NATIONAL HERITAGE FIVE STORY WOODEN PAGODA RESPONSE IN 2011 EAST JAPAN EARTHQUAKE BY USING IMAGE PROCESSING

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SUMMARY
The Five storied pagoda is built of wood and is known as a high earthquake proof structure. The pagoda is composed of the frame and the center column. We began the response monitoring of national heritage five storied pagoda which is located in Ichikawa City close to Tokyo and constructed in 1622; Hokekyo-ji Pagoda. In the monitoring, image processing system is applied. A motion capture camera, which watches the several illuminating marker on each story, is installed at first story beam. The marker positions are obtained instantly in site PC, and stored in site PC hard disk, in 10Hz sampling, continuously. Using the maker positions, the each story displacements to first story are calculated. The relative displacements were compared with two times acceleration integral displacement using filtering. In Great East Japan Earthquake, the displacements about 75mm and small residual were obtained. Long term indicated seasonal periodic structure deformations.

Keywords: Five Story Wooden Pagoda, Image Processing, Structural Monitoring, Great East Japan Earthquake

1. INTRODACTION

In Japan, there are five storied pagodas of more than 22, which were built before 1850. Although there are many reports of its dynamic characteristics under the earthquake and strong winds, there are a few reports on them under both the seismic load and wind load. Many micro tremor measurements of the real pagoda were conducted [1,2]. Shaking table tests of scale models were also done. Seismic response of new-built five story pagoda was obtained under an actual seismic event of the intensity level 5. Our response observations are on the Nakayama Hokekyo-ji Pagoda, which is located at Ichikawa-shi in Chiba Prefecture where is close to Tokyo. It is a statue of Buddha and was dedicated in the 1622. Micro tremor measurement of this pagoda has already been conducted. Natural frequency and vibration mode of the frame and the centre column were reported. In half century, computing and image processing technology have progressed very much. Image processing techniques was applied to displacement measuring in many areas. In seismic response tests using shaking tables, the image processing displacements have been reported. In this research, we presents its response characteristics under seismic loading about 30cm/s ground velocity of 2011 East Japan Great earthquake, but also under the strong wind load by using vibration sensors and image processing.

2. HOKEKYOU-JI TEMPLE FIVE STORY WOODEN PAGODA

The pictures of Hokekyo-ji Pagoda and its location are shown in Figure 1 and 2. It is a five storied pagoda and built of wood without the use of nails. It is a 30.76m-high statue of Buddha. It was dedicated in 1622 and renovated several times, in 1743, 1864 and 1912. The pagoda is composed of a frame and a center column. On the top of the center column, a metal ornament called a sourin is attached. The structure has a square and symmetrical plan. The front of the pagoda is face to the southwest. The difference between pagoda axis and compass axis is 40degree.Figure.3 shows the cross section of the pagoda. The frame is composed of 5 blocks (stories) and the blocks are simply piled together. Each block of the frame is able to move independently from each other and it becomes a flexible frame structure. The center column is hung with the suspension system made up of 4 units of steel plate with two steel rings at the third story of the frame. The bottom head of the center column is not fixed and it is structurally restricted to move freely by the iron dowel. The center column is structurally independent from the surrounding frame. In Great East Japan Earthquake, there was no damage in the Pagoda.

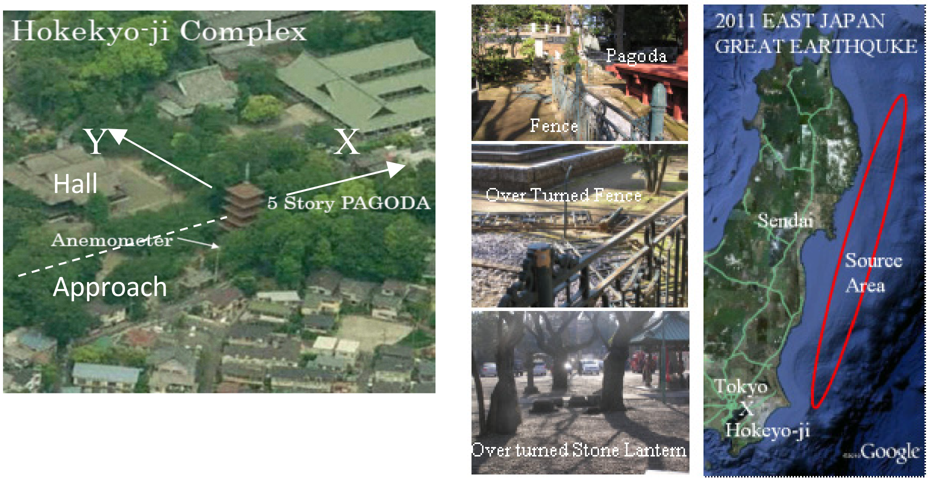


Figure 1. Location and orientation of the pagoda and damages and map of Hokekyou-ji

3. MONITORING SYSTEM

At first, vibration sensors were installed in Hokekyou-ji Five Story Wooden Pagoda. In a year, the image processing system was installed.

3.1 Vibration Sensor System

Vibration sensors and digital recorders were used in the monitoring system. Horizontal accelerations are measured at several points on the frame and centre column. Two accelerometers are set on the fifth story to measure the vertical acceleration. These are shown in Figure 2. Sampling frequency of the record was set to 100Hz at first and missing data was observed in the recorded data of the centre column. It was changed to 1000Hz now. Figure 2 is the Fourier spectra of centre column which include frequency components of more than 100Hz. The system is going at all times. .

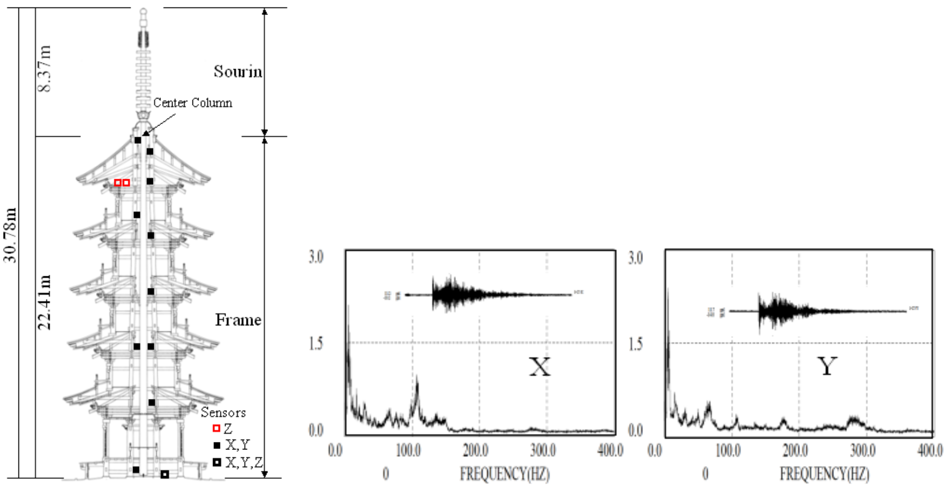
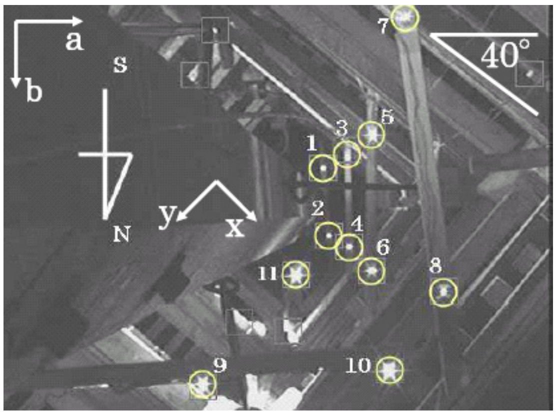


Figure 2. Structure of pagoda and sensor positions and high frequency noise of centre column

3.2 Image Processing System

Image procession monitoring system consists of CCD camera, LED makers and data acquisition computer. Figure 3 shows outline of image procession monitoring system for Hokekyou-ji five storied pagoda. Multiple markers (monitoring targets) are fixed at each story beam of five story pagoda as shown in Figure 3. And the motions of the markers are captured by a CCD camera placed at first story beam. Each marker position (pixels) in camera image is calculated instantly in data acquisition personal computer on site. The marker position data are stored in hard disk, every hour. It takes one second to store one hour data in hard disk. One year data length is about 70GB

Marker No	Height (Distance from Camera)(mm)	Distance of two markers L (mm)	Distance on Image D (pixels)	Coefficient L/D (mm/pixel)
1,2	14,479	500.0	79.27	6.3076
3,4	10,891	500.0	103.87	4.8135
5,6	7,265	500.0	158.29	3.1588
7,8	3,628	500.0	322.90	1.5484
9,10	2,208	200.0	216.52	0.9237
11	-	-	-	about 1.8



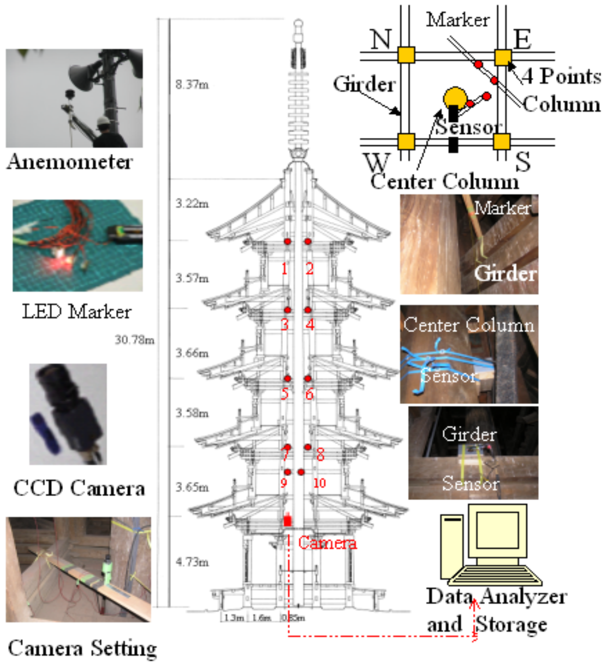


Figure 3. Maker positions and Captured multiple markers imageImage procession monitoring system

3.3 Image Processing

Fundamentally, the marker in camera image is not a point light source, and it was designed to have a resultant spread light area of some pixels on the camera image. Therefore, the light source is blurred in the camera image, and the luminance distribution of the pixels can be obtained from the pixels which were recognized as an image of marker, as shown in Figure 4.The m-th marker position $\left(p_a^{(m)},\ p_b^{(m)}\right)$ is calculated in pixels as follows. The position of the marker on the camera image with some pixels is given by the luminance f_{ij} distribution of the marker, which is over the threshold level $f_{threshold}$. In the monitoring, $f_{threshold}$ is given like this, and luminance is denoted again.

$$f_{threshold} = \lambda \cdot \left(f_{\max} - f_{average}\right) + f_{average} \quad \text{and} \quad f_{ij}^{*} = \begin{cases} f_{ij} \cdots\cdots f_{ij} \geq f_{threshold} \\ 0 \cdots\cdots f_{ij} < f_{threshold} \end{cases} \qquad (1)$$
$$\lambda = 0.1 \sim 0.3$$

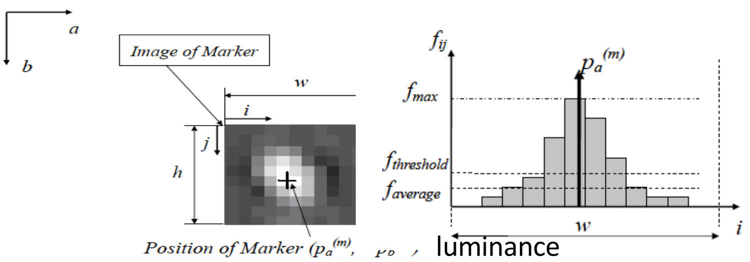


Figure 4. Marker recognition method on camera image two-dimensional

Next, the position of the marker on the images is obtained using centre of gravity calculation method. The positions of a, b directions are given as follow.

$$\left(p_a^{(m)},\ p_b^{(m)}\right) = \frac{\sum_i \sum_j (\ell i,\ \ell j)\cdot f_{ij}^*}{\sum_i \sum_j f_{ij}^*} \tag{2}$$

Calculation area (h, w) have the height of 32 pixels and the width of 32 pixels in the monitoring. f_{ij} in the monitoring is 8bits data. Pagoda displacements are calculated as follows. Pagoda axes are x, y. m) is maker number. $\left(\delta_a^{(m)},\ \delta_b^{(m)}\right)$ are displacements in screen axes for m-th marker. $\alpha^{(m)}$ is coefficient given by L/D of Figure . θ is the angle between pagoda axes and screen axes, 40degree. $\left(\delta_x^{(m)},\ \delta_y^{(m)}\right)$ is displacements in pagoda axes for m-th marker. In the monitoring, there are two LED markers in each story, with distance of 500mm.

$$\left(\delta_a^{(m)},\ \delta_b^{(m)}\right)[mm] = \alpha^{(m)} \cdot \left(\Delta p_a^{(m)},\ \Delta p_b^{(m)}\right)[pixels] \tag{3}$$

$$\begin{pmatrix} \delta_x^{(m)} \\ \delta_y^{(m)} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \delta_a^{(m)} \\ \delta_b^{(m)} \end{pmatrix} \tag{4}$$

4. LONG TERM CONTINUAL RECORDING OF IMAGE PROCESSING DATA

The image processing gave the long term horizontal deformation. Continual observation initiated at 0am from June 1st 2009. The records: elative displacements between fifth and first story beams are given in Figure 5. The seasonal and cyclic data fluctuation was found in the records. East Japan Great Earthquake gave the maximum data during nearly two years, and the relative displacements shifted small about 10mm. However the shift values went back to previous ones. The continual data gathering after East Japan Great Earthquake stopped by electric power outage in five days on March 16.

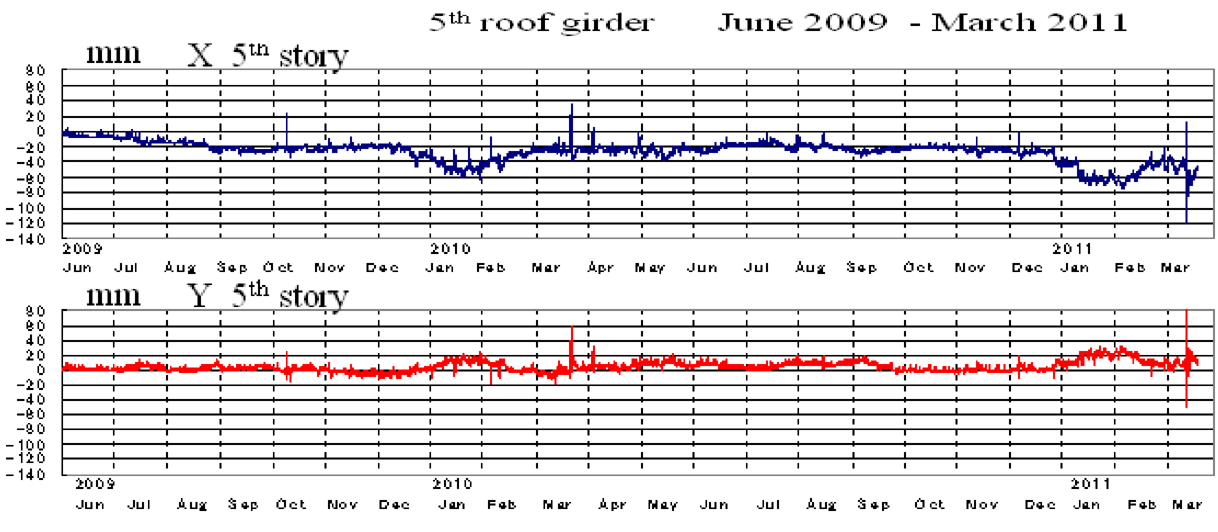


Figure 5. Relative Displacements between Fifth and First Story Beams from June 2009 to March 2011

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5. GROUND MOTION

Seismic Intensity around Ichikawa City, where Hokekyouji Temple locates, was V. Maximum recorded data on ground surface before Great East Japan Earthquake (March 11th 2011) was seismic intensity IV. Maximum acceleration values on ground surface were listed as follows.

				Approach.(X)	Hall(Y)	UD(Z)
May	8th	2008	Ibaraki–oki	0.039G,	0.028G,	.0.013G
March 11th		2011	East Japan	0.279G,	0.135G,	0.167G

Acceleration time histories of Great East Japan Earthquake at Hokekyou-ji Temple are shown in Figure 6. One time Integral velocity time histories through 0.01Hz HPF(High frequency Pass Filter) are shown in Figure 6. Maximum velocity value was about 30cm/s. The response velocity spectra of the data are Figure 7. Biggest Peak natural periods are about 0.7second in approach direction, 3.5second in hall direction. Longest natural period was about 20second.

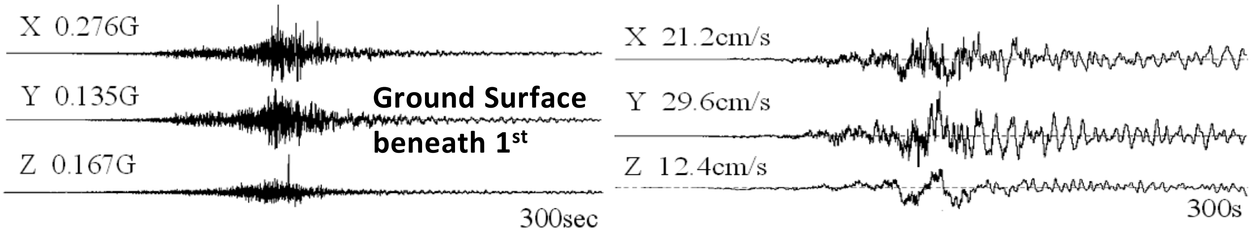


Figure 6. Observed ground surface acceleration and integral ground surface velocity (HPF0.01Hz)

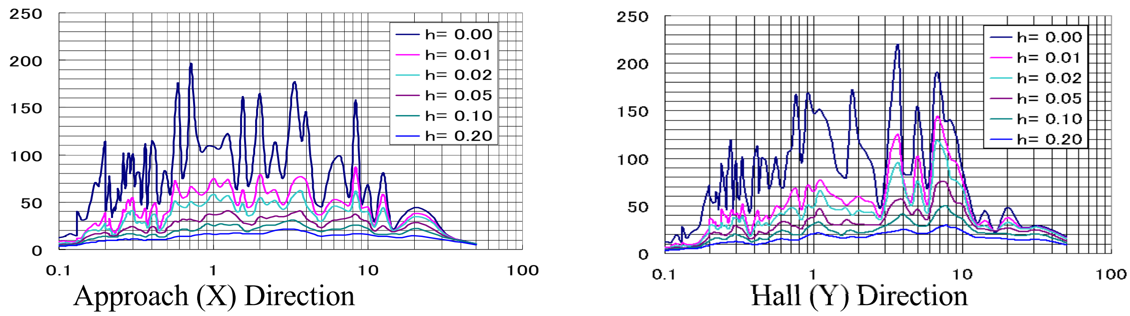


Figure 7. Velocity Response Spectra

6. ACCELERATION DATA OF FIVE STORY PAGODA

6.1 Frame Data

The data without an approach direction component of first story beam acceleration recorded successfully. However many components were saturated. The acceleration data, which were observed at fifth and third story beams, went over the saturated levels in many times. The frame acceleration time histories of two directions are shown in Figure 8. The reason of saturation was estimated to be

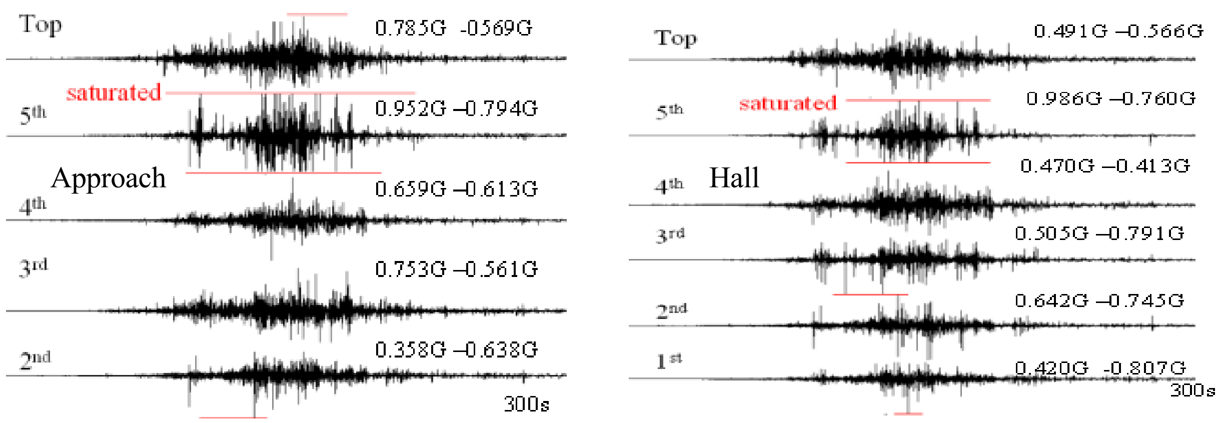


Figure 8: Frame acceleration in approach and hall directions

caused by the crashes of piping close to sensors. The acceleration data of top and fourth roof girders would be reliable. Therefore, the maximum response acceleration values were estimated about 0.8G in approach direction, 0.6G in hall diction. Acceleration response time history is not suitable to estimate the behavior, because of high frequency noises. Thus, one time integral through 0.2Hz HPF were conducted to estimate velocity time histories, as shown in Figure 9. The wave shapes of integral velocity of saturated date were different from appropriate ones. The maximum velocity values of top roof girder were about 40cm/s.

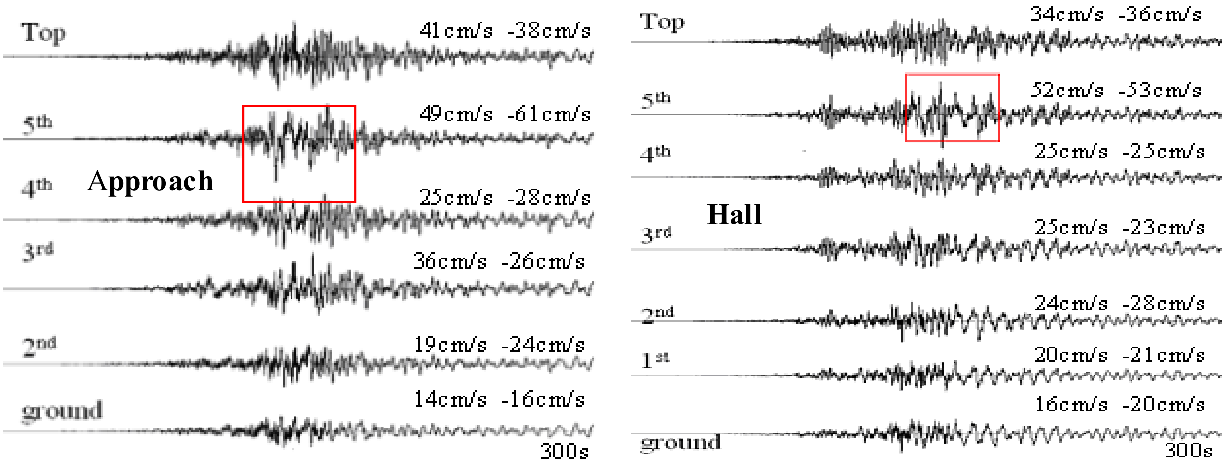


Figure 9. Frame integral velocity in approach and hall directions

6.2 Centre Column Data

All components of centre column acceleration went over the saturated levels. The acceleration values were out of considerations. The data recorded in 1000Hz sampling frequency. The saturation did not continue. In the integrals, saturation effects were considered to be small. Therefore, the time histories of one time integral velocity through 0.2Hz HPF indicated the reasonable ones. Acceleration time histories of centre column are shown in Figure 10. and time histories of one time integral velocity are shown in Figure 11.

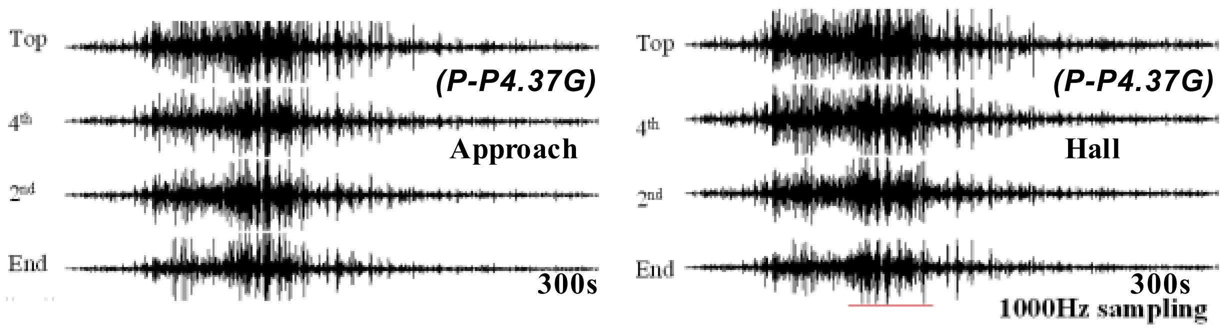


Figure 10. Centre column acceleration in approach and hall directions.

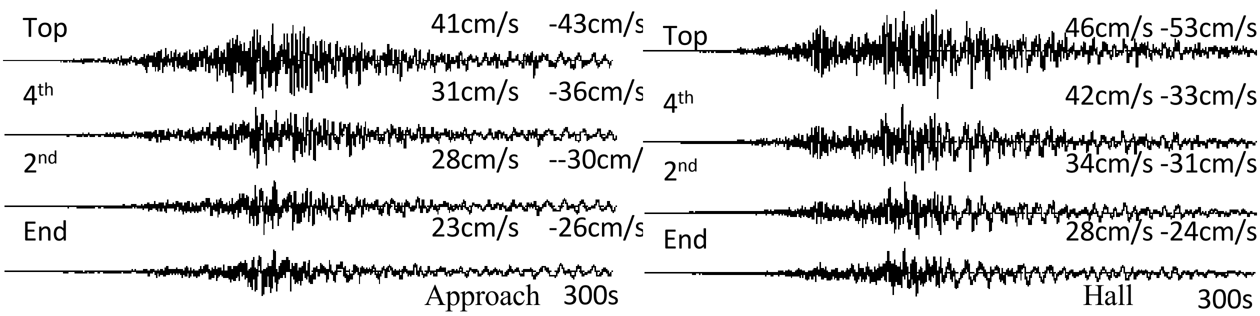


Figure 11. Centre column integral velocity in approach and hall directions

7. RELATIVE DISPLACEMENT OBSERVATION USING IMAGE PROCESSING

Relative displacements between each marker position and first roof girder were obtained by using image process methods. The earthquake occurred at 2:47pm, and the sunlight glared with the LED markers. The automatic marker selection program wandered, and generated shock noises, as shown in Figure 12. Two markers were installed at each roof girder. If two marker positions differed very much, reasonable marker position was selected. In the case of no suitable positions, linear interpolation was bases on the data before and after If CCD camera might tilt, the image processing relative displacement data would include the tilt effects.

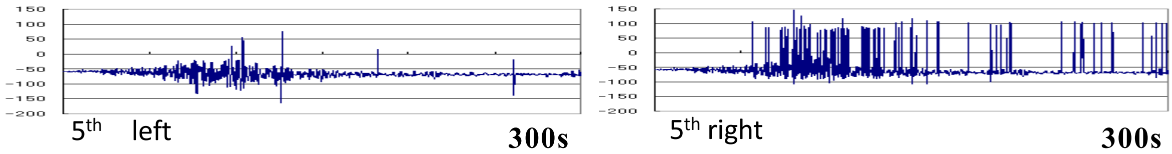


Figure 12. Pulse noises by sun light in the image data

7.1 Frame Data

Relative displacements between fifth marker and CCD camera positons in approach direction presented the maximum value about 75m, and residual relative displacement of 10mm remained,as shown in Figure 13. This relative displacement on March 16 after five days was gone. The fifth relatvie displacement in hall direction moved about 70mm. The residual relative displacements in hall direction were very small in comparison with approach direction components in Figure 13.
Plotting the vertical distributions of relative displacement at three main time points, It can be seen that go upward in accordance with increasing relative displacements, as shown in Figure 14. Witness said large deformations of higher position more than third roof. The vertical distribution of image processing data were agreed with the observation description of Hokekyouji temple monk witness

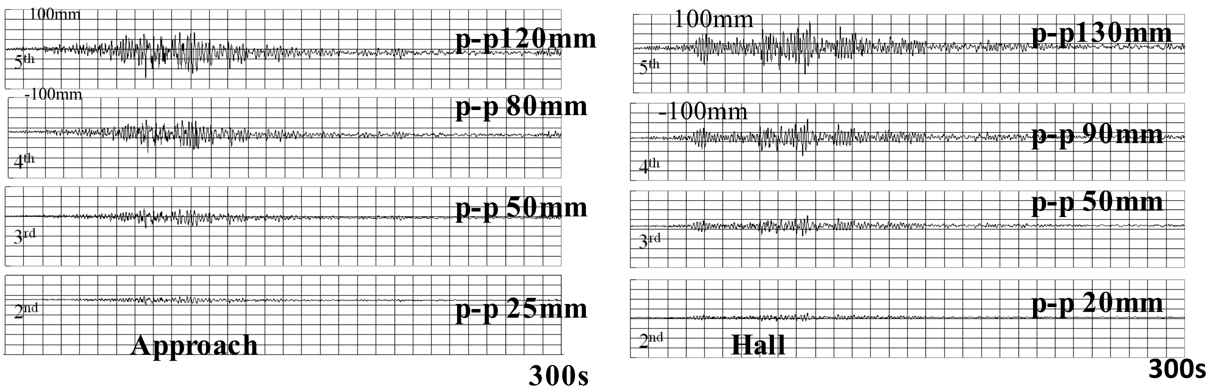


Figure 13. Relative displacements in approach and hall directions

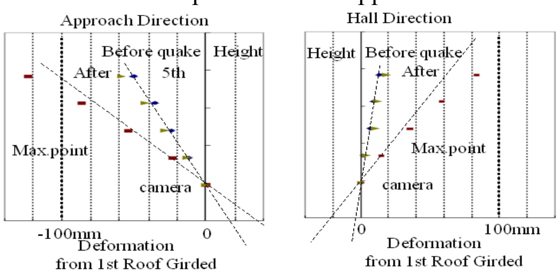


Figure 14. Vertical distribution of image processing data.

7.2 Center Column Data

There is a marker for the observation at height position corresponding to near second frame marker, this centre column behavior was recorded as shown in Figure 15. Observed data in approach direction described the one side movement in the negative region, The hall direction data gave the gradual movement and pulse-like motion was mixed, and moved about 25mm on both sides, the residual seen.

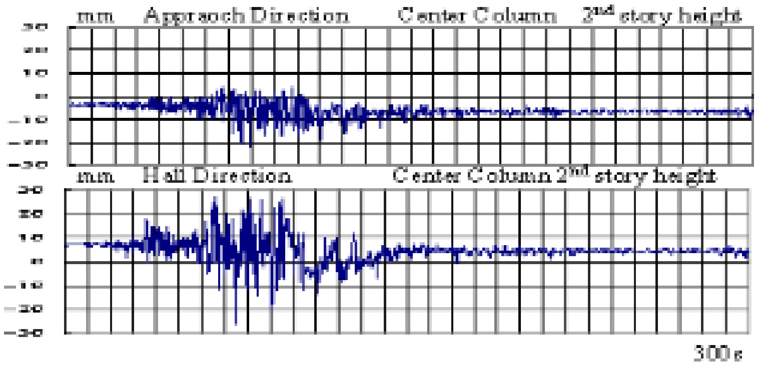


Figure 15. Image processing data of centre column

7.3 Comparison with Acceleration Data Integral Displacement

Two times integrals of acceleration data through 0.2Hz HPF were carried out to estimate relative displacement from ground and verify the reliability of image processing relative displacement from first story beam, as shown in Figure 16. Frame marker positions were same as acceleration sensor positions. No saturated components of acceleration record would provide more reasonable displacements. So, using the marker and acceleration data of second roof girder, also ground acceleration data, the story displacement in approach direction of first roof girder, which was image processing camera position, would be estimated as 25mm approximately. Integrated relative displacements between top position and ground were estimated as 85.7mm in approach direction, and 84.1mm in hall direction. The values would be suitable. Figure 17 is the over-lay plots of the integral relative displacement at top position and image processing data at fifth marker in hall direction.

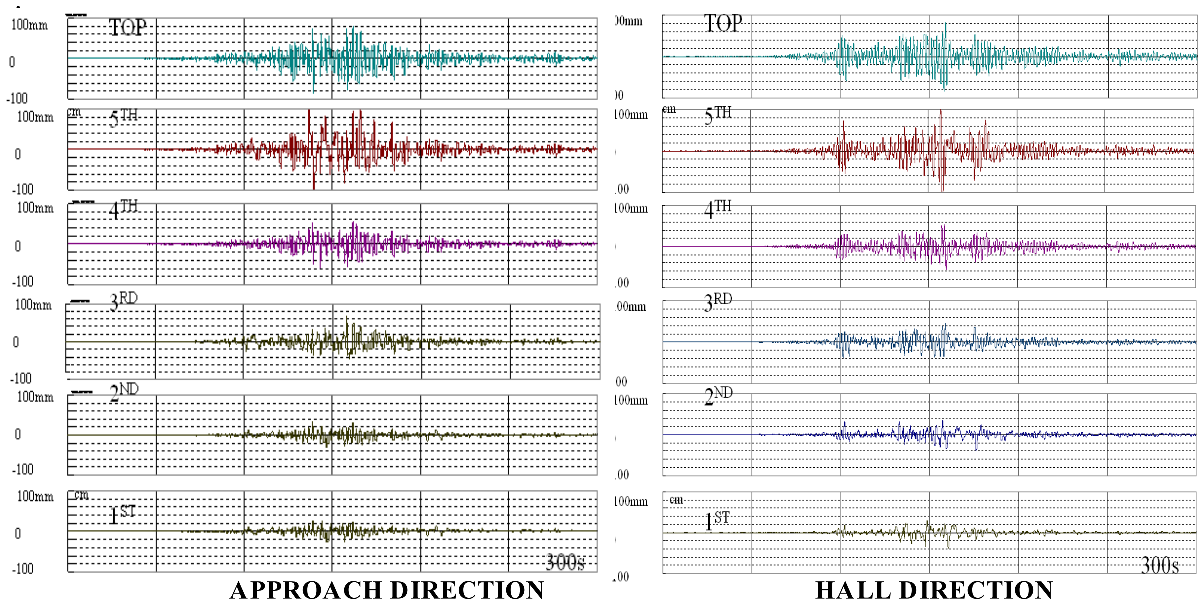


Figure 16. Integral relative displacements from ground .

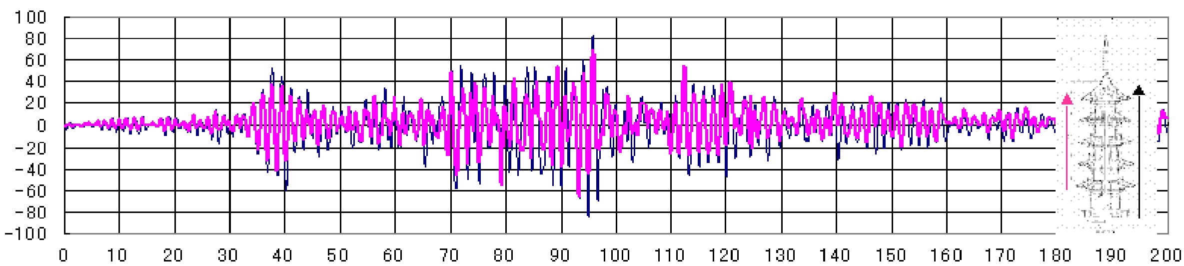
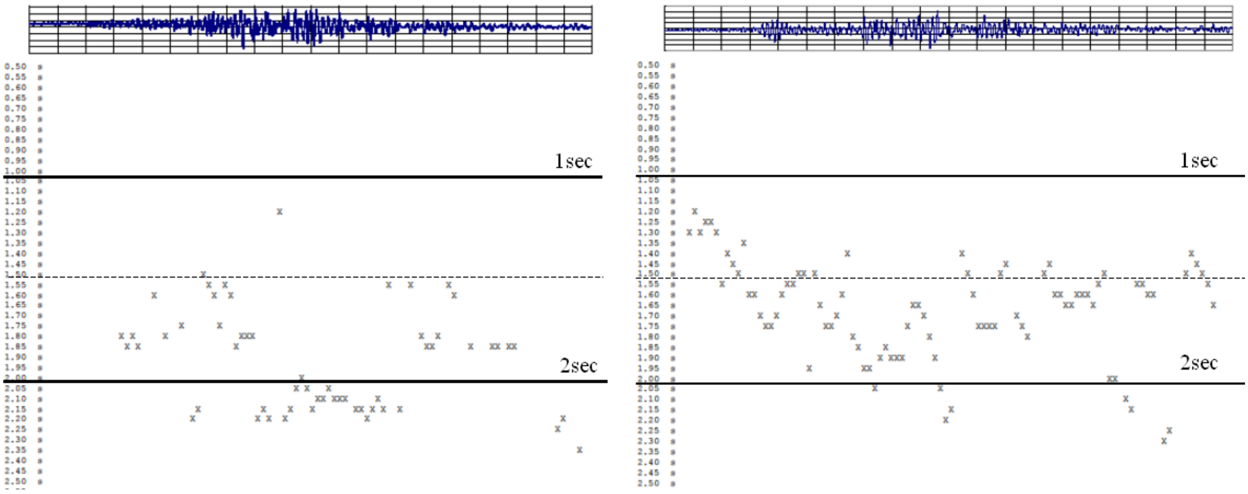


Figure 17. Two times integral of top position and image processing at fifth position in hall direction



APPROACH DIRECTION **HALL DIRECTION**

Figure 18. Running spectra of image processing data at fifth story position

7.4 Running Spectra

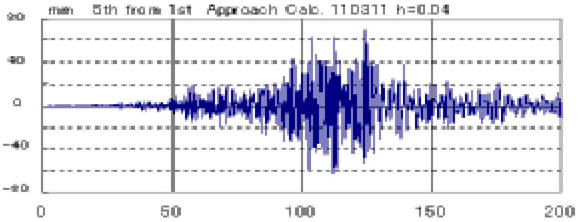
Running spectra analysis was conducted to take the information for rigidity degradation depending on amplitude. Relative displacements between fifth and first roof girder of 200second length were used for the analysis. The frame time is 10secon, and shift time is 1second. At beginning of small amplitude, the dominant period was about 1.25second approximately. And at large amplitude more than 50mm, dominant period was enlarged to about 2second. After main quakes, dominant period returned to the original period. The rigidity of pagoda is estimated to decrease to 40% at amplitude of about 50mm as shown in Figure 18.

8. MODEL ANALYSIS

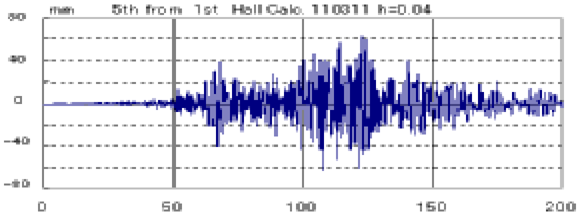
Primitive model analysis was carried out. In observed response of Great East Japan Earthquake, the relative displacement between fifth and first roof positions remained only 10mm residual. So, elastic analysis could be used for the discussion. The analysis methods already presented in WCTE paper (Minowa et. 2010) of the assumed mode method were used. Major parameters in the analysis were same as the analysis of the WCTE paper Calculated natural frequencies are 0.56Hz(1.78s) of first mode, 1.27Hz of second mode, 1.60Hz of third mode.

8.1 Responses to 2011 EAST JAPAN GREAT EARTHQUKAE

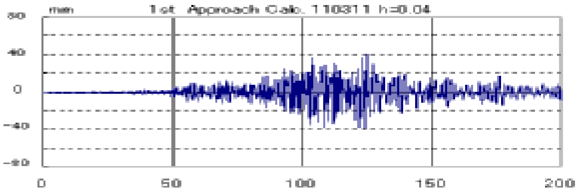
Five story pagoda responses to 2011 East Japan Earthquake of Hokekyou-ji for each direction, approach and hall direction are calculated. Equation without wind force inputs is used for the calculation. The inputs were the ground time histories, which were recorded at 14:47 on March 11th 2011. The input waves ware through low pass filter 20Hz. The model and constants are same as that of previous modal analysis. Calculation step interval time in the case is 0.0001sec. Figure 19 is the calculation results. The calculated relative displace between 5th and 1st stories are recognized to meet with the image procession observed data. The first story displacements were not observed. In the calculations, the first story displacement about 40mm were taken in each two direction.The centre column would be estimate to demonstrate linear shape response. In the calculation, the damping 4% was used. The damping 20% was used in wind response calculation.



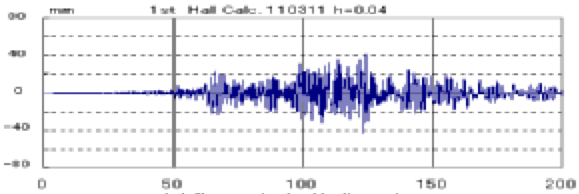
Between 5th and 1st stories In approach direction



Between 5th and 1st stories In hall direction



1st Story in approach direction



1st Story in hall direction

Figure 19 . Calculated relative displacement time histories to 2011 East Japan Great Earthquake

CONCLUSIONS

At five story pagoda of Hokekyou-ji temple which is a national culture heritage, relative displacement records of almost two years were obtained, and the seasonal fluctuations of the horizontal deformations were found. In addition, in the earthquake of March 11, 2011 East Japan Great Earthquake, seismic intensity V was observed.

Image processing gave relative displacement data successfully. Concerning acceleration observation, some data saturated partially. Every observed acceleration data of center column saturated. However, one time integral velocities provided reasonable time histories, because of high frequency sampling 1Hz.

Image Processing gave the maximum relative displacement of 75mm, and residual relative displacement 10mm. The residual ones vanished in as few days.

The dominant frequency elongation was observed. The rigidity of the pagoda was estimated to decrease at 40% of initial one in large amplitude.

Elastic response analyses to the earthquake and strong wind were carried out. Damping in the earthquake is estimated to be 4%. High damping would be estimated at strong wind.

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