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Seismic Retrofit of Kumamoto Castle Keep Towers Damaged At 2016 Earthquakes

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Abstract

Kumamoto Castle was constructed around 400 years ago. There were over 90 buildings and gates in the site. The most iconic buildings are the two keep towers reconstructed in 1960. The keep towers were damaged by Kumamoto earthquakes at 2016. Currently the keep towers are under restoration work using passive controlled structural system.

The original keep towers were burnt down in 1877. In 1960 the keep towers were reconstructed on the original stone wall and new concrete piles. The stone wall and the ground are designated as cultural heritage since 1955 just before reconstruction. Even though the keep towers were damaged by earthquakes, the stone wall and the ground should be untouched or recovered as it was.

The general methods used to improve the seismic performance of the existing buildings include installing additional reinforced concrete walls, etc., to increase the building's rigidity to reduce deformation during an earthquake. However, recently there have been reports of the foundations of buildings that have been severely damaged in earthquakes rendering the buildings unusable. Thus, it will be necessary, not only to reinforce the above ground structures of buildings, but also to consider reinforcement of the foundations. The foundations of this building cannot permit reinforcement work on them because they are located on national historic site. Thus, we have employed the latest vibration control system as a method of ensuring quake-resistance in the above ground structures of the building, while also reducing the seismic force of earthquakes to the foundations.

To improve the basic seismic performance more, enlightened the weight of the building by replacing the damaged concrete wall and slab to the autoclaved light weight concrete and the steel. Also, the columns and girders were reinforced by carbon fiber and the steel plate to prevent the shear fracture.

We separated the keep tower structures and stone walls below to prevent the effect between the building and the stone wall during the earthquake. The outside frame of the keep towers is suspended the steel rods from the center core frame. The hanged frame was designed stronger against the vertical vibration caused by the earthquake.

The restoration work includes not only the seismic retrofit but also upgrading the museum function and accessibility of the wheelchair.

This paper describes the challenges of structural design in our restoration. The other paper titled “Reconstruction of Kumamoto Castle keep Towers in 1960 and Seismic damage Investigation after 2016 Eathquakes” describes the reconstruction of keep towers and investigation of damages by earthquakes.

Keywords: Kumamoto Castle; Seismic design; passive controlled structure; friction damper; stone wall

1. Introduction

Kumamoto Castle is a hilltop Japanese castle located in Kumamoto Prefecture in Japan. The castle was constructed around 400 years ago. It has an area of around 1 million square meters and has a circumference of 5.3km with 49 towers and 47 gates in the castle ground. Approximately, 0.578 million square meters of the area are designated as a national special historic site. With the history of over 400 years, the signature curved stone-walls and the gallant tower's façade, Kumamoto castle is considered as the pride of Kumamoto.

The most iconic buildings in Kumamoto Castle are the two keep towers. The floor dimension of large keep tower is 20m x 20m at first floor level. The smaller keep tower's is 17m x 17m. The keep towers were burnt down during the civil war in 1877 and they were reconstructed in 1960. During the 2016 Kumamoto earthquake, Kumamoto Castle suffered two unexpected consecutive strong shakings. After the earthquake, we performed damage investigation and designed a restoration that upgrades the seismic performance of the structures and ensures visitors' safety in the future while fully considering the cultural heritage protection.

This paper describes the challenges of structural design in our restoration.

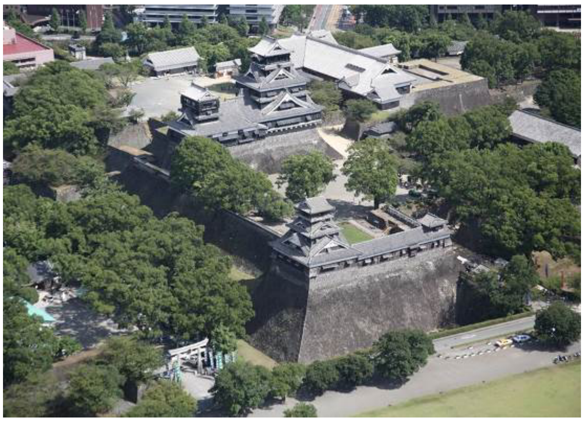

Fig.1 – Kumamoto Castle

Fig.2 – Keep Towers

2. Reconstruction and Damage by Kumamoto Earthquake

Originally, the two keep towers were wooden structure supported by ground and stone walls before being burned down in 1877. The current keep towers were reconstructed in 1960 based on their old photos and documents. The larger keep tower (left one in Fig.2) is a 6-story building. The smaller keep tower (right one in Fig. 2) is a 4-story building. Both of them have a basement floor inside the stone-walls.

In 2016 Kumamoto Earthquake occurred in April 14th and April 16th with a seismic intensity of 7 and moment magnitude levels were 6.5 and 7.3. There is no official record about consecutive strong earthquakes from 1885's observation starts. The center of this earthquake is only about 12km from Kumamoto Castle. Several strong aftershock followed for long time. The strong earthquake seems to occure repeatedly around 100years based on the old documents.

During earthquakes, the stone walls at the foot of the smaller keep tower collapsed partially, and large amounts of roof tiles were damaged and fell from the rooftop. Nevertheless, the main structure of the two keep towers withstood the strong shakings. We investigated the damages in detail after the earthquake and confirmed some structural damages. Based on these detailed investigation, we concluded that two keep towers were suitable for continuous use with the restoration.

3. Restoration of Keep Towers

3.1 Restoration Scheme

The kumamoto Castle is loved by Kumamoto people and can be seen from the center of Kumamoto city. The restoraiton project is regarded as a symbol of the recovery from the earthquake. The restoration must be completed urgently. It was decided that the order would be to restore the exterior first, followed by the seismic retrofit work on the interior. A large portion og the exterior is not on the structural frame and have no interfarence with reinforcement work. Also the restoration work must be done from top to bottom to be seen from a distance.

The exterior was kept same shape and materials as the original. The damaged exteriors were changed by traditional construction method. At the beginnning of the restoration construction, 3D scanning and detailed measurement were conducted to figure out the all dimensions.

To prevent the fall of the roof tiles is very important for safety. At the reconstruction in 1960, the roof tiles were set on the soil to maitain the special curb exactlly by traditional construction method. At the earthquake the soil and the roof tiles were fallen down to the ground. To prevent the damage, each roof tile has been fixed with a nail on the roofing board. This method works to reduce the dead load of the roof too.

The keep towers were used as a museum for 60 years since reconstruction. During the restoration, the museum functions are remodeled up to date. Also the EV and slope to the entrance will be installed for wheelchair accessibility.

Fig.3 – Restoration Construction Site

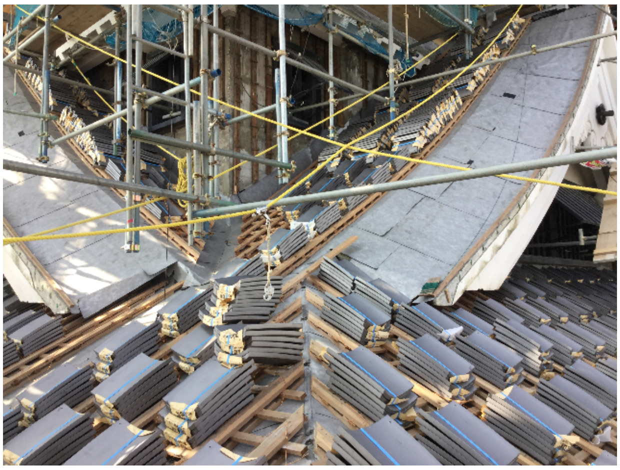

Fig.4 – Restoration of Roof Tiles

3.2 Structural Design Outline

The reconstructed keep towers were damaged by the continuous earthquake. To prevent the damage from the next earthquake that will happen near future, we designed the improved the structural system and the seismic performance for the keep towers.

The keep towers stood on the piles constructed in 1960 and the smaller keep tower's outer frame stood on the stone-walls underneath because the tower couldn't have the pile neare the large keep tower. As the design term for the stone-walls restoration collapsed by earthquakes were thought to be longer than that of the keep towers, the separation of the keep tower and the stone-walls were thought to be necessary. To solve this problem the cantilever floor system from the smaller keep tower's core was adopted. The floor betwee the two keep towers were hanged from both side.

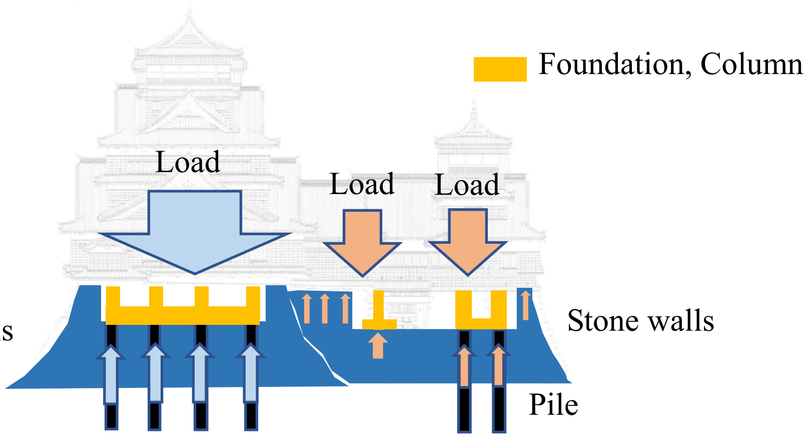

Fig.5 – Section of Keep Towers

The larger keep tower stood on the piles. The peripheral part of the floor is suspended by the diagonal column. The diagonal column was designed to support the long-term load only. For the vertical load caused by the vertical earthquake shock, the diagonal columns were reinfoced with the steel rods.

Originally two keep towers were constructed separatly and connnected exterior only. The expansion joint was hidden with the exterior materials. The joint was damagede by the earhquakes. To eliminate the expansion cover, the two keep towers were designed to connect each other. The two buildings have different floor hight and decenter in plan. To transfer the horizontal force caused by the earthquake, transfer beams were installed underneath the roof.

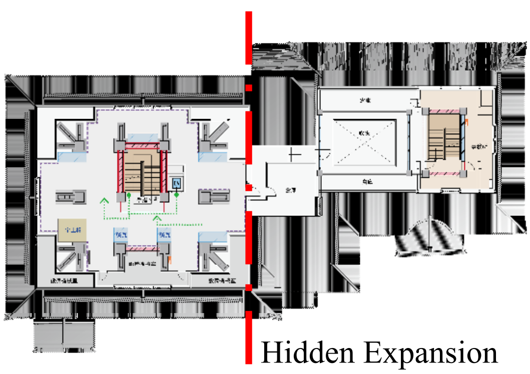

Fig.6 – Plan view of Keep Towers

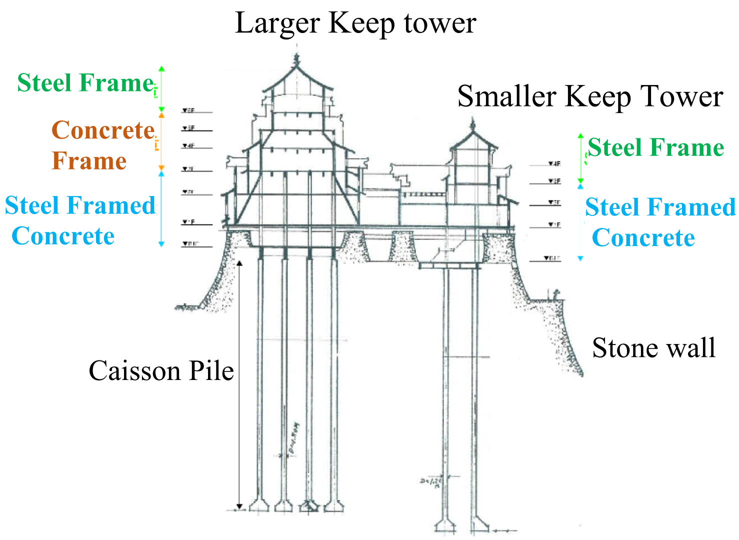

Fig.7 – Section view of Keep Towers

3.3 Seismic Retrofit Design

The seismic retrofit policy for the keep towers of Kumamoto Castle follows the design policy in the 1960's reconstruction. Understanding the extent of the damage from the recent earthquake and deploying the latest technology designed to prevent damage re-occurring will rebuild a strong Kumamoto Castle.

The general methods to improve the seismic performance of the existing buildings include installing additional reinforced concrete walls, etc., increase the building's rigidity to reduce deformation in an earthquake. However, recently there have been reports of the foundations of the buildings that have been seismically reinforced being severely damaged in earthquakes rendering the buildings unusable. Thus, it will be necessary, not only to reinforce the above ground sections of buildings, but also to consider reinforcement of the foundations. The foundations of this building do not permit reinforcement work on them as they are located below the ground level, which has been designated as a national historic site. Thus, we have employed the latest vibration control system as a method of ensuring quake-resistance in the above ground sections of the building, while also reducing the seismic force of earthquakes on the foundations.

As the latest vibration control device, we picked up the friction damper and the oil damper. Friction damper give the keep towers rigidity to reduce the deflection and the oil damper give the keep towers damping to absorb the energy of the earthquakes. The combination of these two different dampers will work from small earthquake to large earthquake.

We installed dampers as vibration control devices to efficiently absorb the energy of earthquakes and achieved enough seismic performance on the above ground sections by having the dampers bear over 60 percent of the energy an earthquake applies to the building. Also, we confirmed the seismic safety of the foundations obtained by this method as it reduces the seismic force of earthquakes on the foundations by around 30 percent compared to the method of reinforcing buildings by increasing the building's rigidity. Using this method also reduces the impact of earthquakes on the stone walls, which are located at the base of the building, and are highly valued as cultural assets.

The top floor of the keep tower has a steel frame. As the stiffness of the steel frame is much more soft compared with the concrete frame below, the accelelation of the steel frame is much higher. We installede the small viscoelatsic damper as knee brace instead of standard brace type. The knee brace allow the visitor to walk around the top floor which has very small floor area.

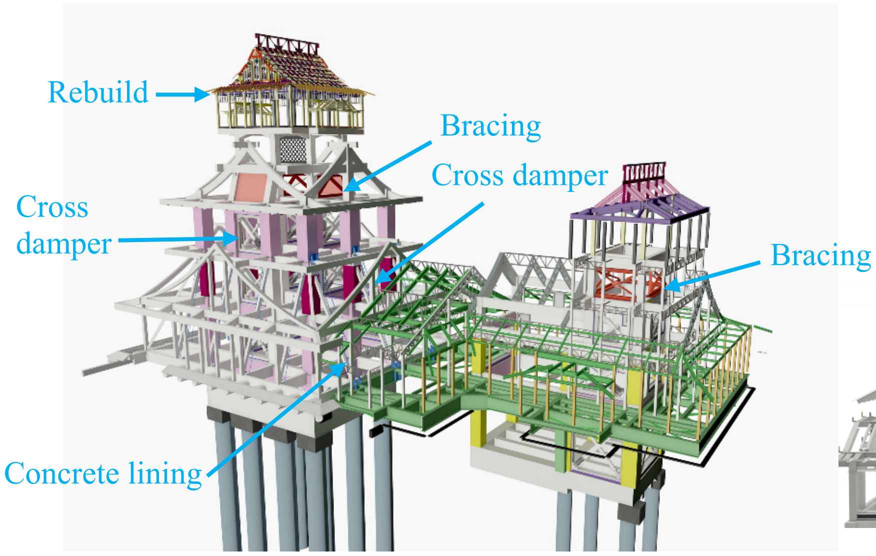

Fig.8 – Seismic Reinforcement Layout

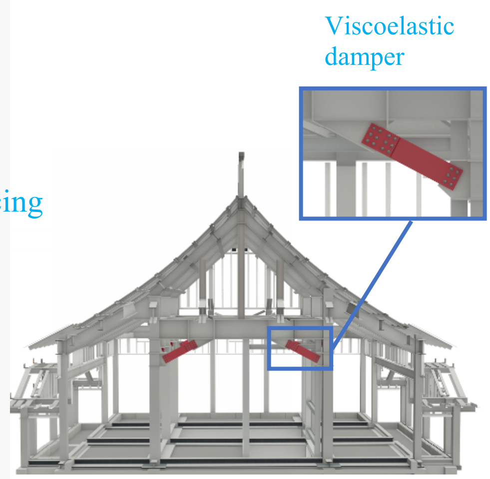

Fig.9 – Close up of Top Story

3.4 Cross Damper System

The keep towers are used as a museum and have very small floor area. (Smaller keep tower: 17m x 17m) We have come up with an idea to implement the dampers using the limited space available for reinforcement while also ensuring the space for the visitor circulation flow required in the exhibition plan. The conventional method only permits one damper to be installed in a space surrounded by columns-and-beams. However, the method adopted this time allows a through-hole to be bored in the middle of one damper so that a second damper can then be inserted through the hole allowing two dampers to be co-located in the one location. This initiative allows the keep towers to have flexible access as a museum while also improving its seismic performance to ensure the visitor safety. This system was named “Cross Damper”.

Friction damper works as bracing until axial force is smaller than its friction while oil damper absorbs vibration. When axial force goes beyond the friction force, the friction damper together with oil damper starts consuming seismic energy.

Using the excitation machine, this Cross Damper system was verified the combination performance in stress-deformation curves.

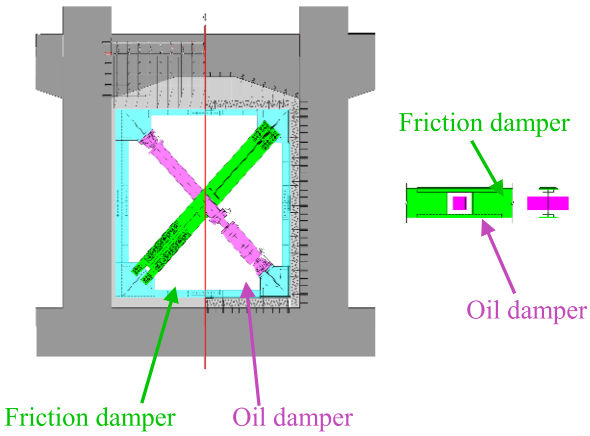

Fig.10 – Cross Damper Image

Fig.11 – Cross Damper experiment

3.5 Analysis of Existing Pile

Large keep tower has 8 piles and smaler keep tower has 4 concrete piles. There were no major damages for existing piles after the eqrthquake. To analyse the detail stress, three dimensional model was applied. The lateral force caused by the earthquake was distributed equaly to each piles by controlling the stiffnes of the brace in bottom floor. Based on the detail analysis, the piles do not affect the stone-walls underneath the keep towers.

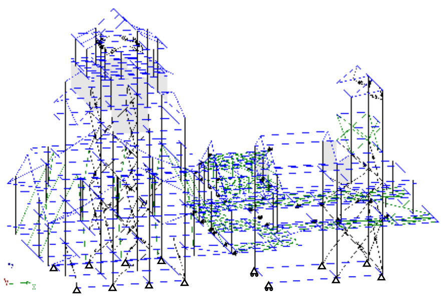

Fig.12 – Dynamic Responce Analysis Model

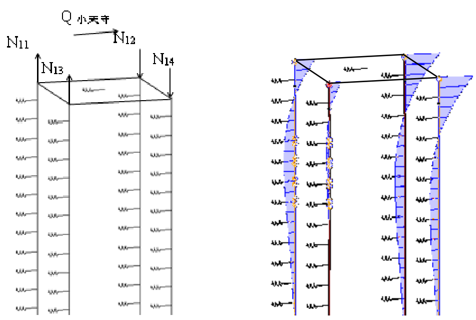

Fig.13 – Incremental Analysis of lateral and axial foce

3.6 Protection of Roof Tiles

The roof tiles were sitting on the soil and fallen down because of the movement of earthquake. The roof tiles are fixed on the roofing board at the restoration. The steel nails to fix the roof tiles are used as japanese traditional method and there are no design and guidelines. Especially combined roof tiles of plain type and convex type have no experiment.

We made a real size specimen of roof top having steep slope and ridge tiles on the top. Three dimensional excitation was used to inspect the strength of roof tiles and nails using the dynamic response of the large keep tower. The dynamic response are three direction X,Y,Z simultaneously. The roof tiles were slightly moved at the acceleration at 2.8G and no damages found at rooftiles, nails,and roof boards.

Fig.14 – Real size specimen

Fig.15 – Close up of Specimen

The plain type roof tiles are connected by steel nails at the two corners. The convex type roof tiles are connected by cupper wire at the top end. The connecthion strength of the nails were inspected by the random pickup during the construction.

Fig.16 – Connnection of plain type roof tiles

Fig.17 – Inspection of nail Strength

4. Conclusions

Kumamoto Castle keep towers have been close to the hearts of the people of Kumamoto for more than 400 years. During the Kumamoto earthquake in 2016, the stone walls and roof tiles of the towers were severely damaged. However, the keep towers withstood the strong shakes with restorable damages. The early restoration of Kumamoto Castle keep towers after the quake was regarded as a way of kick starting the healing process for the citizens. The protection of cultural heritage, the replication of the appearance, and the safety of the buildings and visitors were the core concerns in the 1960's reconstruction and remains the same over the years in the current restoration. The technologies used have been improved, allowing us to tackle more challenges.

The current restoration holds technically-challenging issues in many aspects. The latest vibration control system was installed as a method of ensuring quake-resistance in the above ground sections of the building, while also reducing the seismic force of earthquakes on the foundations. The keep towers are not only restored but to be improved over the restoration work, such as installing elevators, wheelchair accessibility, and so on.

We do believe that our endeavor in restoration make the keep towers safer and more usable.

5. Acknowledgements

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6. Copyrights

7. References

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