built using local tree species such as Inumaki (*Podocarps macrophyllus*) and Iju (*Schima wallichii*) for structural elements. The Inumaki and Iju are rarely used in other prefectures in Japan. For this reason, their standard mechanical properties have not been precisely determined yet.

This study aims to evaluate the actual mechanical properties of wood materials and the seismic capacity of the structure of Okinawan traditional houses. Especially those which are designed as an important cultural asset.

2. Target building

The target building is Mekaru house which located in a remote island so-called "Izena-island", which is located 80km north-east from Naha city. This building was built in 1906 and was determined and publicly notified as important cultural properties in 1977. Fig. 1 shows the floor plan of the target house, and Fig. 2 shows its external view.

The floor plan is a layout often seen in traditional wooden houses in Okinawa. On the south side, there are "Omote-za" called "Ichi-ban-za", "Ni-ban-za" and "San-ban-za", and on the north side, there are each "Ura-za". The Omote-za is used for family dining and reception of guests, and the Ura-za is used as a private space such as a bedroom. In Okinawa, there is a tradition that places importance on the east where the sun rises, and in the Omote-za arrangement, the "Ichi-ban-za", which is a reception area for visitors, is located at the most east side. and the "Ni-ban-za" with a Buddhist altar and the "san-ban-za" as a dining and a living room are located adjacent to the "Ichi-ban-za" western side, and the kitchen is located on the most western side.

At the structure elements, timbers called Inumaki are used. Inumaki is harder than cedar, and its fiber contains a termite-killing component called Inumaki lactone A. Therefore, it has been being treasured in the Okinawa region since ancient times for its resistance.

In the traditional wooden structure, each column is placed on a foundation stone without fixing, and Each column base and middle are fixed by penetrated the binding material called "Nuki", and each column capital is fixed by surrounding beams. Also, for the joining method of building structural elements, no nails are used for fixing each wooden structural element as shown in Fig. 3. It is said that the traditional construction method seen in the Okinawa region is like Shoin-zukuri, which is seen in mainland Japan during the Muromachi era (1336CE-1573CE).

The walls are generally made of wooden boards, and mud walls are used only in the kitchen and part of the Ura-za such as Fig 1. Also, Okinawa is a stable and warm climate with annual temperature changes of 17 to 30 degrees, so the outer walls are reduced to ensure ventilation. In general, many houses have large openings on the south and east sides.

The roof structure is a "Wagoya" style roof, which is the structure that supports the ridgepoles and purlins with vertical members and distributes the weight of the roof into columns as shown in Fig. 4.

The roof is a hipped roof which was tiled red roof tiles, and the eaves on the roof are long and are extended outside the outer walls to create a characteristic space called “amahaji” such as Fig. 5. The roof is covered with red tiles, after covering the rafters with a field board and applying red clay. As a result, this structure becomes very heavy, but it is a counter-measure for typhoons that often struck the Okinawa archipelago. Also, the soil under the roof has high water absorption and ventilation, Therefore, it also plays a role in protecting the environment of the attic and preventing the roof members from decay.

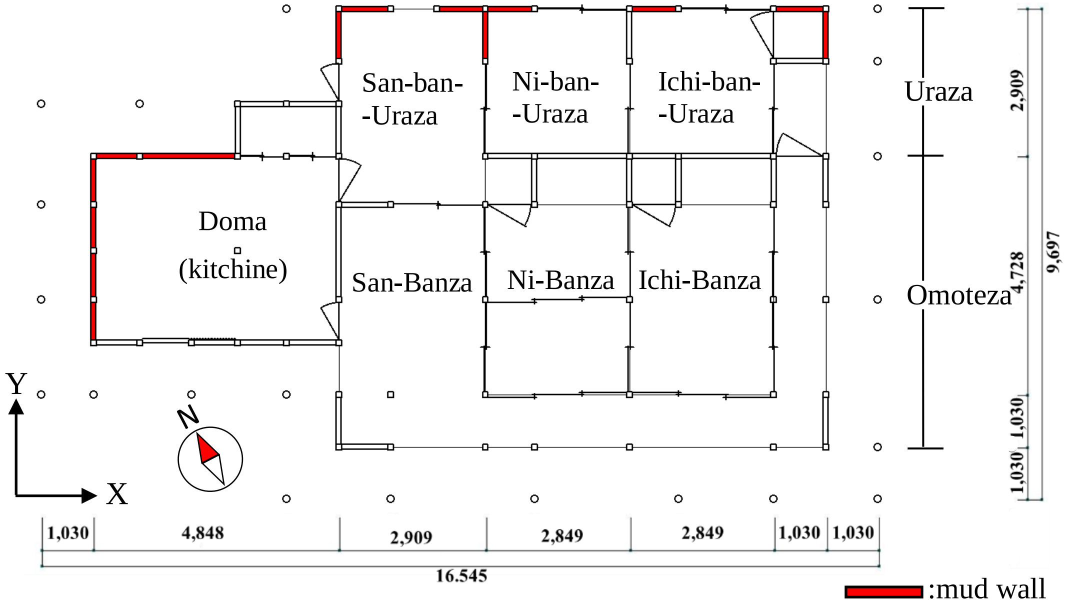


Fig. 1 – Floor plan (Unit=mm)

Fig. 2 – External view

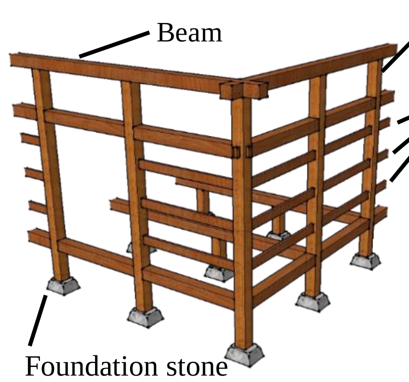


Fig. 3– Traditional wooden houses

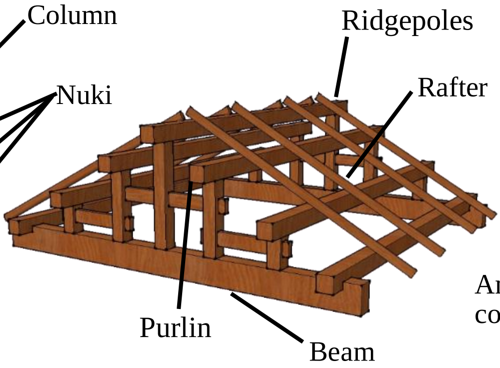


Fig. 4 – Wagoya structure

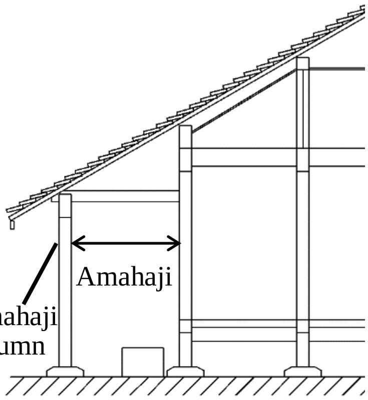


Fig. 5 – Amahaji space

3. Member strength measurement

Inumaki wood used in the traditional houses in Okinawa does not have a standard strength set by Japanese agricultural standards (JAS). Therefore, non-destructive test on site was conducted to determine their actual material strength, also the effects of time deterioration of mechanical properties were verified. This value will be used for structural analysis.

To measure the mechanical properties of the wood material, non-destructive stress wave velocity tests were used. In the test, the time required for the stress wave generated at the input sensor pin by the impact of the hammer to reach the output sensor pin was measured.

To avoid damage to the wood member during the test, as shown in Fig. 6, Fig. 7 and Fig. 8, the sensor pin was driven vertically into a zelkova wood, and the sensors were placed on the same surface of the measurement member so that the sensors faced each other.

The sensor was hit by dropping a 100 grams test hammer from a height of 50cm. and the minimum distance between sensors was set to 40 cm, and the distance was increased to 120 cm in 20 cm increments, and multiple measurements were made at each measurement location.

The Young's modulus measured by non-destructive was calculated using the following formula (1).

$$E_f=\rho V^2 \tag{1}$$

Where E_r is the dynamic Young's modulus (kN/mm^2), ρ is wood density (kg/m^3), and V is the stress wave propagation velocity (m / sec) which is calculated by the gradient ($\Delta L/\Delta T$) of the regression line between the sensor distance" L (m)" and the measurement time "T (sec)".

Fig. 6 – Test equipment

Fig. 7 – Jig for fixing zelkova wood

Fig. 8 – Testing view

For the field survey, 3 columns located at the ichi-banza and ni-banza were selected to carry out the nondestructive tests of the dynamic Young’s modules.

Sine, it has been reported that the value of the dynamic Young’s modulus estimated by the nondestructive test (Ef) become higher than those values of Young’s modulus measured by the bending destructive tests (MOE) [3,4], a correction factor was applied as shown in formula (2). This correction factor was obtained from previous researches by the authors [5]

$$MOE_{Inumaki}=0.66E_f \tag{2}$$

Table1 shows the corrected values of Young’s modulus. The average value of Young's modulus of the Inumaki wood elements at the Mekaru house was 6.7 kN/mm^2.

For reference, Fig. 9 shows Young's modulus of Inumaki obtained from filed surveys of other traditional wooden houses in Okinawa [5], together with the results of this survey. The average value Young’s modulus of Inumaki used in traditional wooden houses in Okinawa is 6.6 kN/mm^2. Thus it was confirmed that the value of Young's modulus of Inumaki used in the Mekaru house is in correspondence to those values measured in other traditional houses in Okinawa. The Young's modulus of Inumaki obtained for Mekaru house (6.7 kN/mm^2) was 1.1 times higher the values given by local organizations (6.3 kN/mm^2)[6], therefore, the wood elements of the target building are supposed to have no deterioration even though they were built more than 100 years ago.

Table 1 － Survey results

Specimen	**Moisture content (%)**	**Young's modulus (kN/mm^2)**
1	18.3	7.0
2	21.1	6.9
3	25.8	6.1
average	21.7 (3.09)	6.7 (0.40)

*()value is standard deviation

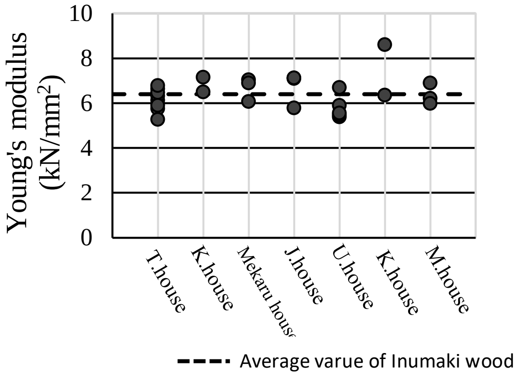


Fig. 9 – Average strength of Inumaki

4. Analysis model overview

The seismic performance of Mekaru House was evaluated by the limit strength calculation method using the restoring force characteristics of the target building. The restoring force characteristics used for the calculation were calculated by pushover analysis using structural analysis. In the pushover analysis, a model incorporating elastic properties was used.

For the material information of the model used to calculate the restoring force characteristics of the building, the value of Young's modulus of Inumaki obtained by the field survey was used. The dimensions of the column members and the roof structure members were 12.5 cm in both width and depth, and the beam dimensions were 12.5 cm in width and 20 cm in depth.

The column and beam members of the frame were made of elastic elements, and when there was a place where the bending load was concentrated in the analysis results, an elastic-plastic rotating spring was arranged in that part to consider breakage due to bending. The joints were modeled using elastic-plastic rotating springs [7]. Fig. 10 shows the restoring force characteristics used for modeling the connections.

Beam-column connections as shown in Fig. 11 have a strong axis and a weak axis, so only the tenon where the load acts on the strong axis was set. The beam-column joint was modeled as a pin joint.

Also, since cogging like Fig. 12 used for the beam-to-beam connection, the rotational rigidity of the halving joint was determined by the formula (3) [8]

$$KR=\frac{7}{400}b^2hE \tag{3}$$

Where KR is the rotational rigidity (kN.cm/rad) of the missing joint, b is the width of the grid material (cm), h is the height of the grid material (cm), and E is Young's modulus of the grid material (kN / cm^2).

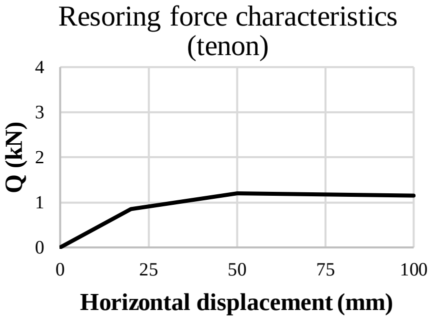


Fig. 10 – Restoring force characteristics

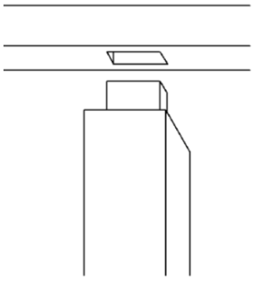


Fig. 11 – Tenon

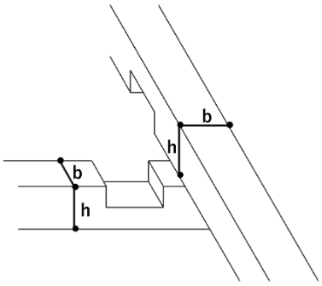
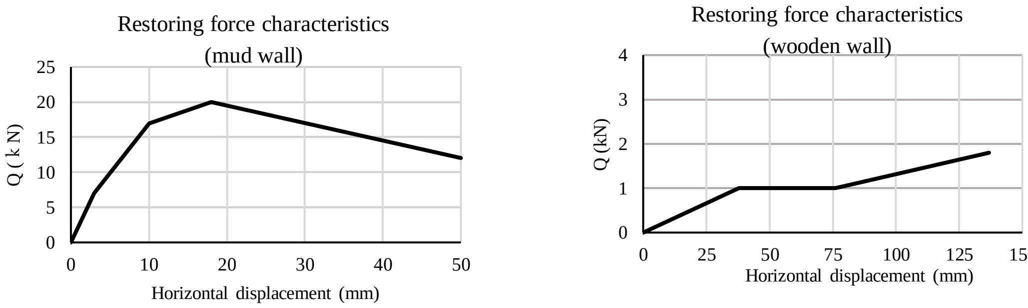


Fig. 12 –Cogging

The shear force generated on the vertical structure was modeled by brace replacement. For the restoring force characteristics, two types of soil wall and wooden wall [9, 10] as shown in Fig. 13 were used.



a) the mud walls

b) the wooden walls

Fig. 13 – Restoring force characteristics of the walls

The uplift of the columns was confirmed by the axial force applied to the column from the analysis results, and a spring considering tension was placed at the place where the uplift was confirmed. Fig. 14 shows a conceptual diagram of the vertical structure model.

The fixed load and the live load to be set for the target building were set based on the Building Standards Law in Japan. Also, the analysis model was a flat roof, and the roof load was equally divided into each horizontal member located at the capital. Table 2 shows the values used for the analysis model.

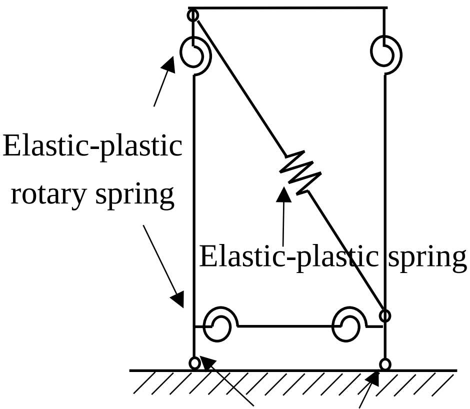


Fig. 14 – Conceptual scheme

Table 2 – Fixed load and live load

Elements	Supplement	Unit load (kN/m^2)	Load (kN)
Roof	Tiled roof	1.34	149.3
Exterior wall	framework+ backing board	0.25	27.6
Ceiling	Decorative crosspieces	0.2	156.3
Floor	-	1.7	18.6
Live load	For earthquake	0.6	0.6

Fig. 15 shows the analysis model and Fig. 16 shows the restoring force characteristics of the target building obtained by the pushover analysis for X and Y direction respectively, For the X direction the maximum shear force of 200 kN was observed of 1/17 rad. On the other hand, for Y direction the maximum shear force of 83 kN was observed at a drift angle of 1/34 rad.

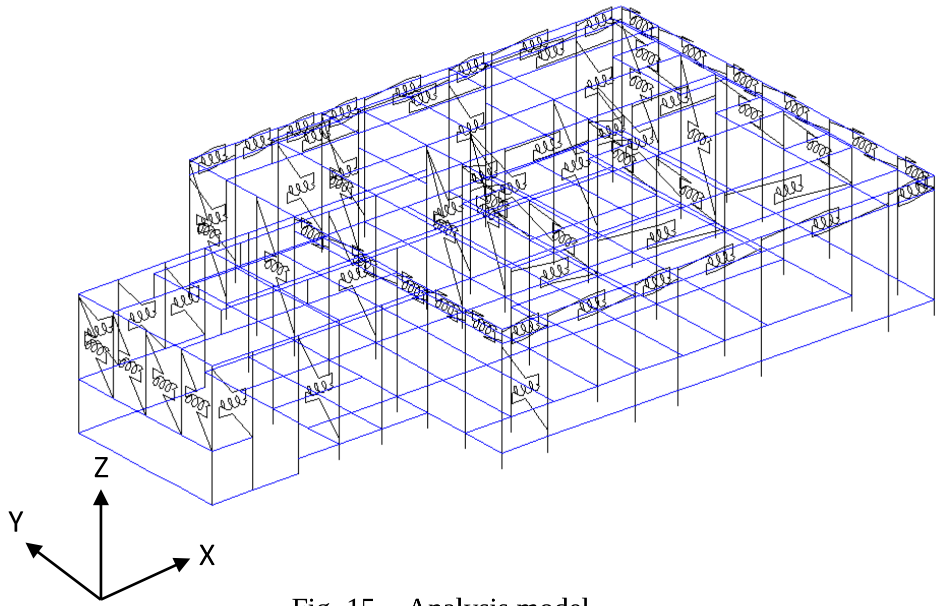


Fig. 15 – Analysis model

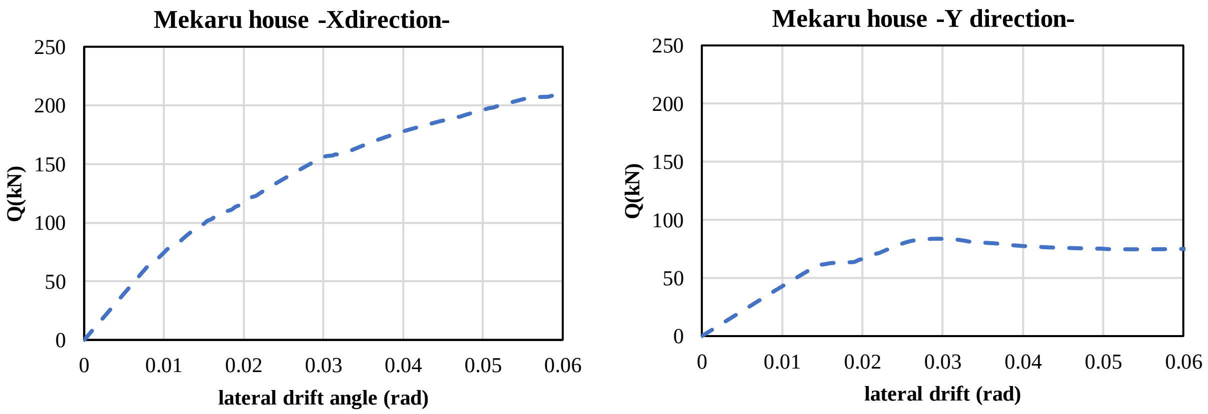


Fig. 16 – Restoring force characteristics of Mekaru house

5. Seismic performance evaluation

The seismic performance is evaluated using response values obtained from the relationship between the restoring force characteristics of the analytical model obtained by pushover and the seismic response spectrum.

The seismic force was calculated for mid-range earthquake (case e-1) and extensive earthquake (case e-2) as a response spectrum assumed for calculating the seismic force indicated in Enforcement Ordinance of Construction, Building Standard Law Article 82-2. Large-range type earthquakes are set to be five times larger than mid-range type earthquakes. As a study method, at the mid-range type earthquake, confirm that the response value is below 1/120 rad, which is damage limit, and at the extensive earthquake, confirm that the response value is below 1/30 rad which is the safety limit. Formulas (4),(5) were used to calculate the seismic acceleration response spectrum [11].

mid-range earthquake (case e-1) : $S_{Ad}=S_{0d}\cdot G_s\cdot F_h\cdot p\cdot q\cdot Z$ (4)

large-range earthquake (case e-2) : $S_{As}=S_{0s}\cdot G_s\cdot F_h\cdot p\cdot q\cdot Z$ (5)

Where S_{0d} is acceleration spectrum on engineering bedrock corresponding to 5% attenuation constant such as shown in Fig. 17 and Table 3, G_s is the acceleration amplification by surface ground, F_h is acceleration reduction rate due to vibration damping, p is the adjustment coefficient according to the number of floors and equivalent period of the building, q is the adjustment factor according to the ratio of the effective mass to the total mass of the building and Z is seismic zoning factor given by the Japanese seismic code.

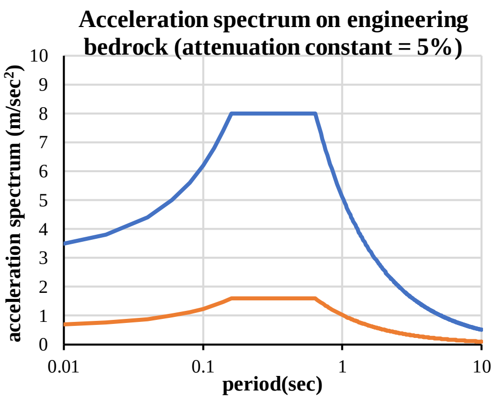


Table 3 — Acceleration on engineering bedlock

Equivalent period (sec)	Acceleration spectrum (m/sec^2)	
	S_{0d}	S_{0s}
T_e<0.16	S_0=(0.64+6T_e)	S_0=(3.2+30T_e)
0.16≦T_e<0.64	S_0=1.6	S_0=8
0.64≦T_e	S_0=(1.024/T_e)	S_0=(5.12/T_e)

Fig 17— X acceleration on engineering bedrock

The response value was calculated using formulas (6),(7) and (8) with an effective mass of 352.4 kN and an effective floor height of 2.7 m.

$$Q_n=M_u \cdot S_A \tag{6}$$

$$S_D=\left(\frac{Te}{2\pi}\right)^2 \cdot S_A \tag{7}$$

$$\gamma_n=\frac{S_D}{He} \tag{8}$$

Where Q (kN) is the shear force, Mu (kN) is effective mass, S_A is the seismic acceleration response spectrum, S_D (rad) is representative displacements, Te (sec) is equivalent period, γ_n is response deformation angle.

Fig. 18 shows the relationship between the seismic response spectrum and the restoring force characteristics of the house, and Table 4 shows the response values for each seismic force in terms of lateral drift angles.

Table 4 — Response value

Direction	**Lateral drift angle (rad)**	
	e-1	**e-2**
X	1/166	1/29
Y	1/68	1/24

For the mid-range earthquake, in the X direction, the structure showed to have a seismic capacity 38% higher than the required by the seismic forces, however, in the Y direction, the seismic capacity was 43% lower than the required value. These values were calculated for a lateral drift angle of 1/120 radians.

On the other hand, for an extensive earthquake, in the X and Y directions, the seismic capacities were respectively, 3.3% and 20% lower than required by seismic forces. These values were calculated for a lateral drift angle of 1/30 radians.

The results showed that for both earthquakes the seismic capacities in the Y direction are lower than the required capacity. This is considered to be a consequence of the large openings on the south and east sides of the house, and the outer wall which is an earthquake resisting element is placed only on the north side and around the kitchen. Also, the heavyweight of the roof is considered to be one of the affecting factors.

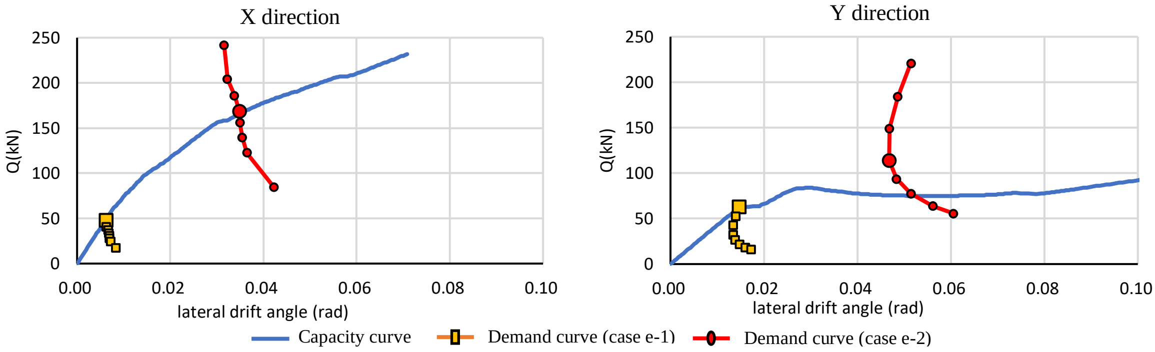


Fig. 18 – Capacity - demand curves

6.Conclusions

This paper presents a review of the seismic capacity of a traditional wooden house in Okinawa. The Young's modulus of the structural original wood materials obtained by the non-destructive test was 6.7 kN/mm^2. This value was similar to the new Inumaki wood, then no influence was observed due to deterioration.

The seismic evaluation of the Mekaru house indicates, in case of earthquake e-1 that the seismic capacity in the Y direction was 43% lower than the required value, and in case of earthquake e-2 that the seismic capacity was lower than the required value in both the X and Y directions. The reason for low seismic capacity is considered due to the large openings on the south and east sides and the heavy roof. Hence, when an extensive earthquake occurs, there is a risk that this traditional house will collapse.

These results apply to many other old traditional houses that remain around Okinawan islands. Therefore, it is necessary to have a more exhaustive survey for other traditional houses designated as important cultural properties and prepare a plan with proper retrofit methods to preserve the Okinawan cultural asset.

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