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[Paper]

Perspectives on the Resilience of Okinawan Housing against Typhoons

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Keywords

Typhoon damage, reinforced concrete structures, wooden structures, housing resilience

Introduction

The Okinawa Islands have experienced the actions of typhoons over their long history. As a result, since ancient times, typhoons have caused damage to houses and other infrastructure. Although the route and strength of typhoons have become predictable to some extent, they still represent a threat to the islands' communities.

In the last 70 years, the amount of damage to houses has shown a remarkable decrease. This may mean that the number of typhoons passing close to the Okinawa Islands decreased or that they became less powerful. Another possibility could be that the number of houses has decreased or that the houses have become more robust. Out of these possibilities, this paper examines closely how and why Okinawan houses have become more robust against typhoons.

Several research studies on typhoon's characteristics and the amount of damage caused to Okinawan houses have been carried out (Tamaki 2014a). These studies have examined how communities have dealt with restoration and their resilience after typhoon disasters. However, here it is necessary to explain what kind of technology was used to restore the communities' houses. In other words, it is essential to clarify from an engineering viewpoint why damages occurred and why the amount of damage has decreased in Okinawa.

This chapter presents the progress of the construction style of Okinawan houses from the Meiji era to the present. Based on this information, the author discusses the relationship between houses' structural characteristics and typhoon damages from an engineering viewpoint, that is, how Okinawan house construction has changed in the last 70 years to deal with typhoons' strong winds, considering concrete or wooden materials, protection

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of materials against deterioration caused by insects or a salty environment, structural elements, and new reinforcement methods and how they improve houses' strength against typhoons.

Typhoon Damage in the Okinawa Islands

Frequency of Typhoons

The frequency of typhoons is summarized in figure 1 from the year 1950 up to the present. The typhoons included in figure 1 are those whose paths were within a radius of 300 km from the Okinawa Islands. Figure 1 also shows those typhoons that struck the mainland of Japan. Notably, the number of typhoons that hit the Okinawa Islands is significantly more than those that reached the mainland (Amano 1988), indicating that the southern islands are prone to more damage from typhoons. Table 1 shows the ranks of the typhoon intensity given by the Japan Meteorological Agency. The maximum velocity indicated in the table represents the maximum value of 10 minutes average velocity.

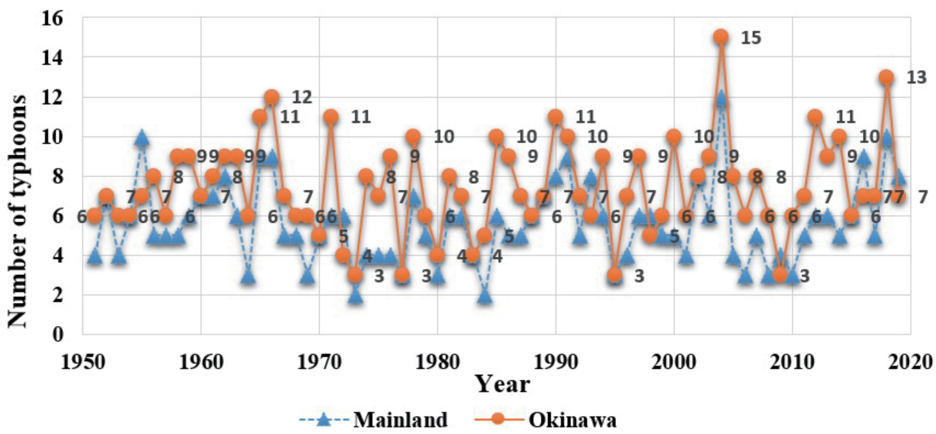


FIGURE 1. Record of typhoons

TABLE 1. Rank of typhoon according the maximum velocity

Maximum Velocity	Rank
Maximum Velocity < 33 m/sec	Typhoon
33 m/sec ≦ Maximum Velocity < 44 m/sec	Strong Typhoon
44 m/sec ≦ Maximum Velocity < 54 m/sec	Extremely Strong Typhoon
54 m/sec ≦ Maximum Velocity	Intense Typhoon

Degree of Damage by Typhoons

According to the resolution damage certification (Fureibo No. 518, June 28, 2001) by the Disaster Management Bureau of the Cabinet Office, damage caused to houses by strong winds is classified in five categories: a) total collapse, b) half collapse, c) partial damage, d) inundation above the floor level and e) inundation below the floor level. Details are shown in table 2 and figure 2.

TABLE 2. Definition of Damage

Classification	Definition
a) Total Collapse	The affected area of the house is greater than 70 % of the total floor area. It is not possible to restore it by repair work.
b) Half Collapse	The affected area is between 20% and 70 % of the total floor area. Through repair work, it is possible to restore its function.
c) Partial Damage	The house suffers only slight damage that can be repaired quickly. It is possible to use the house.
d) Inundation above the floor level	Water inundates the house above the floor level. Even though the damage cannot be considered as total or half damage, the dwellers temporarily cannot use the house.
e) Inundation bellow the floor level	Water inundates the house bellow the floor level. Although some repair becomes necessary, the dwellers can use the house.

(a) Total Collapse

(b) Half Collapse

(c) Partially Damages

(d) Inundation above the floor level

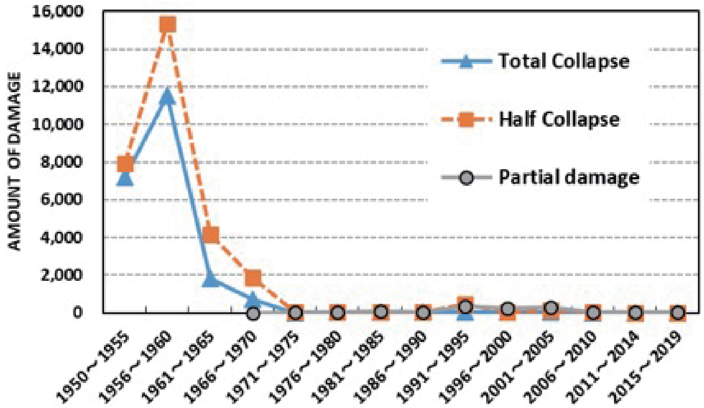
(e) Inundation under the floor level

FIGURE 2. Classification of Damage

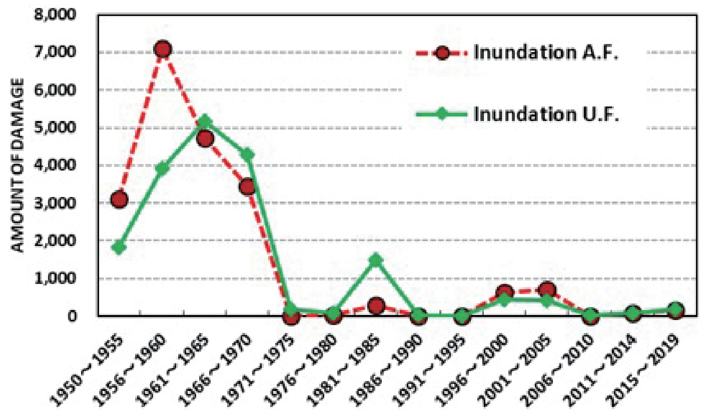
Amount of Damages by Year

This section looks at the trends in damage to houses caused by typhoons since 1950. The damage is grouped in five years intervals. Figure 3 shows the amount of structural damage and inundation. The number of damaged houses in terms of total damage and half damage peaked between 1956 and 1960, then decreased quickly after 1970, as shown in figure 3 (a) (Asato 2016).

The amount of damage caused by inundations shows a trend similar to that of structural damage, with a peak between 1950 and 1960, as shown in figure 3 (b). However, in the mid 1980s and between 2001 to 2005, there were many cases of inundation of houses due to heavy rainfall.



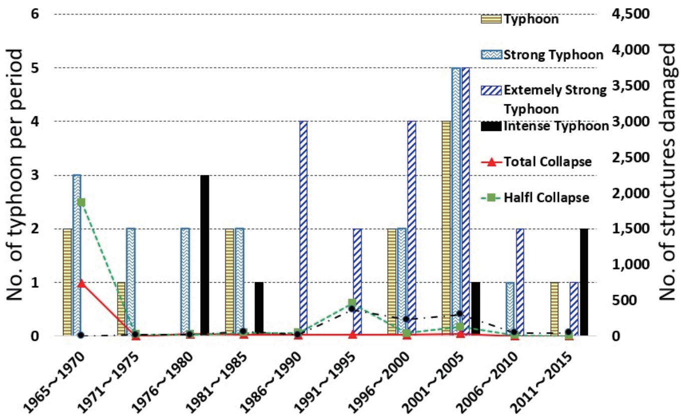
(a) Structural damage to houses



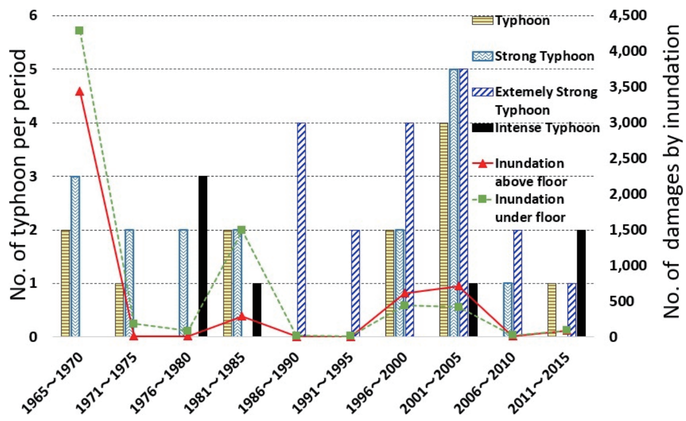
(b) Inundation of houses

FIGURE 3. Variation in damage by year

Figure 4 shows structural damage by wind and that caused by inundations between 1965 and 2015 for the Okinawa main island only. These figures also include the intensity of the typhoons according to the scale given in table 1. As shown in figure 4 (a), for the period between 1976 to 2015, even though there were events classified as "extremely strong typhoon" or "intense typhoons," the amount of structural damage was less compared with the period before 1970. This indicates an improvement in the structural resilience of houses, as will be explained in the latter part of this chapter. On the other hand, even though damage by inundation showed a conspicuous decrease after 1975, there were some periods such as 1991–1995 and 2000 – 2005, with cases of substantial inundation damage. This may indicate that Okinawan houses were still not resilient enough against typhoons that produced intense rainfall.



(a) Structural damage to houses



(b) Inundation of houses

FIGURE 4. Variation in damage by year and typhoon intensity

The amount of damage produced by typhoons is closely related to their translational velocity, or how fast they move from one point to another, and wind velocity. As shown in figure 5, the damage is concentrated in the region where the translational velocity of a typhoon is under 20 km/h and the wind speed is greater than 25 m/sec (Sunakawa 2019).

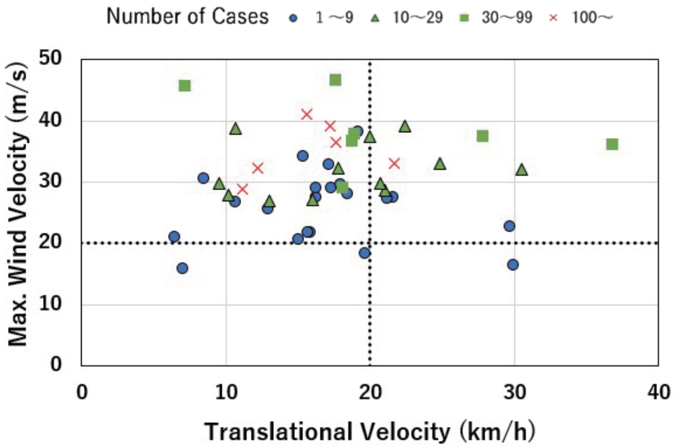


FIGURE 5. Damage distribution according to typhoon velocity and wind speed

Figure 6 shows the amount of reported damage related to typhoon translational velocity and rainfall. The house damage plotted in the figure is that associated only with inundation below the floor level. The results indicate that only a little house damage was reported when the amount of precipitation was under 200 mm, independent of the translational velocity. On the other hand, the damage increased when the translational velocity was under 20 km/h, and the precipitation was over 200 mm. When a typhoon moves slowly, it affects the region for a longer amount of time, creating a problem with water drainage (Sunakawa 2019).

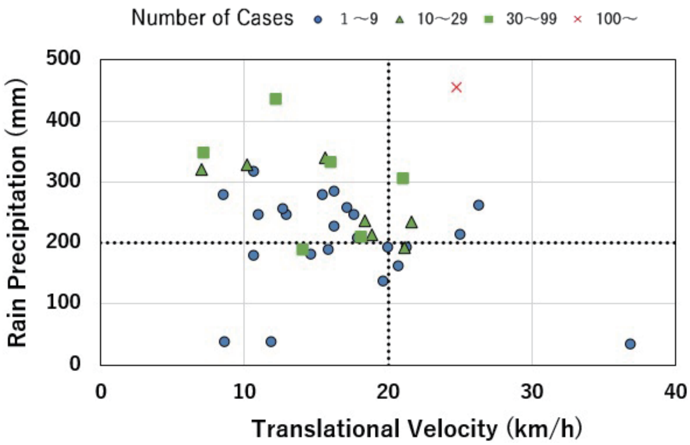


FIGURE 6. Inundation damage distribution according to typhoon velocity and rainfall

Review of Housing Materials and Construction Methods

This section explains changes in the materials and construction methods used for houses over the years. Both materials and construction methods have significantly evolved in the last 150 years. After the Meiji era (1868), due to Japanese industrialization, there was an expansion in the number of choices for new construction materials such as steel, cement, concrete, and concrete blocks. In addition, there were variations between local, domestic, and imported materials. The market situation and government policies influenced the selection of materials and construction methods over the years. The resilience of houses was affected not only by the materials used themselves but also by quality control of the materials, as will be explained in the following paragraphs.

From Late Nineteen Century to 1945

From the Meiji era to WWII, the conventional construction material used was wood. The traditional Okinawan house structure (kominka house) was composed of vertical (columns) and horizontal (beams) elements without foundations. Some of these traditional houses constructed during the Meiji and Taisho era still remain in good condition, as shown in figure 7. Traditional houses used thatched roofs until the late nineteenth century. Later, the roof material was gradually changed to red tile, as shown in figure 8. These changes in the roof material enhanced the resistance of the houses against strong winds due to their heavier weight. Before construction, local wood materials used in those traditional houses were placed in salt water to prevent insect damage (Chinen 2018).

FIGURE 7. Okinawan kominka house (Izena Island, constructed in 1906)

FIGURE 8. Red tile roof under repair

The joints of the structural elements of these traditional houses were made without using nails or any other metal connectors (see fig. 9). The carpenters carved the wood elements on construction sites to join them together, as shown in figure 10. Recent research showed that traditional houses could sustain wind forces with average wind velocities up to 40 m/sec as long as the wood materials did not have pronounced aging deterioration (Omi 2019). In other words, the traditional houses were strong enough to withstand strong wind forces.

FIGURE 9. Kominka house (Nago, 1906)

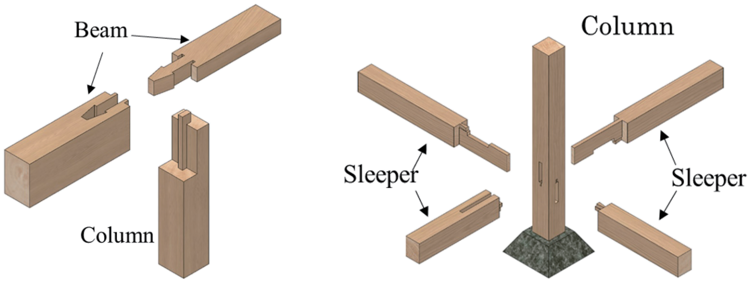


FIGURE 10. Number of houses constructed per year

From 1945 to 1950

As WWII ended, 90% of the houses in Okinawa were burned out. Therefore, housing supply was an urgent issue for the reconstruction in the Okinawa Islands.

Reconstruction started with the collaboration of the American forces, who provided construction materials such as wood for the structural elements and nails to build the houses.

By the end of 1949, 73,500 houses had been constructed. As shown in figure 11, the houses were very simple, with one room and a kitchen, with a total area of approximately 20 square meters (Fisch 1988; Kinjo 2019). These houses were called standardized houses.

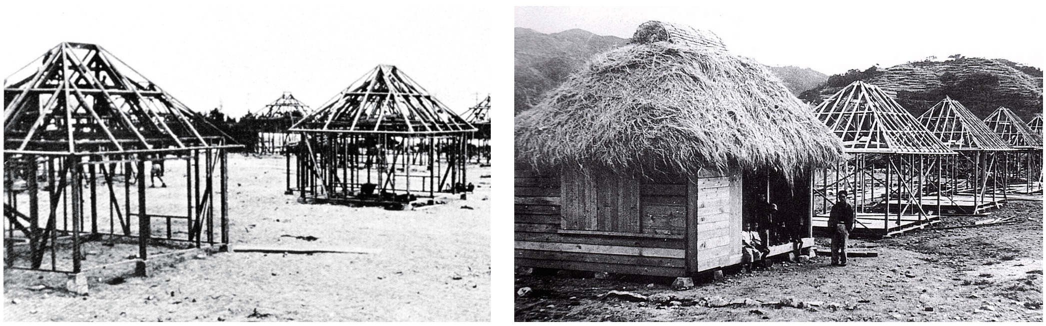


FIGURE 11. Construction of standardized houses

Standardized houses were built with wood materials of poor quality, which means the wood was not well dried. Therefore, these wood materials did not maintain enough strength against the strong wind forces created by typhoons. Similarly, according to documentation (Kinjo 2019), the number of nails provided for joining the structural elements was insufficient to sustain the house against typhoons. Also, termite attacks on the wood induced a severe deterioration of the structural elements.

The strong typhoons that struck the Okinawa Islands in the second part of the 1940s, such as Typhoon Libby (64 m/sec winds) in 1948 and Typhoon Gloria (78 m/sec winds) in 1949, destroyed almost half of the standardized houses constructed by that time (Fisch 1987). The main reason for the housing collapse was the lack of diagonal structural elements and no suitable connectors to resist the wind forces, as shown in figure 11.

From 1951 to 1970

In collaboration with local construction companies at the beginning of the 1950s, the American military forces started reconstructing their facilities with reinforced concrete and concrete block structures to counter the strong wind forces.

By the 1960s, materials for reinforced concrete houses began being produced in Okinawa Prefecture. A cement factory, concrete aggregate plants, and ready-mix concrete plants were established to provide service to the developing construction industry. This local production industry resulted in lower costs for the reinforced concrete construction of houses. In addition, the Ryukyu government implemented a housing policy that gave preferential treatment to house owners who selected reinforced concrete structures instead of wooden structures in those years. Also, the cost of the wooden houses increased because of a lack of material supplies in the Okinawa Islands.

As shown in figure 12, wooden houses continued to be the most commonly constructed until 1957, in accordance with the traditional Okinawan house style (Tamaki 2014a). However, as construction costs became lower due to the local availability of concrete materials, reinforced concrete structures became popular. As a result, the number of newly constructed wooden houses decreased, and by 1962, reinforced concrete houses became the most common type in Okinawa.

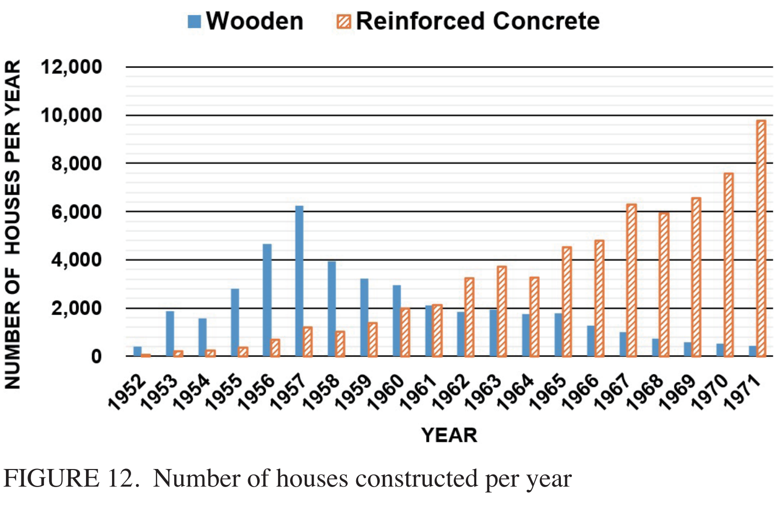


FIGURE 12. Number of houses constructed per year

The incremental increase in reinforced concrete houses is directly related to the decrease in damage to houses caused by typhoons because reinforced concrete structures provide a solid continuity between the houses' structural elements. That then makes a house more resistant to the horizontal forces induced by strong winds.

On the contrary, wooden structures mainly rely on the joints between beams and columns. Without proper joint connectors to assure the appropriate force transference between structural elements, the standardized houses mentioned above were not strong enough to resist the wind forces of typhoons.

After the 1950s, marine sand was used as a coarse aggregate to produce concrete. The chloride contents of the concrete mix caused gradual corrosion of the reinforcing bars, which caused cracks in the concrete. As a result, concrete spalling became conspicuous. Eventually, the poor quality of concrete used in the 1950s appeared to become a social problem (Gushi 1973).

A lack of appropriate natural resources and facilities led to the use of marine sand. In many cases, the concrete was mixed at the construction site with poor control over the water-cement ratio. For instance, at a construction site, water was added to enhance the workability of the concrete. The addition of water to the concrete decreased the concrete strength and durability (see fig. 13).

FIGURE 13. Concrete deterioration due to salt content

From 1971 to 1981

This period coincided with the restoration of the Okinawa Islands to the Japanese government. Concrete specialists from mainland Japan came to Okinawa to enhance the quality control of ready-mix concrete production. However, according to Oshiro (2010), with the redevelopment of the Okinawa Islands after restoration to Japan, several governmental housing projects were carried out at the same time, producing a shortage of materials, especially washed marine sand. Even though in that period the salt content of sand was eventually restricted by JIS A 5308 (Japan Industrial Standard Handbook) and the Japanese Ministry of Construction to less than 0.04% in weight proportion, the salt content of concrete sand was as high as 0.14% in Okinawa during this time. Many houses, as shown in figure 13, constructed of concrete with a high salt content still remain in Okinawa islands. These structures have not collapsed due to typhoons, but the deteriorated concrete may peel off, producing so-called partial damage to the structure.

From 1981 to 1999

In 1981, a new building standard regulation was established in Japan. The regulation provided new calculations for seismic design loads with new seismic zone values. The seismic design loads increased; therefore, new buildings became more robust than those previously constructed. During that period, piloti-type reinforced concrete structures became stronger against earthquakes because the new standard regulations became stricter regarding the design of columns, changing the size of the columns and the amount of minimum reinforcement.

In the 1995 Great Hanshin earthquake, known as the Kobe earthquake, most of the reinforced concrete buildings in Osaka and Kobe that collapsed were constructed before 1981. That is, the buildings constructed after 1981 behaved well against the earthquakes. On the other hand, wooden houses built after 1981 collapsed due to a lack of structural elements. In summary, the new building standard regulations in 1981 were sufficient for reinforced concrete structures but not for wooden structures.

Although the number of new wooden houses continued to be small compared to reinforced concrete houses, wooden house builders entered the Okinawan housing market, making the start of a new era as the cost of reinforced concrete houses increased.

From 2000 to 2020

As a result of the collapse of wooden houses in 1995 in the Kobe and Osaka area, the regulations for the structural design of wooden houses were changed in 2000, increasing the ratio of wall thickness to floor area. Also, the regulations enhanced the strength of structural elements through the use of steel connectors. These new regulations promoted a stronger resistance of wooden houses against earthquakes and strong winds.

In addition, the Japanese government established the "Act on Promotion of Use of Wood in Public Buildings" in 2010, subsidizing wooden houses and increasing the popularity of wooden structures.

Based on the new concepts for the structural design of wooden houses and promotion of subsidies, by the year 2010, local construction builders started promoting wooden houses, beginning that year with 3% of the total new houses constructed and reaching 40% in 2020, as shown in figure 14.

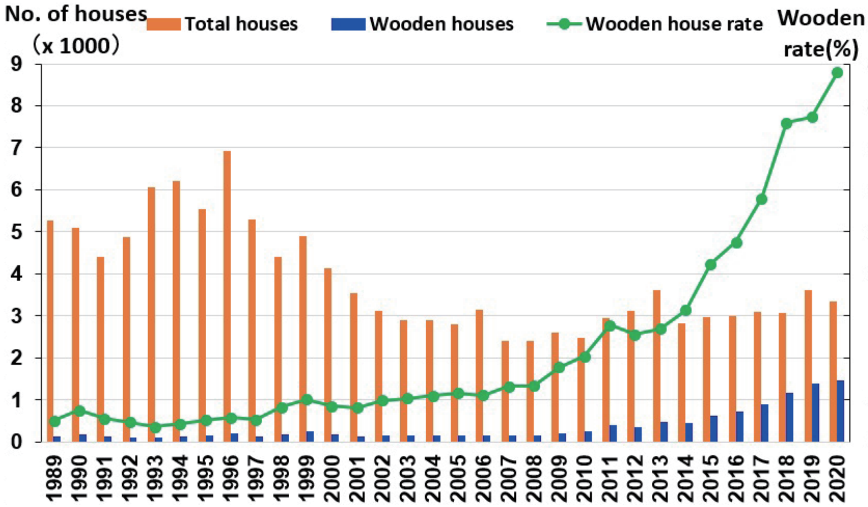


FIGURE 14. Number of houses constructed per year after 1989

The Resilience of Okinawan Houses

As discussed in previous sections, the amount of damage caused by typhoons decreased after 1970, as shown in figure 3. The reason for the decrease can be addressed in terms of reinforced concrete and wooden structures, respectively.

Reinforced Concrete Houses

The decrease in the amount of damage is directly related to the increase in the number of reinforced concrete houses after 1960 because they are less affected by wind forces. Even though there are no reports of the collapse of any of this type of house, there was some partial damage related to the deterioration of the concrete.

From the material deterioration viewpoint, reinforced concrete houses can be divided into two categories; those houses constructed before 1971 using unwashed marine sand, and those constructed after that year with the new regulations for concrete materials to control the salt content of marine sand, as explained above. High salt content in concrete materials produces corrosion of the steel reinforcing bars, which leads to extensive cracking of the concrete structural elements, which then chip off due to typhoons' wind action. Even though such damage does not affect the structure enough to produce its immediate collapse, it is partial damage and affects the function of the buildings and could threaten people using them. Nowadays, the salt content of concrete is being strictly controlled during the construction process. However, recent research indicates that airborne chloride ions transported by marine winds affect concrete houses located in coastal zones (Sakihara et al. 2016). Airborne chloride ion penetration into concrete produces corrosion of the steel bars, which affects the resilience of concrete houses in the long term.

Moreover, in the Okinawa Islands, there is a significant percentage of buildings that were constructed before 1981 with little consideration of the seismic loads, and although can be considered resilient enough against typhoons, they might not be strong enough against seismic actions.

Wooden Houses

In Okinawa, the majority of people believe that wooden houses are weak against typhoons. Therefore, most of them prefer to live in reinforced concrete houses because they are safe against wind forces. However, this is not necessarily true from an engineering viewpoint.

Closely examining the damage caused by typhoons, wooden houses are divided into three types according to their construction period and style. The first category corresponds to traditional houses mainly constructed before WWII. The second category refers to the reconstruction period after the war. Third are those houses commonly seen in mainland Japan.

In Okinawa, many traditional houses in the first category have remained strong for over 100 years. Through the years, they have survived intensive typhoons. This means that these houses that do not use any nails or steel connectors can be strong enough against typhoons when the structural elements are well joined and without deterioration caused by insects.

The second category consists of the standardized houses constructed as temporary houses to meet the housing shortage immediately after WWII. These houses had two fatal problems. The first problem pertains to the poor quality of materials used for construction. Reportedly, they were not well dried, causing permanent deformations of the structural elements when weight loads were applied. Also, that created a perfect environment for the dissemination of termites.

The second problem is the poor structural design of these standardized houses. The lack of well-designed connections between the structural elements, with fewer diagonal elements to sustain typhoons' horizontal forces, led to their collapse. Moreover, these standardized houses were provided with a light thatched roof that was more easily blown off than the red tile roofing used in traditional houses.

The third category of wooden houses refers to the wooden frame type commonly seen in mainland Japan, not the traditional Okinawan houses. The number of these types of houses constructed per year in Okinawa started to increase steadily from 2000, reaching 40% of the total newly built houses by 2020. So far, there are no reports that these houses have sustained structural damage due to typhoons. This can be explained by the materials, structural calculations, and steel connectors between structural elements. First, the wooden materials receive anti-insect treatment to protect them against termites, and they are well dried before construction; thus, wooden material deterioration has been controlled. Second, according to the new structural regulations established in 2000 described above, the ratio of wall thickness to floor area was increased, making them more robust against the horizontal forces induced by earthquakes, and as a result, of typhoons as well.

The structural calculations of these wooden-frame type houses are designed to resist wind velocities up to 46 m/sec, which is the reference wind velocity assigned to the Okinawa Islands by the building standard law (Hasegawa 2013). Unlike the traditional houses and the standardized houses, there is no reported damage for these types of wooden-frame houses. Third, the development of new steel connectors for structural joints makes them strong enough for strong winds (see fig. 15). These steel connectors join the structural elements in both horizontal and vertical directions, increasing the structures' stiffness.

FIGURE 15. Steel connectors in wooden houses

Conclusion

This paper discusses the effect of typhoons on Okinawan houses over the last 70 years. The types and degree of house damage have been changed by changes in the construction materials over the years.

Most of the standardized wooden houses built after WWII had collapsed by 1960 due to the poor quality of the materials and deficient structural joints. This widely spread a negative image of wooden houses in Okinawa for a long time. At the same time, the number of reinforced concrete houses increased in Okinawa while the number of damaged houses decreased because they were more robust against strong winds than the wooden houses. However, the use of marine sand caused deterioration of the concrete structures leading to partial damage, which may be very dangerous for inhabitants.

After 2000, the structural performance of wooden-frame houses against earthquakes was improved by new regulations to become more robust against typhoons. The essential factors for sustainability and resilience against typhoons are not the type of house such as reinforced concrete or wooden houses, but rather the quality of the structural materials, their pre-treatment, structural calculations, steel connectors when necessary and integrated maintenance.

Structural materials were seen to be the primary factor in determining the degree of damage to houses. With the application of new technologies for material conservation and techniques to improve structural resistance against typhoons, it became possible to enhance the resilience of Okinawan housing.

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