DEVELOPMENT OF EARTHQUAKE COUNTERMEASURES ON HERITAGE BUILDINGS IN JAPAN

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This paper shows an overview of recent development of earthquake countermeasures on Japanese heritage buildings, which are mostly wooden buildings, and the paper also introduces its past history in order to provide the background.

Fig. 1 - Collapse of Shariden of Enkaku-ji. (Source: Special report on the survey and restoration of Enkakuji Shariden: National Treasure).

Recently, big earthquakes occurred frequently not only in Italy, but also various earthquake-prone countries, and these earthquakes brought serious damage to heritage. Therefore, it is one of the recent biggest problems for heritage conservation how to protect heritage from earthquake damage.
The writer had been engaged in earthquake countermeasures on heritage buildings as a specialist of Agency for Cultural Affairs in the Japanese government from 2011 to 2016. Japan is one of the most earthquake-prone countries in the world. A lot of heritage buildings have been damaged in recent big earthquakes, while earthquake countermeasures on heritage buildings have been developed. Knowing the situation of Japan must be useful in considering the above problem.

PAST HISTORY OF EARTHQUAKE DAMAGE

Japanese heritage buildings have high possibility to have experienced earthquake damage in the past, because these buildings have remained for a long time in the earthquake-prone country. Various records including old documents and traces remaining in buildings show past earthquake damage. For example, a big earthquake struck western Japan in 1596. *Kodo* (lecture hall for Buddhist monks) of *To-ji* (Buddhist temple) in Kyoto totally collapsed and re-erected using original wooden parts. Some traces of damage and repair at that time still remain at the top and bottom of its inner columns. *Higashidaimon* (great east gate) of the same temple was also damaged and largely repaired with replacement of two columns and some parts of roof structure. The investigation in a recent restoration revealed that the gate was structurally modified with changing diagonal braces to horizontal beams penetrating columns at that time. Some traces of the modification were found on the columns.
Nagatoko (pavilion for worship) of *Kumano-jinja* (Shinto shrine) collapsed due to an earthquake in 1611, and its scale was reduced in re-erecting in order to re-use damaged parts.
Toto (three-storied east pagoda) of *Yakushi-ji* (Buddhist temple) was damaged by an earthquake in 1854, and its upper part was inclined. Two years later, the tilted pagoda was pulled upright with ropes, and damaged its spire and center column were repaired.
Earthquake damage in the modern times can be known more concretely by referring to some written reports and photos. In 1911, the Great Kanto Earthquake hit the Kanto area, which includes Tokyo and nearby area. *Shariden* (reliquary hall) of *Enkaku-ji* (Buddhist temple) collapsed, and the roof landed with keeping its shape (Fig.1). A lot of heritage buildings in nearby temples and shrines including *Kencho-ji* (Buddhist temple) and *Tsurugaoka-hachimangu* (Shinto shrine) were also severely damaged.
Tenshu (keep) of *Maruoka* castle totally collapsed due to destruction of its stone base in an earthquake in 1948. After that, the stone base was re-piled up with installation of reinforced concrete frame into it, and the keep was re-erected on it.
As above examples, a lot of heritage buildings have been damaged, sometimes collapsed, in an earthquake and have been repaired, after that.

PAST HISTORY OF EARTHQUAKE COUNTERMEASURES

These records also show past countermeasures, which were performed after an earthquake.
The former building of *Kodo* of *To-ji* mentioned above was added some reinforcing horizontal beams after earthquakes in 1362.

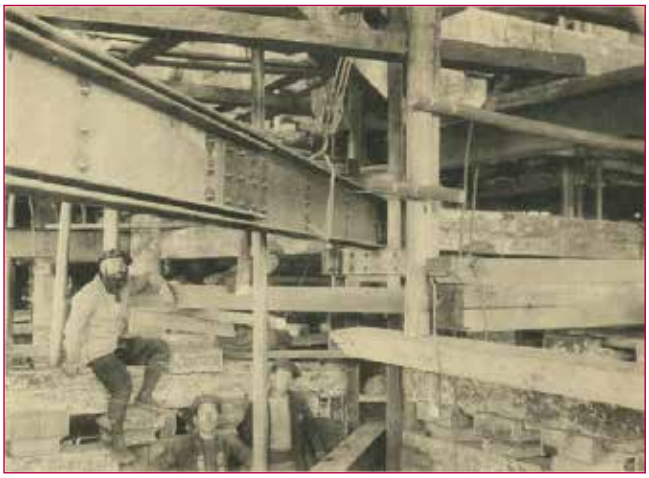

Fig. 2 - Reinforcement of Nandaimon of Todai-ji (Source: Report on the restoration of Todaiji Nandaimon: National Treasure).

After the earthquake in 1596 as mentioned above, it was ordered that some buildings were re-built without using roof tiles in order to avoid earthquake damage due to top heavy. Some oars of *Hirosaki* castle was reinforced with wooden diagonal braces, which still remain in the oars, after an earthquake in 1766.
Soon the beginning of the legal protection of cultural property by Japanese government in 1897, some heritage buildings in Nara started to be repaired with large-scale reinforcement.
For example, *Kondo* (main hall) of *Toshodai-ji* (Buddhist temple) was repaired from 1898 to 1900. Then its traditional-style roof frame was totally changed to a European-style truss frame in order to modify the roof structure.
Daibutsuden (hall for Great Buddha) of *Todai-ji* (Buddhist temple) was repaired from 1903 to 1913. In this repair, a steel truss frame was put above its ceiling, steel bars were attached on side of brackets supporting eaves, and L-shaped steels were inserted in columns. The steel parts were imported from Britain.
Nandaimon (great south gate) of the same temple was repaired in 1929. Then H-shaped steels were installed in some beams with these beams split in half (Fig.2).
Though these reinforcements were mainly intended to support heavy weight of a roof and prevent its deformation, it should be noted that some heritage buildings in this area were damaged due to the earthquake in 1854 mentioned above and an earthquake in 1891 causing catastrophic damage in central Japan.
In 1934, a large-scale restoration project of *Horyu-ji* (Buddhist temple) was started. 22 heritage buildings, including *Kondo* (main hall) and *Gojunoto* (five-storied pagoda), were repaired in this project. The repair of *Gojunoto* was from 1942 to 1952, and that of *Kondo* was from 1949 to 1954.
Before the repair of *Kondo*, a study on its earthquake resistance was conducted because its invaluable interior mural paintings must not be damaged due to deformation of the building in an earthquake. Professor Shizuo Ban, who had made notable achievement in advanced field of civil engineering and was also engaged in some restoration projects of heritage buildings as an expert on reinforcement, performed many experiments on structural elements of the building and conducted a numerical analysis based on these experimental results. He concluded that *Kondo* would not collapse in a big earthquake but would deform largely, damaging its mural paintings. After that, unfortunately these paintings were severely damaged due to a fire accident during the repair period and were replaced to a conservation facility. Therefore, reinforcement as an earthquake countermeasure became unnecessary and only reinforcement of its roof structure was conducted.
In the repair of *Gojunoto*, it was discussed how to reinforce its roof structure, which has deep overhanging eaves. The eaves had sunk and were supported by unsightly poles. The first suggestion of reinforcement was the same way with *Nandaimon* of *Todai-ji* mentioned above: splitting original beams and installing H-shaped steels. But this suggestion was rejected because of intrusive intervention to original beams. Finally, the roof structure was reinforced with steel plates and rods pulling up the eaves in the roof structure. This way gave minimum intervention to original parts and structural system, and this also made it possible to maintain, replace, if necessary, remove the reinforcing parts in the future.
As described above, before the modern times, countermeasures mitigating earthquake damage had been performed based on experience, and in the early modern times, advanced technology started to be used for reinforcement, and the view and method of reinforcement had been developed through some projects.

Fig. 3 - Collapse of the building No. 15 of the former settlement in Kobe (Source: Report on the restoration of No.15 building in the former settlement og Kobe: Important Cultural Property).

RECENT EARTHQUAKE DAMAGE

In 1995, the Great Hanshin-Awaji Earthquake struck Kansai Area, which is in western Japan and abounds in heritage. A lot of heritage buildings, including 116 Important Cultural Property buildings, were damaged and collapsed.
The No.15 building in the former foreign settlement of Kobe, which was used as a restaurant at that time, totally collapsed (Fig.3). Because the earthquake occurred in early morning, there were no deaths from the collapse. But if it had occurred in daytime, some users would have lost their lives. Necessity of earthquake countermeasures on heritage buildings was strongly re-recognized. This building was repaired in about 3 years, and a base isolation device was installed.
In 2011, the Great East Japan Earthquake brought a catastrophe to a wide area of Eastern Japan. Not only strong

Fig. 4 - Collapse of the shop building of Otokoyama (Source: staff of the Agency for Cultural Affairs).

Fig. 5 - Collapse of Kumamoto castle (Source: staff of the Agency for Cultural Affairs).

quakes, but also a big tsunami struck heritage buildings. The number of damaged heritage buildings, including 116 Important Cultural Property buildings and 438 Registered Cultural Property buildings, became considerable.
The shop building of *Otokoyama* (Japanese Sake brewery), which had three stories before the earthquake, lost its lower 2 stories due to a crash of a fishing boat swept away by the tsunami (Fig.4). This building is remaining in a state applied emergency treatment.
The old winery facility of *Chateau Kamiya*, consisting of five heritage brick buildings, was damaged by the quakes, and a lot of cracks were generated on walls. These buildings were repaired with reinforcement over 5 years.
In 2016, big earthquakes occurred in succession in Kyushu Area, which is in southern Japan. This 2016 Kumamoto Earthquake brought severe damage to a lot of heritage buildings including 39 Important Cultural Property buildings and 67 Registered Cultural Property buildings.
Kumamoto castle, which is an important symbol for local people, was severely damaged. A lot of stone bases crumbled, and some buildings on these felt down and collapsed (Fig.5).
Some heritage brick buildings in Kumamoto University were also severely damaged, a lot of cracks were generated on walls, and a lot of chimneys fell down (Fig.6).
Unfortunately, these heritage buildings of Kumamoto castle and Kumamoto University had earthquake damage in the middle of earthquake countermeasures.
As mentioned above, recent earthquakes have brought huge damage to various heritage buildings.

DEVELOPMENT OF EARTHQUAKE COUNTERMEASURE

On the other hand, there is a growing expectation on heritage buildings to generate tourism benefits. Therefore, a particular emphasis has been put on how to make a good balance among preservation, good use and safety, and earthquake countermeasures have been developed.
After the Great Hanshin-Awaji Earthquake in 1995, Agency for Cultural Affairs organized expert meeting for developing guidelines, then "Guideline for ensuring safety of cultural properties (buildings) during earthquakes"[1] was established in 1996, and "Guideline for assessing seismic resistance of important cultural properties (buildings)"[2] was established in 1999. At that time, earthquake countermeasures on heritage buildings, almost all of which were traditional wooden buildings, were not so common yet. Therefore, the agency provided heritage owners and experts its basic view and method by these guidelines. The countermeasures also came to attract the attention of researchers, then a lot of surveys and experiments have been conducted, and a considerable amount of data has been accumulated.
In addition, after this earthquake, there were no effective measures to stop the trend of demolishing damaged heritage buildings, which were not designated as a cultural property. One of its reasons was a lack of awareness of owners. In 1996, the agency established the cultural property registration system in addition to the previous system for designating Important Cultural Property. The registration system is more liberal than the designation system. By the registration system, the number of cultural property has been increased, and awareness of more heritage-building owners has been raised. Today, over 20 years after the establishment, the number of Registered Cultural Property buildings exceeds 10,000, which is more than twice of that of Important Cultural Property buildings.
After the Great East Japan Earthquake in 2011, in order to survey huge number of damaged heritage buildings widespread, the agency establish a framework of damage investigations in corporation with some institutions of architects and researchers. A lot of experts were dispatched systematically to investigate damaged heritage buildings and provide technical advice to owners.
In addition, the agency developed a brochure[3] and a manual.[4] It is important to share the information of disaster risks with owners of heritage buildings, so the brochure was mainly intended for the owners and explains why earthquake countermeasures are needed. It is also important to share the technical information between related experts like conservation architects and civil engineers, so the manual was mainly intended for experts and explains how to progress earthquake countermeasures on heritage buildings in terms of both heritage conservation and structural engineering.
In this way, while overcoming problems occurring in several earthquakes, earthquake countermeasures on heritage buildings have been promoted.

PROCEDURE OF EARTHQUAKE COUNTERMEASURE

The basic steps of earthquake countermeasure are the following: first an earthquake resistance is evaluated, second a method of countermeasure is examined and implemented.
In the first step, it is required to correctly evaluate an earthquake resistance and to find a structural weak point. Because, not only evaluating it higher than it really is will lead to a lack of countermeasure, but also evaluating it lower will lead to an excessive reinforcement.
The necessary earthquake resistance is determined according to building use and likelihood to be repaired. The guideline mentioned above introduces its standards with three-grade. The necessary earthquake resistance of a building opened to public or used by a lot of people should be high, but that of a building not used much or a monument building can be low. In addition, that of a building, which cannot be repaired when it is damaged in an earthquake, should be also high.
Then, a numerical examination is conducted with a suitable analytical method and model. When needed, structural experiments with samples/models and non-destructive/slightly-destructive inspections on site are performed in order to get

Fig. 6 - Dropping chimney of Kumamoto University building (Source: staff of the Agency for Cultural Affairs)

Fig. 7 - Himeji castle (Source: Shuji Kato, a conservation architect).

Fig. 8 - Experiments of earthen wall of Himeji castle (Source: Yoshiaki Tominaga, a structural engineer).

sufficient data for the analytical model. It is also effective to examine a result of analysis by comparing it with a record of past earthquake damage.

For example, the earthquake countermeasure of *Daitenshu* (great keep) of *Himeji* castle was implemented in the restoration project from 2009 to 2014 (Fig.7). Experiments of some structural elements, including earthen wall (Fig.8), were conducted, and a vibration observation on site was also performed. By using these results, its behavior during an earthquake was simulated by a time history response analysis with a three-dimensional model (Fig. 9). Then it was clarified that some columns and floors can be damaged severely in a big earthquake. Based on the result, the keep was reinforced with minimum intervention: attaching hardware only on the danger part of columns and floors.

Like this example, if a structural weak point is found, a countermeasure method is examined in the second step. There are two types of measures: structural measures like a reinforcement and a base isolation device and non-structural measures like evacuation guide drill and restriction of use in order to reduce a risk. When a complete countermeasure is impossible to be implemented at once, it can be implemented at several stages with a long-term plan.

When examining a reinforcing method, it is required not only to select a suitable reinforcing material matching a building structurally, but also to be careful not to impair cultural value by reinforcement. Since each heritage building has different structural characteristic and cultural value, a reinforcing method should be examined depending on each building's condition. Regarding the requirements related to cultural value, the manual mentioned above introduces the following points: 1) preserve original design, 2) Do not damage original components, 3) Make reversible interventions, 4) Make reinforcement distinguishable, 5) Minimal intervention.

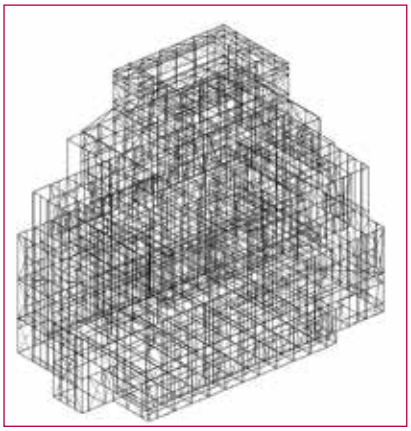

Fig. 9 - Analitical model of Himeji castle (Source: Tateishi structural engineering office).

For example, *Kannondo* (building dedicated to *Kannon*) in *Eiho-ji* (Buddhist temple) was reinforced in the roof repair project from 2009 to 2012. Wooden lattice panels were installed in a space between its roof and ceiling (Fig.10), and additional beams were attached on the bottom of columns under its floor. These reinforcing materials have high deformability, which traditional wooden buildings also have, so the reinforcement matches the building structurally. In addition, all reinforcement was added out of sight almost without any change of original components, so original design and components were totally preserved. Furthermore, it can be restored to the original state by removing the additions if necessary in the future.

Thus earthquake countermeasures on heritage buildings are examined based on numerical analysis and experiments, while taking both structural engineering and heritage conservation into account.

CONCLUSION AND FUTURE WORK

As described in this paper, earthquake countermeasures on heritage buildings have been developed through a lot of earthquakes in Japan. From this case study, it can be said that the following points are important for earthquake countermeasures on heritage buildings: 1) Awareness rising about heritage and disaster risk, 2) Information sharing with owners, experts, etc., 3) Earthquake damage investigation system, 4) Preliminary countermeasure to mitigate disasters, 5) Development of suitable method of diagnosis and reinforcement for heritage buildings.

On the other hand, there are still some problems in Japan. One of them is a countermeasure on heritage brick build-

Fig. 10 - Reinforcement of Knanondo of Eiho-ji (Source: Masahiro Kato, a conservation architect).

ings. Though, a lot of experiences of countermeasures on heritage wooden buildings have been accumulated, it is hard to say that on heritage brick buildings. Recently, more and more brick buildings have been evaluated as a heritage building to symbolize the modernization of Japan. Most of the buildings are located in the central urban area and are used by a lot of people. However, brick buildings had been built only during a limited period of the beginning of the modern times in Japan, and one of its reasons is vulnerability to an earthquake. Now some of these have been subjected to countermeasures, but suitable methods of diagnosis and reinforcement for heritage brick buildings are still under development and discussion. This problem can be shared with Italy, which is earthquake-prone and abounds in heritage brick buildings.

Finally, the writer adds a view on the possibility of another outcome of earthquake countermeasures on heritage buildings. In general, the countermeasure is conducted only for protecting heritage and ensuring safety. However, accumulations of earthquake resistance diagnosis results may make it possible to explain development of building structure scientifically. Numerical simulations may provide more detailed explanation of past earthquake damage than old documents. Then, it would help us to understand what happened in past earthquakes, how people coped with earthquake damage, and how people have developed building structure.

Culture has been formed, being influenced by natural environment, so it can be said that building structure, which has been developed coping with earthquakes, represent the culture of an earthquake-prone country, and the history of earthquake damage and countermeasures against them is its testimony.

Notes

1 http://www.bunka.go.jp/seisaku/bunkazai/hogofukyu/pdf/kokko_hojyo_taisin10_e.pdf
2 http://www.bunka.go.jp/seisaku/bunkazai/hogofukyu/pdf/kokko_hojyo_taisin11_e.pdf
3 http://www.bunka.go.jp/seisaku/bunkazai/hogofukyu/pdf/pamphlet.pdf (in Japanese)
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Abstract

In Japan, heritage buildings have repeatedly been damaged in earthquakes. Therefore, earthquake countermeasures on heritage buildings are strongly required in order to protect them from earthquake damage and ensure users' safety in an earthquake. Recently the countermeasures have been developed with preparing guidelines etc., raising awareness of owners, establishing an earthquake damage investigation system, and implementing countermeasure projects on each building. In the projects, earthquake resistance is evaluated by numerical analysis and experiments etc., and countermeasure is examined with taking both structural engineering and heritage conservation into account.

Keywords

Heritage; earthquake; damage; countermeasure; reinforcement; Japan

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