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ESTIMATION OF WHOLE BUILDING SEISMIC RESPONSE USING LIMITED NUMBER OF SENSORS

– Verification of Large Shaking Table Test of 18-Story Steel High-Rise Building –

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Abstract

Structural health monitoring systems of buildings are being developed, in order to evaluate the structural safety and function recover of buildings shortly after an earthquake. However, the applicability of an evaluation method has not been examined in detail for nonlinear deformation of buildings and for the effects of location and the number of sensors in a simulated response. The estimation method according to the mode shape (participation function) based on the design model of a building was applied to a large shaking table test of a 1/3-scale 18-story steel high-rise building in December 2013 at E-Defense. In this paper, we can draw our conclusions as follows: 1)The estimated results from 5 sensor points (1, 4, 10, 15 and RFL) correspond approximately to the observed results in the 18-story steel high-rise building specimen up to 0.03 radians of the maximum story drift angle. 2) It is important that sensors should be properly installed on the building by considering the mode shape of the design model in order to evaluate better seismic response. 3) It is true that more sensors give better accuracy in evaluating building response. Especially, more sensors are needed if the building shows strong nonlinearities over 0.02 radians.

Keywords: structural health monitoring system; 1/3-scale 18-story steel high-rise building; modal analysis method; estimation of seismic response; maximum story drift angle

1. Introduction

Recently, demand has increased to evaluate the structural safety and function recovery of buildings shortly after they are subjected to an earthquake. The seismic response of each floor of a building can be easily measured if sensors are installed on every floor. High performance sensors are generally expensive, so it is difficult to install sensors on every floor of a building, especially a high-rise building.

Several methods have been proposed to estimate the seismic response of each floor of a building by utilizing sensors installed on a limited number of stories [1, 2]. Most of these methods are techniques based on modal analysis, and have already reached a practical application level. The main aim of these methods is to estimate structural health determination and damage-identification on each floor by using a limited number of high-precision conventional servo-type accelerometers. Some papers have been published on the estimation method based on model updating [3, 4], others have been published on the evaluation method by using less sensors, for example only 2 sensor points [5]. However, the applicability of these methods has not been examined in detail for nonlinear deformation of buildings and for effects of location and numbers of sensors on simulation response analyses.

In this paper, we will examine the applicability and effects of our estimation method according to the mode shape calculated on the basis of the design model of a building by using experimental data of the large shaking table test of the 1/3-scale 18-story steel high-rise building executed in December 2013 at E-Defense [6]. Artificial generated earthquake motions were used as input for the large shaking table test, and the amplitude levels of the input motions were repeatedly increased until the model specimen collapsed. We installed 25 servo-type accelerometers in the model specimen on each floor. Response states of the whole building were evaluated by using a few sensor points. From the viewpoint of structural health monitoring, we focus on the maximum story drift angle of buildings. We analyzed the results estimated from limited point accelerometers by comparing them with observed data from all sensors in addition to other data such as displacement meters.

2. Estimation method of whole building seisemic response

Fig.1 shows the general outline of an estimation method of whole building seismic response based on a limited number of sensors and mode shape. In this paper, we assume that the mass and the stiffness of each story in the building are determined from the structural design model. The distributions of the mass and stiffness are represented as $\boldsymbol{m} = [m_1 \cdots m_{n_f}]^T$ and $\boldsymbol{k} = [k_1 \cdots k_{n_f}]^T$, respectively, where n_f is the number of stories. The mass matrix $\boldsymbol{M}$ and the stiffness matrix $\boldsymbol{K}$ are expressed from the following mass distribution and stiffness distribution, respectively.

$$\boldsymbol{M} = \begin{bmatrix} m_1 & & \\ & \ddots & \\ & & m_{n_f} \end{bmatrix} \quad (1)$$

$$\boldsymbol{K} = \begin{bmatrix} k_1 + k_2 & -k_2 & & \\ -k_2 & \ddots & \ddots & \\ & \ddots & k_{n_f-1} + k_{n_f} & -k_{n_f} \\ & & -k_{n_f} & k_{n_f} \end{bmatrix} \quad (2)$$

The participation matrix $\boldsymbol{\Gamma} = [{}_1\gamma \cdots {}_{n_f}\gamma]^T$ is calculated from the mass matrix $\boldsymbol{M}$ and stiffness matrix $\boldsymbol{K}$ by solving an eigenvalue program, where ${}_j\gamma$ is a column vector whose element is a participation factor of jth mode. Supposing the first n_m modes dominate the seismic response of a building, the response absolute acceleration $\boldsymbol{a}_{ps}$ at each sensor is approximated from

$$\boldsymbol{a}_{ps} = \boldsymbol{D}_m \cdot u + {}_m\boldsymbol{\Gamma}_s \cdot {}_m\boldsymbol{q} \qquad (3)$$

where $\boldsymbol{D}_m = [1 \cdots 1]^T \in \mathbb{R}^{n_s}$, the ground acceleration u, ${}_m\boldsymbol{\Gamma}_s$ is a submatrix of $\boldsymbol{\Gamma}$ where the rows corresponding to the floors with sensors and the corresponding to the first n_m modes are extracted. ${}_m\boldsymbol{q} = [{}_1q \cdots {}_{n_m}q]^T$ is the modal response relative acceleration vector for the 1st to n_m modes. In this time, the number of modes n_m equates with the number of sensors n_s installed on the floors of the building except the 1st floor. Then the estimate of the modal response is obtained from

$${}_p\boldsymbol{q} = {}_m\boldsymbol{\Gamma}_s^{-}(\boldsymbol{a}_o - \boldsymbol{D}_m \cdot u) \qquad (4)$$

where ${}_m\boldsymbol{\Gamma}_s^{-}$ is the inverse matrix of ${}_m\boldsymbol{\Gamma}_s$, $\boldsymbol{a}_o$ is observed in the data of the attached accelerometers. The response absolute acceleration $\boldsymbol{a}_p$ on each story is now estimated by

$$\boldsymbol{a}_p = \boldsymbol{D} \cdot u + {}_m\boldsymbol{\Gamma} \cdot {}_p\boldsymbol{q} \qquad (5)$$

where $\boldsymbol{D} = [1 \cdots 1]^T \in \mathbb{R}^{n_f}$, ${}_m\boldsymbol{\Gamma}$ is a submatrix of $\boldsymbol{\Gamma}$ where the columns corresponding to the first n_m modes are extracted. Then, the calculations of story drift displacement $\boldsymbol{d}_p$ are obtained by taking differences between displacements of adjacent floors that are calculated from $\boldsymbol{a}_p$ by numerical integration. Next, the story drift angle is defined by dividing the story drift displacement $\boldsymbol{d}_p$ and the height of the story.

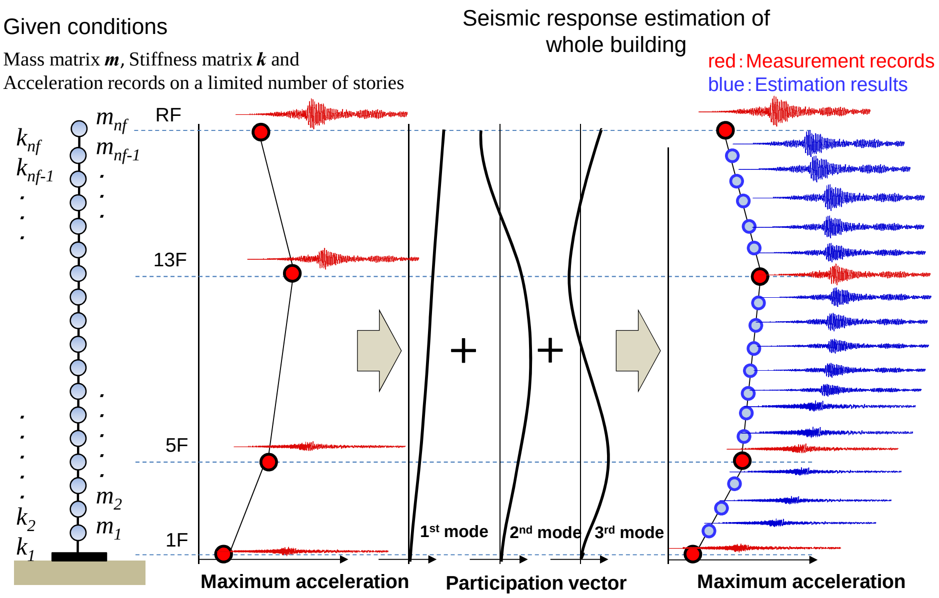


Fig. 1 – General outline of estimation method of whole building based on a limited number of sensors and mode shape

3. Shaking table test of 1/3-scale 18-story steel high-rise building

3.1 Outline of shaking table test

The large shaking table test of a 1/3-scale 18-story steel high-rise building model was executed in December 2013 at E-Defense [6]. Fig.2 shows the 1/3-scale 18-story steel high-rise building. The specimen was designed 1/3 scaled 18-story steel high-rise building, the plan is 5×6m, the height is 25.3m and the weight is 4179kN.

Employed input motions for the shaking table test were an artificial seismic wave and a random wave as illustrated in Fig.3. The artificial seismic wave was created by assuming the Nankai Trough Earthquake.

Periodic characteristics of the pseudo velocity response spectrum of the artificial seismic wave was almost 110cm/s between 0.8s and 10s under damping ratio h=0.05. The amplitude levels of the input seismic motions were repeatedly increased until the model specimen collapsed as listed in Table 1. The random wave with the same amplitude level was employed after a seismic motion in order to understand the vibration characteristics of the model specimen. These waves were input only in the x direction of the specimen.

3.2 Structural health monitoring system

A structural health monitoring system generally consists of servo-type accelerometers, a data recording system and an analysis system based on a personal computer. We installed 25 servo-type accelerometers in the model specimen on each floor to verify the estimation method as depicted in Fig.2. The accelerometers placed at X1Y1 points on each floor, and X2Y4 points on 1, 5, 10 and 15 floors and the roof floor. The accelerometers were fixed on concrete slab by using bolts. Regarding the conditions of experimental data recording, a cable was cut in case 420-1 and the others 24 cables were cut in case 420-2. Therefore we dealt with the experimental data between case 20 and case 340-2 as listed in Table 1. In this model specimen, the acceleration data converted to displacement by numerical integration after elements of less than 0.1Hz were cut in the frequency domain.

To understand the dynamic behavior of the model specimen, others sensors such as displacement meters were set up in the 18-story steel high-rise building specimen. Fig.2 shows the location of laser and wire displacement meters employed in this test. We analyzed the results estimated from limited point accelerometers by comparing them with observed data from all sensors in addition to experimental data such as displacement meters.

3.3 Damage condition and vibration characteristics of specimen

(a) Maximum drift angle and damage condition of specimen

Input waves for shaking table test and damage condition of the specimen are listed in Table 1. We select several input motions such as cases 110-1, 180-1, 220, 300 and 340-1, and describe the maximum story drift angle R_{max} and damage status of the specimen as follows.

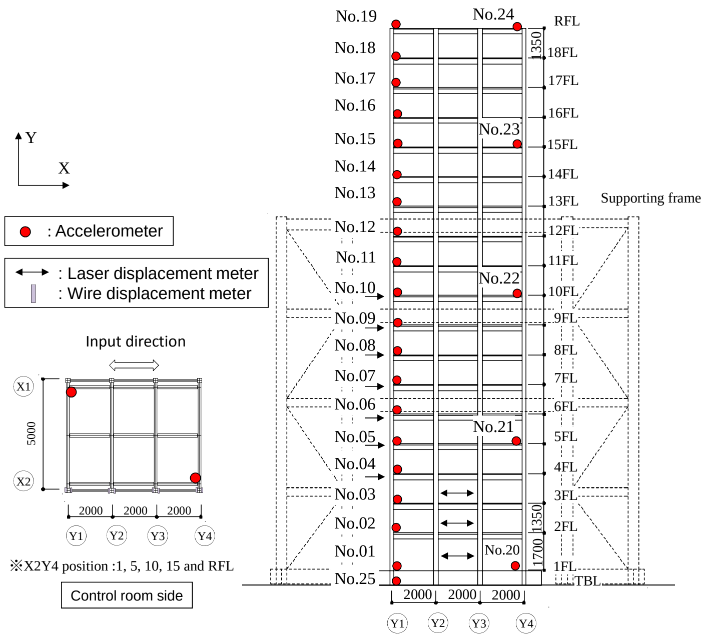
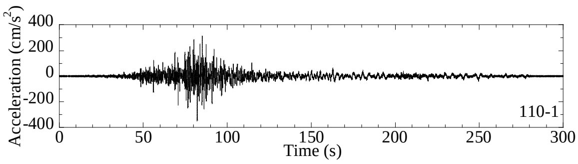
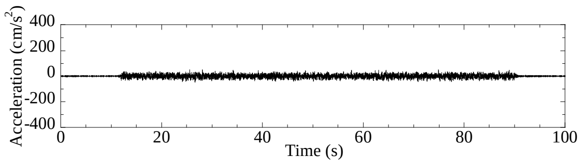


Fig. 2 – 1/3-scale 18-story steel high-rise building and structural health monitoring system



(a) Artificial seismic wave



(b) Random wave

Fig.3 – Input motions for shaking table test

Table 1 – General information of shaking table test and damage status of specimen

Case name of input wave※1	Amplitude level (Multiplying factor)	Maximum story drift angle※3 (Occurrence story)	Damage	Case name of input wave※1	Amplitude level (Multiplying factor)	Maximum story drift angle※3 (Occurrence story)	Damage
00-r※2	40 cm/s (0.37)	0.0021 rad (8th story)	Elastic deformation (No damage)	180-2	180 cm/s (1.64)	0.018 rad (11th story)	Yielding of beam end (1st～13th stories), Crack of beam end (1st～4th stories)
20	20 cm/s (0.18)	0.0027 rad (14th story)	Ditto	220	220 cm/s (2.0)	0.019 rad (11th story)	Fracture of beam flange (1st story)
40	40 cm/s (0.37)	0.0057 rad (14th story)	Ditto	250	250 cm/s (2.27)	0.024 rad (2nd story)	Fracture of beam flange (1st-2nd stories)
81	81cm/s (0.74)	0.0096 rad (14th story)	Yielding of beam end (a part of 1st -3rd stories)	300	300 cm/s (2.73)	0.032 rad (2nd story)	Fracture of beam flange (1st-4th stories)
110-1	110 cm/s (standard =1.0)	0.011 rad (3rd story)	Yielding of beam end (a part of 1st-6th stories), and column base (1st story)	340-1	340 cm/s (3.1)	0.058 rad (2nd story)	Fracture of beam flange (upper stories), Local buckling of column base (1st story)
110-2	110 cm/s (1.0)	0.011 rad (14th story)	Ditto	340-2	340 cm/s (3.1)	0.074 rad (2nd story)	Ditto
180-1	180 cm/s (1.64)	0.016 rad (11th story)	Yielding of beam end (1st-13th stories), Crack of beam end (1st-4th stories)	420-1,2,3	420 cm/s (3.8)	–	Fracture of all beam flanges (1st-4th stories), Fracture of column base (1st story)

※ 1 Case name of random wave is represented with the " -r " after the case name of input wave.

※2 Random wave excitation in virgin state of specimen.

※3 Maximum drift angle are calculated from integration of acceleration records in the case of 00-r to 220, from laser displacement meter in the case of 250 to 300.

In case 110-1, the maximum story drift angle R_{max} is 0.011 radians, column bases of the 1st story and several beams ranged from the 1st to 6th stories and the 13th story yielded. As for case 180-1, R_{max} is 0.016 radians, the beam ends are cracking on the 1st to 4th stories. Then, R_{max} reaches to about 0.019 radians, the fracture of bottom flanges of the beam ends is initiated on the 1st story in case 220. In case 300, R_{max} becomes about 0.032 radians, the fracture of bottom flanges is confirmed in most of the beam up to the 4th story. In addition, R_{max} is about 0.058 radians, the local buckling of column bases occurred on the 1st story in case 340-1. The shaking table test of the specimen finishes in case 420-3, when the specimen collapses at the lowest part of the 4th story and leans against support frame.

(b) Vibration characteristics of specimen

The vibration characteristics of the specimen were investigated from the results of random wave excitation. Fig.4 shows the spectral ratios of the specimen during case 00-r and case 340-1-r. The spectral ratios of the roof floor (RFL) to the 1st floor were computed from observed acceleration, which were averaged by two sensors on the same floor, based on the method of fast Fourier transform (FFT). Natural frequencies of the specimen were identified by using a nonlinear least-squares method [7]. This figure indicates that natural frequencies are identified accurately even after the specimen is damaged greatly such as in case 340-1-r. In the initial state (case 00-r), the 1st natural period is 1.1s, the 2nd is 0.37s, the 3rd is 0.2s and the 4th is 0.14s.

Fig.5 shows the variations of the natural period of the specimen in the 1st to 4th modes. Even though the specimen has some fractures of beam ends at the 1st to 2nd stories, the natural periods hardly change until case 220-1. In case 300-r, the natural period of the 1st mode alters greatly because the fractures of beam ends are spread up to the 4th story. Then, the 1st natural period increases more due to the buckling of the column base on the 1st story in case 340-1-r. Finally, the 1st natural period gets longer, to about 2.3s, during case 340-2-r, so it is about 2 times that of the initial state. From this figure, the natural periods in the 2nd to 4th modes seem not to vary. The variations of the participation vector of the specimen in the 1st and the 4th modes are depicted in Fig.6. We confirm that the participation vector also alters little until case 250-1-r. In case 300-r, the deformations of lower stories increase in the 1st mode. By comparing the 1st mode with the 4th mode, the shapes of the 4th mode are changed more than the 1st mode.

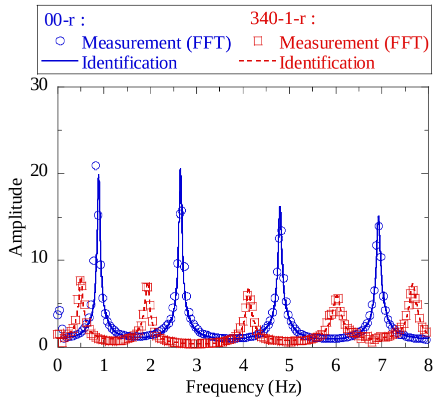


Fig.4 – Example of spectral ratios

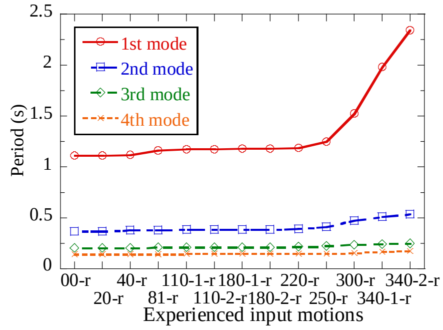
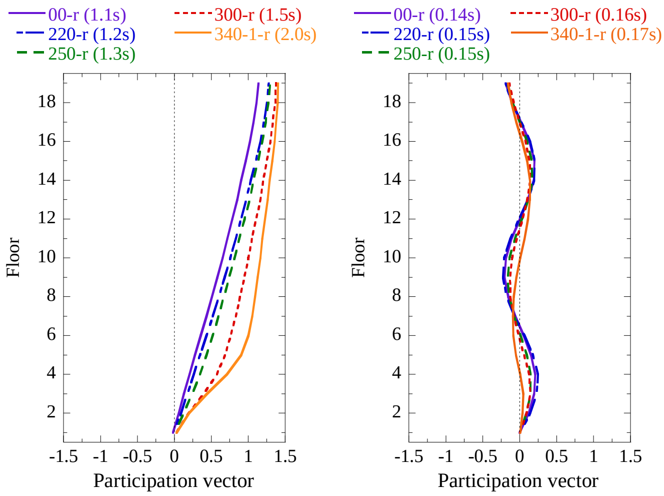


Fig.5 – Variations of natural period of specimen



(a) 1st mode (b) 4th mode

Fig.6 – Variations of participation vector

4. Application for shaking table test of 1/3-scale 18-story steel high-rise building

The proposed our estimation method based on the mode shape and a limited number of sensors applied to the large shaking table test of the 1/3-scale 18-story steel high-rise building executed in December 2013 at E-Defense.

4.1 Eigenvalue analysis model for response estimation

Table 2 shows the information of the structural design model of the model specimen, and Fig.7 shows the participation vector of the specimen as the result of eigenvalue analysis. The strucural design model is determined from the result of push-over analysis by using a frame model of the supecimen. The natural periods and the participation vector shape of the structural design model are similer to the observed results as illustrated in Fig.5. We evaluated the seismic response of the model supecimen from the results of eigenvalue analysis based on this structural design model as follows.

Table 2 – Information of structural design model

Story	Height (cm)	Weight (kN)	Stiffness (kN/cm)	Yield drift angle (rad)
18	135	202	363	0.0056
17	135	206	491	0.0066
16	135	206	562	0.0074
15	135	206	619	0.0080
14	135	206	660	0.0084
13	135	206	712	0.0091
12	135	206	788	0.0091
11	135	208	824	0.0097
10	135	208	840	0.0098
9	135	208	876	0.0096
8	135	208	938	0.0096
7	135	208	963	0.0099
6	135	208	990	0.0099
5	135	208	1028	0.0099
4	135	208	1028	0.0095
3	135	208	1073	0.0090
2	135	208	1092	0.0088
1	170	208	1155	0.0069

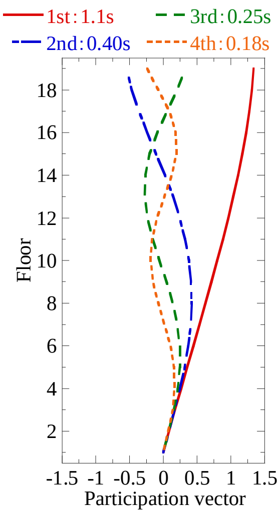


Fig. 7 – Participation vector of design model

4.2 Estimation results

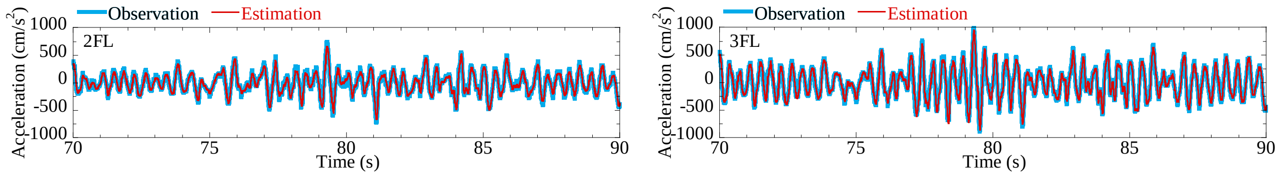
The seismic responses of the 1/3-scale 18-story steel high-rise building were estimated by using 5 sensors, which were installed on 1, 4, 10, 15 floors and the roof floor. The position of these sensors was made considering the mode shape that was determined from the results of section 5.2. The number of sensors on the upper floor is 4, the estimation method considered up to the 4th mode.

Fig.8 shows the time history of the response acceleration on the 2nd and 3rd floors, and Fig.9 shows the time history of the story drift angle on the 2nd story, respectively. These figures are comparing the estimated results with the observed data and experimental data in case 180-1. These waves are extracted between 70s and 90s including principal shock from the response wave. The deformation level of the specimen becomes a nonlinear region. From these figures, the estimated results accurately correspond to not only the observed data but also the experimental data.

The distributions of maximum response acceleration and maximum story drift angle are illustrated in Fig.10 and Fig.11, respectively. In these figures, input cases 110-1, 180-1, 220, 300 and 340-1 are selected from a series of shaking table tests. In these figures, red lines denote the estimation values from a limited number of sensors, blue lines denote observation values from accelerometers on every story and green lines denote experimental values from displacement meters. In cases of 110-1, 180-1 and 220, although the specimen reaches to a nonlinear region with some damage such as the yielding and fracture of part of the beam end, the results of the estimation are almost identical with the observed values and experimental values on the entire building model in all response indices. We think that our estimation method can evaluate the observed value and experimental value accurately because the natural periods and participation vector of the specimen are not much changed until case 220, as shown in Fig.6.

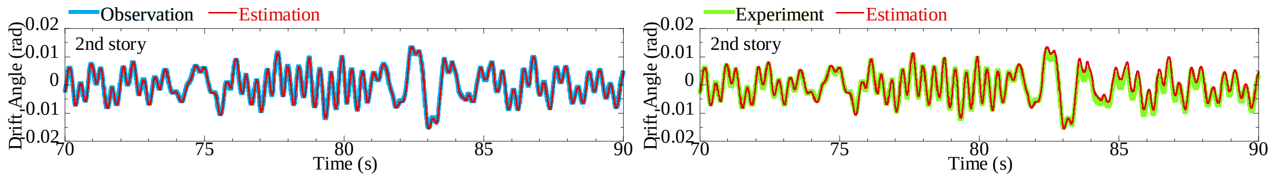
In case 300, the fractures of beam ends are distributed from the 1st to 5th stories in the specimen, and the estimated values start to depart from the observed values in maximum response acceleration. On the other hand, in the maximum story drift angle, the estimated values match the observed values and the experimental values, even though the specimen attains to a strong nonlinear region that is over 0.03 radians. We think that obtained data normalize the maximum value because accelerometers are installed near the peak points of participation vectors. Finally, in case 340-1, the estimated values differ greatly from the observed values and the experimental values for each seismic response index. Especially, the estimated values of maximum story drift angle are underestimated on the 2nd to 3rd stories as shown in Fig.11(e).

As mentioned above, the results are estimated from only 5 sensor points (1, 4, 10, 15FL and RFL) that correspond approximately to the observed results and experimental results until the specimen is 0.03 radians in maximum story drift angle.



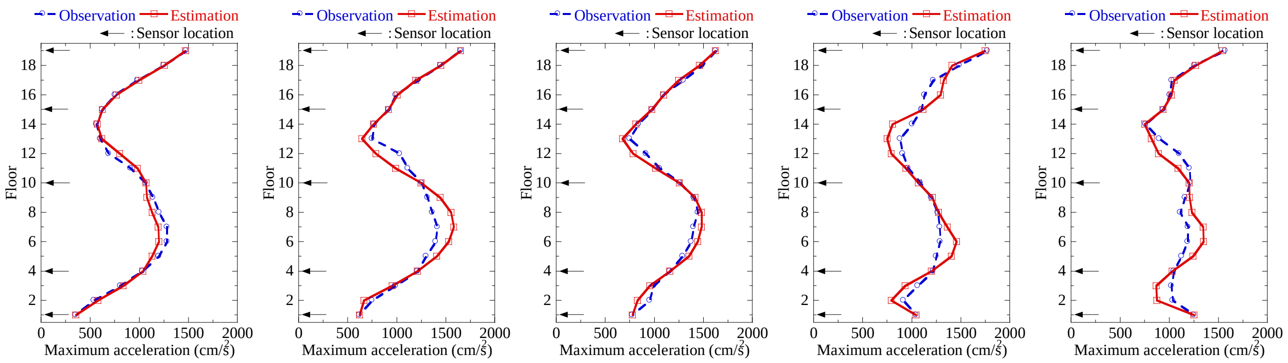
(a) 2nd floor (b) 3rd floor

Fig. 8 – Comparison of time history of response acceleration



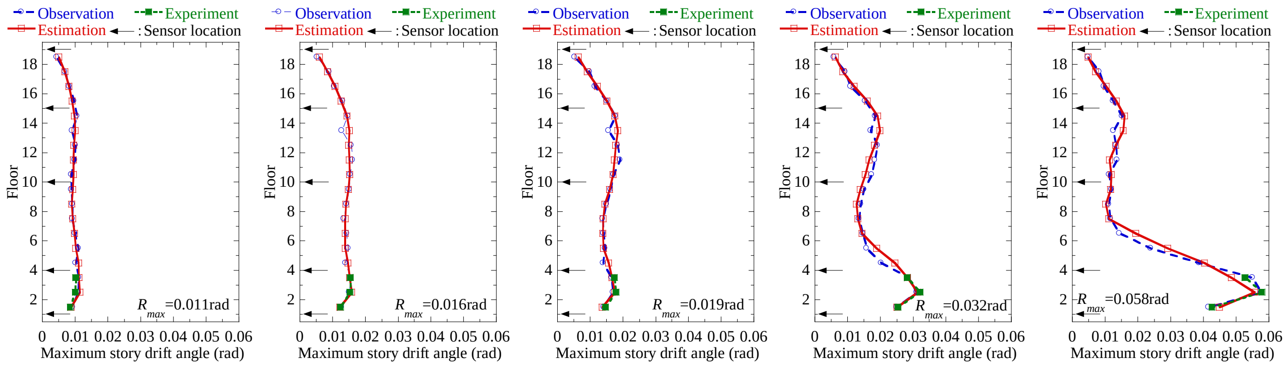
(a) Comparison of observed data (b) Comparison of experimental data

Fig. 9 – Comparison of time history of story drift angle on 2nd story



(a) Case 110-1 (b) Case 180-1 (c) Case 220 (d) Case 300 (e) Case 340-1

Fig. 10 – Estimated results of maximum response acceleration



(a) Case 110-1 (b) Case 180-1 (c) Case 220 (d) Case 300 (e) Case 340-1

Fig. 11 – Estimated results of maximum story drift angle

5. Effects of setting parameters on estimation results

In order to examine the applicability of our method in detail for nonlinear deformation of the building and for the effects of location and numbers of sensors on simulation response analyses, parametric studies were performed by using experimental data of the shaking table test of the 18-story steel high-rise building executed in December 2013 at E-Defense.

The quantitative evaluation results of estimation were performed by using the estimated error *Er* and fit index *Bf*. From the results of the analysis, the ratio of the estimated response *Pr* to the observed response *Or* was defined as the fit index *Bf* on each story and each floor. Then, the estimated error *Er* is determined as follows:

$$Er = \sum_{i=1}^{n_f} \sqrt{(1 - Bf_i)^2} \ / \ n_f \qquad (6)$$

where n_f is the number of stories. The fit index *Bf* indicates that the accuracy degree is high as the value of *Bf* is closer to 1. Then the estimated error *Er* expresses that the accuracy degree becomes high as the value of *Er* becomes small. The fit index *Bf* and estimated error are calculated for each response index such as maximum response acceleration and maximum story drift angle. In this section, we dealt with the observed values from all sensors as true values, and compared them with the estimated values.

5.1 Influence of sensor location

First, we studied the effect of sensor location on the estimation results. Two ways for sensor placement were prepared: 1) the way of arranging sensors at uniform intervals in the height direction (equal placement); 2) the way of installing sensors on the building by considering the mode shape of the design model (mode placement). We think that these two ways improve the accuracy of response estimation, and verify the influences. In the mode placement, sensor location was determined from peak points (antinode) of the only mode, which equals the number of sensors on the upper story except for the 1st floor in the building. For example, 5 sensor points are installed on 1, 4, 10, 15 and RFL by considering only the 4th mode; 4 sensor points are installed on 1, 5, 13 and RFL by considering only the 3rd mode; 3 sensor points are installed on 1, 8 and RFL by considering only the 2nd mode. The mode shape of participation vector was calculated from the structural design model, as shown in Fig.7.

Fig.12 shows variations of the estimated error by using 3 sensor points. In this figure, the results of all combinations by using 3 sensor points are depicted in case 110-1. In case 110-1, the maximum drift angle of the specimen is about 0.011 radians, the specimen is nearly in the elastic deformation level. Then, the red points denote the estimated error of maximum acceleration Er_A and the blue points denote the estimation error of the maximum drift angle Er_R. Accelerometers are positioned in sequence from a low-rise side such as 1, 2, 3FL, 1, 2, 4FL, …, 1,2 and RFL. The minimum error placement means the minimum value of the sum of Er_A and Er_R, and one is 1, 7 and 18FL in this figure. The values of Er_A and Er_R alter greatly depending on the sensor deployment. For example, for 1, 4 and RFL, the lopsided placement of sensors decrease the accuracy of estimation. In comparison of the fit index of acceleration Bf_A, the results of the equal placement and mode placement differ from the observed values in the low-rise side of the building as shown in Fig.13. On the other hand, in the fit index of story drift angle Bf_R, the difference is not so large, the results of the equally placement and mode placement are consistent with observed results on the whole building.

Next, the number of sensors varies from 3 points to 5 points; the influence of sensor location on the estimated results is shown in Fig.14. This figure compares the results due to the difference of placement in each seismic response index. In the case of 4 or 5 sensor points, the estimated error of the mode placement and the equal placement almost coincide with the one of the minimum error placement in each seismic response index. The fit index Bf_{Rmax}, which is 0.011 radians at the 3rd story, is also the same as the value of the minimum error placement, and Bf_{Rmax} of the mode placement and equal placement are near 1. In addition, the precision of the mode placement is higher than that one of the equal placement in this figure. On the other hand, the sensor locations of the minimum error placement are changed due to the number of sensors: 3 sensor points are 1, 4 and

18FL; 4 sensor points are 1, 6, 9 and 16FL; 5 sensor points are 1, 8, 14, 17 and RFL, and the regularity of the minimum error placement is not confirmed.

From these figures, it is clear that the mode placement and equal placement successfully achieve a global and stable estimation. Therefore, it is important that sensors should be properly installed on the building by considering the mode shape of the design model in order to evaluate a better seismic response.

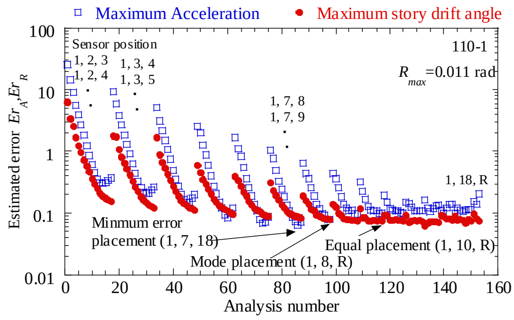
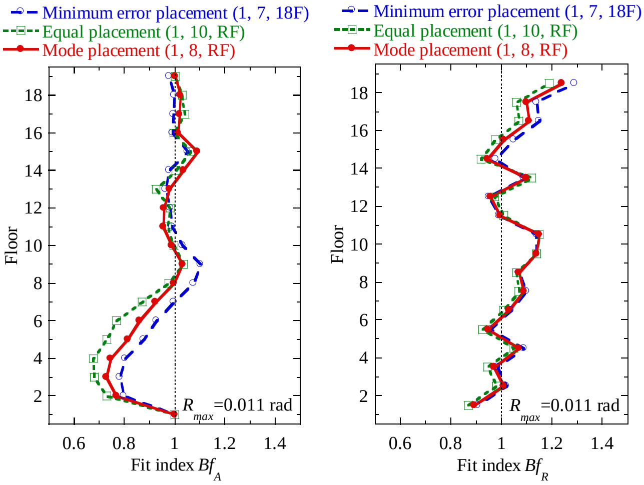
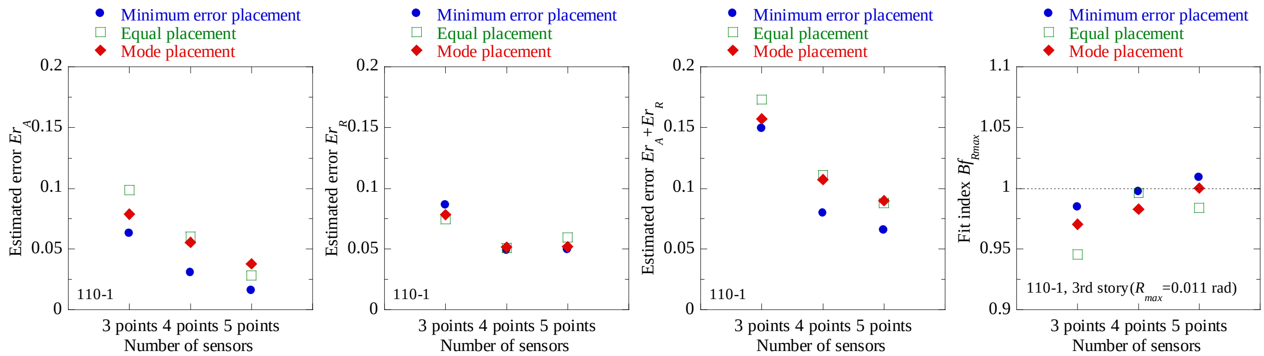


Fig. 12 – Variations of estimated error due to sensor location in 3 points



(a) Acceleration Bf_A (b) Story drift angle Bf_R

Fig. 13 – Distributions of fit index in 3 sensor points



(a) Estimated error Er_A (b) Estimated error Er_R (c) Estimated error Er_A +Er_R (d) Fit index Bf_{Rmax}

Fig. 14 – Influence of sensor placement on estimated results

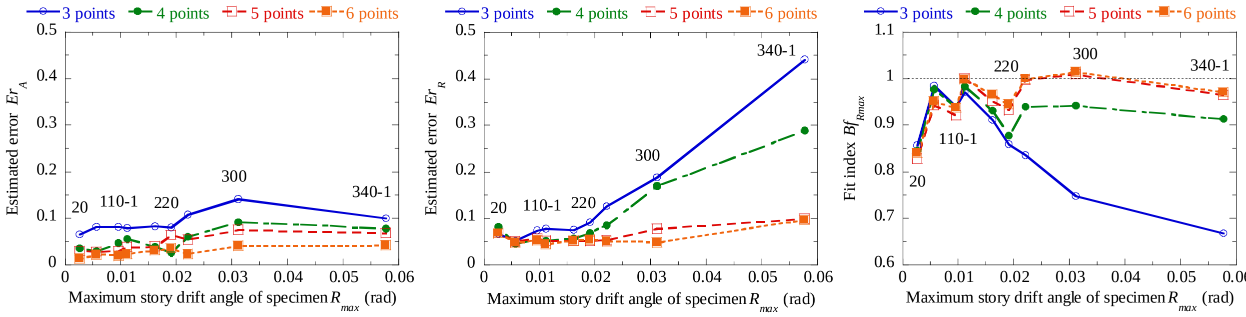
5.2 Effects of number of sensors on applicability of nonlinear response level

Finally, we examined the effects of the number of sensors on the applicability of a nonlinear response level. The number of sensors altered from 3 to 6, and the experimental data between case 20 and case 340-1 were investigated.

Fig.15 shows the influence of the number of sensors on the applicability of a nonlinear response level. From the results of section 5.1, sensor position was used for the mode placement, and the number of sensors varies from 3 to 6 in each input wave. This figure shows the relationship between the maximum story drift angle of the specimen and the estimated error Er_A, Er_R or fit index Bf_{Rmax}. The estimated error of acceleration Er_A is not changed according to the number of sensors. On the other hand, the estimated error of the maximum story drift angle Er_R and fit index of the maximum story drift angle Bf_{Rmax} change greatly depending on the deformation level of the specimen.

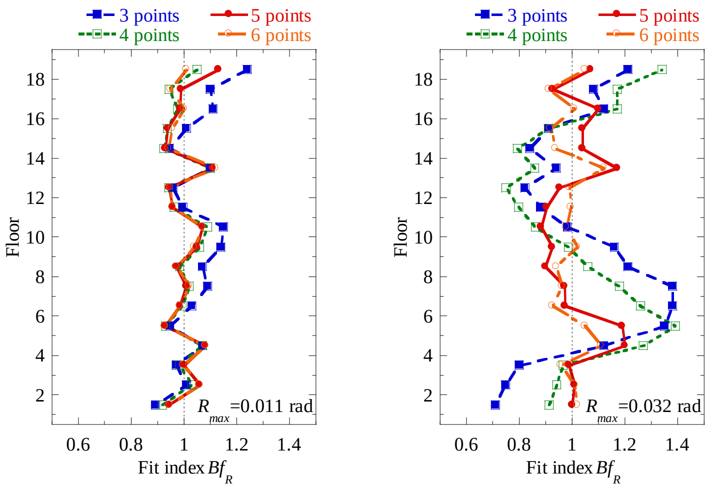
In the elastic deformation level ranged less than 0.01 radians of the maximum story drift angle, the effects of the number of sensors on the estimation accuracy are not so large. Therefore, our method by using only 3 sensor points can evaluate the observed value. On the other hand, in the strong nonlinear deformation level ranged more than 0.02 radians of maximum story drift angle, the influence of the number of sensors on the estimation precision appears largely. At the time, our method of using 3 sensor points underestimated the observed values, and the values of Bf_{Rmax} become about 0.75 at about 0.03 radians. However, by using more than 5 sensor points, the values of Er_R become less than 0.1 and the values of Bf_{Rmax} nearly become 1, and the proposed method is able to evaluate the observed results with high accuracy. We also confirm the influence of the number of sensors from the distributions of the fit index of the maximum story drift angle Bf_R as shown in the Fig.16.

It is true that more sensors give better accuracy for evaluating building response. Especially, more sensors are needed if the building shows strong nonlinearities over 0.02 radians. Thus, we think the number of sensors should be determined from the required accuracy of evaluating buildings response and the relations between damage criteria and judgement in target buildings.



(a) Estimated error Er_A (b) Estimated error Er_R (c) Fit index Bf_{Rmax}

Fig. 15 – Influence of numbers of sensors on estimation results



(a) R_{max}=0.011 radians (b) R_{max}=0.032 radians

Fig. 16 – Fit index of maximum story drift angle Bf_R

6. Conclusion

In this paper, we examined the applicability and effects of our estimation method according to the mode shape calculated on the basis of the design model of a building by using experimental data of the large shaking table test of the 1/3-scale 18-story steel high-rise building executed in December 2013 at E-Defense. Artificial generated earthquake motions were used as input for the large shaking table test, and the amplitude levels of the input motions were repeatedly increased until the model specimen collapsed. We installed 25 servo-type accelerometers in the model specimen on each floor. Response states of the whole building were evaluated by using a few sensor points. From the viewpoint of structural health monitoring, we focus on the maximum story drift angle of buildings. We analyzed the results estimated from limited point accelerometers by comparing them with observed data from all sensors in addition to other data such as displacement meters. In this paper, we can draw our conclusions as follows.

1) Up to 0.03 radian in the maximum story drift angle, results estimated from 5 sensor points (1, 4, 10, 15 and RFL) correspond approximately to the observed results in the 18-story steel high-rise building model.
2) It is important that sensors should be properly installed on the building by considering the mode shape of the design model in order to better evaluate the seismic response.
3) It is true that more sensors give better accuracy of evaluating building response. Especially, more sensors are needed if the building shows strong nonlinearities over 0.02 radians. Therefore, we think the number of sensors should be determined from the required accuracy of evaluating buildings response and the relations between damage criteria and judgement in target buildings.

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