EFFCT OF DETERIORATION OF STRUCTURAL MEMBERS AND JOINTS ON EARTHQUAKE RESPONSE OF JAPANESE TRADITIONAL WOODEN TEMPLE

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ABSTRACT :

This paper examined the effect of aged deterioration of structural members and joints on the earthquake response of a traditional Japanese wooden temple in Kyoto. First, the effect of deterioration at the joints was studied. Push-over analysis and nonlinear earthquake response analysis showed that deterioration of the beam-column joints decreased the ultimate horizontal resistant force, and increased the maximum response displacement of the temple. Next, the effect of deterioration due to age of the structural member was studied. The structural members of the objective temple are made of old zelkova wood, the Young's modulus of which decreased continuously once it has been used as a structural member 350 years ago. Static and dynamic analyses showed that the smaller Young’s modulus decreased the ultimate horizontal resistant force and increased the maximum response displacement of the temple. However, the risk of total collapse is considered to be low if the deterioration ratio of the modulus is linear to the ages.

KEYWORDS: wooden structure, aged deterioration, push-over analysis, cultural heritage nonlinear earthquake response analysis

1. INTRODUCTION

Traditional old wooden temples and shrines are invaluable cultural heritages in Japan, which gives us mental richness. As earthquakes occur frequently in Japan, it is important for us to protect traditional wooden structures from earthquakes.

Aged deterioration is one of the most important problems on old structures against earthquakes. Photo. 1 shows a deteriorated beam-column joint in a temple. As the beam column joints are important seismic element of Japanese traditional wooden temple, distortion and inadequate spaces between the beam and the column because of aged deterioration decrease the seismic performance of the joint. Photo. 2 shows a deteriorated column bottom. The column has internal loss due to termite and decay. The internal loss results in decrease of the effective sectional area to resist earthquake loads as well as other loads.

Photo. 1 Deteriorated beam-column joint

Photo. 2 Column with internal loss

Many kinds of wood species are used for the structural members of Japanese traditional temples. The strength deterioration of wood by ages is different according to the wood species (Hirajima, 2004, 2005, Kohara, 2003). The strength of cpuressaceae or pinaceae increases for hundreds of years after it is used as a structural member. But the strength of zelkova decreases once it is used as a structural member. It is therefore important to check the seismic performance of old cultural heritage structure in consideration of strength change of wooden members by ages. This research evaluated seismic performance of old wooden structure in consideration of aged deterioration through the nonlinear earthquake response analysis and push-over analysis.

2. OBJECTIVE STRUCTURE

The objective structure of this research is Kiyomizu temple in Kyoto. It was built in 805, and reconstructed in 1633 following a fire. It's a traditional Japanese wooden temple which has no nails nor metal devices to assemble the columns and the beams. As it is located on a steep hillside, a large open-air stage is attached to the main hall. The dimension of the building is 40m×36m wide and 18m high, and the stage columns are 13m high at the maximum. Fig. 1 shows the plan view of the building and frame names used for the analysis.

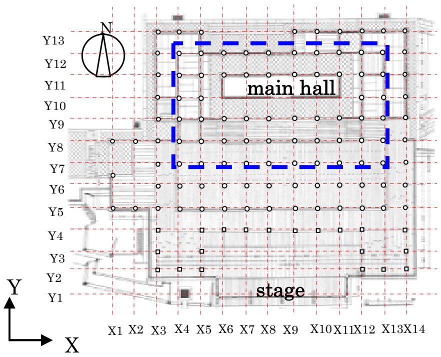


Fig. 1 Plan view

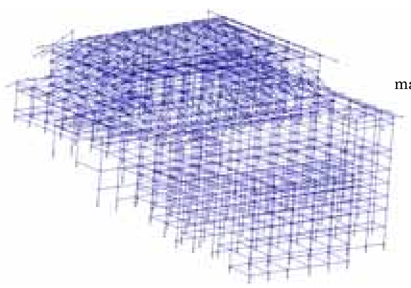


Fig. 2 Numerical model

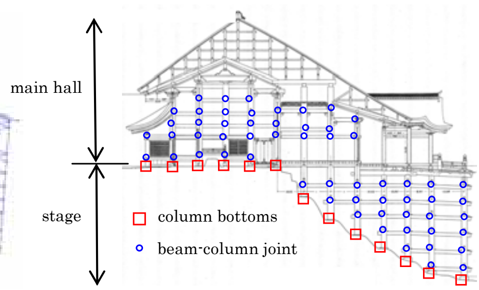


Fig. 3 Assumed deteriorated parts

The size of each member was measured, and the numerical analysis model was made (Suzuki, 2007) according to the measurement and the references. In a numerical model, joints and walls were modeled as nonlinear springs, while columns, beams and girders were modeled as elastic members. The main structural members of the building are made of zelkova. The Young's modulus of zelkova was assumed to be 8.8GPa. Fig. 2 shows a numerical model which consists of more than 3,000 elements.

3. DETERIORATED PARTS WHICH AFFECT SEISMIC PERFORMANCE OF BUILDING

3.1.Assumed deteriorated parts

Assumed deteriorated parts in this chapter were column bottoms and beam-column joints, because these parts easily deteriorate and many examples of deterioration are seen in this type of structure. Push-over analysis and nonlinear earthquake response analysis evaluated the seismic performance of the building using the model with assumed deterioration. The assumed deteriorated parts are shown in Fig. 3.

3.1.1 Column bottoms

The rotation springs due to column rocking (Fig. 4) and the horizontal springs due to friction were used at the column bottoms. The rotation spring was modeled as a nonlinear elastic rotation spring which does not have hysteretic attenuation as shown in Fig. 5. The horizontal spring was modeled as a bilinear spring for friction.

The section areas of the column bottom were assumed to 10% of the healthy ones due to deterioration. The deterioration of the column bottoms was assumed to affect none to the horizontal springs according to the preliminaly computations.

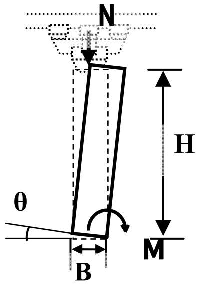


Fig. 4 Column rocking

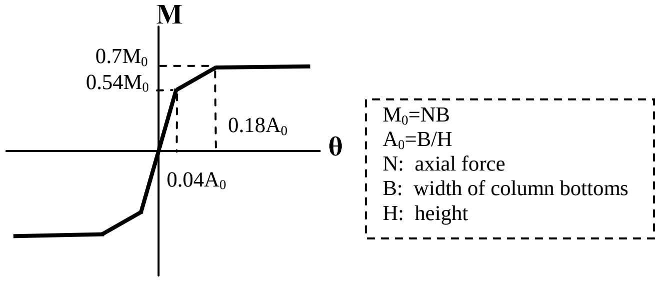


Fig. 5 Skelton curve for column rocking

3.1.2 Beam-column joints

The rotation spring to react the compressive stress by Inayama's theory (Inayama, 1991) was set to each beam-column joint. The hysteretic model used was a slip-bilinear type. Moreover, the horizontal spring due to friction of slipping out of the beam from the column was used at every beam-column joint in the N-S direction, because this temple is located on the slope in this direction. The hysteretic model was assumed as a bilinear type. The modeling of the rotation spring is shown in Fig. 6. The hysteretic model of the rotation spring is shown in Fig. 7, and that of the horizontal spring is shown in Fig. 8. As shown in Figs. 6 and 7, the performances of the rotation springs were calculated from the contact area of the beam and the column. So, performance of the rotation spring decreases with defect of section area in the members due to decay or internal loss. In this chapter, the strength and rigidity of the rotation spring were set to 50% of the healthy one. Furthermore, as the horizontal spring was influenced by the strength of the rotation spring, the strength and yield displacement of the horizontal spring was assumed to decrease by 50%.

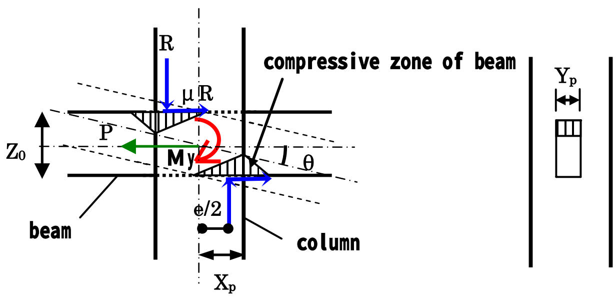
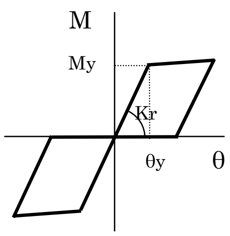


Fig. 6 Restoring force distribution at beam-column joint



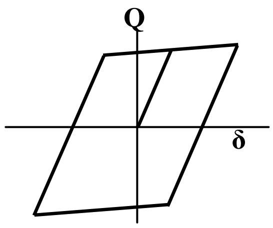
$$My = \frac{K_r \cdot Z_0 \cdot F_m}{x_p \cdot E_\perp \cdot C_{xm} \cdot \sqrt{C_{ym}}} \quad [\mathrm{kN \cdot m}] \qquad C_{xm} = 1 + \frac{4Z_0}{3x_p}$$

$$Kr = x_p{}^2 \cdot y_p \cdot E_\perp \cdot \left\{ \frac{x_p}{Z_0} \left(C_{xm} - \frac{1}{3} \right) + 0.5C_{xm} \right\} \quad [\mathrm{kN \cdot m/rad}] \qquad C_{ym} = 1 + \frac{4Z_0}{3ny_p}$$

$$\theta y = \frac{My}{Kr} \quad [\mathrm{rad}]$$

F_m 2.4×compression strength
$E_\perp$: Young's modulus in the direction perpendicular to grain
n : coefficient

Fig. 7 Hysteretic model of rotation spring (Inayama, 1991)



$$e = \frac{2}{3}B \quad [\mathrm{mm}]$$

$$R = \frac{My}{e} \quad [\mathrm{kN}]$$

$$Qy = \mu\left(\frac{My}{e}\right) \quad [\mathrm{kN}]$$

Fig. 8 Hysteretic model of horizontal spring

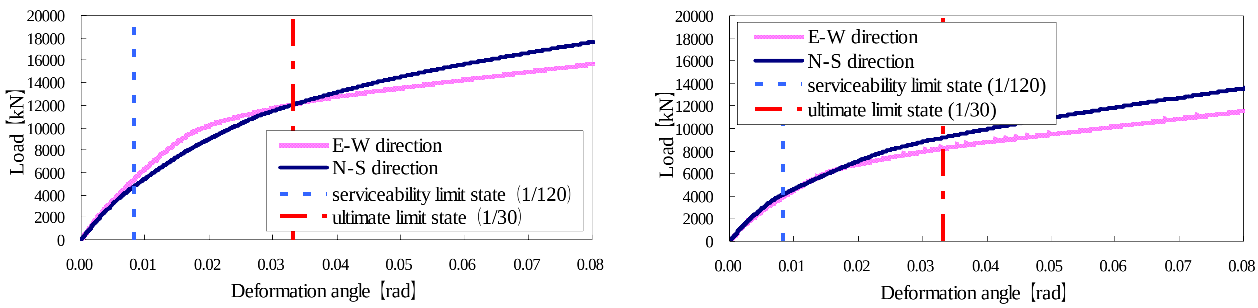
3.2. Numerical Simulations

Since this building is one-layered, the horizontal external force used to push-over analysis is applied at the ceiling. The input earthquake waves used for nonlinear seismic response analysis were Hanaore wave and JMA Kobe wave with the maximum velocity of 50kine. Hanaore wave is an assumed earthquake wave at Hanaore fault in Kyoto, which is supposed to cause the worst influence on Kiyomizu temple. JMA Kobe 50kine wave is a normalized wave of 1995 Kobe earthquake which is used as very rare and strong earthquake. Nonlinear earthquake response analysis was conducted using Newmark'β method (β= 1/4). The integration time increment used was 0.002 seconds, and the damping factor was set to 5% as stiffness proportional damping based on the fundamental mode.

3.3. Results and Discussions

3.3.1 Results from push-over analysis

Push-over analyses for healthy and deteriorated structures were conducted. The rigidity of rotation springs at beam-column joints for the deteriorated structure was set to 50% of the healthy structure. The load-deformation angle relations are shown in Fig. 9.



(a) Healthy (b) Deteriorated

Fig. 9 Results from push-over analysis

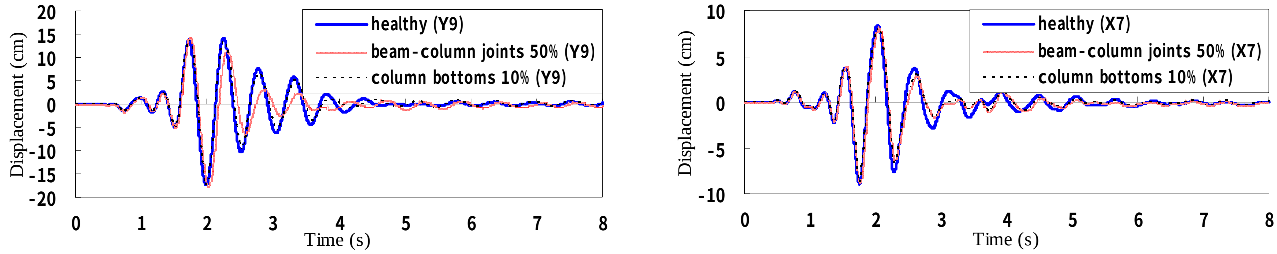
The serviceability limit state is 1/120rad and the ultimate limit state is 1/30rad. Fig. 9 shows that the load at 1/30rad decreased by deterioration to 69% in the E-W direction, and 76% in the N-S direction. Because many beam-column joints exist in the E-W direction, deterioration of the beam-column joints affected on the seismic performance more in this direction.

3.3.2 Results from eigenvalue analysis

The natural periods of the healthy and deteriorated structures are shown in Table 1. The natural periods became longer only in 5% by deterioration.

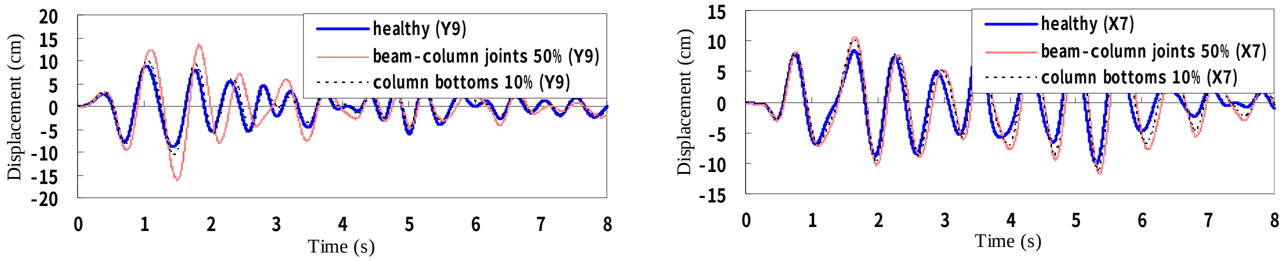
Table 1 Natural periods (sec)

	Healthy	Deteriorated
First mode (N-S)	0.599	0.626
Second mode (E-W)	0.521	0.566
Third mode (rotation)	0.268	0.278



(a) E-W direction (b) N-S direction

Fig. 10 Displacement-time histories for Hanaore wave



(a) E-W direction (b) N-S direction

Fig. 11 Displacement-time histories for JMA Kobe 50kine wave

3.3.3 Results from nonlinear earthquake response analysis

Fig. 10 shows the displacement-time histories of the healthy and the deteriorated structures for Hanaore wave, while Fig. 11 shows those for JMA Kobe 50kine wave. The response displacements were plotted for Y9 frame and X7 frame near the building center. Y9 frame shows the response in the E-W direction, and X7 frame shows that in the N-S direction.

Fig. 10 shows that the deterioration affects little on the maximum response of the structure. On the contrary, Fig. 11 shows 80% increase of the maximum response if deterioration occurs at the beam-column joints. This difference was caused by the characteristics of the input waves. The displacement response spectrum of Hanaore wave doesn't change much for the natural periods around 0.6 seconds which corresponds to the healthy and deteriorated structures shown in Table 1, while that of JMA Kobe wave changes remarkably in this range of natural periods. Furthermore, Fig. 11 shows that the deterioration of the beam-column joints affected more on the earthquake response of the structure than deterioration of the column bottoms.

4. EFFCT OF YOUNG'S MODULUS DECREASE ON SEISMIC PERFORMANCE

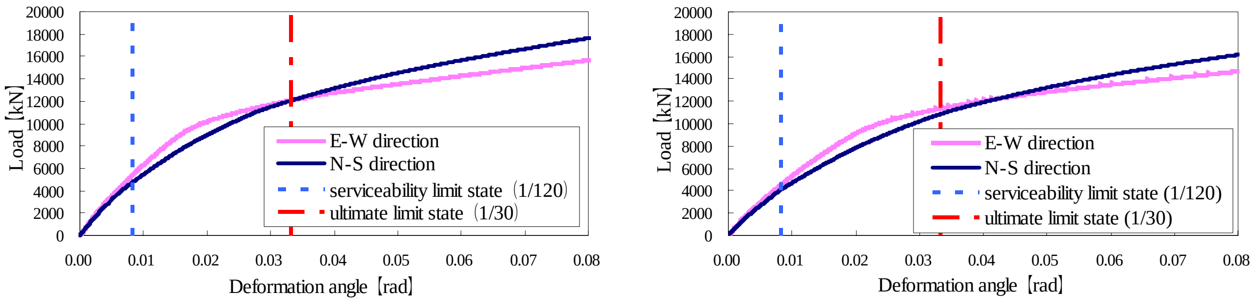
4.1. Deteriorated spring models

In this chapter, decrease of the Young's modulus of zelkova was assumed to evaluate the effect on the earthquake responses. The changed parts in a numerical model were the rotation springs of beam-column joints, girder-column joints and bracket complexes joints.

4.2. Results and Discussions

4.2.1 Results from push-over analysis

Push-over analysis was performed for the case that the Young's modulus of zelkova was 80% of the healthy structure. The load-deformation angle relation of the building is shown in Fig. 12. Fig. 12 shows that the load at 1/30rad decreased by deterioration to 94% in the E-W direction, and decreased to 89% in the N-S direction. Because only a few beams tie adjacent columns in the N-S direction, the aged deterioration affected on the seismic performance more in this direction.



(a) Healthy (b) Young's modulus reduction

Fig. 12 Results from push-over analysis

4.2.2 Results from eigenvalue analysis

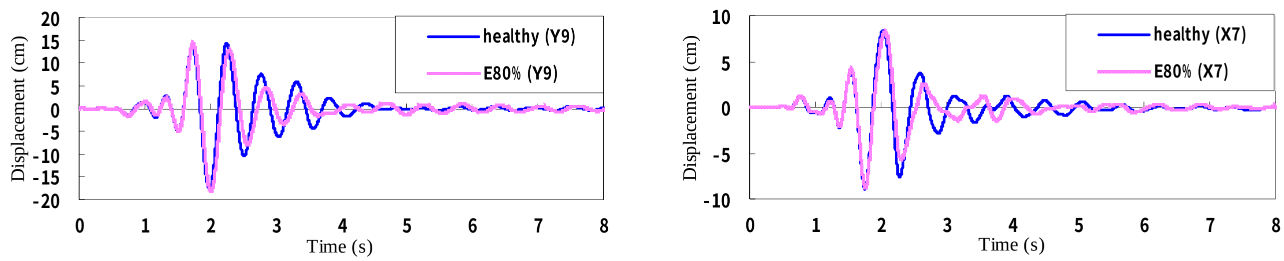
The natural periods of the building for its Young's modulus of 100% (healthy), 80% are shown in Table 2. The natural periods became longer a little by 10%.

Table 2 Natural periods (sec)

	Healthy	E80%
First mode（N-S）	0.599	0.660
Second mode（E-W）	0.521	0.576
Third mode（rotation）	0.268	0.296

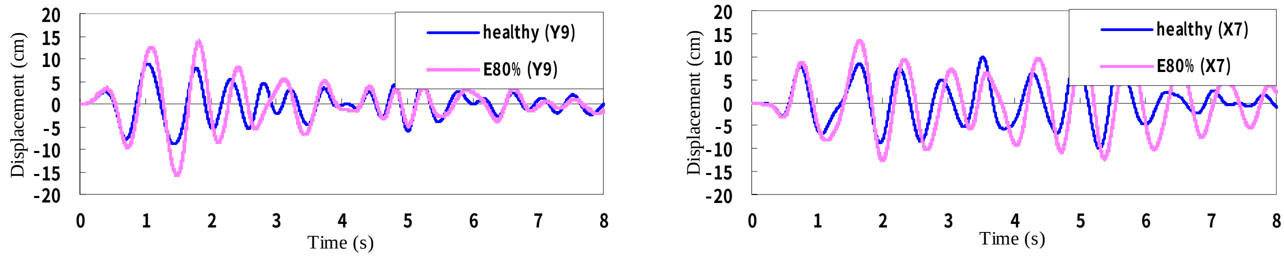
4.2.3 Results from nonlinear earthquake response analysis

Figs. 13 and 14 compare the displacement-time histories for the healthy structure and the deteriorated structure with decreased Young's modulus of 80%: Fig. 13 shows the results of Hanaore wave and Fig. 14 shows that of JMA Kobe 50kine wave. Fig. 13 shows that there was no difference in the maximum response displacement for Hanaore wave. On the contrary, JMA Kobe 50kine wave resulted in larger maximum response displacement by 76%. This result was caused by the characteristic of the input waves as described in the previous chapter.



(a) E-W direction (b) N-S direction

Fig. 13 Displacement-time histories for Hanaore wave

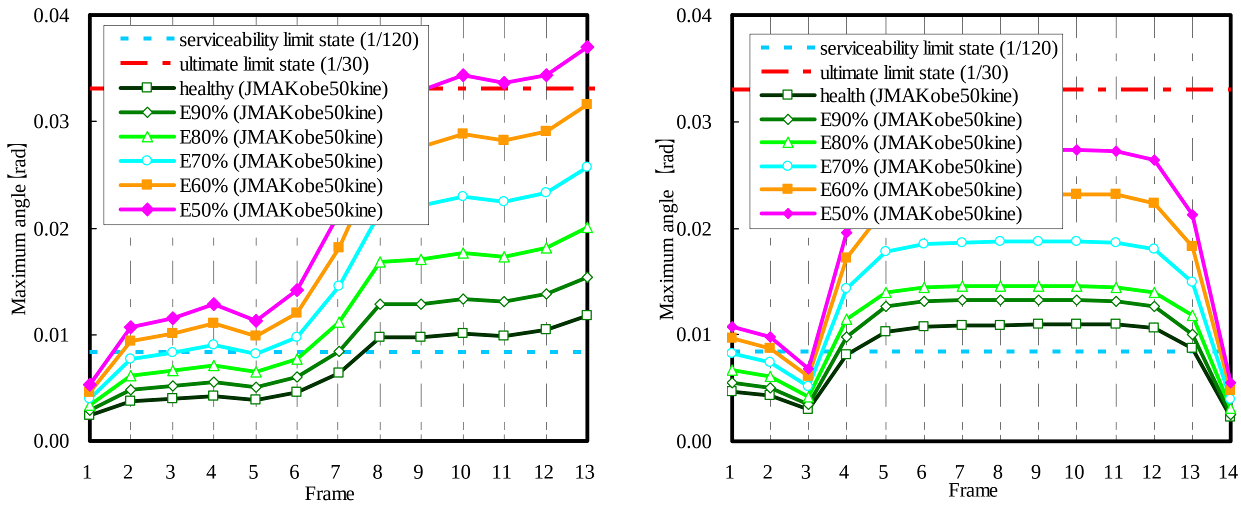


(a) E-W direction (b) N-S direction

Fig. 14 Displacement-time histories for JMA Kobe 50kine wave

4.2.4 Maximum angle of columns

The maximum angle responses of the columns for the decreased Young's modulus are shown in Fig. 15. Decrease of Young's modulus affected much on the column angle response because of the decrease of flexible rigidity of the members. Fig. 15 shows that there was frames exceeded 1/30rad in the E-W direction when Young's modulus decreased to 50%. In the N-S direction, however, there was no frame which exceeded 1/30rad even if Young's modulus decreased to 50%.



(a) E-W direction (b) N-S direction

Fig. 15 Maximum angle of columns at each frame

4.2.5 Prediction of the maximum angle of columns for further deterioration

Considering the Young's modulus decrease of zelkova, this article predicted how the maximum angle for JMA Kobe 50kine wave would change in the future. First, the Young's modulus was predicted based on the age of the structure. The relation of the Young's modulus and elapsed years of zelkova as the structure is shown in Fig. 16. Three experimental results (Hirajima, 2004, 2005) were plotted along the linear deterioration line of Young's modulus. The Young's modulus of new zelkova is about 8.8GPa according to the handbook. Kiyomizu temple has passed 374 years after reconstructed in 1633. Therefore, it can be assumed from Fig. 16 that the present Young's modulus of the zelkova of the building is about 80% of the new one. It is expected that the maximum angle of Y13 frame exceeds 1/30rad most early from Fig. 15. The relation between Young's modulus and the maximum angle of Y13 frame is shown in Fig. 17. Fig. 17 shows that the Young's modulus, at which Y13 frame exceeds 1/30rad, is about 57% of the new one. Therefore, from Fig. 16, if the deterioration ratio of Young's modulus is linear, the maximum angle of the columns will not exceed 1/30rad even after 400years.

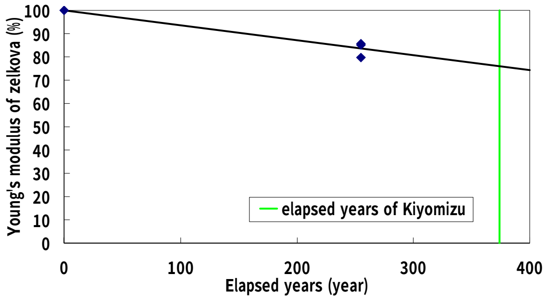


Fig. 16 Relationship between Young's modulus and elapsed years of structure

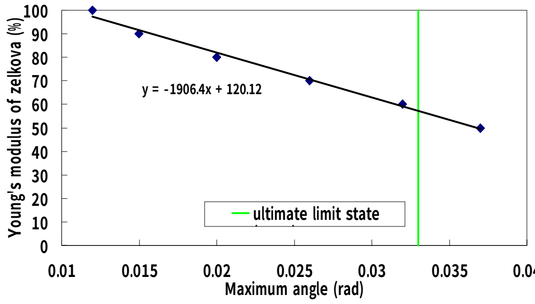


Fig. 17 Relationship between Young's modulus and the maximum angle (X13)

5.CONCLUSIONS

This paper studied the effect of aged deterioration of structural members and joints on the earthquake response of a traditional Japanese wooden temple in Kyoto. The major results obtained in this study are as follows.

1) Push-over analysis showed that the deterioration of beam-column joints had more influence on the ultimate horizontal resistant force in the E-W direction than the N-S direction. Because many beam-column joints exist in the E-W direction, deterioration of the beam-column joints affected on the seismic performance more in this direction.
2) Nonlinear earthquake response analysis showed that deterioration of the column bottoms affected little on the seismic performance of the building, while deterioration of the beam-column joints affected on the seismic performance of the building especially for the JMA Kobe wave.
3) Nonlinear earthquake response analysis showed that no frame exceeded the ultimate limit of 1/30rad even if the ultimate strength and rigidity of rotation springs at beam-column joints decreased to 50% of the healthy structure.
4) Push-over analysis showed that the aged deterioration in the Young's modulus of the wooden members had more influence on the ultimate horizontal resistant force in the N-S direction than the E-W direction. Because only a few beams tie adjacent columns in the N-S direction, the aged deterioration affected on the seismic performance more in this direction.
5) Nonlinear earthquake response analysis showed that the decrease in the Young's modulus of the members affected the maximum response angle of the columns. But, if the deterioration ratio of the Young's modulus is linear to ages, the maximum angle will not exceed the ultimate limit even after 400 years.

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