



1. Introduction

There are many historical wooden buildings in Japan, from Horyuji temple built about 1,300 years ago to the ones built in the modern era. These buildings are an extremely valuable heritage that, even now, convey the superior skills of the Japanese predecessors and form beautiful city landscape. In recent years, the number of tourists coming to Japan has been increasing year by year, and these buildings contribute to communicate the wonderful Japanese culture to people all over the world. It is very important to continue to carry such high value buildings to the future. Yet, Japan is also known for its frequent occurrence of severe natural disasters. Earthquakes in particular have damaged countless historical wooden buildings many times in the past. As a facility meant to be visited by many local people and people coming from abroad, it is necessary to avoid building collapse and loss of human life at the time of an earthquake. Out of the seismic diagnosis of historical wooden buildings performed by the author, so far only a few of them retained sufficient seismic capacity to withstand the current expected earthquake intensity (Fig.1). However, it does not mean earthquake resistance capacity was not considered at all for these buildings. Each building was devised to withstand earthquakes and other severe natural phenomena using all the technology available at the time. It simply means that the demand level at the time, differs from the currently required level. Because of the lack of seismic capacity, it is necessary to improve the building performance by performing seismic retrofit. However, as declared in the Venetian Charter adopted by ICOMOS, the seismic reinforcement for buildings of high cultural value must be performed under the consideration not to modify existing parts of the building as much as possible to keep its authenticity. The following chapter, shows how to ensure necessary earthquake resistance while maintaining cultural value.

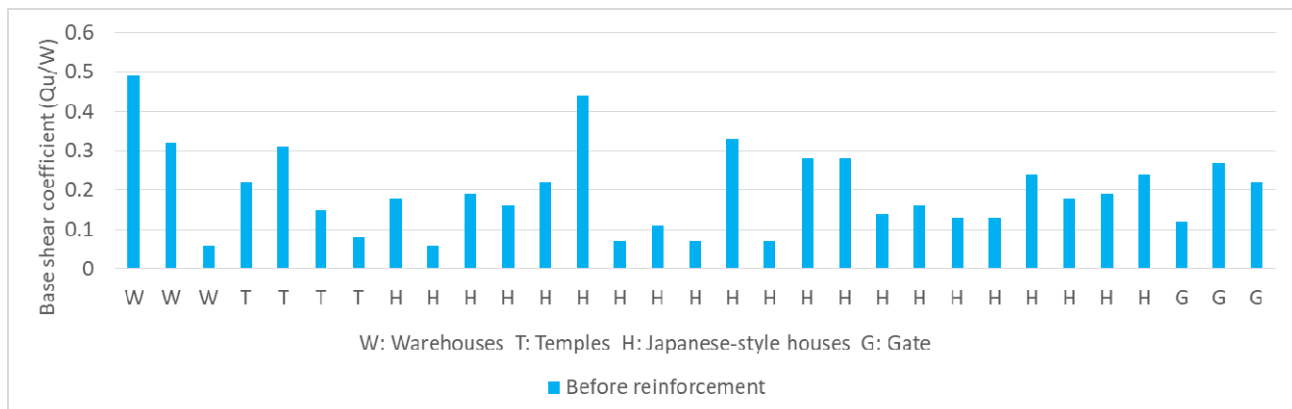


Fig.1-Examples of seismic capacity of Japanese historical wooden building

2. Seismic issues and reinforcement method

2.1 Seismic issues

The historical wooden buildings which the author of this paper has so far been in charge of retrofitting, include; temples, shrines, old Japanese-style houses (Minka), warehouses and gates. They each have various kinds of characteristics, but there are common seismic issues that can be pointed out. They can be largely summarized into the following five points.

- Lack of ultimate lateral capacity
- Breakage of pillars
- Disengagement of connections
- Pull out of the pillar leg
- Lack of horizontal stiffness

The subsequent chapter introduces these problems and reinforcement methods for their improvement.



2.2 Lack of ultimate lateral capacity

A common feature in Japanese traditional wooden buildings is their openness (Fig.2). Consequences of this, the number of walls that will be part of the earthquake resistant system is quite less, leading the seismic assessment to conclude that the seismic capacity of the building is insufficient. Furthermore, the connections between pillars and nuki (penetrating beams) or other beams contribute to the earthquake resistance performance, but unless the connection is between large elements, fulfill the lateral capacity demand with only these joints is of extreme difficulty.

Then, in order to compensate for the lack of ultimate lateral capacity, Existing walls are replaced with high capacity elements, and other earthquake resistant elements are newly installed.

2.2.1 Structural Plywood

Structural plywood is a very common material also used in modern wooden buildings. It is used to increase the lateral strength by using it as replacement for walls with low earthquake resistant properties such as earthen walls or lath and plaster walls. It is often used as a shin-kabe (wall with exposed timber pillars) because it does not greatly impair the appearance after replacement. At this time, it is required to leave the existing nuki as long as it is possible, so it is necessary to pay attention to the installation of backing material which is receiving structural plywood (Fig.3).



Fig.2-Openness of Japanese historical wooden buildings, Fig.3-Installation of backing material

2.2.2 Lattice Wall

Lattice walls consist of many members connected through halving joint, each joint resists as the contact surface sinks during an earthquake. Although the initial rigidity is low, its toughness is extremely high, and the softening of its maximum shear strength when subject to repeated load is low, so its reliability as an earthquake resistant element is high (Fig.4-1)[1,2]. As a design aspect, the vertically and horizontally composed shape is easy to harmonize with traditional buildings, and since light and wind can pass through, it has been used in practical cases for seismic retrofitting (Fig.4-2).

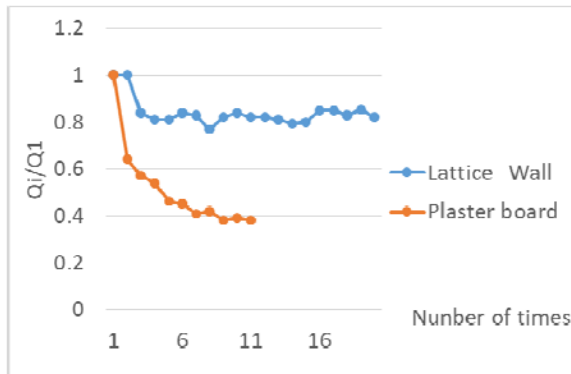


Fig.4-1- Degrading of maximum shear strength, Fig.4-2-Example of lattice wall

2.2.3 Wood lath

Wood lath is a material meant to accommodate plaster, it has around 30mm width and it is nailed 9mm apart each other. Lath installed horizontally or vertically are common, but improvement of strength can be expected by installing it in an oblique pattern. In addition, placing the planks in a densely manner, makes it easier for the plaster to peel off, which was also confirmed by the damage of the Kumamoto earthquake in 2016 (Fig.5).

2.2.4 Earthen Wall

According to Implementation Guidance for Basic Seismic Assessment of Important Cultural Properties (Buildings) [3], the ultimate strength of the earthen walls improves in proportion to its thickness, so it may be considered to increase the thickness as an earthquake resistant reinforcement, but as the weight also increases at the same time, efficiency is not so high. In addition, when the earthen wall is Oo-kabe (wall with no exposed pillars), the surroundings are not restrained by frames, leading to its performance not being the same as one confined by frames (shin-kabe portion). Furthermore, the Oo-kabe part easily peels off at the time of the earthquake if backing material of the wall is not constituted properly (Fig.6).



Fig.5-Plaster wall that is peeled off, Fig.6-Earthen wall that is peeled off

2.2.5 Knee brace

The earthquake resistant system is made by placing a knee brace on the pillar-beam corner and, by doing so, a rigid frame is formed (Fig.7). If the knee brace is placed directly in between the pillar and the beam, there is a possibility that the stiffness becomes too high and the balance with other parts becomes inappropriate. However, by placing the knee brace on the side surface of the pillar or beam and fixing it through bolts, the stiffness of the system can be adjusted. However, it is necessary to set the dimension of the



member so that the wood does not split-break before the bolt yields. In Fig.7, this type of frame is not only assuring seismic performance but also has the role of supporting the second floor where there was a large deflection. Furthermore, since the existing beam was not straight, a tenon was installed at the top and bottom of the packing material and it was inserted into both the existing beam and the new frame, achieving transmission of the shear force from the existing frame to the new frame at the time of the earthquake.

2.2.6 Steel frame

Steel frame is useful when high earthquake resistant seismic elements are required at extremely limited places. In the case of Fig.8-1, the vertical wall is made of a thin steel plate, and the rigidity and strength are adjusted by the length of the plates. In this case, a large pull-out force is generated at the bottom of the pillar, but its rising is prevented by the weight of the partial foundation (Fig.8-2). This foundation was needed to be minimised because this site was nominated as historic site and it is severely restricted to modify.



Fig.7-Rigid frame that is consisted of knee brace



Fig.8-1- Installation of steel frame, Fig.8-2- Partial foundation

2.2.7 Buttress

If it is difficult to install a reinforcing wall in the internal space, but there is a method of securing seismic performance by providing a buttress on the external side of the building (Fig.9). Although a space margin is required between the building and the site boundary, even if existing buildings cannot be disassembled, they can be installed and high strength can be expected.

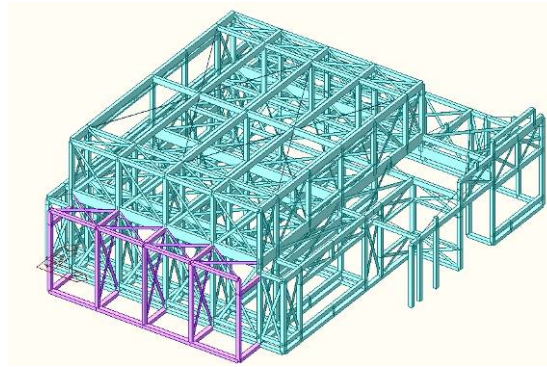


Fig.9-Analysis model of butress

2.3 Breakage of pillars

Pillars with over-hanging walls can be considered horizontal elements for seismic resistance. If the pillar has sufficient cross-section area and the ultimate bending strength of the pillar is larger than that shear yield strength of the hanging wall, the wall yields first when subject to big deformations. On the contrary, if the pillar is small, the pillar may break before the yield of the wall. If the pillar breaks, the seismic resistance of that section will be suddenly lost, as well as the capacity to support the vertical load may be lost, and, in the worst case, partial collapse may occur. Therefore, it is necessary to carefully verify the breakage of the pillars, apart from judging whether the overall seismic performance satisfies the criteria or not. The following items describe how to prevent breakage of pillars or how to deal with breakage.

2.3.1 Weakening the Hanging Walls

In some cases, weakening of the wall may be effective as to prevent the breakage of the pillars. As a method of weakening, changing the material of that over-hanging wall to a weaker specification or deliberately not to allow the beam to reach the above the ceiling, in order to lose the effect of restriction on the pillars (Fig.10).



Fig.10-Lath wall that is not reached to the beam

2.3.2 Reinforcement of Pillars

It is also effective to strengthen the pillar instead of weakening the over-hanging wall. For example, increasing the cross-sectional performance of the pillar by bonding carbon fiber [4]. In this case, a thin layer of timber is removed from the pillar and it is used to cover the reinforcement, after the carbon fiber has been added, because it is undesirable for the appearance of the carbon fibers to be seen. An experiment was conducted in order to confirm the reinforcement effect on 120mm section pillars by single point loading test (Fig.11).



2.3.3 Attached additional pillar

Placing and fixing an additional pillar along an existing one that is likely to break will guarantee that the vertical load supporting capacity is maintained. However, special attention should be given at the time of installation, as the transverse members (nageshi: non-penetrating tie, kamo: rail of sliding door) will be an obstacle when attaching it to an existing pillar (Fig.12).



Fig.11- Specimens of reinforced columns, Fig.12-Attached additional pillar

2.3.4 Pillar restraint on both sides

The stress diagram of a pillar with hanging wall when subject to the horizontal force is as shown in Fig.13. On the other hand, consider the case where an additional partial wall is attached to the bottom of the pillar. In both cases, the magnitude M_u (ultimate bending moment) at which the pillar breaks is the same, but the magnitude of the shear force acting becomes 3.3 times less. If Q_{wy} (shear yield strength of the wall) is $Q_{u1} < Q_{wy} < Q_{u2}$, restraining both ends of the pillar by reinforcing the walls makes it possible to yield the walls before breakage of the column occurs.

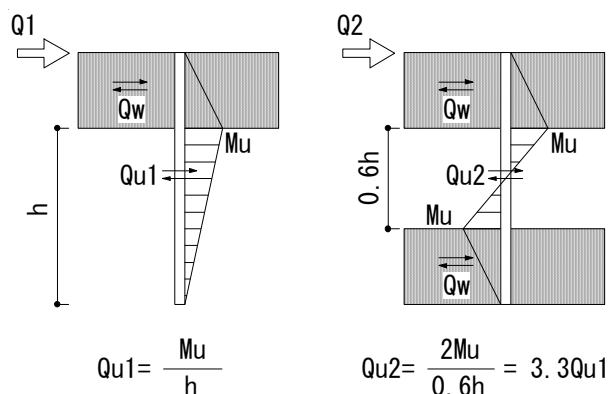


Fig.13- (left) Pillars with hanging wall, (right) Pillar restraint on both sides

2.4 Disengagement of connections

Seismic diagnosis is based on the premise that connectors and joints are not pulled out so that the forces can be transmitted. If this premise does not hold true, unexpected destruction may occur. For example, as shown



in Fig.14, when the connector pulls out, even if the building as a whole maintains sufficient seismic capacity, the earthquake will cause serious damage. It is difficult to judge the adequacy of the joint only from the appearance, but the existence of a wood pin or wedge should be checked (Fig.15), and if necessary, reinforce with a metal object.

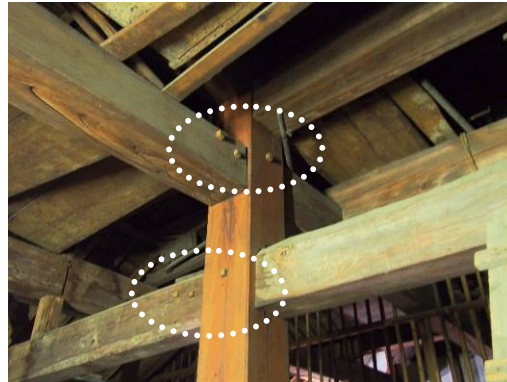


Fig.14-Disengagement of connections, Fig.15- Pin and wedge of connections

2.5 Pull out of pillar leg

When the shear walls are resisting the horizontal force, pulling-out force is generated in the pillar on one of the corners. If the pillar is pulled out before the shear wall reaches the ultimate strength, the wall cannot reach the expected capacity (Fig.16). Therefore, measures to prevent pull out of the pillar are required. In a general wooden construction work, pillars are tightened by using a metal plate with bolts anchored to the foundation. However, since in Japanese traditional wooden buildings the pillars are mostly just placed on top of the stone foundation, it is impossible to prevent them to be pulled out. In that case, design method that reduces the allowable shear strength of the shear wall by allowing the pillar to be pulled out should be adopted. On the other hand, instead of allowing pull out of the pillars, installing a steel beam under the floor to resist the pulling-out force of the pillar through its flexural strength is also possible. At this time, since a large reaction force acts on the position that will become the support of the steel beam, it is necessary to properly fix it so that splitting of the bolts does not occur at the pillar-steel beam section (Fig.17).

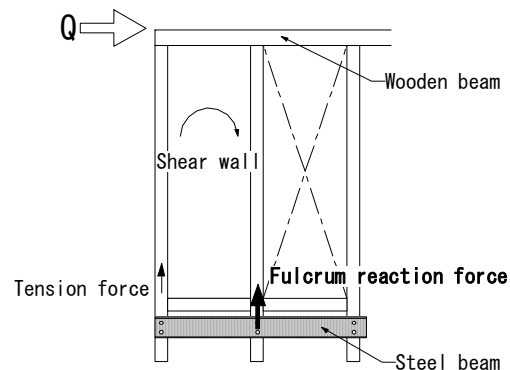


Fig.16- Pull out of pillar leg, Fig.17-Installation of steel beam

2.6 Lack of stiffness of horizontal plane

Generally speaking, structural analysis of buildings, is done under the assumption that a rigid diaphragm is



established, but the horizontal plane, such as the floor and the roof of the historical wooden buildings, in most cases, lacks enough stiffness. In this case, the diaphragm can be reinforced so that the assumption holds true. On the other hand, the calculation can be done on the diaphragm as it is as long as proper precautions are taken into consideration.

2.6.1 Reinforcement for the rigid diaphragm Assumption to be achieved

The first method is to reinforce the floor and the roof so that the rigid diaphragm assumption is accomplished. Methods to improve rigidity by nailing the floorboards obliquely (Fig.18), or reinforcement with steel bar brace (Fig.19). When strengthening the horizontal plane and bearing a large shear force, a large axial force acts on the boundary member. Therefore if there is a joint on the tension side, reinforcing with a metal plate becomes necessary (Fig.20).



Fig.18- Floorboards nailed obliquely, Fig.19- Steel bar brace for horizontal plane

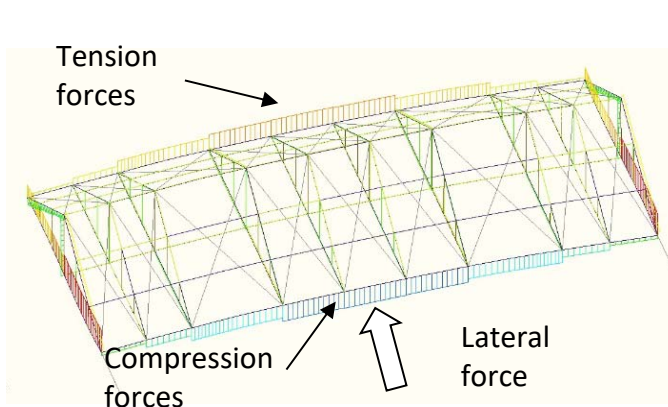


Fig.20- Analysis model of horizontal plane, Fig.21- joint of girder

3. Conclusions

This paper showed that the seismic issue can be summarized into five points and it is necessary to install the reinforcement for them. The results of applying the reinforcement described above to the building indicated by Figure 1 are shown on Fig.22. It was confirmed that the seismic performance is effectively improved by these reinforcements.

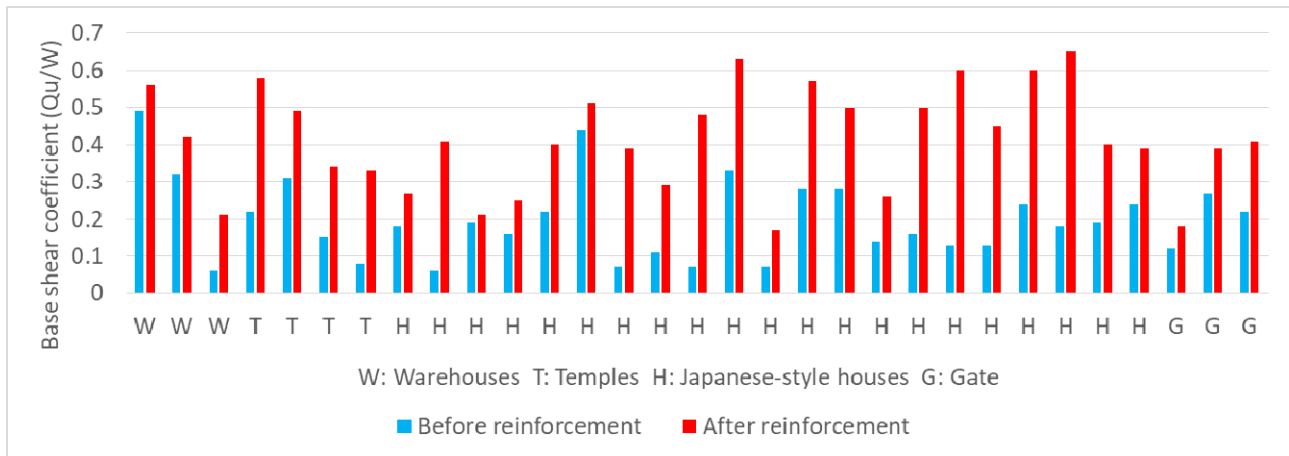


Fig.22-Results of reinforcement

4. References

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