Journal of Japan Association for Earthquake Engineering, Vol.4, No.1, 2004

VISION-BASED MEASUREMENTS FOR SEISMIC DAMAGE MONITORING

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ABSTRACT: Motion tracking with optical devices such as surveillance cameras can be particularly powerful for measuring earthquake induced motions. We propose a vision-based system with motion tracking for providing additional safety functions to detect seismic damage to interior elements and thus reduce risks in a building. Shaking table tests were carried out to evaluate the system's ability to detect structural collapse and overturning of interior elements using conventional video cameras. Results from this exploratory study show that vision-based measurements are promising in terms of capturing small to large deformations and identifying various kinds of seismic damage.

Key Words: optical sensor, shaking table test, damage detection, health monitoring, vision-based

INTRODUCTION

A lot of surveillance cameras are installed in buildings for security. Furthermore, optical motion tracking techniques, often termed vision-based measurement techniques, have been utilized for monitoring movement of objects especially in laboratories (Tateishi 2001, Yoshida et al. 2003). However the purpose of those vision-based systems were not for practical use in real buildings, but mainly for experimental studies as a motion sensor. Vision-based systems also have great potential for detecting various kinds of seismic damage such as collapse, overturning, and falling of elements in a facility. This information would be useful to warn people to evacuate, isolate the area, or shut down the critical service system in real buildings. The objective of this study is to evaluate the feasibility of the vision-based system for monitoring seismic damage using conventional charge-coupled device (CCD) cameras such as surveillance cameras widely installed in buildings.

Since video cameras for experimental studies demanding high accuracy need high-speed (more than 30 frames per second (fps)) and high-resolution (more than 720x480 pixels) performance, they are expensive and thus disadvantageous for application to real buildings. For instance, the sampling rate of accelerometer for the monitoring of building structures is usually 100Hz to analyze frequency contents of up to 20Hz. If the same accuracy for frequency contents is necessary in the vision-based measurements, the capture rate of a camera should be 100 fps. However, such a high-speed camera costs more than several times compared to a home video camera or a surveillance camera with frame rate of 30 fps. If a conventional video camera for a surveillance system is available for seismic damage monitoring systems, the vision-based system can be installed permanently in many facilities at a relative low cost. It is necessary to investigate whether the frame rate and resolution of a surveillance camera is sufficient for this purpose.

In this study, various kinds of motion tracking technologies are reviewed and the reasons why the optical technique is selected for the seismic damage monitoring are clarified first. Shaking table tests are carried out to evaluate the proposed vision-based approach. Damaged objects on the shaking table are monitored by conventional video cameras with capture rates of 30 fps and resolution of 720x480 pixels. The measured results are compared with records obtained by accelerometers, laser displacement sensors, and strain gauges to confirm that their accuracy is sufficient for seismic damage detection. Two digital video cameras are located in front of the shaking table to measure three-dimensional behavior using the triangulation technique. Passive spherical markers discretely attached to models are tracked in time to measure the dynamic displacements of the models subjected to earthquake motions.

Typical interior elements in a building are classified into two types from the viewpoint of damage monitoring. One comprises structurally weak components that may suffer from deformation and collapse, and the other comprises rigid components that may overturn during earthquakes.

A two-storied small structural model with weak-columns made of aluminum is used for the test of collapse damage detection. The first-story columns are designed to collapse first. We gradually increase the scaled amplitude of the input motions while measuring column strains to obtain detailed information at the instant of structural damage. The results of tracking of motions such as horizontal deformation are compared to those of other sensors to estimate the performance of vision-based measurements. The collapse process is carefully analyzed from the engineering aspect to identify damage behavior in real time.

Secondly, several rectangular pieces of wood with different aspect ratios are also mounted on the shaking table for the overturning detection test. These pieces imitate rigid equipment and elements unfixed to a floor or a desk. The scaled input motion amplitudes increase while the behavior of the shaking pieces of wood is observed by video cameras. The occurrence of overturning is identified on the basis of the rotation angle calculated from the relative displacement between the top and bottom of a specimen.

This experimental study is just a preliminary phase and we have not developed a real-time system yet. Two digital cameras captured image data. Then we stored the image data to PC and performed offline analysis for motion tracking. However, the real-time system can be estimated to be theoretically feasible. For example, the resolution and frame rate of a conventional camera (24bit/pixel) result in acquisition of approximately 30MB/s of data per camera, which can be compressed and transferred through the IEEE1394 (FireWire) bus, the PCI bus, and a CPU to hard disk in time. The data transfer capacity is within the limitation of the products on the market. The CPU can calculate the displacement of markers of each image frame within 30ms. The only problem is that the image data in the hard disk becomes huge, if all the acquired data is required to store.

MOTION TRACKING METHDOLOGIES

Overview of motion tracking technologies

Motion tracking is a most remarkable new technology and has been successfully employed in biomechanics, robotics, virtual reality, gaming and cinema. Earthquake engineering is also a promising application field, in which it may be used as a tool for structural health monitoring.

The methodologies of motion tracking include mechanical, magnetic, acoustic, and optical (vision-based) techniques. The mechanical motion tracking technique using a displacement sensor can achieve high-resolution and accurate measurements. However, there are limitations in its measuring points due to cost and instrumentation, and it may add mass, stiffness and friction. The magnetic technique uses a magnetic field generated by an emitter and monitored by a receiver. Though it may have less limitation than the mechanical technique, it is sensitive to metal components and other magnetic fields. It is unsuitable for application to real buildings where large magnetic noise is introduced by the environment. The acoustic motion tracking technique has the same limitations. It uses ultrasonic sounds instead of a magnetic field and measures time flight from the target to receivers. The problems are that electric devices may generate ultrasonic noise that disturbs its measurements, and its sampling rate is too slow for dynamic measurements.

Vision-based Systems

The vision-based motion tracking technique has less limitation, but only if a camera can capture the object within a scene. Since it is not necessary to attach devices directly to the object, it is easy to install the system in various kinds of environment. There is an example of application of a surveillance camera for input motion measurements (Hori 2000). If existing surveillance cameras are available, we have only to add the data processing system for vision-based measurements to the existing system.

Vision-based systems are classified into either image-based or marker-based. Image-based systems rely on feature detection between frames of a color texture map such as edge detection (Hutchinson and Kuester 2002). Though it needs no target makers to trace the movement, feature detection, image processing and reconstruction technique is necessary (Fu and Moosa 2002, D'Apuzzo et al. 2000). There are many issues to be resolved for practical use.

Marker-based systems are quite popular and reliable. These systems use reflective markers, charge-coupled devices (CCD) cameras and lights such as light emitting diodes (LEDs), to identify points of interest. Each marker consists of multiple pixels in the image. The positions of the markers are measured by identifying their respective centroids in the image. The spatial position of the corresponding points is then matched between image pairs obtained from two or more cameras and calculated by triangulation using the direct linear transformation (DLT) method (Abdel-Aziz and Karara 1971). The 2D coordinates (u, v) in the image plane of a camera is related to 3D object-space coordinates (x, y, z) using the DLT parameters $L_1 \sim L_{11}$ as follows:

$$u = \frac{L_1 x + L_2 y + L_3 z + L_4}{L_9 x + L_{10} y + L_{11} z + 1} \quad (1)$$

$$v = \frac{L_5 x + L_6 y + L_7 z + L_8}{L_9 x + L_{10} y + L_{11} z + 1} \quad (2)$$

In the camera calibration prior to motion tracking, the DLT parameters for each camera are obtained from known object-space coordinates of more than six control points using the least square method. The 3D coordinates of the makers in the object space can be computed for each image frame on the basis of the DLT parameters. The marker-based measurements procedure is used for the following experimental studies.

STRUCTURAL COLLAPSE MONITORING

Experimental set-up

An experimental study was carried out to investigate the applicability of a vision-based motion tracking system for capturing seismic damage. In the first case, a 2-story frame structure subjected to uni-axial seismic motion was tested. The frame structure was 60cm high, as shown in Fig. 1, and mounted on a shaking table. Its columns consisted of slit thin plates made of aluminum designed to buckle during shaking. Ten spherical tracking markers were mounted at the floor levels and at the column centers.

They were 25mm in diameter and wrapped in reflective tape. Two digital video cameras were set in front of the specimen to track the 3D movement of the markers.

Conventional sensors were also installed to evaluate the accuracy of the vision-based system. A laser displacement sensor installed at an outer protection frame measured the deformation of the top of the structure, and accelerometers were mounted on the top and bottom floor levels. Strain gauges were attached to the column connecting points.

Prior to the shaking table experiments, a free vibration test was conducted. The measured displacement of the top floor is shown in Fig. 2. The profile of the specimen was identified as 0.90Hz for the fundamental frequency and 0.5% for the damping ratio.

The input motion applied as a base excitation to the structure was the JMA Kobe acceleration record (NS component) from the 1995 Kobe earthquake. The shaking table tests were conducted repeatedly, as the scaled amplitude of input motion was gradually increased until structural collapse of the specimen. Table 1 shows the test number and the corresponding maximum acceleration recorded at the base.

Vision-based Measurements

The positional information of the markers was calculated by triangulation of the image data from each camera using the DLT method. Calibration should be conducted prior to the shaking test. Three-dimensional coordinates of more than six marking points were precisely defined in the initial image of the specimen. In this case, the resolution size of camera image was 1.2~1.5mm/pixel. The positional resolution of the measurement can be improved to less than the size of a pixel, by using the centroid of the pixels identified as a marker (Sato et al., 2003).

In test #8, the structure collapsed as shown in Photo 1. The process of structural damage was clearly understood through the streaming of the image data. The lower column buckled and the second floor collided with the base. Then its crash impulse was transmitted to the upper floor and finally the total structure collapsed. The large deformation and crash impulse at collapse caused saturation of the records of the accelerometers, displacement sensor and strain gauges. Vision-based motion tracking, however, could successfully measure deformation of the structure.

The displacement of the top floor relative to the base from vision-based measurements is compared to the results measured by the laser displacement sensor and accelerometers, except for test #8. The record from accelerometer was converted to displacement time history by numerical integration. Fig. 3

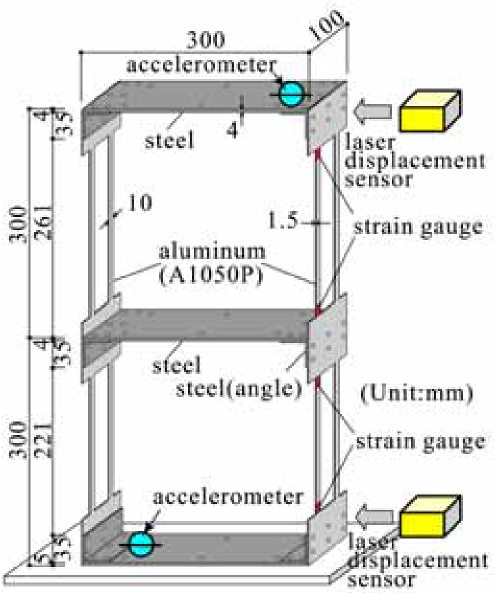


Fig. 1 Experimental specimen for structural collapse.

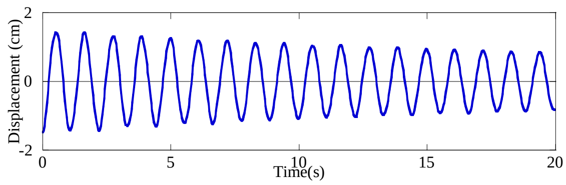


Fig. 2 Displacement of top floor in a free vibration test.

Table 1 Test cases and corresponding maximum acceleration recorded at base for each test.

Earthquake Motion	Test #	Max.. Base Accel.(Gal)
JMA Kobe(NS)	1	43.4
	2	61.7
	3	71.8
	4	80.4
	5	99.8
	6	109.2
	7	123.2
	8	256.9*

*Since the recorded data are saturated at collapse, it shows the maximum value before collapse.

compares the relative horizontal displacement time histories of the top to base among sensors for tests #2, #6 and #7. Their maximum responses are compared in Fig. 4. Little discrepancy is detected between the relative displacement time histories obtained from the optical measurements and the displacement sensor. Since the accelerometer measurements in the frequency range less than 5Hz are not so precise due to its performance, these results are worse. It is noted that the vision-based system is very promising for measuring displacement. Furthermore, it is found that the vision-based measurements can monitor residual drift as well as the displacement sensor, as shown in the lowest figure (test #7). This figure also shows that the accelerometer can’t measure residual drift due to its poor measurement characteristics in the low frequency range.

Positional data at the floor level is taken as the average from two spherical makers mounted at each floor level because of improvement of measurement accuracy. Table 2 summarizes the errors in the vision-based measurements estimated from the difference between the measurements of the laser displacement sensor and the vision-based system. The root mean square (RMS) of error, denoted as average error, is about 0.03cm. It should be noted that average positional resolution is about one fifth of a pixel for vision-based tracking with a spherical marker. There are wide differences in maximum error, which occurred at peak displacement. It seems that error increases when the object rapidly moves in the scene.

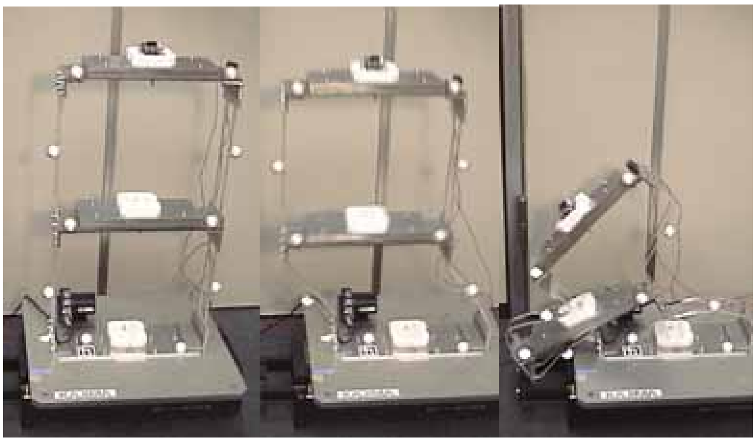
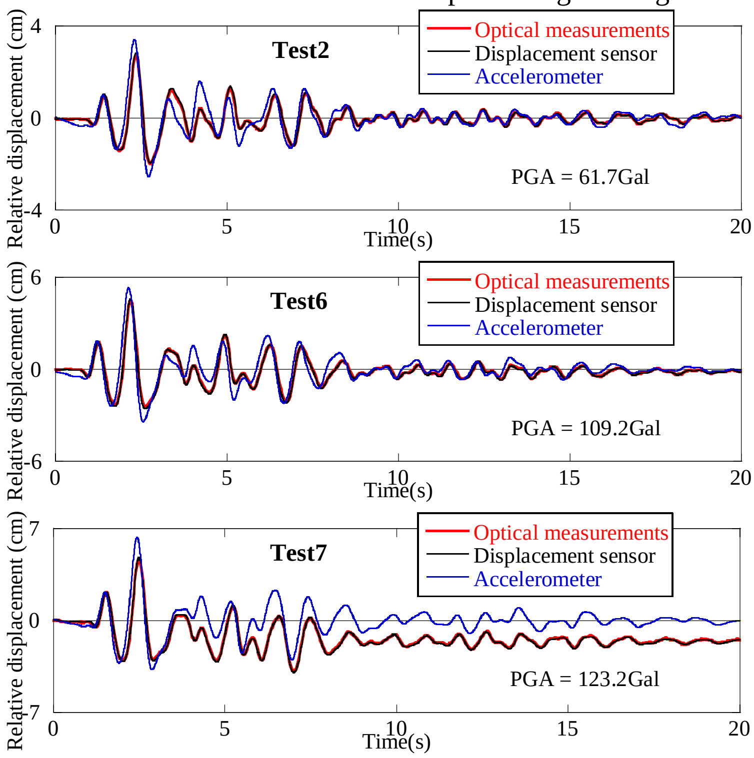


Photo 1 Process of structural collapse during shaking.



Fig, 3 Relative horizontal displacement time history of top story.

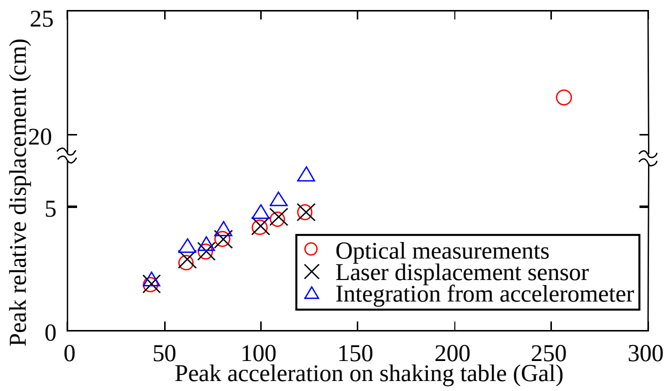


Fig. 4 Comparison of maximum relative horizontal displacement measurements among sensors.

Table 2. Error in vision-based measurements estimated from difference with laser displacement sensor.

Test #	Maximum Displacement* (cm)	RMS of Error (cm)	Maximum Error (cm)
1	1.900	0.023	0.097
2	2.899	0.029	0.157
3	3.235	0.026	0.119
4	3.699	0.022	0.063
5	4.254	0.030	0.140
6	4.596	0.038	0.173
7	4.804	0.046	0.164

* Maximum relative horizontal displacement was measured from laser displacement sensor. There is no observed data from the laser displacement sensor in test # 8, because maximum displacement was out of range of measurements.

Damage Detection

Strain data from strain gauges at the foot of the lower column are shown in Fig. 5, in order to evaluate the damage level for each test case. The relationship between maximum strain and maximum input acceleration shows nonlinearity. Though the increase in maximum strain in test #5 seems to decrease due to increase in hysteretic damping, the strains of tests #6 and #7 significantly increase due to column buckling. No residual strain is observed in tests #1 and #2, and generated strain should be within the elastic range. The residual strain rapidly increases and reaches 331μ in test #6 and 2132μ in test #7. Since test #7 exceeds the 0.2% offset strain, which is commonly used for practical capacity, structural damage clearly occurred in the columns.

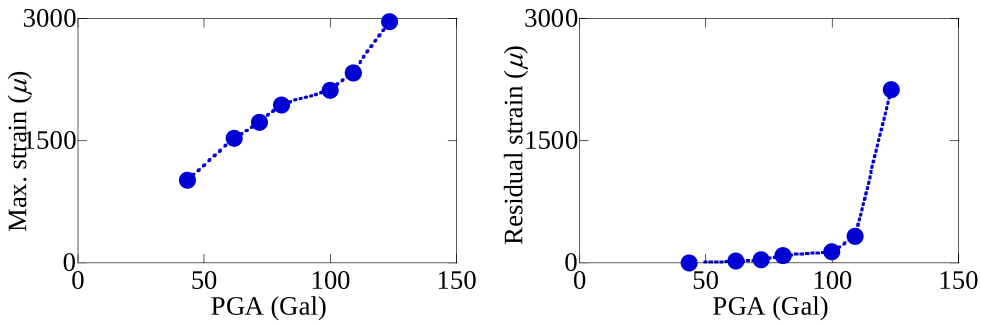


Fig. 5 Strain from gauges at foot of first-story column. Test #8 has no data because strain exceeds the limit of measurements.

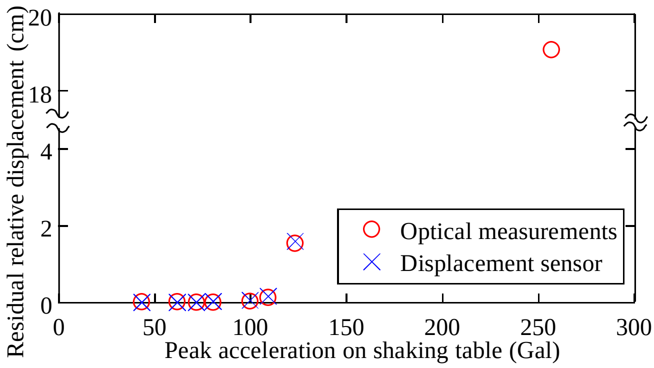


Fig. 6 Horizontal residual relative displacement.

The residual relative displacement from top to bottom is shown in Fig. 6. There is no significant difference between residual relative displacements obtained from optical measurement and laser displacement sensor. Though no reliable residual deformation is observed in tests #2 through #4, 0.05cm in test #5, 0.16cm in test #6 and 1.59cm in test #7 were measured. It is interesting to note that the trend of residual deformation is closely related to the increase in residual strain at the column foot, as shown on the right of Fig. 5. It is clear that vision-based measurements can be of great potential when measuring movement and detecting damage from small deformations as well as the monitoring with strain gauges.

Furthermore, horizontal and vertical displacement time histories by vision-based measurements for test #8 are shown in Fig. 7. Horizontal residual displacement increases at about 8 seconds, and the vertical displacement increases downward past 10 seconds. This means that a vision-based system with measurements of relative displacement can capture damage processes such as column buckling and structural collapse.

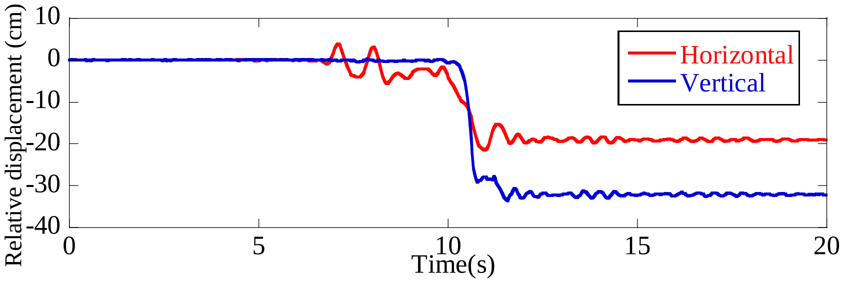


Fig. 7 Relative displacement of top story measured by optical motion tracking (Test #8).

These test results suggest that the vision-based measurements can not only detect small damage with the same accuracy as other conventional sensors, but also monitor heavy damage with large deformation such as collapse. However, the measurements don't work well when conventional sensors are directly attached to objects. This is due to the inadequate measuring range or damage to the sensor itself, as in test #8. Optical sensors can, however, be installed at a safe and remote point and monitor objects, only if there are targets distinguished by colors.

When we install the vision-based system in a real building, we have to solve problems due to the shaking of the camera itself during earthquake. The shaking may result in blurred image and reduction of measuring accuracy. It is found that stiff mounting for the camera and adequate shutter setting are necessary for clear images. Furthermore, it is noted that little compensation may be needed to correct for the shaking camera when damage to the object is detected by corresponding relative displacement. There is little effect of shaking camera in the relative displacement waveform calculated from a difference between two points in the image. Therefore, it is important to monitor the movement of reference points on which the object is mounted.

OVERTURNING MONITORING

Outline of Experiments

Most elements in a room are too rigid to collapse during earthquakes. With respect to seismic damage, overturning of bodies may be one of the most important phenomena to be monitored.

Several rectangular pieces of wood with different aspect ratios were also mounted on the shaking table and subjected to bi-axial seismic motions. The input motions consisted of horizontal and vertical components analytically simulated as floor response time histories of the 1952 Taft in the model building (T = 1.9s, h = 3%). The amplitude of the horizontal input motion was scaled and increased step by step. The specimens imitated important equipment and elements in a building. Selected aspect ratios denoting height divided by breadth of the rectangular bodies were 2, 3, 4, 5 and 6. The breadths of all were 10cm.

An example of an overturning shaking table test is shown in Photo 2. The black circles on the rectangular specimens were markers attached for optical motion tracking. The behavior of the shaking pieces of wood was observed by two digital video cameras. The displacements of the markers were measured using the vision-based approach using the same method as the collapse experiment. The occurrence of overturning is identified on the basis of the rotational angle calculated from relative displacement between the top and bottom markers on the pieces of wood. Some of the markers were occluded during motion capture, because they were hidden behind another element in the scene. Though the vision-based tracking was terminated at that time, this was after the overturning phenomena were detected.

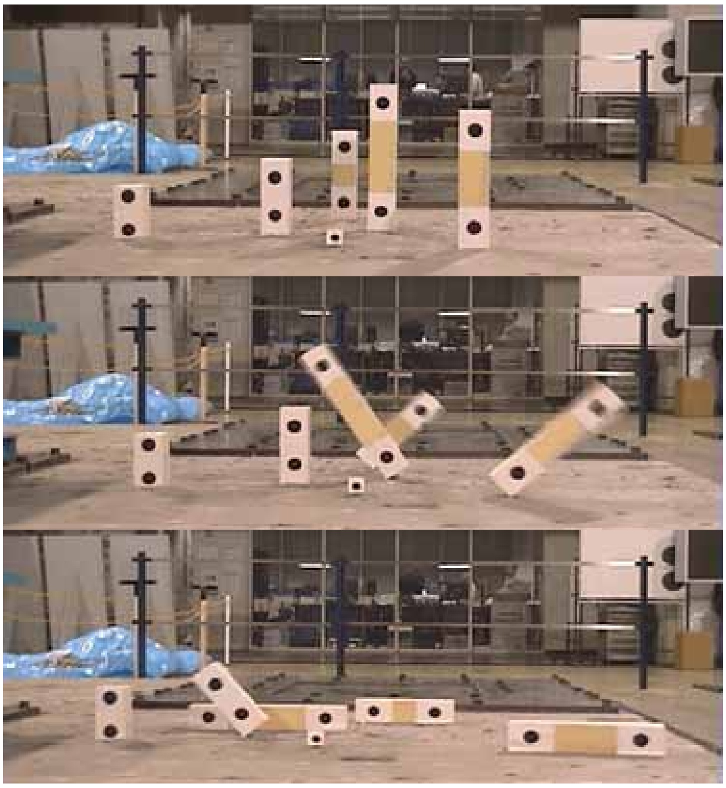


Photo 2 Scenes of an overturning shaking table test.

Detection of Overturning Elements

When the elements on the shaking table fall down, their vertical axes rotate horizontally. That is how overturning is detected by motion tracking. Table 3 shows whether overturning has occurred or not for each case. The vertical motions (PGA =920.0cm/s^2) are the same for all cases and don't affect the occurrence of overturning.

The motions of a reference point on the shaking table measured by vision-based motion tracking are compared with the accelerometer on the shaking table as shown in Fig. 8. Numerical differentiation is applied to calculate acceleration and velocity time histories from the vision-based measurements. The displacement and velocity measured by the vision-based tracking are fairly accurate. However, the acceleration time history contains high frequency noise and its error is not negligible, because the vision-based measurements can't capture high frequency contents precisely due to the slow capture rates of 30 frames per second.

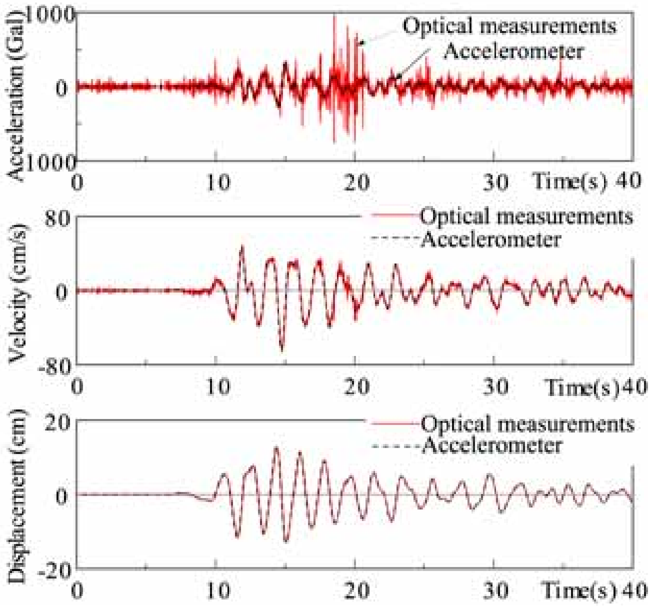


Fig. 8 Comparison of motions on shaking table measured by vision-based motion tracking with accelerometer.

Table 3 shows the results of all test cases. Overturning phenomena are related to level of input and size of the rectangular body. Ishiyama (1982) proposed the following criteria for overturning in terms of maximum acceleration a_0 and velocity v_0:

$$a_0 \geq \frac{B}{H} g \tag{3}$$

$$v_0 \geq 10 \frac{B}{\sqrt{H}} \tag{4}$$

where B and H are breadth and height of a rectangular body, respectively, g is gravitational acceleration, and units of all parameters are cm and seconds. The test results are plotted in the figure of the overturning criteria as shown in Fig. 9. In this case, the criterion of acceleration given by Eq. (3) is critical for overturning. It is noted that the results satisfy the criteria except for the H/B=3.0 and the 100% input case, and are reasonable.

The time histories of displacement, velocity and rotational angle measured by the vision-based motion tracking where H/B=5.0 and 100% input are shown in Fig. 10. The rotational angle is obtained from the combination of horizontal and vertical components at the top and bottom target points of a rectangular body. A high horizontal velocity generates a rocking motion in the body and it succeeds the overturning phenomena. The rectangular body can be clearly identified to overturn at past 11 seconds based on rotational angle monitored by the vision-based measurements.

CONCLUSIONS

Vision-based measurements using digital video cameras were evaluated for their accuracy in monitoring seismic damage of interior elements such as buckling collapse of frame structures and overturning of rectangular bodies. Shaking table tests were carried out, and reasonable motion tracking performance was achieved using the triangulation technique when comparing

Table 3. Test cases and occurrence of overturning in terms of aspect ratio of rectangular specimens.

Scaled Amplitude	PGA (Gal)	Aspect Ratio (H/B) 2	3	4	5	6
30%	93.1	X	X	X	X	X
50%	149.7	X	X	X	X	X
70%	213.5	X	X	X	O	O
90%	282.8	X	X	O	O	O
100%	314.4	X	O	O	O	O

O and X denote results with and without overturning, respectively. PGA is the maximum acceleration of a base excitation. H and B are height and breadth of rectangular specimens, respectively.

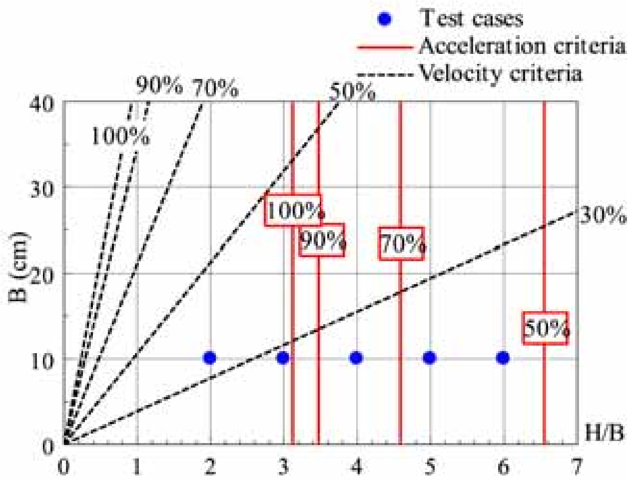


Fig. 9 Relationship between aspect ratio of rectangular specimens and overturning criteria [Eq.(3) and (4)]

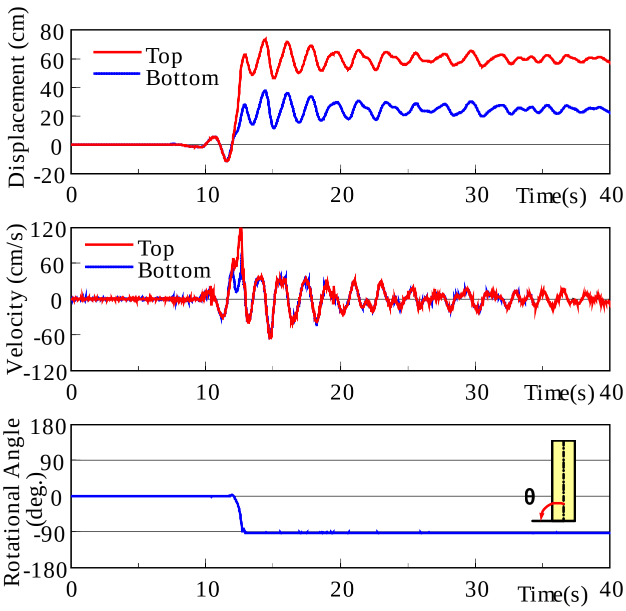


Fig. 10 Time histories of horizontal displacement, horizontal velocity and rotational angle of a rectangular specimen measured by vision-based motion tracking (H/B=5.0,100% Taft input)

vision-based measurements with those by conventional sensors such as accelerometers and laser displacement sensors.

It is noted that resolution of vision-based measurements is improved to about one fifth the size of a pixel by tracking the centroids of spherical makers. Measured displacements and differentiated velocity time histories are reasonable compared to those obtained from conventional sensors. Relative displacement is efficient in detecting damage to elements and in resolving the problem of cameras shaking during earthquakes.

Laboratory tests indicated that optical motion tracking has great potential for capturing small to large deformations and identifying various kinds of seismic damage. A high-resolution high-speed camera is not necessary. A conventional surveillance camera may be used. This means that the vision-based system is promising in terms of cost and practical application.

ACKNOWLEDGMENTS

Useful comments and suggestions by Professors Tara C. Hutchinson and Falko Kuester, UC Irvine, are greatly appreciated. Fruitful discussions with Dr. Yuji Sako, Dr. Narito Kurata, Mr. Yoshitaka Suzuki and Mr. Hachiro Ukon of Kajima Corporation and their helpful assistance in the experimental studies are also appreciated.

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(Submitted: May 5, 2003)