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# RESEARCH AND DEVELOPMENT OF THREE-DIMENSIONAL MEASUREMENT METHOD FOR DYNAMIC DISPLACEMENT IN SHAKE TABLE TESTS APPLYING IMAGE PROCESSING TECHNIQUE

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## SUMMARY

National Research Institute for Earth Science and Disaster Prevention in Japan has been constructed a large three-dimensional shake table test facility in Kobe prefecture, Japan since 1995. In this shake table, it is purpose to do research a fracturing process of various architectural, civil or mechanical structure by shaking a real scale structural model in three-dimension. Current measurement systems with a contact, however, are not suitable for the measurement such fracturing tests because the test model will be shaken with large deformation and flexible behavior. Therefore, a new measurement system, which can measure a three-dimensional large deformation without any contact, has been desired. This study has been doing research and development of new three-dimensional measurement method using an image processing technique to measure the dynamic displacement in shake table test. This measurement system is a very convenient system because it can measure the three-dimensional dynamic displacement in shake table test in which the several makers are only attached to the surface of an experimental structure. The system therefore is the most suitable measurement system for an evaluation of complex three-dimensional behavior of experimental model. Fundamental hardware and software for the measurement system has been constructed until now. The fundamental dynamic measurement accuracy and effectiveness of the measurement system has been also confirmed from several shake table tests. This paper describes the synthetic performance of the proposed measurement system, and also the measurement performance in actual fracturing test using the full scale wooden house model which is the second-storey house of a Japanese conventional model.

## INTRODUCTION

As the experimental approaches evaluating the seismic reliability of structures, shake table tests using scale model or pseudo dynamic tests using partial structural element are the most popular methods and

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have been taken place for long years. However, we sometimes find difficulties in validating seismic resistant design capabilities of the real structures especially in the case of clarifying the fracturing process of them because the limitations regarding the size of experimental structures and the table capacity. National Research Institute for Earth Science and Disaster Prevention is now constructing the largest three-dimensional shake table in Miki, Hyogo prefecture to evaluate fracturing mechanism and process of many types of structures such as bridges, buildings, containment vessels, electric power facilities, soils, foundations and underground structures of the full scale.

In this study, the research and development of three-dimensional measurement method of non-contact type is now being carried out for establishing a suitable system to measure the structural fracturing process accurately during the shake table tests using the real scale model[1]. This paper describes the synthetic performance of the proposed measurement system, and also the measurement performance in actual fracturing test using the full scale wooden house model which is assumed the second-storey house of a Japanese conventional model.

## MEASUREMENT METHOD

### Outline of measurement method

The desired measurement method suitable for seismic testing is being examined to fulfil the following design requirements.

1) To measure large displacement in excess of elastic deformation in real scale model
2) To measure three-dimensional structural deflexion
3) To measure structure without any direct contacts
4) To measure structural motion in at least cm order precision till collapse
5) No special environment for measurement is required
6) To capture data at 5ms resolution for continuous 60 seconds

### Progress of the development

This study has passed through large two stages of the research and development. The progress of the development is shown in below.

Stage I-1: The technology survey of existing dynamic displacement measurement system using image processing, the extraction of the problem for the existing systems, and the construction of the fundamental concept of the system suitable for the research purpose[1]. [Preliminary experiment on the static test]

Stage I-2: Design and trial manufacture of the dynamic displacement measurement system using image processing[2]. [Shake table test using the five-story shearing type building model]

Stage I-3: Synthetic performance evaluation of the fundamental measurement system[3]. [Shake table test using the collapse building model]

Stage II-1: Development for the practical application of the three-dimensional measurement system[4]. [Shake table test using the inverted pendulum and collapse building model]

Stage II-2: Upgrading of the measurement system for the practical use in the large three-dimensional fracturing test facility, and the synthetic performance evaluation using the three-dimensional shake table[5]. [Three-dimensional shake table test using the rigid body model and the wooden house model]

### Theory of measurement method

The three-dimensional dynamic displacement of the experimental model on shake table test is obtained from the camera image data captured by the CCD cameras. Since the dimension between the input and output is different, some transformation method is necessary in the process of the conversion from the 2-dimensional camera image coordinate system to three-dimensional object coordinate system. This study has been used the transformation matrix, which is called 'camera parameter'[6][7]. The relation between the object coordinate system (x,y,z) and the camera image coordinate system ($X_C$,$Y_C$) is obtained from the following equation.

$$\begin{bmatrix} HcXc \\ HcYc \\ 1 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & C_{14} \\ C_{21} & C_{22} & C_{23} & C_{24} \\ C_{31} & C_{32} & C_{33} & C_{34} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} \qquad (1)$$

Here, [$C_{ij}$] is called as the camera parameter. The coordinate transformation formula using *n* camera units to measure the optional marker becomes the following equation, when camera parameter of the *n* number is made to be $C^n$.

$$\begin{bmatrix} C^1_{11} - C^1_{31}Xc^1_{11} & C^1_{12} - C^1_{32}Xc^1_{11} & C^1_{13} - C^1_{33}Xc^1_{11} \\ C^1_{21} - C^1_{31}Yc^1_{11} & C^1_{22} - C^1_{32}Yc^1_{11} & C^1_{23} - C^1_{33}Yc^1_{11} \\ \vdots & \vdots & \vdots \\ C^n_{11} - C^n_{31}Xc^n_{11} & C^n_{12} - C^n_{32}Xc^n_{11} & C^n_{13} - C^n_{33}Xc^n_{11} \\ C^n_{11} - C^n_{31}Yc^n_{11} & C^n_{12} - C^n_{32}Yc^n_{11} & C^n_{13} - C^n_{33}Yc^n_{11} \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} Xc^1_{11} - C^1_{14} \\ Yc^1_{11} - C^1_{24} \\ \vdots \\ Xc^n_{n1} - C^n_{14} \\ Yc^n_{n1} - C^n_{24} \end{bmatrix} \qquad (2)$$

By obtaining x, y, z from above equation, the three-dimensional coordinate of the object can be derived from the two-dimensional camera image coordinate. Besides, it is necessary to measure the measurement targets at least two cameras theoretically.

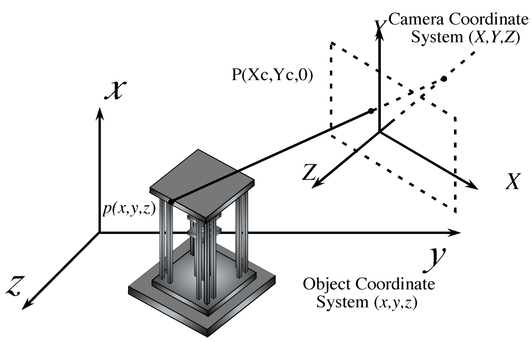



Fig. 1 The relation between object and camera coordinate system

**Marker recognition method**

The position of the marker on the camera image with some pixels is given by the luminance distribution of the marker which is over the optional threshold level. Fundamentally, the marker used for this study 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. The luminance for the x direction, $f_x$ ,means the summation of the luminance, *c*, for the y direction on the i*th* pixel for the x direction. The luminance value, $f_x(i)$, on the i*th* pixel of x direction is expressed as,

$$f_x(i) = \sum_{p=1}^{h} c(i,p) \qquad (3)$$

then the luminance value $f_y(j)$ on the j*th* pixel of y direction is given by,

$$f_y(j) = \sum_{p=1}^{g} c(p, j) \tag{4}$$

Next, the position of the marker on the $g \times h$ images is obtained using centre of gravity calculation method. The position for the x direction is given as,

$$x = \frac{\sum_{s=is}^{ie} f_x(s)s}{\sum_{s=is}^{ie} f_x(s)} \tag{5}$$

then the position in y direction is also given by,

$$y = \frac{\sum_{s=js}^{je} f_y(s)s}{\sum_{s=js}^{je} f_y(s)} \tag{6}$$

Since the obtained position is the position on the camera image, the position of the marker in the camera image can be obtained from the relation of the position in between the pixels for marker and the pixels of whole camera image.

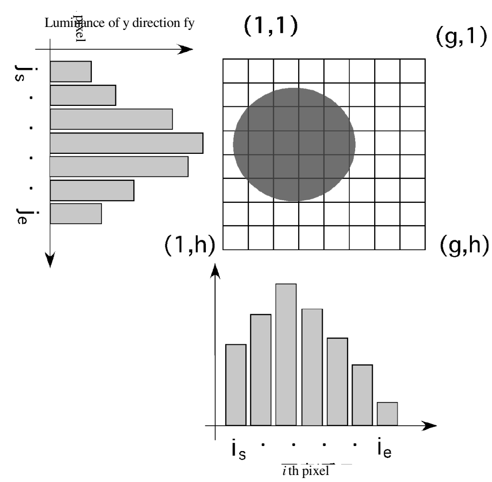



Fig.2 Marker recognition method on two-dimensional camera image

## MEASUREMENT SYSTEM FOR THREE-DIMENSIONAL DYNAMIC DISPLACEMENT USING IMAGE PROCESSING

### CCD camera and Marker

Figure 3 shows a CCD camera unit in order to capture the dynamic behavior of the test object on the shake table. It is desired that the dynamic displacement of the experimental object is measured at the adequately high sampling frequency to capture the fracturing process of the test model during an earthquake input with highest accuracy. The camera can take 200 flames per second in order to satisfy the design requirements mentioned above, and the higher speed photographing is also possible at 400 flames per second if the camera images are reduced to the half size. The resolution of camera has 504(H)×241(V). The lowest subject luminance is 10 [lux] and it is also suitable for measurement in the experimental environment without high-lighting.

The marker used for the shake table test is shown in Fig. 4. The spherical diameter is 70mm and the seventeen red LEDs are placed on it as shown in the figure. The marker can emit light for 90 minutes using a 6[V] lithium power battery which is contained inside the marker box. The marker is equipped with the wireless switch to turn on and off the LEDs. Since the marker becomes cordless, it is possible to attach it into the structure without considering the wiring of the cable for the power supply in any optional position. Moreover, by placing seventeen LEDs around the centre LED with some inclination, it is possible to recognize the position of the marker when the object structure has some rotational angle during the shake table test.

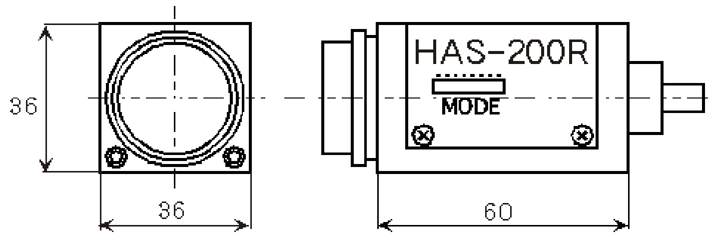



Fig.3 High speed CCD camera used for the test

Table 1 Basic specification of CCD camera

| | |
|---|---|
| Photographing system | Exclusive Solid-State Imaging Detector |
| Resolution | 504(H)×241(V) |
| Photographing speed | 200FPS(full)/400FPS(half) |
| Useful detection area | 4.9mm(H)×3.69mm(V) |
| Lowest subject luminance | 10 lux |
| S/N ratio | Over 45dB |

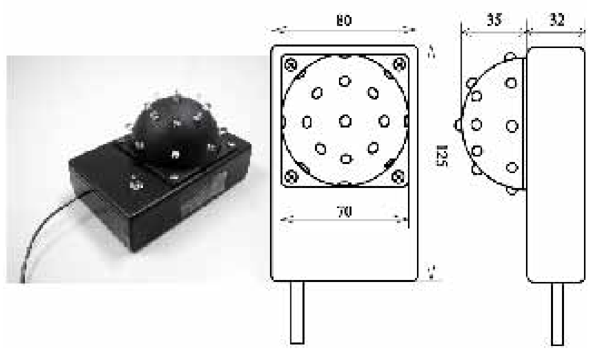



Fig.4 LED marker used for the test

## SHAKE TABLE TEST FOR THE EVALUATION OF SYNTHETIC PERFORMANCE OF THE PROPOSED MEASUREMENT SYSTEM

The fundamental measurement performance of the proposed measurement system using the image processing technique had been mainly evaluated from the shake table tests in the one-dimensional excitation. It is necessary to verify the measurement accuracy for the dynamic behavior at three-dimensional excitations, because the three-dimensional shale table facility will be used for the actual test to investigate the fracturing process of the real-scale structure. In this test, the measurement accuracy on three-dimensional rotating behavior was also verified with the three-dimensional translating behavior.

Moreover, the synthetic performance for the measurement system was evaluated from the seismic wave excitation test and various static and dynamic tests including the rotational excitation mentioned above. The experimental contents carried out this time are shown in the following.

Case I: Measuring accuracy for the rotational behavior
Case II: Measuring accuracy by the distance between cameras
Case III: Measuring accuracy by the angle between cameras
Case IV: Measuring accuracy by the measurement distance
Case V: Measuring accuracy on three-dimensional shake table test

**Experimental condition**

Figure 5 shows the picture of the experimental model used for the test and Fig.6 shows the schematic view of the test object whose size is $3.2^{W}$[m] $*3.2^{D}$[m] $*4.0^{H}$[m]. This object is the steel structure and was estimated as a rigid body because the natural frequency of the main frame was about 50 [Hz]. Then, this figure also shows the attached condition of the markers on the experimental object. Twenty-two markers were placed in each face including the top of the model. The initial three-dimensional position of these markers was measured by the space instruments before the shake table tests for using the camera parameter matrix.

Nine CCD cameras were used for the test and the cameras were placed around the object as shown in Figs.7 and 8. In the camera position in Fig.7, Camera No.2 and No.3 were placed at the second floor level, and the other cameras were set up on the ground level. Then, Camera No.1, No.4, No.5 and No.6 were placed to become the camera arrangement that the distance between cameras is set about 3, 5, 7, 8, 12 and 15 [m]. This camera arrangement was used for the test except for Case II. Besides, in the test of Case III, the cameras were placed to be the camera arrangement that the angle between cameras become about 20, 45, 60, 75, 90, 135 and 180 [°] as shown in Fig.8.

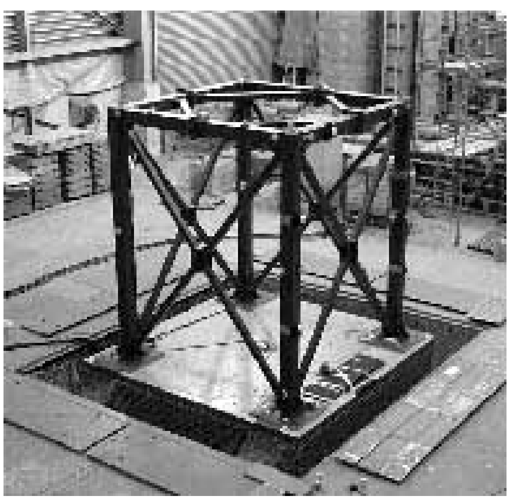


Fig.5 Experimental object used for the test

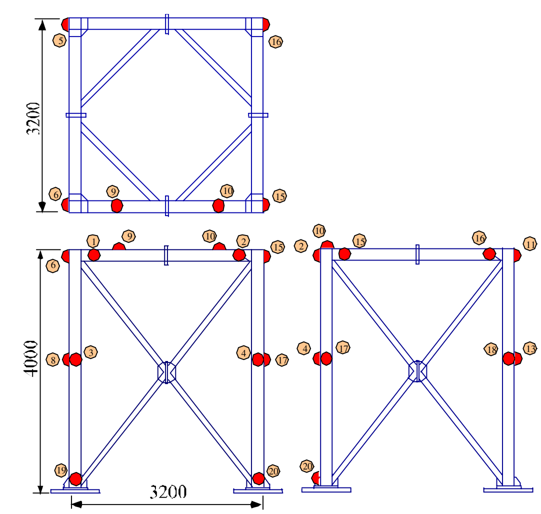
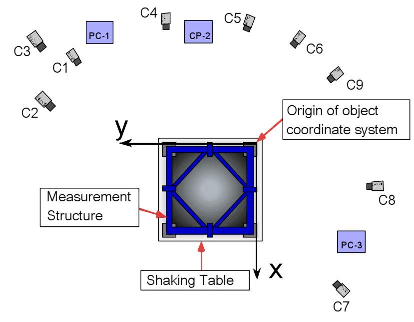


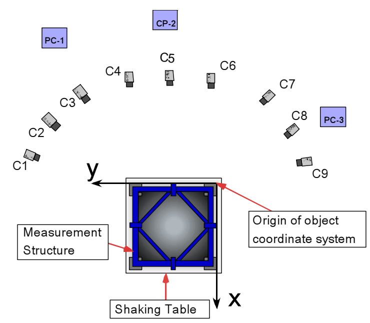

Fig.6 Schematic view of the experimental model and the attached condition of the marker

The shake table in Tokyu Construction laboratory was used for the test. The size of the table is 4 [m]*4 [m], and then this shake table can induce the seismic wave to the object in three dimensions. Table 2 shows the specification of the shake table. In this test, the seismic wave, which was recorded in Takatori station at Kobe earthquake in 1995, was used as an input wave. Maximum accelerations in the horizontal X and Y-direction are 741 and 624 [Gal], respectively. Besides, the sampling frequency was set to 100 [Hz] in the all of test. Moreover, the experimental results were obtained from the mean value of the response in the markers No.3 and No.4. In the measurement, the infrared ray filter was installed to the camera lens to reduce the effect of the lighting in the facility and natural light from the windows.




| | Axis [m] | | |
|---|---|---|---|
| | x | y | z |
| 1 | -11.0 | 8.28 | 1.42 |
| 2 | -7.98 | 9.92 | 6.44 |
| 3 | -11.0 | 9.93 | 6.44 |
| 4 | -11.0 | 2.06 | 1.41 |
| 5 | -11.0 | -3.15 | 1.41 |
| 6 | -8.93 | -5.83 | 1.41 |
| 7 | 10.9 | -7.82 | 1.32 |
| 8 | 1.49 | -8.36 | 1.41 |
| 9 | -6.39 | -7.88 | 1.39 |

Fig 7 The layout condition of CCD cameras in Case I, II, IV and V




| | Axis [m] | | |
|---|---|---|---|
| | x | y | z |
| 1 | -0.82 | 11.0 | 1.40 |
| 2 | -6.73 | 8.50 | 1.41 |
| 3 | -8.49 | 6.82 | 1.44 |
| 4 | -9.66 | 3.24 | 1.44 |
| 5 | -9.68 | 1.70 | 1.45 |
| 6 | -9.66 | 0.31 | 1.45 |
| 7 | -8.44 | -2.57 | 1.45 |
| 8 | -6.68 | -4.97 | 1.44 |
| 9 | -0.51 | -7.58 | 1.42 |

Fig.8 The layout condition of CCD cameras in Case II

Table 2 Specification of shaking table

| | Direction | | |
|---|---|---|---|
| | X | Y | Z |
| Max. disp. [m] | ±0.5 | ±0.2 | ±0.1 |
| Max. vel. [m/s] | ±1.5 | ±1.0 | ±0.99 |
| Max. acc. [G] | ±1.0 | ±1.0 | ±1.8 |
| Shaking freq. [Hz] | DC～30 | DC～50 | DC～50 |
| Max. rotation [°] | ±2.8 | ±2.8 | ±4.0 |

**Measurement result**

*Experimental Case I*

Figure 9 shows the example of the measurement results in the marker No.3 when the sinusoidal wave (X-direction: 0.5 [Hz], ±2.8 [°], Y-direction: 0.55 [Hz], ±4.0 [°]) was induced. The figure is constructed from six measured waves and three error waves. The left column show the calculated results based on the monitored results of the shake table behavior. These results were used for the index waves in order to evaluate the measured wave using the proposed system. The middle column means the measured waves using the image processing system. Then, the right column indicates the error wave which was obtained from the difference in between the left and the middle columns. Moreover, the figures show the wave in X, Y and Z-direction from upper figures, respectively.

The maximum displacements in each direction became about 80, 170 and 50 [mm] with flexible rotational behavior. However, the measurement error was several millimeters. From the result, it is confirmed that the measurement system can measure the complicated behavior with the rotation which will occur the initial stage of fracturing process.

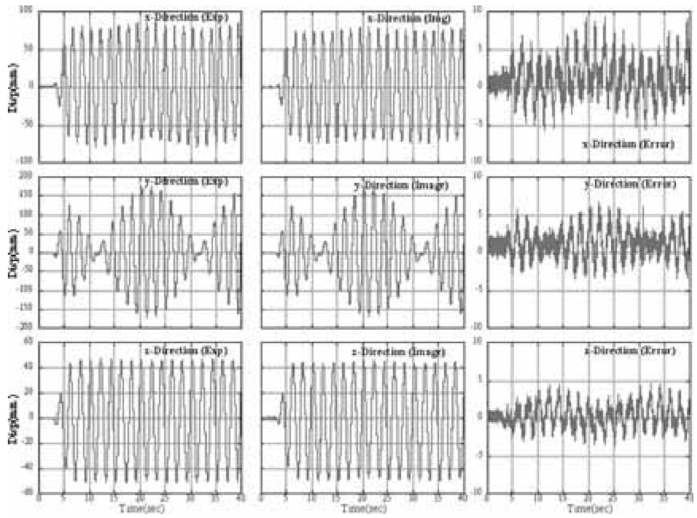


Fig.9 The comparison with the measurement results on the time history in Case I

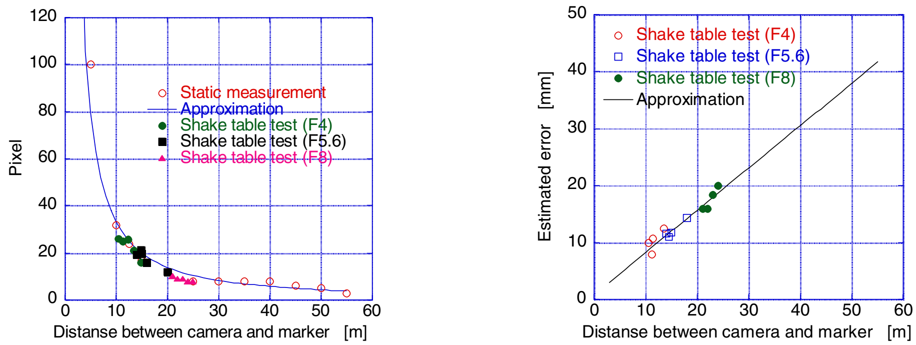
Table 3 Maximum and RMS error in Case I

| Direction | Max. error [mm] | RMS error [mm] | Error at max. disp. [mm] |
|---|---|---|---|
| X | 9.4 | 2.8 | 9.2 |
| Y | 6.7 | 2.0 | 6.1 |
| Z | 4.5 | 1.5 | 1.9 |

*Experimental Case II ~ IV*

In the experimental Case II~IV, it was confirmed the relation of measuring accuracy by the distance and the angle between cameras, and also the measuring accuracy by the measurement distance. It was confirmed that the relation between the distance and the angle between cameras are desired to become over 3 [m] and to be the angle from 45 to 135 degrees for stable good measurement accuracy from the shake table test. Besides, the measurement accuracy in the vertical direction, which means Z-direction in the figure, is not to be depended on the camera placement.

Figure 10(a) shows the relation between the recognized pixel on the camera image and the measurement distance which means the distance between the camera and the marker. This result was composed from the static and dynamic experimental results. The white plots are the static experimental result. In this test, the recognized pixel on the camera image was investigated when the position of the marker is kept straight away from the camera from 5[m] to 55[m] in 5[m] step in which the camera position was fixed. Then the black plots are the results obtained from the shake table test in X direction shaking. The excitation wave is the sinusoidal wave in 0.2[Hz] shaking frequency and 50[mm] amplitude. Here, the measurement distance was made to change imaginarily by the variation of F number of the camera. In this time, the similar shaking tests were carried out using three different F numbers. The recognized pixel on the camera image exponentially decreases for the measurement distance as shown in the figure. It is shown that the tendency of the results on the static and dynamic test agrees with each other. Therefore, changing F number can assume the change of the measurement distance. Figure 10(b) shows the relation between the measurement distance and the measurement error based on the static and dynamic measurement tests. As the result, the measurement error increases linearity with the increase of the measurement distance. It has been confirmed that it is desirable that the marker is recognized over 15 pixels on the camera image in order to obtain the measurement error at least 15[mm]. This result was verified the tendency from dynamic testing. As the result, it was confirmed that dynamic displacement measurement under about 20 [m] measurement distance is prefer to obtain the good measurement accuracy.




(a) (b)

Fig.10 The relation with the measurement distance, recognized pixel and measurement error

*Experimental Case V*

Figure 11 shows the measurement result in which JR Takatori wave induced to the experimental object in three-dimension. The results were arranged as same as Fig.7, and then the measurement errors were summarized to Table 4. Although the measurement error like a spike was shown in Y and Z direction, the measurement accuracy become fundamentally under 10 [mm]. It was confirmed again that the relation between the measurement distance and error mentioned above can apply for the actual experimental results on three-dimensional shake table tests. From the results, it is considered to obtain the sufficient accuracy in the actual three-dimensional shake table test by applying the measurement method using the image processing technique which was set to the measurement condition as this time.

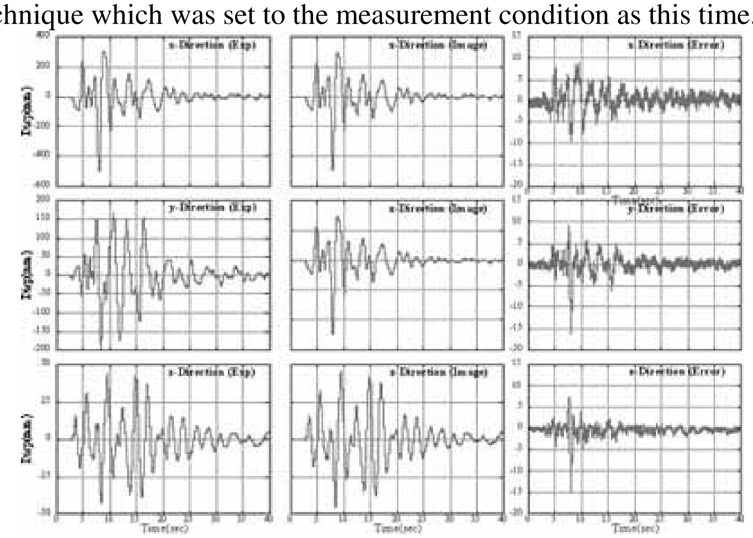


Fig.11 The comparison with the measurement results on the time history in Case V

Table 4 Maximum and RMS error in Case V

| Direction | Max. error [mm] | RMS error [mm] | Error at max. disp. [mm] |
|---|---|---|---|
| X | 9.6 | 2.2 | 7.1 |
| Y | 16.3 | 1.9 | 4.7 |
| Z | 14.8 | 1.5 | 1.2 |

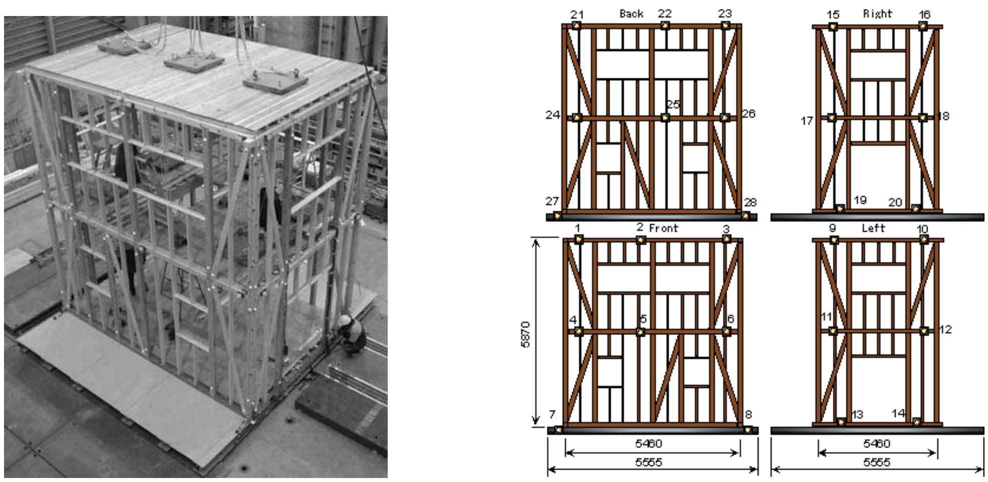
## FRACTURING TEST USING WOODEN HOUSE MODEL

**Measurement object of Wooden house model**

Figure 12 shows the full scale model of two-story wooden house used for the shake table test. The size of the test object is $3.640^{W}$[m] $*5.450^{D}$[m] $*5.820^{H}$[m]. Natural frequency and damping coefficient are shown in Table 5. This wooded house was modelled as a Japanese conventional wooden house under the old Japanese structural code for seismic safety. The strap bolt was used in the edge of the beam, and also the T shape metallic element was used in the top and the bottom part of the column for estimating the conventional wooden house based on 1979's code. The total mass is 6400 [kg] including the additional mass in 1st and 2nd floor.

Table 5 Basic specification of test model

| | Natural frequency (Hz) | Damping ratio (%) |
|---|---|---|
| X direction | 2.49 | 1.8 |
| Y direction | 1.98 | 2.7 |




(a) Exterior of wooden house model (b) Size of the model and layout of markers

Fig.12 Wooden house model used for the shake table test

### Measurement and experimental method

Figures 12(b) show the layout of markers on the test objects. The each face of the object had six markers on the beams to measure the dynamic behavior in the first and second floors. Two markers were also placed in the front and back of the shake table. Therefore, twenty-eight markers were used for the test. The initial three-dimensional positions of these markers were measured by the space instruments before the shake table tests for using the camera parameter matrix.

The nine CCD cameras were placed around the shake table as shown in Fig.13. The distance between the camera and the origin of the object coordinate system, which was set to the corner of the shake table, was from about 6 to 17 [m]. The shake table in Tokyu Construction Laboratory was used for the tests. JR Takatori wave was induced to the experimental model in the same way as before tests.

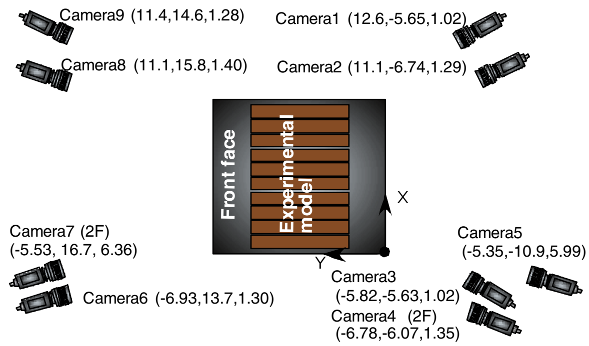



Fig.13 The layout condition of CCD cameras

**Measurement result**

Figure 14 shows the fracturing process of the two-story wooden house model induced the seismic wave. Figure 15 shows the time history of fracturing process at the time, and also the comparison with the dynamic displacement in the superstructure. These figures show the X, Y and Z-direction from the left column, and then the results of second story and first story in the upper and lower line are shown. Especially, the measured results of the first floor and the second floor in the lower line were indicated along with the measured results using the displacement transducer of wind type shown as a dotted line in the same figures. In this test, the wooden house model was collapsed. As shown in these figures, it was evaluated that the image processing system has an adequate performance to be able to measure the fracturing process of real scale structure, which is difficult to measure by using a conventional displacement transducer. Then, it is possible to express the fracturing process as shown in Fig.16 by using the captured results. Besides, in the shake table test, the camera were placed in the distance from 6 [m] to 17 [m] against the origin of the coordinate system, and then the image processing system measured the instrumental space in about 14*14*6.5[m]. Although the resolutions of the camera became about 28, 35 and 27[mm/pixel] in X, Y and Z-direction, respectively, it is beforehand confirmed that the image processing system can measure the experimental space on the accuracy of the sub-pixel order.

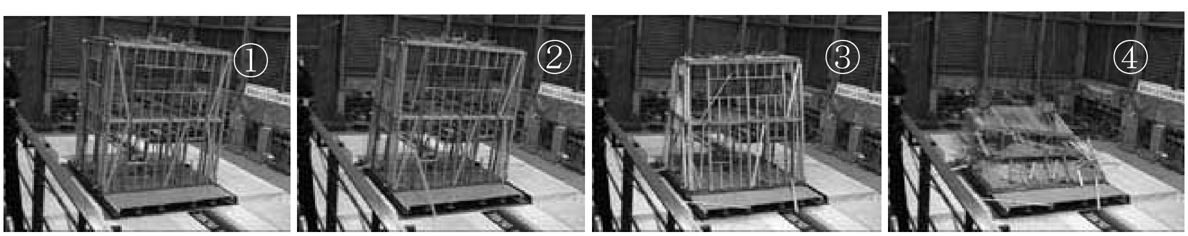



Fig.14 Fracturing process of two-story wooden house model

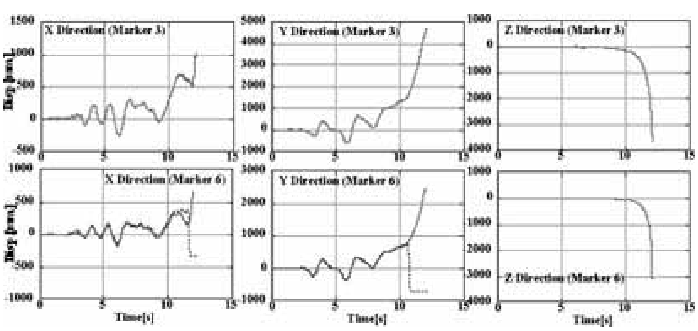



Fig.15 The comparison with the measurement results of the superstructure

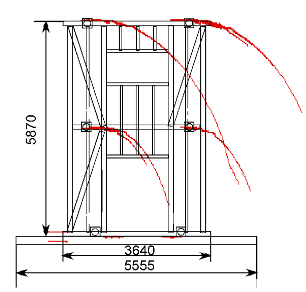



Fig.16 The fracturing process of the wooden house model

## CONCLUSIONS

This study has been done the research and development of the three-dimensional measurement method without any contact applying for the motion capture technique in order to measure the fracturing process of the real scale structure model on shake table test. This paper described the synthetic performance evaluation of the measurement system, and also the measured result of fracturing test using the real scale wooden house model. The synthetic performance including the measurement accuracy in several measurement conditions were summarized. As a result, it was confirmed that the measurement system was able to measure the three-dimensional dynamic behavior of experimental model with the measurement accuracy in sub-pixel order. Therefore, this measurement system has a sufficient performance to measure the three-dimensional fracturing process of real scale experimental model. Moreover, this system can apply for the measurement system to measure the dynamic displacement in any tests by changing the measurement distance and the lens of CCD camera.

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