Seismic Isolation Retrofitting of Japanese Wooden Buildings

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Summary

Base-isolation retrofitting for a pair of 145-year-old wood shrines, with Japanese traditional architectural style, is introduced. In the renovation, lateral stiffness and strength of the superstructures are increased by traditional wood works such as wood piecewise-walls and beam-column joints. Additionally high endurance concrete and epoxy resin coated reinforcing bars are used for the newly constructed structure. Existing shrine buildings were lifted up 2m and set on a temporary pedestal to construct isolation system under it.

1. Introduction

Takebe-taisya Shrine located at southeast of Lake Biwa in Shiga Prefecture, Japan and has a long and distinguished history. Its historical records tell the place was hit by a big earthquake in 1627 and most of the shrines collapsed. The existing Honden and Gonden, which are main buildings in the shrine, were built in parallel and in the same shape in 1861 after a long absence. Their exterior view is shown in Fig. 1. Honden and Gonden enshrine Yamatotakeru-no-mikoto and Oonamuchi-no-mikoto respectively. The former and the latter are a hero and a god respectively in Japanese myths. But they believe the former is an existed prince lived around the 3rd century. Base-isolation retrofitting has been applied to the two buildings.

Fig. 1 Exterior view

2. Japanese Structural Design of Seismic Isolated Structure

One of major methods to design seismic isolated structure in Japan is to determine static earthquake loads by the maximum response values of earthquake response analysis. The analyzed loads are used in static stress analysis and each element is designed by allowable stress design method. Based on the above method, in this building design, earthquake response analysis is done on the following 2 levels.

1. Rare earthquake motion: level 1 earthquake motion
2. Extremely rare earthquake motion: level 2 earthquake motion

The earthquake motions for each level are scaled three observed motions and three motions compatible to spectra defined by Japanese seismic code. Motions compatible to spectra are made based on the following method. First, surface ground model above engineering bed rock is defined. Here, engineering bed rock is chosen from ground, which has more than 400m/sec shear wave velocity. Second, acceleration at the engineering bed rock is convolved to the surface ground considering nonlinear characteristics of the soil layers. The resulted earthquake motions are to be input at the foundation of the building model of earthquake response analysis. Here, these earthquake motions are called code spectra compatible motions.
3. **Outline of the Building**

Outline of the buildings is described below. The 28,000m² lot has more than 20 buildings with variety of sizes as shown in Fig. 2. Worshippers come from the west and turn to the north along the main street, and go through the gate toward Honden and Gonden. The buildings are surrounded by holy fences with a grove of the shrine on their right backs. Fig.3 shows architectural plan, Fig.4 and Fig.5 show cross section and south elevation view.

**OUTLINE**

- **Building name:** Takebe-taisha shrine / Honden and Gonden
- **Building site:** Otsu City, Shiga Prefecture, Japan
- **Completion:** March, 2006 (retrofitting work)
- **Building area:** 21.38m²
- **Floor area:** 6.54m²
- **Building height:** 6.62m
- **Superstructure:** Japanese traditional wooden structure
- **Base isolation system:** Ball Bearings, Oil Dampers
- **Foundation:** Mat foundation, Soil improvement

![Fig. 2 Layout plan](image)

![Fig. 3 Plan (unit mm)](image)

![Fig. 4 Cross section (unit mm)](image)

![Fig. 5 South elevation](image)
4. Structural Planning

4.1 Structural outline

Fig. 6 and Fig. 7 show isolation device layout and Kidan floor level framing plan respectively. Fig. 8 describes applied structural methods on a framing elevation drawing. Ball bearing isolators and oil dampers are installed underneath a reinforced concrete floor slab, which is newly constructed to support the shrines. Fig. 9 is a photo of the isolation devices set in the pit during construction. Ball bearing isolators have isolating and restoring function, and oil dampers give appropriate damping force.

One of strengthening concepts for the superstructures is to keep traditional structural methods as much as possible. Based on this, weathered wood piecewise-walls, OTOSHIKOMI-ITAKABE and beam-column joints are improved.

High endurance concrete and epoxy resin coated reinforcing bars are applied to the all new structure to cover the long life span of cypress used for the superstructures.

Furthermore, to prevent liquefaction, Grid-Form Ground Improvement work has been adopted. It also supports the whole building weight at the base slab.

Fig. 6 Isolation device layout (unit mm)

Fig. 7 Kidan floor level framing plan (unit mm)

Fig. 8 Framing elevation

Fig. 9 Isolation device layout in the pit (under construction)
4.2 Input earthquake motion

In this project Level 1 and Level 2 earthquake motions are applied according to the Japanese code. Additionally to confirm seismic safety margin, “Lake Biwa West Bank Fault Earthquake Motion” has been simulated as a site motion and applied, which is considered one of the largest earthquake with relatively high event probability at the site. Maximum velocity and maximum acceleration of each motion are illustrated in Table 1.

<table>
<thead>
<tr>
<th>Table 1 Input earthquake motion</th>
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<tbody>
<tr>
<td><strong>Earthquake Motion</strong></td>
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<tr>
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<tr>
<td>Code spectra compatible motion</td>
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<tr>
<td>Motion A</td>
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<tr>
<td>Motion B</td>
</tr>
<tr>
<td>Motion C</td>
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<tr>
<td>Observed motion</td>
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<tr>
<td>El Centro 1940 NS</td>
</tr>
<tr>
<td>Taft 1952 EW</td>
</tr>
<tr>
<td>Hachinohe 1968 NS</td>
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<tr>
<td>Simulated motion</td>
</tr>
</tbody>
</table>

V: Velocity  A: Acceleration

4.3 Restoring force characteristic of the superstructure

The existing buildings did not have enough lateral stiffness and strength because they had less asismatic elements. In this kind of case, a wooden building is reinforced by modern asismatic methods like metal bracings or structural plywood in the past. However, like many Japanese shrines, their traditional structural members are finishing materials as they are. Therefore, traditional wooden works, which work as structural members, are chosen as reinforcement elements to keep their traditional external appearance as same as the original. The following two methods are applied to gain enough stiffness and strength.

1. Wood piecewise-walls, OTOSHIKOMI-ITAKABE, are improved. Each wall consists of plural wooden boards connected each other by wooden shear connectors, DABOs, filled in a frame. Weathered 18 mm thick wallboards without DABOs are replaced by 30 mm thick wallboards with DABOs as shown in Fig. 10.

2. Beams, KOSHINUKI, are processed to penetrate the columns at its both ends as shown in Fig. 11. The joints are evaluated as semi-rigid joints.

Fig. 10 Structure of wood piecewise-walls
Restoring force characteristics of the superstructures are evaluated and modelled for seismic response analysis referring to experiment studies. It evaluates boards’ compressive strain inclined to the grain of columns or girders, boards’ shearing deformation, slip between boards, and boards’ partial collapse by compression. Since there are no nail work used at any joints and small clearances exist between wood materials, restoring force of the superstructure shows slip from original point like dot-lines plotted in Fig. 12. Here, elastic nonlinear equivalent shear stiffness, which is plotted in solid line in Fig. 12, is defined and applied to models for earthquake response analysis. Additionally analysis is done also with half of the initial stiffness $K_1$ and double of $K_1$. This variation of the initial stiffness is caused expansion and shrinkage of wooden elements caused by mainly fluctuant humidity of surrounded air. Damping ratio of the superstructures is set at 3% to critical, considering material shrinkage with age.

4.4 Isolation devices

Ball bearing devices illustrated in Fig. 13 and oil dampers are applied for the buildings to get appropriate isolation effect. This combination of devices has the following advantages besides the high performance.

1. [High reliability] already used in hundreds of houses in Japan
2. [Easy maintenance] less residual displacement after earthquake makes maintenance relatively easy for the owner.

It can be said that materials have to behave prescribed performance with easy maintenance as well as they have to have high performance.

4.5 Result of the seismic response analysis

Generally a Japanese traditional building has very large and heavy roof. In this kind of building, when story displacement increases, a building itself collapse by P-delta effect, which made by the lateral displacement and the weight of the roof.

Maximum displacement responses of the building are plotted in Fig. 14. Results show that maximum story drift is 1/93, by Lake Biwa West Bank Fault Earthquake Motion, which is less than the collapse limit of 1/30. Results of seismic response analysis are illustrated in Table 2. Stress of each element is less than allowable stress to confirm high isolation effect.
### Table 2 Criteria and result of earthquake response analysis

<table>
<thead>
<tr>
<th></th>
<th>Level 2</th>
<th>Lake Biwa West Bank Fault Earthquake Motion</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Criteria</td>
<td>Result</td>
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<tr>
<td>Wooden Super-structure</td>
<td>Story drift</td>
<td>1/60 and below</td>
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<td></td>
<td>Element stress</td>
<td>Allowable stress and below</td>
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<tr>
<td>Isolation level</td>
<td>Displacement</td>
<td>27cm and below</td>
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<tr>
<td>Foundation</td>
<td>Element stress</td>
<td>Allowable stress and below</td>
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<tr>
<td></td>
<td>Bearing capacity</td>
<td>Allowable stress and below</td>
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### 5. High durable materials

The existing superstructure is made of cypress. The material life span is more than several hundred years. To make the whole buildings’ life span long, high endurance concrete and epoxy resin coated reinforcing bars are used for the all newly built structure, such as concrete foundation slab, retaining walls and so on.

In high endurance concrete, neutralization is controlled because neutralization of concrete is one of dominant factors, which shortens the material life span. Neutralization is promoted by air included in the concrete itself and also in water led along cracks. To prevent concrete from neutralization, water-cement ration is restricted lower, and air in the concrete is reduced by adding durability improving additives. Relation between neutralization speed and covering depth is described in Fig. 15. More than 500 years of life span is expected for the concrete used in this project.

### 6. Construction scheme

Construction had to be done in very limited space because a grove of trees exist right behind on the north side of the buildings and also holy fences surround the buildings. To set isolation system, the fence on the north side was removed and the existing buildings were lifted up 2m with chain hoists as shown in Fig. 16 and Fig. 17. Each building was fixed on temporary steel pedestal set over the site and construction works were done under it. It enabled to use small size heavy machineries to excavate and carry soil out of the site.

However, machineries for general ground soil improvement were still too tall to be operated under 2m high pedestal. To solve it, High Pressure Jet Agitation method is selected instead of general agitation method. In the method, big machineries were not necessary on the ground because soil is agitated by jet pressure of fixation agent in the ground.

Additionally simple construction was achieved by a flat slab foundation without beams. It also reduces the amount of soil excavation and makes the concrete work simple.
7. Conclusion

Base-isolation retrofitting for Japanese traditional shrines is introduced. In the seismic renovation, lateral stiffness and strength of the superstructures are given by traditional wood works such as piecewise-walls and beam-column semi-rigid joints. Use of metal elements for reinforcement is minimized.

High endurance concrete and epoxy resin coated reinforcing bars are used to the newly constructed structure for base isolation, because the cypress of superstructure has more than hundreds year life-long. Existing shrines are lifted up 2m and set on a temporary pedestal to make construction work enable under it.

Only a few base-isolation retrofitting designs for traditional buildings are seen in Japan yet. This project will be one of the first examples of seismic isolation retrofitting for Japanese traditional buildings reinforced only by traditional wood works. It is expected that retrofitting by combinations of modern technology and traditional structural are developed more and get more popular. Additionally it is longed that, knowledge about damping effect of traditional wooden works increases in the future to design them more rationally.