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APPLICABILITY OF NUMBER OF SENSORS AND SIMPLE STRUCTURAL DESIGN MODEL FOR SEISMIC RESPONSE ESTIMATION SYSTEM OF WHOLE BUILDING

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Abstract

In Japan, there is a demand for evaluating the structural safety and function recovery of buildings shortly after they are subjected to an earthquake. In the event of a big earthquake, it is necessary to confirm the damage status of buildings after the earthquake and determine whether they can be continuously used. However, conventional judgment methods of building damage based on field surveys by experts may not be performed in metropolitan areas during large-scale earthquakes because of the sheer number of buildings in these areas. Therefore, from the viewpoints of ensuring earthquake resilience of buildings, the installation of a structural health monitoring system is necessary.

We have developed a structural health monitoring system that estimates the seismic response of a building during an earthquake based on a limited number of sensors. This system comprises several servo-type accelerometers, a data recording system, and an analysis system based on a personal computer. The seismic response of each floor of a building can be easily measured if sensors are installed on every floor. However, since high-performance sensors are generally expensive, it is difficult to install sensors on each floor. Our system estimates the response of the whole building by means of a modal analysis method based on the information of the accelerometers installed on specific floors. We assume that the modal shapes of buildings are determined by the mass and stiffness of the structural design model. However, as yet, the optimal number of sensors to be employed for such methods has not been examined from the perspectives of its dependence on the number of building floors and the effects of differences in modal shapes on the estimated responses.

In this study, we examine the optimal number of sensors depending on the number of floors in a building and the applicability of a simple structural design model on the estimated seismic response of buildings. From the viewpoint of evaluating structural safety and function recovery of buildings, we focus on the maximum story drift angle and maximum floor acceleration to judge the intensity of building damage. First, the optimal number of sensors depending on the number of building floors was theoretically determined from the results of a modal analysis. Then, a method to build a simple structural design model for the seismic response estimation of the whole building was developed. Finally, we validated the proposed method by using experimental shaking table test data obtained from the Archives of Shaking table Experimentation Database and Information. The results obtained by the proposed method were compared with the observed data from all sensors and with other data from sensors such as displacement meters.

The contributions of this study are as follows: (1) We proposed response estimation method to determine the optimal number of sensors according to the number of stories in a building and a method to build a simple structural design model. (2) The proposed simple structural design model can be applied for evaluating building response based on the results of shaking table tests.

Keywords: Structural Health Monitoring System, Modal Analysis Method, Seismic Response Estimation, Optimal Number of Sensors, Simple Structural Design Model

1. Introduction

Being prone to earthquakes, Japan recently has witnessed a demand for the early recovery of building functions via the structural safety evaluation of buildings immediately after an earthquake. After a major earthquake has occurred, it is necessary to check the damage status of buildings and determine whether they can be used continuously. However, the traditional method of assessing earthquake damage to building is based on on-site inspections by experts, and this method may not be feasible for large earthquakes and metropolitan areas because of the large number of buildings. Therefore, from the viewpoint of building resilient buildings, a system for the structural health monitoring of buildings is essential. We developed a structural health monitoring system that estimates the seismic responses of all floors of a building during an earthquake based on information from a limited number of sensors. In this paper, we propose (1) a method to determine the optimal number of sensors according to the number of floors for estimating the full-story response of a building and (2) a simple structural design model for estimating the seismic response of a building. In addition, we establish the validity of the seismic response estimation method using publicly available shaking table test data in order to examine the applicability of these methods.

2. Structural health monitoring system

Our structural health monitoring system [1] estimates the response of the whole building using the seismic measurement records of a small number of sensors installed on certain floors and determines the soundness of the target building. The degree of damage to the structural skeleton and the finishing material is determined based on response values such as the maximum story drift angle and acceleration during an earthquake. Fig. 1 shows the equipment configuration of the developed system. The observation sensor uses a three-component accelerometer (servo-type, semiconductor-type, etc., which meet the necessary performance requirement for seismic response measurement) and records the data to a data logger or a personal computer for data analysis. The recorded data are immediately applied for seismic response estimation, and the presence or absence of damage can be determined within about 1 min. The results are displayed using different colors to notify the building manager and the user. The system outputs the determined damage of the structural frame using the story drift angle as an index as well as information such as seismic intensity class, long-period ground motion class, and the degree of damage to the interior material using acceleration as an index. This information can be checked using a browser on another PC or smartphone connected to the network.

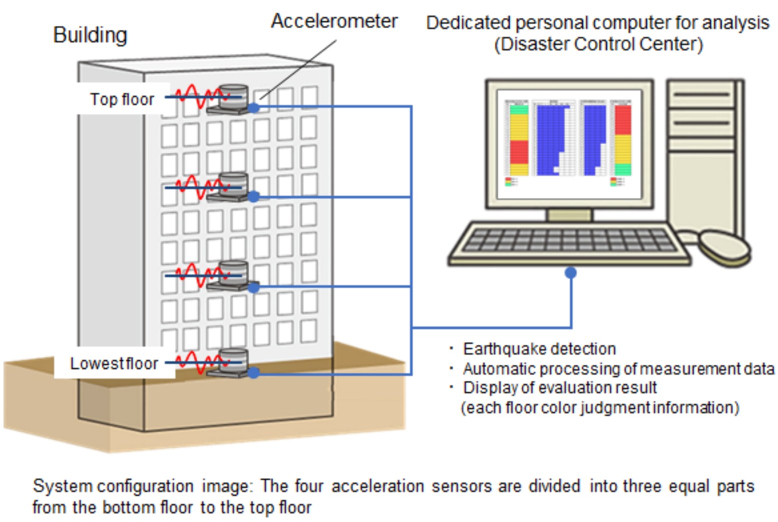


Fig. 1 Overview of the structural health monitoring system applied in a building

3. Seismic response estimation method

The method for the seismic response estimation of a building uses the eigenvalue of the mass system analysis model (mass m, stiffness k distribution) set in advance and the observation data of a small number of sensors. This is a method for estimating the time history response waveform in all stories of the building from the natural vibration mode (participation vector) of the mass system analysis model and observation data. Fig. 2 shows an outline of the response estimation method [2] based on a small number of sensors. The acceleration waveform obtained by the sensor is used as an acceleration record of a limited floor and is estimated by a mode synthesis method. A velocity waveform and a displacement waveform are obtained by numerically integrating the acceleration waveforms of all stories obtained by the response estimation. Low-cut filter processing is performed during the numerical integration. Further, the story drift is calculated from the difference between the displacement waveforms of adjacent floors, and the story drift angle can be obtained by dividing the story drift by the floor height. From these obtained waveforms, quantities such as the measured seismic intensity and long-period seismic intensity class (equivalent to the velocity response) are calculated as the corresponding maximum response values. These response values are then compared with the corresponding threshold values to the determine soundness of the building.

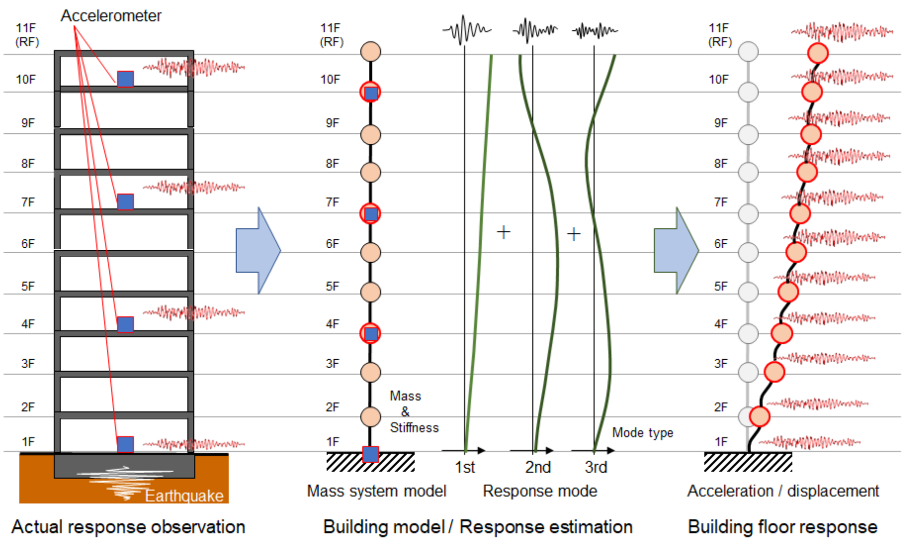


Fig. 2 Overview of the estimation method for overall response from data of a small number of sensors in a building

4. Optimal number of sensors required for response estimation

The various parameters set by the system include an eigenvalue of the mass system analysis model of a building, the floor for sensor installation, and the number of installed sensors. In a previous work [3], the effects of the building of mass system model and sensor floor on the accuracy of response estimation were examined. In this study, we examined the approximate number of sensors to be installed according to the number of floors in a building based on the results of time history response analysis.

First, we assumed buildings with 6, 18, 30, and 42 stories. The buildings were assumed to have a well-formed steel structure with well-balanced rigidity in the height direction. This system was based on the mode synthesis method of linear analysis, and the mode order to be considered was determined as one less the number of installed sensors. We examined the mode order determined based on the predominant period of the seismic wave input to the building and the assumed natural period of the 6th to 42nd floor. Considering the relationship between the natural period of the building and the mode order, based on the dominant periods of 0.3 and 0.5 s of the input seismic wave, the mode orders to be considered are summarized in Table 1 for each building floor.

Table 1 Mode order range considered and period range of the seismic wave

Period range of seismic wave	Building floors			
	6F	18F	30F	42F
Up to 0.5 seconds	2	3	4	5
Up to 0.3 seconds	2	4	7	9

Next, primary to tertiary sine waves were input to each building mass system model, normalized to the maximum velocity of 3 to 100 cm/s, and the results were examined based on the results of nonlinear response analysis. Since the estimation accuracy of number of installed sensors varies, the estimation error of the maximum story drift angle in the resonance state in each mode was examined. With an 18-story building number of installed sensors, four points are required for the linear range and five for the nonlinear range. Similarly, considering the estimation accuracy based on the results of the sensitivity analysis for each floor, the number of sensors installed according to the deformation level is summarized in Table 2.

Table 2 Deformation level and number of installed sensors

Response deformation level	Building floors			
	6F	18F	30F	42F
Linear response	3	4	5	
Nonlinear response	4	5	6	

Based on the above results, Fig. 3 shows the approximate number of sensors to be installed for response estimation according to the number of floors. With respect to the number of sensors installed, the responses for buildings in the fourth-order mode and higher tend to have a small effect on the overall response of the building. The emphasis, here, is on the effect of the seismic wave on the periodic band and the nonlinear response. In brief, 3–4 point sensor arrangement can be set for a six-story building, and four to five sensors for an 18-story building. Furthermore, the optimal number of sensors can be set as a guide, with five to six sensors for a 30-story building and six to seven sensors for a 42-story building. The response estimation can be improved by increasing the number of sensors for each building floor.

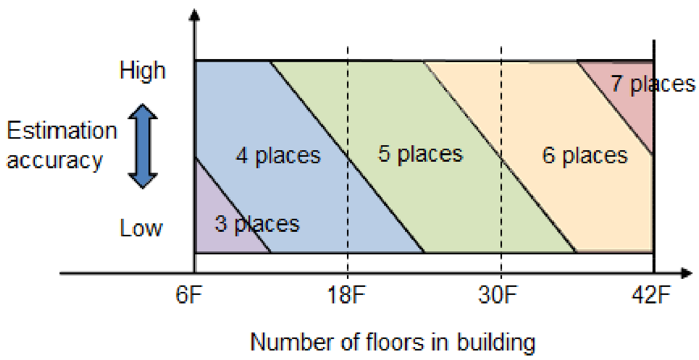


Fig. 3 Estimated number of sensors to be installed according to the number of floors

5. Simple structural design model

No structural design model will be required for response analysis if the distribution of mass and stiffness, which are the parameters of the design model used in response estimation, can be automatically generated. These parameters are set such that the model matches the cycle given by the empirical formula [4] of the primary cycle T1 for building design. This empirical formula is an experimental regression formula given by the structure type (S-structure, RC/SRC-structure) and shows the relationship between the eave height in an actual building and the first-order natural period obtained from vibration measurements in that building. Several formulas have been proposed for the primary cycle T1. Here, we take the example of a log–log regression formula considered suitable for low- to high-rise buildings. The regression equations for S and RC/SRC are shown in (1) and (2).

S-structure regression equation $\log10(T1) = 1.2 * \log10(H)-2.3$ (1)

RC/SRC-structure regression equation $\log10(T1) = 1.1 * \log10(H)-2.0$ (2)

Here, T1 represents the primary natural period (s), and H represents the eave height (m).

As the information given by the system, only the floor number is given, and the eave height is determined from the standard floor height. The standard floor height is 4.0 m for the S-structure and 3.3 m for the RC/SRC-structure. The model is then to be matched to the building so that the model cycle is the primary natural period of the building for the given number of floors. In the mass system model, the mass m of each story is set to a constant value of 1.0 ton. With regard to the stiffness k of each story, consider an example in which the uppermost story is assigned a trapezoidal distribution shape of 1 and the lowermost story, a triple shape. The stiffness k is obtained from equation (3), which is the natural period of the one-degree-of-freedom system, and the stiffness obtained from equation (4), and then deriving an initial stiffness distribution by multiplying the rank by the order.

Natural period of SDOF system $$T_1 = \frac{1}{2\pi} \cdot \sqrt{\frac{k}{m}} \quad (3)$$

Stiffness of SDOF system $$k = m \cdot \left(\frac{2\pi}{T_1} \right) \quad (4)$$

Fig. 4 shows a model image obtained via the above calculations as the initial information in the present system. Fig. 5 (a) shows the change in the natural frequency (1/natural period) of the S-structure from 1 to 100 stories (1 story to 100 stories) of the model obtained by this calculation. The horizontal axis indicates the natural frequency to be set, and the vertical axis indicates the natural frequency in the mass system model (blue line with circles). In the actual calculation, there is a shift in the natural frequency, and the coefficient value (correction magnification) of the natural frequency required for the correction is indicated by a red line with x symbols. The rigidity of the design model is corrected by using the coefficient for each natural frequency. Fig. 5 (b) shows the relationship between the natural frequencies in the final corrected mass model. Regarding the relationship with the natural frequency of the target, the rigidity distribution for a correction magnification of 1 and a mass of 1.0 ton for each story can be determined. The rigidity distribution of the design model described above can be generated in any shape distribution form.

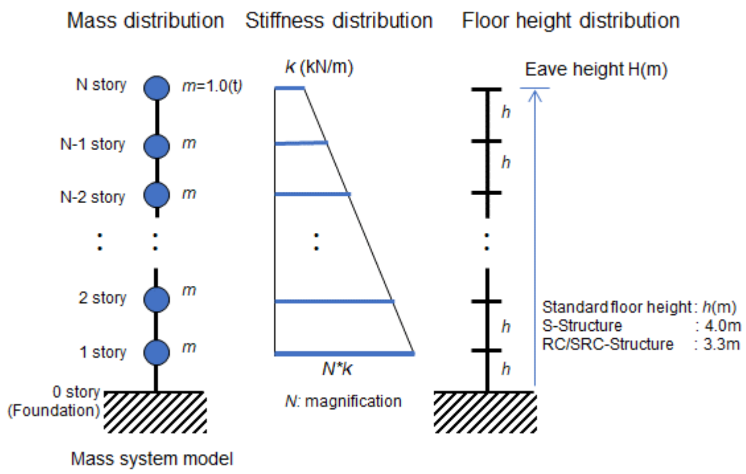


Fig. 4 Building mass system model parameters (automatic generation of stiffness distribution k: example 1 story N times)

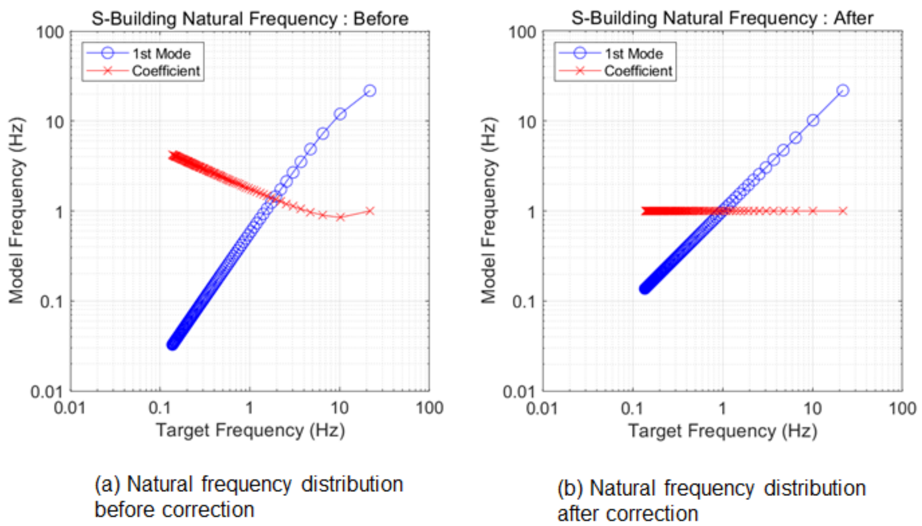


Fig. 5 Relation of primary natural frequency of S-structure model given initial information (1st floor to 100th floor)

Fig. 6 shows an example of a simple building model automatically generated by specifying the number of floors. The stiffness of the trapezoidal distribution shown in this figure was automatically generated for the 20th floor (20-story model). The rigidity ratio between the uppermost and lowermost stories is 1: 3. The first-order natural frequency is given by the regression equation for this building model. If the same trapezoidal rigidity distribution is generated even for different natural frequencies, then the shapes of the stimulus functions are similar.

6. Applicability of the simple design model

Using the relationship between the number of optimal sensor arrangements and the parameters obtained from the simple building model, we applied the model to response estimation and verified its accuracy. Tests were performed using a 20-story RC building test specimen (15.8 m in height and 0.75 m in height, 1/4-scale model) on a large shaking table belonging to E-Defense [5]; the data for these tests are provided as verification data in the Archives of Shaking Table Experimentation Database and Information (ASEBI). For the test specimen, the records of the horizontal X-direction accelerometers installed on each floor from the 1st floor to the 21st floor (R floor) are used. Fig. 7 shows the sensor arrangement (a) of the test sample and the stimulus function and transfer function (c) of the mass vibration model (b) of the design analysis. The primary natural frequency of this specimen was 1.77 Hz. Table 5 lists the experimental excitation cases used for verification. The table also lists the maximum acceleration response and the maximum story deformation angle of the specimen under the seismic wave excitation (EQ-01 to EQ-05). The seismic excitation level was sequentially increased, and the experiment was performed until the target of the final story drift angle reached or exceeded 1/50.

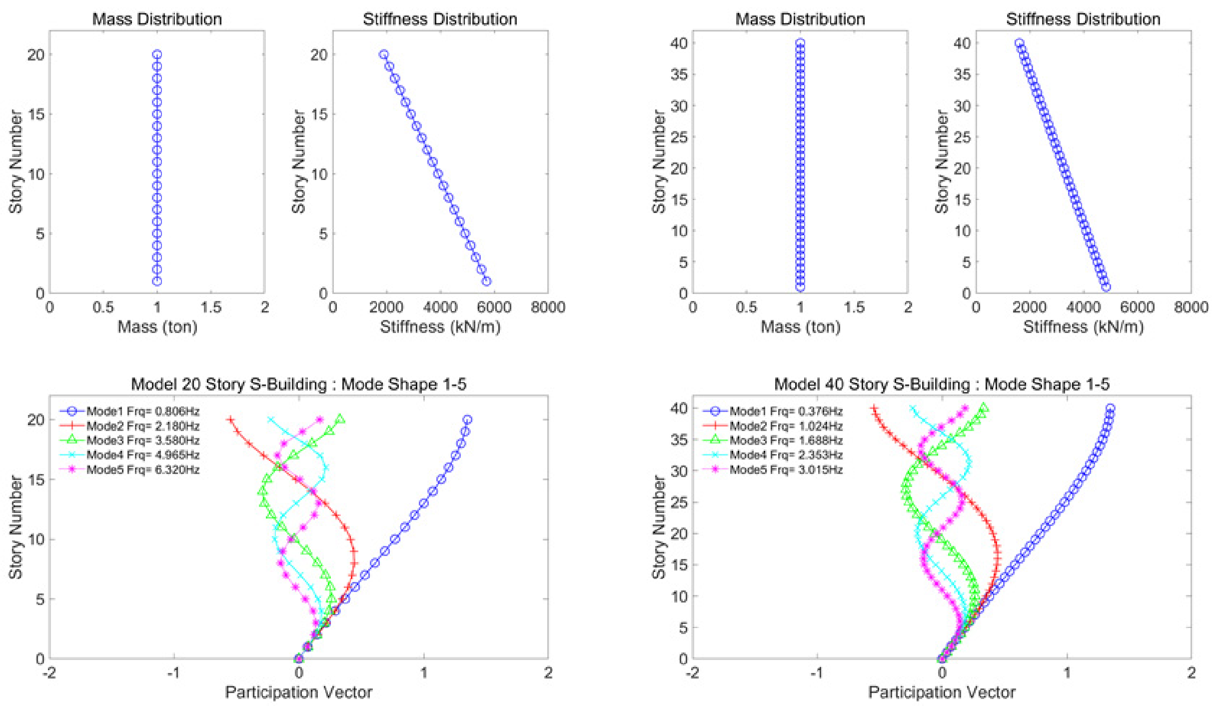
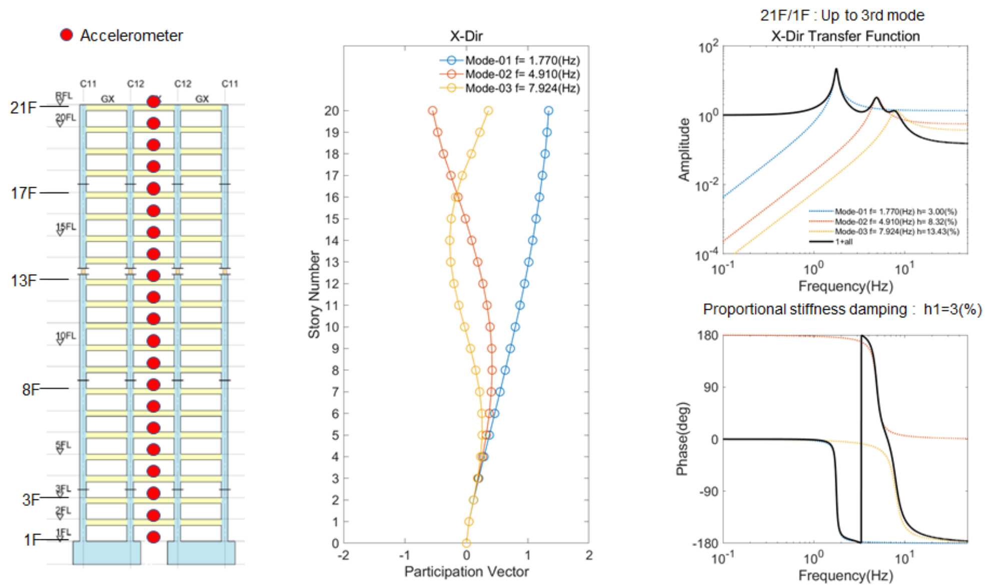


Fig. 6 Models of 20- and 40-story S-structure buildings automatically generated from the floor number (mass distribution, stiffness distribution, and participation vector up to 5th mode order)

6.1 Case of simple parameter setting

Fig. 8 shows the rigidity distribution of the building mass system model in the reduced 20-story RC building test specimen. This figure shows the shape of the rigidity distribution normalized by the top story. For verifying the response estimation, Model 0 to Model 5 were set as building models, and response estimation was performed. Model 0 is the analysis design model of the specimen shown in Fig. 7, and the stiffness distribution pattern at the lowermost story is greatly changed. The following models are simple models created by the method described in Section 5. Model 1 is a distribution type with the same stiffness, i.e., 1 for the lowermost story. Model 2 has thrice the rigidity of Model 0 at the lowest story. For Model 3, a uniform rigidity distribution shape, which changes rigidity five times the bottom story. In Model 4, the stiffness changes greatly in the second story, and the stiffness triples in the lowermost story. In Model 5, the stiffness varies in the fifth story, and it is set as a uniform rigidity distribution shape that varies 5-fold compared with that of the bottom story. Except for Model 0, the mass distribution of the mass model was fixed at 1.0 ton, and the primary natural frequency was set to 1.89 Hz, which is the initial natural frequency of the specimen as obtained in the experiment.



(a) Sensor arrangement (b) Mode shape (c) transfer function

Fig. 7 Specimen sensor arrangement of the 20-story RC building and the mass system model

Table 3 List of cases of seismic wave excitation for the shaking table tests

Case No.	Excitation wave	Maximum response acceleration (cm/s^2)	Maximum story drift(rad)
		X-directiton	X-direction
EQ-01	Tokyo observation waveform 40%	180	1/620
EQ-02	Tokyo observation wave 100%	341	1/201
EQ-03	Tokyo observation wave 200%	455	1/121
EQ-04	Tokyo observation wave 300%	649	1/76
EQ-05	Tsushima observation wave 150%	757	1/59
EQ-06	Tsushima observation wave 200%	793	1/34

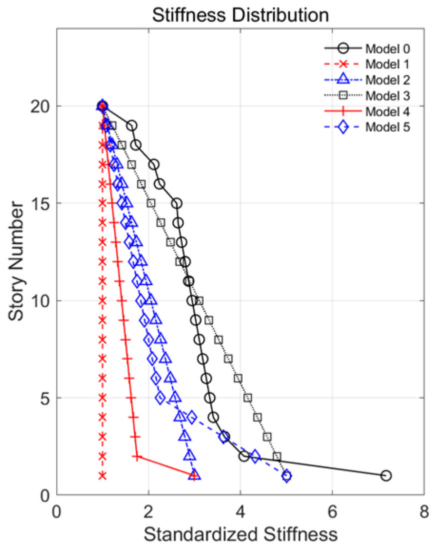


Fig. 8 Stiffness distribution shape of the mass system model of the building (standardized for the top story)

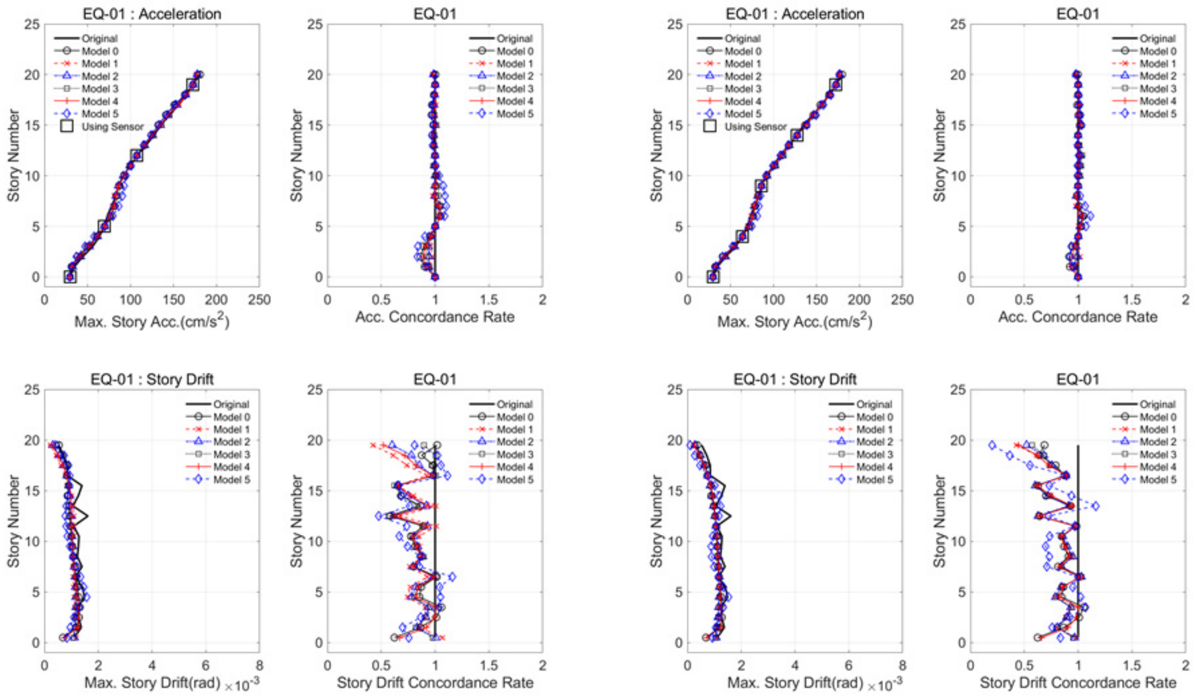
6.2 Validation of response estimation

In response estimation, the number of sensors to be verified was determined by examining the necessary number of sensors (see previous section). Here, a 20-story building was assumed. We used the experimental data of a reduced 20-story RC building test specimen. Since four or five points were optimal as the standard of the number of sensors in the 20-story building (Fig. 3), we examined the two cases. In addition, the experimental data were used to verify six cases from EQ-01 to EQ-06 (Table 3). Further, the suitability of the model was confirmed via response estimation using a small number of sensors and a rigid distribution model from Model 0 to Model 5 (Fig.8).

In the case of a four-point sensor arrangement, the response was estimated by using the acceleration responses at the 1st, 6th, 13th, and 20th floors by arranging the sensors by dividing the 20th floor almost equally as shown in Fig. 7 (a). In the case of the five-point sensor arrangement, the responses of acceleration of the 1st, 5th, 10th, 15th, and 20th floors were used. In the process of response estimation, sensors were placed on the lower floor of the uppermost floor (R floor) considering the mounting of sensors in an actual building.

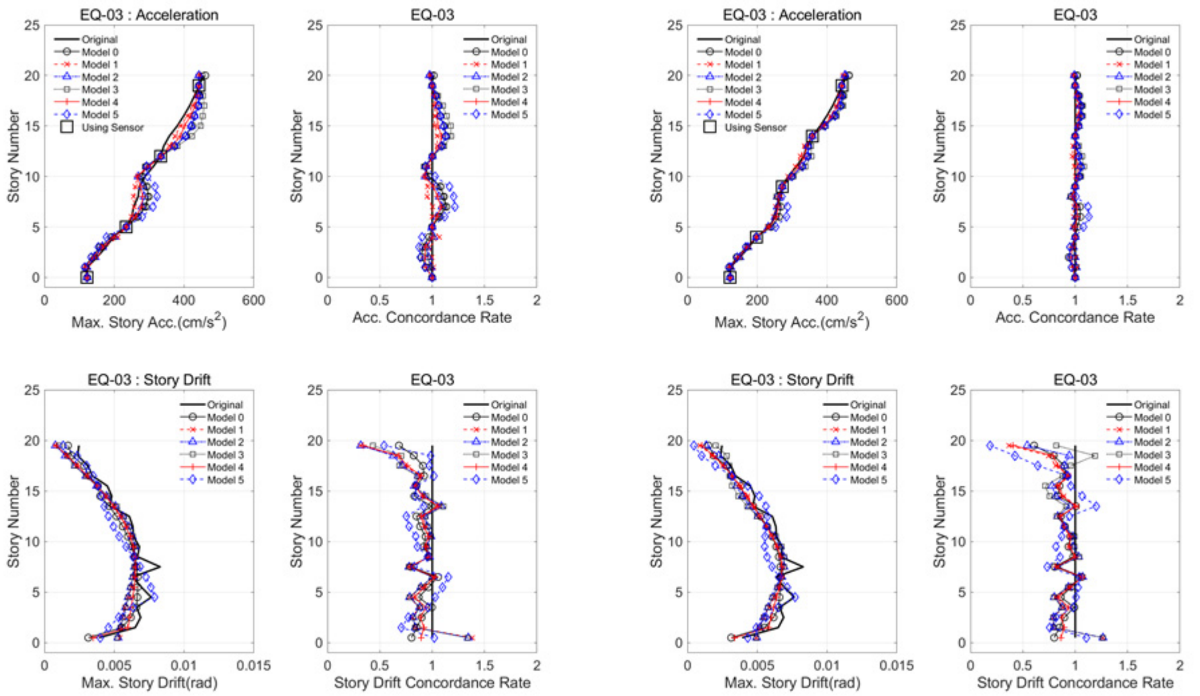
Figs. 9–11 show comparisons of the response estimation results for the four- and five-point sensor arrangements. Fig. 9 shows the results of a linear response (EQ-01); Fig. 10, the results of response estimation with a weak nonlinear response (EQ-03); and Fig. 11 (EQ-05), the result of response estimation with a strong nonlinear response. The figure shows the response estimation for a building mass system model with a stiffness distribution different from the measured value (original). These figures show the maximum acceleration response distribution, the maximum story drift angle distribution, and their concordance rate (the maximum value ratio of the estimated value and the actually measured value). When the degree of conformity is 1.0, the maximum values match the actual values; a value less than 1.0 indicates underestimation, whereas a value greater than 1.0 indicates overestimation. A comparison of the response estimations for the four- and five-point sensor arrangements shows that the variation in the acceleration response distribution tends to be smaller than that in the story drift angle distribution. The concordance rate of the story drift angle distribution tends to indicate underestimation in the upper story and overestimation in the lower story. As the excitation level and nonlinear response increase, this tendency becomes more pronounced. Although there is not much difference in the estimation results among the building mass system models, the estimation results of Model 0 of the structural design model and Model 4 of the simple building model show good overall correspondence. In response estimation, when the stiffness distribution type is closer to the actual design model, the concordance rate of the maximum value of the response estimation tends to increase. In addition, the five-point sensor arrangement with a larger number of sensor points provides better results in terms of the estimated acceleration response distribution, but the tendency of the maximum story drift angle distribution does not change much. In addition, the acceleration response distribution for which the response is estimated shows better results with the five-point sensor, but the tendency of the maximum story drift angle distribution is not good. In setting the building mass system model, there was no significant difference in the response estimation results even if a simple building mass system model was used.

Fig. 12 shows the fitness of the acceleration estimation, and Fig. 13 shows the concordance rate of the story drift angle. This figure also shows the variation of the response estimation result due to the differences in the number of sensors and the building mass system model. In the figure, the horizontal axis represents the case of the building mass system model, and the vertical axis represents the variation in the fitness (○: average value, the error bar is the standard deviation $\pm\ \sigma$) and shows each excitation case. Variations in the concordance rate of the acceleration response estimation are shown in Fig. 12. The standard deviation of about 0.3 fitness of four sensors, the five-point sensor is able to estimate is good the maximum value of about 0.05. On the other hand, the variation in the degree of conformity of the story drift angle response estimation shown in Fig. 13 has a standard deviation of about 0.3 around an average value of 0.93, and the estimation result of the maximum value has a large variation. The above results indicate that the difference in variation among the building mass system models is small, and the optimal model cannot be determined. Considering that it is used as a simple model, Model 4, which has a rigidity distribution closest to that of Model 0—the design model, is considered to have high overall fitness. However, for simplifying the stiffness distribution form, a similar estimation result can be obtained by selecting a trapezoidal distribution in which the stiffness distribution in the lowermost story of Model 2 is tripled. In the response estimation of the story drift angle, the estimated acceleration response waveform is subjected to numerical integration and filter processing to obtain a displacement response, and the difference is obtained at the upper and lower floors and divided by the floor height. It is conceivable that the degree of conformity also changes depending on the method of numerical integration and filter processing.



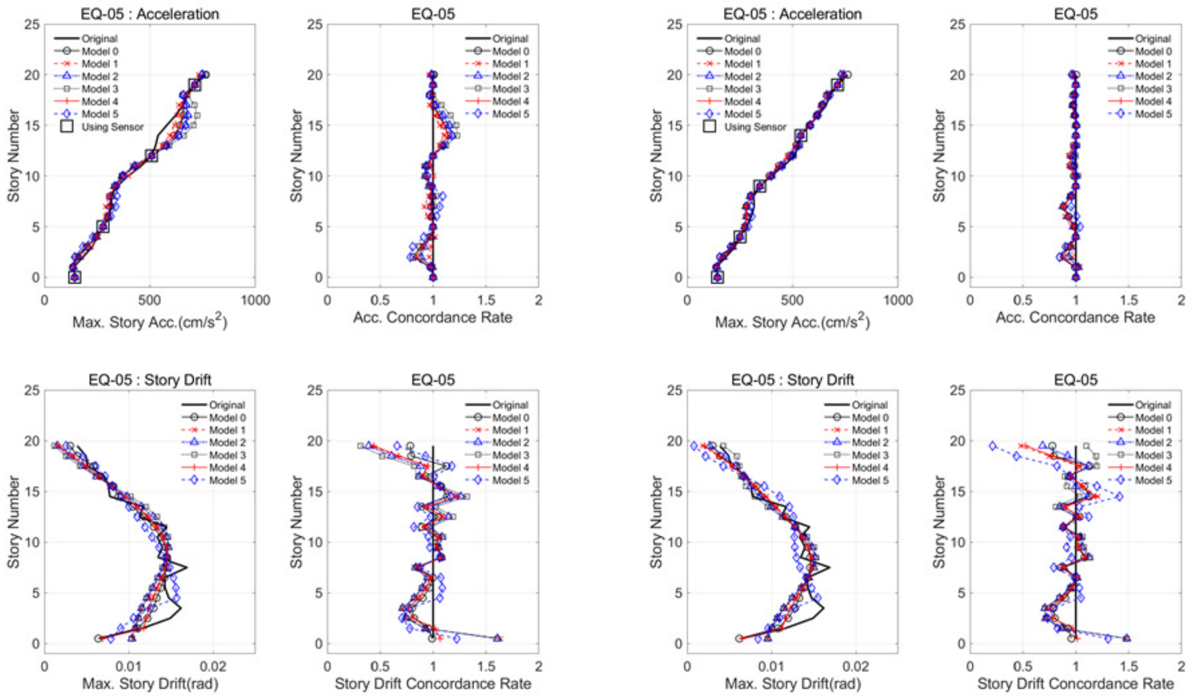
(a) Sensors of 4 places (b) Sensors of 5 places

Fig. 9 Response estimation result (EQ-01: Maximum story drift 1/620). Solid line: Experimental true value



(a) Sensors of 4 places (b) Sensors of 5 places

Fig. 10 Response estimation result (EQ-03: Maximum story drift 1/121). Solid line: Experimental true value



(a) Sensors of 4 places (b) Sensors of 5 places

Fig. 11 Response estimation result (EQ-05: Maximum story drift 1/59). Solid line: Experimental true value

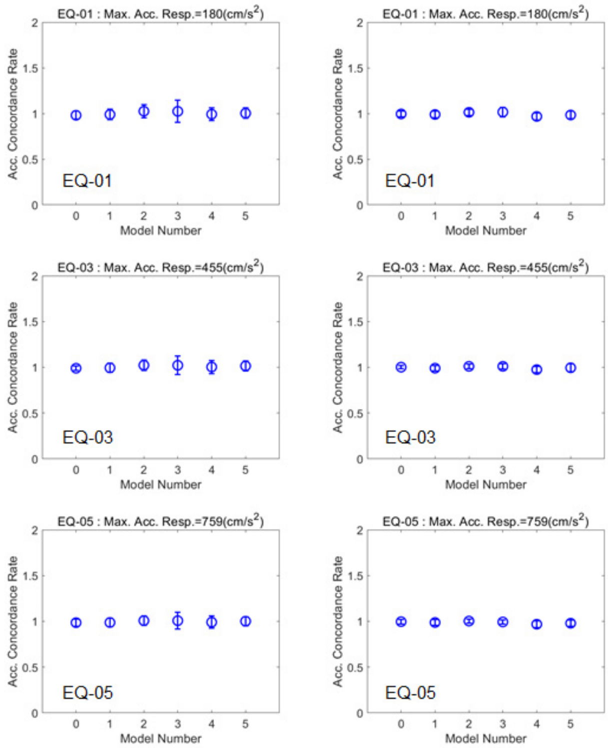
7. Conclusion

In this study, the applicability of the response estimation method used in the structural health monitoring system of buildings was examined. From the viewpoint of evaluating the structural integrity of a building, judgment was made using the maximum acceleration and the maximum deformation angle at each floor as the judgment index of damage to the building. First, the optimum number of sensors according to the number of floors in the building was theoretically examined based on modal analysis results. Next, a method for building a simple structural model necessary for estimating the seismic response of the whole building was proposed. Finally, the proposed response estimation method was verified by using shaking table test data of a reduced 20-story RC building test specimen; the data were obtained from the ASEBI.

Based on the above examination results, the following conclusions were drawn: (1) We proposed adopting the optimal number of sensors according to the number of stories in a building as a response estimation method and proposed a method to build a simple structural design model. (2) The applicability of the proposed simple structural design model was validated and found to be good for evaluating building responses based on the results of shaking table tests.

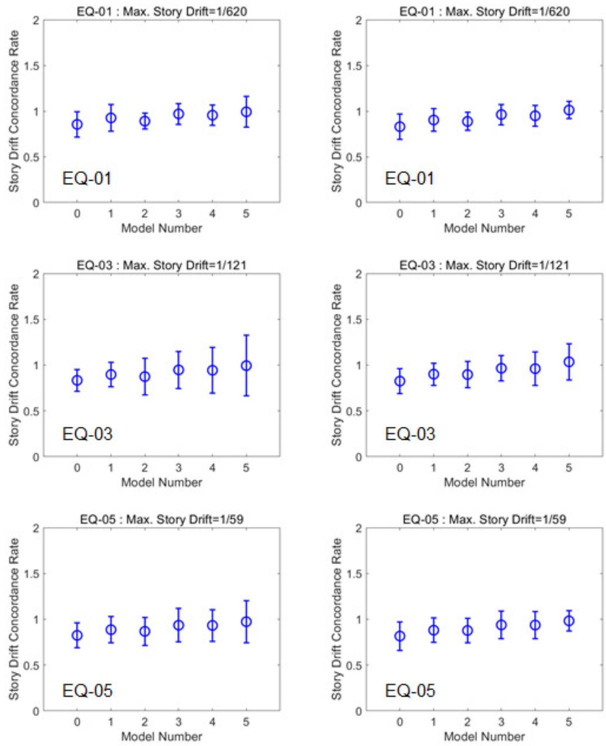
Acknowledgments

In this study, we used shaking table test data of "Shaking Table Test of 1/4 scaled 20 Story RC Building under Long Period Ground Motions" conducted at E-Defense in 2012. The data is available at the Disaster Prevention Research Institute of Science and Technology "ASEBI". I would like to thank the parties concerned here.



(a) Sensors of 4 places (b) Sensors of 5 places

Fig. 12 Concordance rates of acceleration response estimation for different number of sensors and mass system models (by excitation level: ○ average value; the error bar is within ± σ)



(a) Sensors of 4 places (b) Sensors of 5 places

Fig. 13 Concordance rate of displacement response estimation for different number of sensors and mass system models (by excitation level: ○ average value; the error bar is within ± σ)

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