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Damage Evaluation Method for High-rise Buildings Based on Measurement of Relative Story Displacements and its Verification in E-Defense Test

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ABSTRACT

This study presents the verification of a damage monitoring and evaluation method for high-rise buildings based on the measurement of Relative Story Displacements (RSDs) in the E-Defense shaking table test. The damage evaluation method was formulated to detect the damaged locations of structural elements and evaluate their damage degree based on the displacement loading analysis by the time histories of measured RSDs. Furthermore, in the evaluation process, the analytical technique was introduced to compensate for the measurement errors associated with the properties of sensors. The monitoring accuracies were analyzed in the E-Defense shaking table test of an 18-story steel-moment resisting framing building. The results indicated the effectiveness of the proposed damage monitoring and evaluation method in its applications to the Structural Health Monitoring (SHM) system for high-rise buildings.

Contents

Ⅰ. Introduction

To securely mitigate the resulting disasters against earthquakes, Takahashi et al. [1] reported the needs of appropriate strategies based on the information about building damages. Among them, the Structural Health Monitoring (SHM) system can provide viable means both for buildings and their users [2-4]. The SHM system is applied for the diagnosis on structural deteriorations during the building life-span, or the diagnosis on structural damages right after earthquake shocks. The latter one is especially useful for the early recovery of building functions after earthquakes. In utilizing the SHM system to evaluate the structural damages of buildings for earthquakes, the Relative Story Displacement (RSD) can give the direct and clear index. RSD is an important index specifically in the structural design process of buildings, and we can detect detailed structural damages by utilizing the RSDs during earthquakes. To measure the RSDs directly, we have developed a simple RSD measurement system with high accuracy based on two noncontact-type sensors utilizing a Position Sensitive Detector (PSD) and a PhotoTransistor (PTr) array, and verified the basic properties through the shaking table tests [5, 6] and verified the practical effectiveness through the forced vibration test on an actual building [7].

In the application of the SHM system, as an indispensable component with the measurement system, we have to set up an appropriate damage evaluation method for building structures. In the past reports, we can survey two-type methods to evaluate the macro-damage or the micro-damage of building structures. Among the methods to evaluate the macro-damage of building structures, the typical method is to evaluate the changes of story stiffness through the identification scheme [8, 9]. As another approach, Kusunoki et al. [10] introduced the damage index to express the residual seismic capacity of buildings. On the other hand, among the methods to evaluate the micro-damage of building structures, i.e. the damage of structural elements, Inoue et al. [11] reported the two-stage identification scheme, and Tanaka et al. [12] evaluated the structural damage through the dynamic analysis.

To evaluate the micro-damage of building structures right after earthquakes, we have developed a damage

Keywords：monitoring, damage evaluation, relative story displacement, E-Defense, optical sensor, displacement loading

evaluation method based on the displacement loading analysis by measured RSDs, and verified its applicability through numerical simulations on a model building subjected to a large earthquake [13] and experimental analyses of the shaking table test of a full-scale 4-story building [14]. This paper presents the verification of a damage monitoring and evaluation method for high-rise buildings based on the measurement of RSDs. First, we present the formulation of a damage evaluation method to detect the damaged locations of structural elements and evaluate their damage degree based on the displacement loading analysis by the time histories of measured RSDs. Next in the evaluation process, we introduce the analytical technique to compensate for the measurement errors associated with the properties of sensors. Finally, we analyze the monitoring accuracies in the E-Defense shaking table test of an 18-story steel-moment resisting framing building, and clarify the effectiveness of the proposed damage monitoring and evaluation method in its applications to the SHM system for high-rise buildings.

Ⅱ. RSD Measurement System

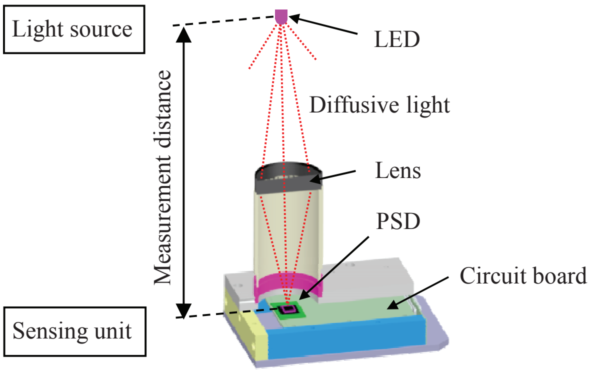


Fig.1　Schematic Diagram of PSD Sensor

In this study, we introduce a noncontact-type optical sensor for the RSD measurement system. The sensor is composed of a light source and a sensing unit. The light source and the sensing unit are located on the upper and the lower floors of the objective story, respectively. The sensor directly measures the relative displacement in the lateral direction between them, i.e. RSD, by detecting the light spot emitted from the light source on the sensing unit. By appropriately setting up the device design parameters, the sensor can measure wide-ranged displacements induced by various intensities of earthquakes, and we can construct the applicable and compact measurement system for buildings [5-7].

Here, we apply PSD sensors in the RSD measurement system [5]. The PSD sensor is composed of an infrared Light-Emitting Diode (LED) as a light source and a PSD with a focusing lens as a sensing unit. Fig. 1 shows the schematic of the PSD sensor. In the PSD sensor, the diffusive light from the infrared LED is focused onto the PSD surface by the focusing lens, and its movement is measured as reduced projections. As a result of this mechanism, we can design the sensing unit as a compact plane through the detailed adjustment of the focusing lens.

Ⅲ. Damage Evaluation Method

1. Displacement Loading Analysis [13, 14]

In the SHM system for earthquakes based on the direct measurement of RSDs, we formulate a damage evaluation method to detect the damaged locations of structural elements and evaluate their damage degree. The proposed damage evaluation method is based on the displacement loading analysis by the time histories of measured RSDs.

First, the building is modeled as a three-dimensional (3D) frame model composed of structural elements, e.g. columns, beams and joint panels, considering the appropriate elasto-plastic characteristics on the stiffness of each structural element. For this analytical model, consider the dynamic equilibrium of this n-degree-of-freedom system with m-known displacement subset subjected to an external excitation. The equation of motion at time instant t is written in the following form as:

$$\begin{bmatrix} \mathbf{k}_{11} & \mathbf{k}_{12} \\ \mathbf{k}_{21} & \mathbf{k}_{22} \end{bmatrix} \begin{Bmatrix} \mathbf{x}_1(t) \\ \mathbf{x}_2(t) \end{Bmatrix} = \begin{Bmatrix} \mathbf{f}_1(t) \\ \mathbf{f}_2(t) \end{Bmatrix} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where $\mathbf{x}_1(t)$ is an m-known displacement vector; $\mathbf{x}_2(t)$ is an (n-m)-unknown displacement vector; $\mathbf{f}_1(t)$ and $\mathbf{f}_2(t)$ are the resisting force vectors composed of inertia, damping and excitation forces, corresponding to $\mathbf{x}_1(t)$ and $\mathbf{x}_2(t)$, respectively; and $\mathbf{k}_{11}$, $\mathbf{k}_{12}$, $\mathbf{k}_{21}$ and $\mathbf{k}_{22}$ are the stiffness subset matrices composed of the structural element properties. Here, let us set each floor displacement of the building given by the corresponding measured RSDs to known displacement vector $\mathbf{x}_1(t)$. Under the rigid floor assumption, $\mathbf{x}_1(t)$ can be represented as two horizontal and a torsional directions. Assuming that the effect of $\mathbf{f}_2(t)$ corresponding to $\mathbf{x}_2(t)$ is negligible since its effect is generally small comparing to that of $\mathbf{f}_1(t)$ corresponding to $\mathbf{x}_1(t)$, $\mathbf{x}_2(t)$ and $\mathbf{f}_1(t)$ can be solved as:

$$\mathbf{x}_2(t) = -\mathbf{k}_{22}{}^{-1}\mathbf{k}_{21}\mathbf{x}_1(t) \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (2)$$

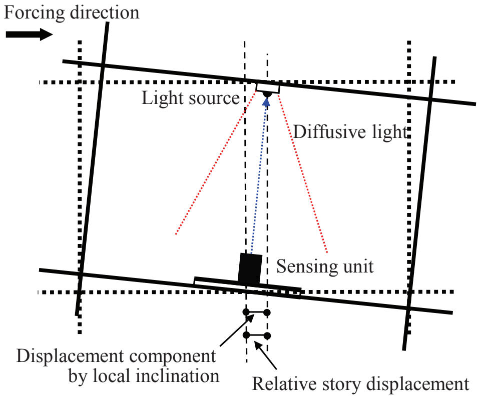
$$\mathbf{f}_1(t) = [\mathbf{k}_{11} - \mathbf{k}_{12}\mathbf{k}_{22}{}^{-1}\mathbf{k}_{21}]\mathbf{x}_1(t) \cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Thus, we can clarify the relationship of forces and displacements of the system expressed as (1). As a result, we can solve the equation of motion expressed as (1) in the time domain only by the measured RSD time histories and the stiffness-relating information on the structural elements of the building, and evaluate the damages of each structural element by expanding (1) to each structural element stiffness matrix.

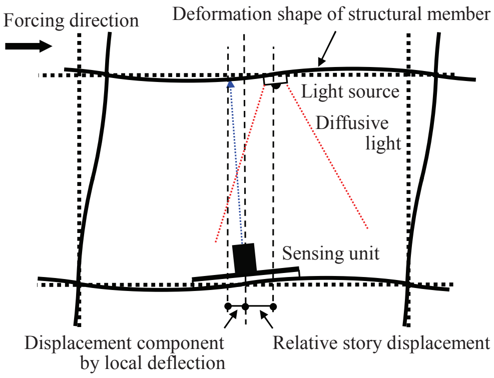
In the evaluation process, right after the earthquake duration, we perform the displacement loading analysis for the building model by the time histories of measured RSDs, and evaluate the hysteretic transitions of the stiffness of each structural element. As a result, we can directly detect the damaged locations of structural elements, and evaluate their damage degree. In the proposed method, we estimate the behaviors and damages of each structural element by directly tracing the building responses during earthquakes, and can evaluate the structural damage only by the stiffness-relating information on the structural elements without any information on the mass or damping properties of the building. As an additional feature, the analysis is not affected by the stiffness of nonstructural members like partition walls in the building, since the effect of the mass, damping and the stiffness of nonstructural members is included in the measured RSDs, the building responses for earthquake inputs, in the evaluation process. Based on these features, the proposed damage evaluation method is analytically robust against the uncertainties intrinsically accompanying the modeling of the building.

2. Correction of Measurement Error induced by Local Rotation

In the RSD measurement system by PSD sensors, it is possible for the displacement component by the local rotation at the locations of the sensing unit to affect the measurement accuracy as shown in Fig. 2.



(a) Bending deformation effect of building (Upper stories)



(b) Deflection effect of structural member (Lower stories)

Fig.2 Local Rotation Effect on Measurement Accuracy

To compensate for the measurement errors associated with this effect, we introduce the following analytical technique in the evaluation process [13-15]:

(i) Assume $\delta_{(1)}$, the estimated RSD time history, to be δ' including the effect of local rotation, the measured RSD time history.

(ii) Perform the displacement loading analysis for the building model by $\delta_{(1)}$.

(iii) Evaluate the updated estimation $\delta_{(2)}$ by removing the measurement error from δ', being estimated by $\theta_{(1)}$, the local rotation angle time history computed in the displacement loading analysis. Here, $\delta_{(2)}$ is expressed as:

$$\delta_{(2)} = \delta' - h\theta_{(1)} \cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

where h is a measurement distance.

(iv) Repeat the steps (ii) and (iii) by applying the updated estimations toward the convergence over the whole time history.

3. Damage Evaluation Flow

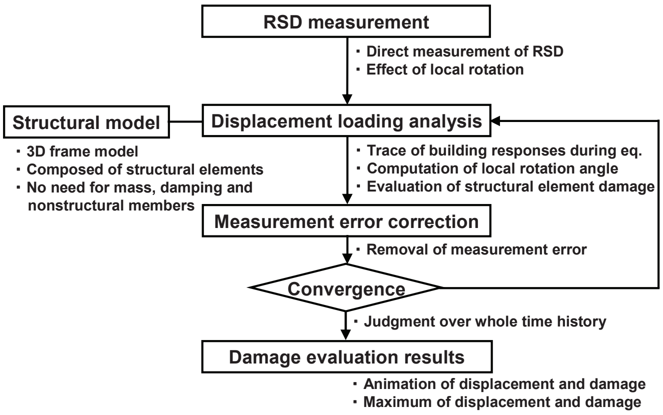


Fig.3 Flow of Damage Evaluation

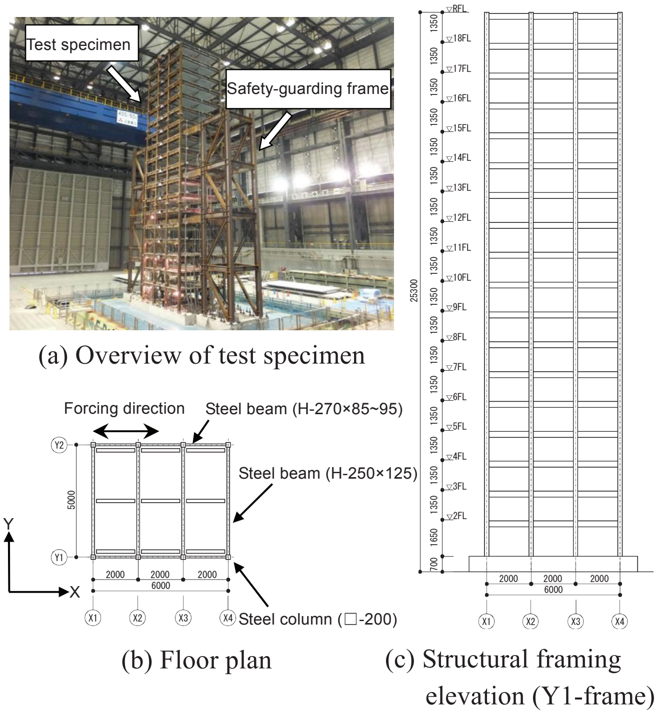
As the complete formulation of algorithm, being composed of the displacement loading analysis and the measurement error correction scheme, the damage evaluation flow is shown in Fig. 3. Following this flow, we can evaluate the structural damage of the building in detail right after earthquake shocks.

Ⅳ. Outline of E-Defense Shaking Table Test

To assess the basic features and verify the applicability of the proposed damage monitoring and evaluation method for high-rise buildings, we analyze the monitoring accuracies in the E-Defense shaking table test.

1. Shaking Table Test

The test specimen is an 18-story steel-moment-resisting framing structure of 25.3m height, weighing about 4179kN, being scaled down to the 1/3 of a full-scale building. Fig. 4 shows its outline. The floor plan measures 2000 mm x 3 spans in the longitudinal X-direction and 5000 mm x 1 span in the transverse Y-direction. The structure is composed of moment resisting frames with box-shaped steel columns of 200 mm x 200mm, and H-shaped steel beams of 270 mm x 85-95 mm in the X-direction and 250 mm x 125 mm in the Y-direction. In the shaking table test, the test specimen is excited only in the X-direction. The 1st natural period of the test specimen is about 1.15 s in the X-direction.



(a) Overview of test specimen

(b) Floor plan

(c) Structural framing elevation (Y1-frame)

Fig.4　Outline of Test Specimen

The earthquake input motion is an artificially-created Tokai, Nankai and Tonankai consolidated-type earthquake occurring at Nankai Trough, being assumed to be recorded at Tsushima, Aichi prefecture in Japan [16]. Its peak ground acceleration (PGA) is about 300 cm/s^2, the velocity response spectrum value (pSv) is about 110 cm/s for the period between 0.8 s and 10 s, and its duration time is about 460 s. In the shaking table test, its time axis is scaled down to the $1/\sqrt{3}$ of the original form for the scale-down of the test specimen, and its maximum excitation levels are set up to various levels and applied to the test specimen multiple times. Fig. 5 shows the acceleration time history of the input motion to the test specimen.

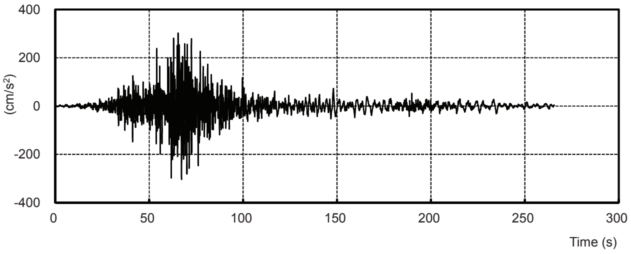


Fig.5　Acceleration Time History of Input Motion for pSv=110cm/s

2. Application of RSD Measurement System

(a) Light source　　(b) Sensing unit

Fig.6　Overview of PSD Sensor

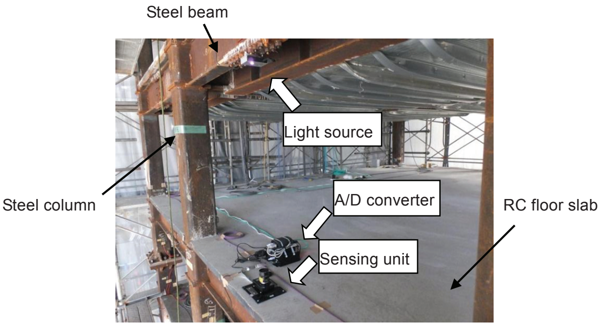


Fig.7　Arrangement Overview of Sensor Units

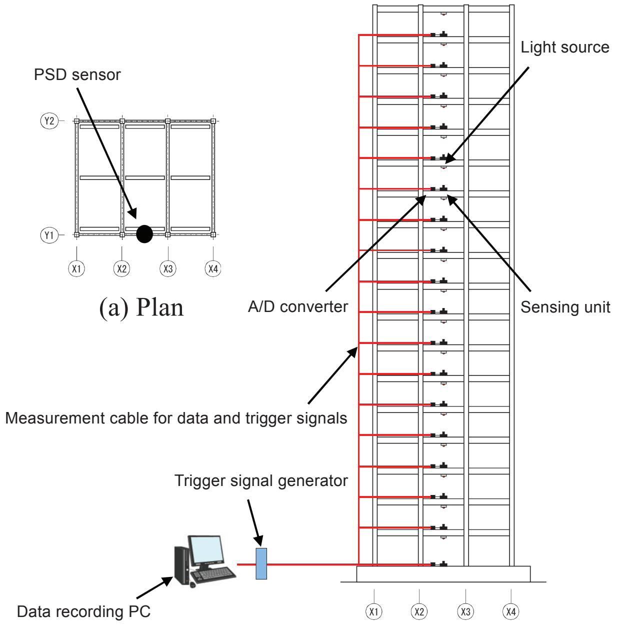
In the E-Defense shaking table test, we apply PSD sensors in the RSD measurement system. The PSD sensor is composed of an infrared LED as a light source and a PSD with a focusing lens as a sensing unit, and they are located on the upper and the lower floors of the objective story, respectively. Fig. 6 shows the overview of the PSD sensor. For their application to the shaking table test, an infrared filter is attached onto each focusing lens to eliminate the effect of external lights other than the light source. Fig. 7 shows the arrangement overview of the sensor units. Both of the light source and the sensing unit are fixed to the structural members of the test specimen to measure the RSDs for earthquake excitations, where the lower unit is attached directly onto the slab and the upper unit is attached to the rigid steel plate connecting with the upper beam.

Table 1 shows the specifications of PSD sensors. We can adjust the measurement range and the resolution of sensors through the adjustment of the sensing units, although being in the trade-off relationship. In the application of sensors here, the sensor components are designed to accommodate the measurement of the RSDs for wide-ranged earthquake excitation levels.

Table 1 Specifications of PSD Sensors

	1st story	2nd - 18th stories
Measurement distance※1	1330mm	1030mm
Measurement range	±70mm	±52mm
Resolution※2	0.2mm	0.15mm

※1 Distance between the bottoms of light source and sensing unit
※2 Within the 1/3 of measurement range



(a) Plan

(b) Elevation (Y1-frame)

Fig.8 Schematic View of RSD Measurement System

Fig. 8 illustrates the schematic of the RSD measurement system. The sensors are installed at the center of X2-X3 spanned beam in the Y1-frame on each floor of the test specimen, totaling 18 units of the PSD sensors. The sensor signals are sampled with 50 Hz and digitized by the A/D converter on each floor. The digitized data are sent to the data recording PC through serial communication lines. In addition, trigger signals are sent to the A/D converters to synchronize the timing of data acquisition among the sensors.

Ⅴ. Results of Damage Evaluation

In the E-Defense shaking table test, we evaluate the structural damage of the test specimen based on the measurement records of the RSDs on the data analyzing PC right after each excitation case.

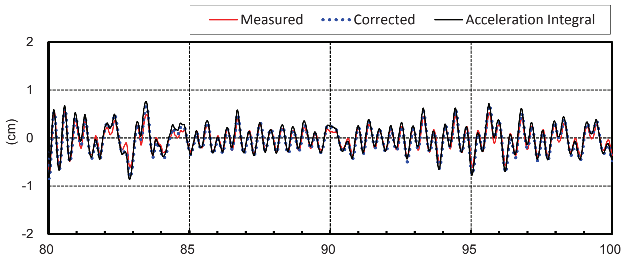
1. Analysis Conditions

For the analysis in the damage evaluation process, the test specimen is modeled as a 3D frame model composed of columns, beams and joint panels under the rigid floor assumption. To evaluate the structural damage, we give the appropriate bi-linear elasto-plastic characteristics on the stiffness of each structural element, being determined by its yield moment. Specifically for each beam, we apply the hysteretic characteristics considering the fracture and the local buckling at beam ends, and use the fracture damage index D as a damage index, where the beam element yields for $D > 0$ and fractures for $D \geq 1$ [17]. In this analysis, to verify the validity of the damage evaluation method itself, each yield moment is based on the measured yield strength of each steel material, and we successively perform the damage evaluations taking over the analytical results for each excitation case.

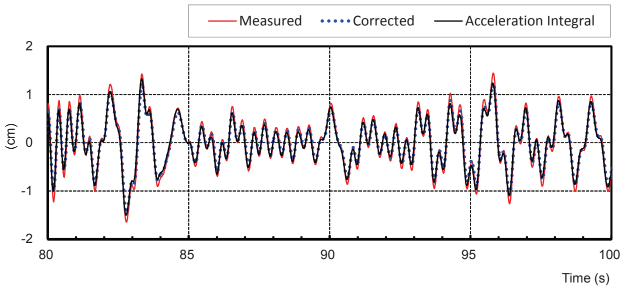
2. Results of Test and Analysis

In each shaking table test, the PSD sensors measure the RSDs in the X and Y directions, and we focus on the results in the earthquake-working X-direction here.

First, let us examine the validity of the measurement error correction scheme for pSv=110cm/s as the average earthquake level. Figs. 9 and 10 show the RSD time histories and the maximum distributions of the RSD angles, respectively, comparing the measurement records of the PSD sensors, the error-corrected values and the RSDs by the accelerographs being given as the precisely-synchronized differences between the acceleration integrals on the upper and the lower floors of the objective story. In this case, the corrected time histories are the results through three iterations. We observe the measurement error associated with the effect of local rotations; on the other hand, the error-corrected values almost agree with the acceleration integrals although the small differences can be observed for the upper stories, indicating that we can remove the measurement errors through the measurement error correction scheme.



(a) 17th story



(b) 3rd story

Fig.9　RSD Time Histories in the X-direction for pSv=110cm/s

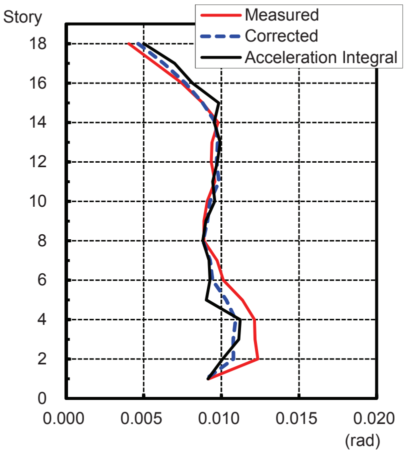
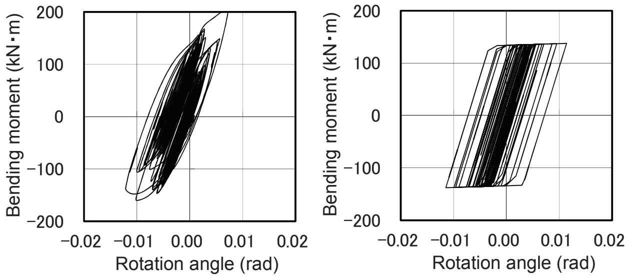


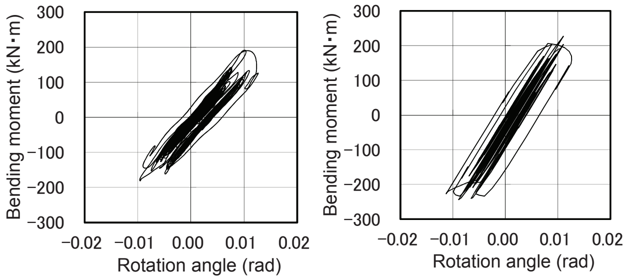
Fig.10　Maximum Distributions of RSD Angles in the X-direction for pSv=110cm/s

Next, let us investigate the damage evaluation results by the error-corrected RSD time histories for pSv=180cm/s as the maximum earthquake level.　Figs. 11 and 12 show the hysteretic curves of a beam and a column, respectively, comparing the test and evaluated damages.　Fig. 13 shows the animation image example of building displacements and the distributions of the fracture damage indices *D*'s. From the comparisons of hysteretic curves, we can estimate the area of hysteretic curves, representing the damage degree of each structural element, through the proposed evaluation method although we give simple bi-linear elasto-plastic characteristics on the stiffness of each structural element in the analytical model.



(a) Test result　(b) Evaluated result

Fig.11　Hysteretic Curve of Beam for pSv=180cm/s (X1-end,X1-X2 span on the 2nd floor in the Y1-frame)



(a) Test result　(b) Evaluated result

Fig.12　Hysteretic Curve of Column for pSv=180cm/s (X1-Y1 column bottom of the 1st story in the X-direction)

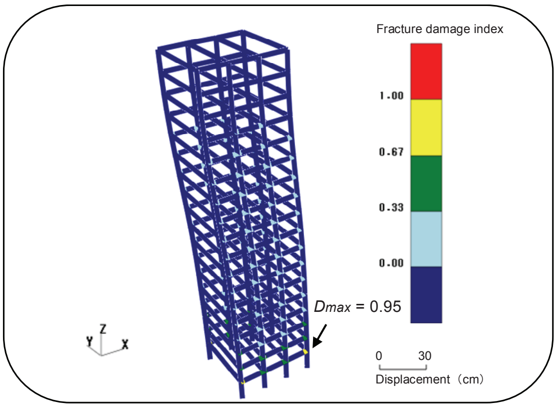


Fig.13　Animation Image Example at 95s for pSv=180cm/s

Ⅵ. Conclusions

In this study, we have presented the damage monitoring and evaluation method for high-rise buildings based on the measurement of RSDs and its verification in the E-Defense shaking table test. The damage evaluation method is formulated to detect the damaged locations of structural elements and evaluate their damage degree based on the displacement loading analysis by the time histories of measured RSDs. In the proposed method, we have estimated the behaviors and damages of each structural element by directly tracing the building responses during earthquakes. Furthermore in the evaluation process, we have introduced the analytical technique to compensate for the measurement errors associated with the properties of sensors. To assess the basic features and verify the applicability of the proposed damage monitoring and evaluation method, we have analyzed the monitoring accuracies in the E-Defense shaking table test of an 18-story steel-moment resisting framing building. The results indicate the effectiveness of the proposed damage monitoring and evaluation method in its applications to the SHM system for high-rise buildings.

Ⅶ. Acknowledgments

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