Seismic Collapsing Analysis of Two-Story Wooden House, Kyo-machiya, against Strong Earthquake Ground Motion

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Abstract: 3-D non-linear collapsing process analysis of an old two-story wooden house, “Kyo-machiya” structure, was conducted against a strong earthquake ground motion with the Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level, in order to investigate the seismic behaviour of Kyo-machoya structure built by a Japanese traditional framed-construction method. A non-linear behaviour of timber elements in the wooden house during a strong earthquake ground motion can be simulated by this collapsing analysis. As a result, seismic response of the wooden house depends on the seismic intensity of the input earthquake motion in the collapsing analysis. Also, there seems to be a possibility that the old two-story wooden house may be collapsed by a strong earthquake motion with the seismic intensity of “6 upper” level.

Keywords: 3-D non-linear collapsing analysis, Traditional framed-construction method, Earthquake ground motion

1. Introduction

There are many Japanese-style 3-story wooden hotels in Japanese spa regions with lower seismic performance against strong earthquakes with a Japan Meteorological Agency (JMA) seismic intensity of “6 upper” level. Generally, seismic retrofit design for wooden houses can be determined by the seismic performance ratio, evaluated from a ratio of the necessary resistance strength of the wooden house against a strong earthquake. It is important for a structural engineer to take account of these seismic responses in the design process, because the relationship between seismic performance ratio and seismic response can be crucial for effective countermeasures.

When the seismic performance behaviour of Japanese-style 3-story wooden hotels built by wood frame-based building method undergoes a numerical analysis, the wooden hotel’s collapsing behaviour needs consideration of the non-linear properties of wooden members breaking or being dispersed. This collapsing simulation is possible by means of analysis based on the Distinct Element Method [1].

In this paper, 3-D collapsing process analysis of wooden house based on the theory of the Distinct Element Method is conducted in order to accurately evaluate the seismic behaviour of wooden house. An earthquake ground motion with the Japan Meteorological Agency (JMA) seismic intensity, $I_{JMA}=6$ upper level, is used in this 3-D collapsing process analysis of a traditional two-story wooden house, Kyo-machiya, in Japan.

2. Collapsing Analysis

Target of the collapsing process analysis in this paper is an old two-story wooden house shown in Figure 1, which is called “Kyo-machiya” and was built by a Japanese traditional framed-construction method. Seismic collapsing process analysis software of “Wallstat” [3] was conducted in order to investigate the seismic response behaviour and the collapsing process of wooden house during a strong earthquake ground motion. This collapsing process software has an original analysis technique [2] using the basic theory of the Distinct Element Method, and can be taken into consideration the extremely non-linear properties of timber members breaking or being dispersed.

2.1. Kyo-machiya Structure

In this paper, 3-D collapsing analysis of Kyo-machiya structure is conducted by two earthquake ground motions with the JMA intensity, $I_{JMA}=6$ upper level in order to investigate the seismic performance of Kyo-machiya structure illustrated in Figure 1. Generally, Kyo-machiya structure has a narrow frontage and a deep depth as shown in Figure 1, and has a frontage of 3 ken (=5.4m) and a depth of 12 ken (=21.6m). Also, the external appearance of Kyo-machiya structure is characterized by dark colour lattice called “Bengara-Koshi”, “Mushiko” windows, “Inuyarai” and so on. Photo 1 shows a typical Kyo-machiya structure.

Figure 2 indicates a sketch of Kyo-machiya structure elevation, and also its framing plans are shown in Figure 3. The width and height of each beam in framing plans are illustrated in Figure 3, too. This Kyo-machiya
structure used in the collapsing analysis has a frontage of 5.94m and a depth of 12.87m. It is found from these figures that this Kyo-machiya structure is structurally characterized by pillars, beams, and mud-plastered walls.

One side width of a continuous pillar with a square shape, which pierces the second or higher floor, is 150mm, and that of normal pillar is 136mm in Figure 3. One side width of the first main pillar (X3,Y9) shown in Figure 3(a) is 210mm, and that of second main pillar (X3,Y5) is 180mm. Structurally, the style incorporates a horizontal beam known as a nuki (penetrating tie beam) illustrated in Figure 4, which is used in combination with pillar to reinforce the structure. Therefore, Kyo-machiya structure with mud-plastered walls shown in photo 2 has no braces inside walls.

Figure 1. Sketch of Kyo-machiya structure

Figure 2. Sketch of Kyo-machiya structure elevation

(a) Framing elevation of Y1

(b) Framing elevation of X1

Figure 2. Sketch of Kyo-machiya structure elevation

2.2 Outline of Collapsing Analysis

In this paper, a structural analysis software of “Wallstat” is employed in order to investigate seismic response behaviour and collapsing process of Kyo-machiya structure during a strong earthquake ground motion. This software has an original analysis technique [2] using the basic theory of the Distinct Element Method [1], and can be taken into consideration the extremely non-linear properties of timber members breaking or being dispersed.

In the collapsing process analytical calculation, Kyo-machiya structure can be modelled by a lot of timber elements such as beam and pillar connected with non-linear spring as shown in Figures 2 and 3, and also can be modelled by lumped mass and the weight of each floor in Kyo-machiya structure model can be obtained from each structural element as illustrated in Figure 5. Timber characteristics of the compression and tensile elastoplastic springs consist of an elastic part and slip-type part indicated in Figure 6(b), and also timber characteristics of the rotational spring are assumed to be a slip-type relationship between the bending moment $M$ and the angle of rotation $\theta$ shown in Figure 6(c).

Vertical shear wall indicated in Figure 7(a) can be modelled by the replacement of truss component with a
load-displacement non-linear relationship shown in Figure 8. Also, the bracing shear wall illustrated in Figure 7(b) can be modelled by the replacement of the compression and tensile truss components defined by a set of bi-linear and slip skeleton curve shown in Figure 8, too.

Because the detailed data concerning the non-linear spring and the load-displacement relationship shown in Figures 6 and 8 are described in reference [2], they are omitted in this paper due to the limited space.

Figure 3. Sketch of Kyo-machiya structure framing plan

Figure 4. Sketch of “nuki” structure

Photo 2: Mud-plastered walls

Figure 5. Weight of floor in the analytical model of wooden house [2]
2.3 Seismic Input Motion
Generally, a measured earthquake ground motion wave data is used in seismic collapsing analysis of a wooden house. In this paper, not only JMA Kobe wave record measured in 1995 but also an assumed earthquake ground motion wave are employed in seismic collapsing analysis. Especially, an assumed earthquake ground motion wave is estimated from the ground boring data near a...
target of collapsing analysis by “DYNEQ” program [4], which can analytically evaluate the non-linearity of a multi-layered soil stratum such as a dynamic deformation characteristic relationship between shear strain, shear modulus and equivalent damping ratio illustrated in Figure 9. In this paper, assumed earthquake motion wave is evaluated using some parameters of Hanaore Fault (M7.5), which can be considered to cause a large damage to Kyoto city. The JMA seismic intensity distribution of Kyoto prefecture based on Hanaore Fault is indicated in Figure 10.

Figure 11 shows an input earthquake motion wave, JMA Kobe wave record, used in the collapsing analysis, which has a peak acceleration of 818cm/s², a peak velocity of 91cm/s, and a peak frequency of 1.43Hz.

Figure 12 shows an assumed earthquake ground motion wave, that is, acceleration, velocity, and displacement waves evaluated by “DYNEQ” program [4] using the ground boring data near a target of Kyo-machiya structure. Displacement wave in EW component in Kyoto city has a peak value of 34cm and its peak velocity is 86cm/s, which is evaluated from an assumption based on the peak velocity of 80cm/s at the engineering bed rock with shear wave velocity of 400m/s.

Table 1 shows the JMA seismic intensity, \( I_{JMA} \), peak ground acceleration, peak ground velocity, peak ground displacement, and peak frequency for each earthquake ground motion indicated in Figures 11 and 12, respectively. In general, there may cause a large earthquake damage like the 1995 Hyogo-ken Nambu earthquake by a strong earthquake ground motion wave with peak ground velocity of over 80cm/s. Therefore, because both NS and EW velocity components of JMA Kobe earthquake ground motion wave are over 80cm/s, it may cause severe damage in comparison with the assumed earthquake motion evaluated by “DYNEQ” program using the ground boring data nearby the target of Kyo-machiya structure in this paper.

3. Collapsing Analytical Results

Seismic collapsing analysis of Kyo-machiya structure is conducted by using two earthquake ground motions shown in Figures 11 and 12. Figure 13 indicates a collapsing analytical model of Kyo-machiya structure, which is modelled based on the elevation and framing plans illustrated in Figures 2 and 3. In this collapsing analysis, the weight of first floor is assumed to be 192.75kN, and that of second floor is 157.19kN. Parameters for hysteretic characteristics of vertical wall shown in Table 2 and those for hysteretic characteristics of elasto-plastic spring between pillar and beam elements indicated in Table 3 are used in this seismic collapsing analysis of Kyo-machiya structure.

Figure 14 shows seismic collapsing behaviour of Kyo-machiya structure during JMA Kobe wave record, 1995. In this collapsing process analysis, both NS and EW components in this earthquake ground motion record are employed as input motion to the ridge direction and the span one of Kyo-machiya’s floor plan illustrated in Figure 3, respectively. If a wall with grey colour will have a large damage during earthquake ground motion, the wall colour changes to other one. When the degree of its damage increases during earthquake ground motion, the wall colour changes from grey to yellow, orange, and red. It is found from Figure 14 that Kyo-machiya structure starts to twist itself after 8 second because of a large velocity of 97 cm/s and then collapses at 16 second. This is because there may cause a large earthquake damage in wooden structure under a strong earthquake ground motion wave with peak ground velocity of over 80cm/s. It should be noted that twisting collapsing phenomenon of Kyo-machiya structure can be analytically evaluated. Based on the collapsing phenomenon of Kyo-machiya structure, its seismic retrofit design can be effectively investigated. Sakai [5] reported that structures at the ground with predominant period of about 0.6s, where has a high correlation relationship with structure damage at severe earthquake, trend to be damaged by a strong earthquake motion. Accordingly, there may be a possibility to be larger against a severe earthquake ground motion from a view point of Kyo-machiya structure’s natural period.

Figure 15 shows collapsing behaviour of Kyo-machiya structure during a strong earthquake ground motion with the JMA seismic intensity of “6 upper “ level indicated in Figure 12, which was evaluated by “DYNEQ” program using the ground boring data nearby Kyo-machiya structure. It is found from Figure 15 that the roof frame part of Kyo-machiya structure starts to de damaged after 12 second and then is destroyed at 17 second. At the same time, some walls on the second floor of Kyo-machiya structure are damaged. Because the assumed
earthquake ground motion wave illustrated in Figure 12 is much smaller after 17 second than before, the damage state of Kyo-machiya structure at 17 second seems to be almost the same until 32 second. It should be found that the seismic retrofit of Kyo-machiya structure against a strong earthquake motion needs some countermeasures such as the roof weight saving and reinforcement techniques of its roof frame.

Figure 11. Acceleration, velocity and displacement waves of JMA Kobe wave record, 1995

Figure 12. Acceleration, velocity and displacement waves obtained from boring data around

(a) Acceleration wave
(b) Velocity wave
(c) Displacement wave
(d) Fourier spectra
Figure 13. Collapsing analytical frame model without walls and braces

Table 2. Parameters for hysteretic characteristics of vertical shear wall [3]

<table>
<thead>
<tr>
<th>Material</th>
<th>$P_1$ (kN)</th>
<th>$P_2$ (m)</th>
<th>$P_3$ (%)</th>
<th>$D_1$</th>
<th>$D_2$</th>
<th>$D_3$</th>
<th>$D_4$ (%)</th>
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<tbody>
<tr>
<td>Clay Wall</td>
<td>0.5</td>
<td>1.75</td>
<td>2.0</td>
<td>0.0</td>
<td>0.010</td>
<td>0.05</td>
<td>0.10</td>
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<tr>
<td>Lath Mortal Wall</td>
<td>1.0</td>
<td>3.50</td>
<td>4.3</td>
<td>0.0</td>
<td>0.002</td>
<td>0.01</td>
<td>0.05</td>
</tr>
<tr>
<td>Structural Plywood</td>
<td>3.0</td>
<td>9.50</td>
<td>10.5</td>
<td>0.0</td>
<td>0.010</td>
<td>0.06</td>
<td>0.12</td>
</tr>
<tr>
<td>Mud-Plastered Wall</td>
<td>2.0</td>
<td>4.00</td>
<td>5.00</td>
<td>0.0</td>
<td>10.00</td>
<td>30.0</td>
<td>50.0</td>
</tr>
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</table>

$h$: viscous damping factor

Table 3. Parameters for hysteretic characteristics of elasto-plastic spring [3]

<table>
<thead>
<tr>
<th>Material</th>
<th>$K_{S1}$ (kN/m)</th>
<th>$K_{S2}$ (kN/m)</th>
<th>$K_{S3}$ (kN/m)</th>
<th>$D_1$ (m)</th>
<th>$D_2$ (m)</th>
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<tr>
<td>Stub Tenon</td>
<td>900</td>
<td>-18.919</td>
<td>-33.333</td>
<td>0.0015</td>
<td>0.020</td>
</tr>
<tr>
<td>Corner Bracing</td>
<td>5,128</td>
<td>651.00</td>
<td>-154.00</td>
<td>0.0027</td>
<td>0.015</td>
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Figure 14. Collapsing behaviour during a strong earthquake ground motion (JMA Kobe wave record, 1995)
4. Conclusions

In this paper, 3-D non-linear collapsing analysis based on the Distinct Element Method was conducted in order to investigate the seismic collapsing behaviour of an old two-story wooden house, Kyo-machiya structure, during two strong earthquake ground motions with the JMA seismic intensity, $I_{\text{JMA}}=“6$ upper" level. In summary, the following conclusions can be made based on the results presented in this paper.

1. Seismic collapsing process analysis can simulate a seismic behaviour of Kyo-machiya structure during an over 80cm/s. Therefore, whether an old wooden house has a sufficient seismic resistant force or not can be numerically investigated by this collapsing analysis.

2. Seismic response of Kyo-machiya structure greatly depends on the spectral characteristics of an input earthquake ground motion used in the collapsing analysis. Therefore, the peak frequency of an input earthquake ground motion plays an important key role in the seismic collapsing process analysis.

3. Because the seismic behaviour of Kyo-machiya structure during a strong earthquake motion is more sensitive to the peak frequency range in Fourier spectrum of an input earthquake ground motion, further investigation may be needed to simulate the collapsing process phenomenon of Kyo-machiya structure against several earthquake motions with different peak frequency range.

5. Acknowledgement

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machiya structure. The author would also like to thank the Japan Meteorological Agency and the National Research Institute for Earth Science and Disaster Prevention in Japan for their earthquake ground motion wave data in K-NET system.

6. References


