17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

ESTIMATION OF SHEAR DEFORMATIONS IN SEISMIC RESPONSE FOR HIGH-RISE BUILDINGS USING SHEAR-BENDING MODEL

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Abstract

Due to the recent and future earthquake disasters in Japan, such as Great East Japan earthquake (2011), Kumamoto earthquake (2016), Tokai-Tonankai-Nankai earthquake, it is strongly desired to build a business continuity plan (BCP) toward disaster-prevented resilient buildings. Structural health monitoring techniques are expected to be useful for rapid decision making after an earthquake disaster to judge whether it is needed to evacuate from the building or not, and the building can be used uninterruptedly or not.

System identification plays an important role in structural health monitoring to identify the structural properties of buildings. The physical parameter identification is one of the system identification methods, where the stiffness and damping coefficients of an analytical model, such as a shear model used for modeling building structures, are objective parameters to be identified. Since the influence of overall bending deformation is remarkable in high-rise buildings, this paper presents a system identification method using a shear-bending model to simulate the actual building behavior. The unknown parameters of the shear-bending model are shear and rotational stiffnesses.

In this paper, seismic horizontal accelerations observed at limited stories and push-over analysis results of a design frame model are used to identify a shear-bending model which represents the objective building. The challenging aspects in this study are how to identify the fundamental natural mode from floor seismic responses at limited stories and base input, and to estimate the rotational stiffness based on the static analysis of a design frame model. To tackle the first issue, we propose a cubic spline interpolation method to estimate the fundamental natural mode. The number and location of acceleration sensors are discussed from the view point of the identification accuracy. As for the second issue, the results of the push-over analysis of a design frame model are used to obtain the relationship between shear and rotational stiffnesses. The information on this design frame model can be derived from the structural properties of the actual building. The epistemic uncertainties are taken into account in constructing the design frame model. Furthermore, assuming the situation where the objective building is subjected to a large amplitude earthquake, the influence of plastic behavior is also considered.

To demonstrate the accuracy and reliability of the proposed system identification method, numerical simulations on a 20-story building frame are shown. The identified shear-bending model is then used to estimate the maximum inter-story deformation of the objective building under earthquake ground motions. It is demonstrated that the proposed method can enhance the accuracy remarkably in predicting the maximum inter-story drifts compared to the previous methods.

Keywords: System identification, Structural health monitoring, Shear-bending model, Static push-over analysis, Cubic spline interpolation

1. Introduction

Due to the recent earthquake disasters in Japan, it is desired to build a business continuity plan (BCP) for important buildings such as disaster base hospitals. In BCP, it is necessary to determine various guidelines in advance to continue business according to the degree of disasters. Furthermore, urgent decision makings to evacuate from the building or not, to restrict the building function are also needed after the disaster. Structural health monitoring (SHM) system where the structural seismic responses are observed by sensors installed to the building is expected to play an important role in BCP. Although SHM has been applied to some actual buildings, installed sensors are on limited floors due to initial and maintenance costs. Therefore, recorded seismic responses cannot be used directly to evaluate the maximum response of the building [1-3].

A physical parameter identification is known as one of the branches of the system identification (SI) where the stiffnesses and damping coefficients of a physical model are identified to represent the sesimic behabior of the actual building. It should be carefully determined what kind of physical models is suitable for the objective building. The shear model shown in Fig.1 (a) is often used as a simplified structural analysis model where each lumped mass represents the floor mass and the shear springs connecting each node correspond to the story stiffness of the building. Since the interstory drift of the building is given only by the shear deformation in the shear model, the influence of overall bending deformation of building cannot be considered. While, a shear-bending model shown in Fig.1 (b) where shear stiffness and rotational stiffness are connected in serise between each node is also used to represent the behavior of buildings [4-7]. As for the stiffnesses to be identified, both the shear and rotational stiffnesses are unknown in the shear-bending model. Since the observed record that can be used for identification is limited, e.g. horizontal floor accelerations, it is difficult to identify rotational stiffness stably.

In this paper, we propose a new SI method based on the shear-bending model, where observed records of the objective building at limited stories and the push-over analysis of a pre-prepared analysis frame model called as a design model are used. Since the modelling error between the anlysis frame model and the actual building is not negligible, the fundamental natural frequency of the identified shear-bending model is estimated based on the observed data. The feature of the proposed method is that the stiffness ratio defined as the ratio of shear stiffness to rotational sitffness in the shear-bending model is evaluated from the result of the push-over analysis in the elastic range of the design model. Furthermore, in order to consider the influence of plastic behavior of the objective building under large amplitude ground motions, the plastic response in shear stiffness is also considered. Plasticity properties, i.e. yielding displacement and second stiffness ratio, are detemined so as the hysteresis area to be equivalent with the restoring force characteristic derived from the push-over analysis.

For verification of the proposed method, since the true value of the physical parameters doesn't exist in the actual building, the sesimic responses of the objective building is estimated by the identified shear-bending model. From the time-history analysis of the identified shear-bending model subjected to the observed ground motion, it is possible to estimate the maximum response of the objective building, e.g. maximum interstory drift and actual shear deformation shown in Fig.1 (c), even for unobserved stories.

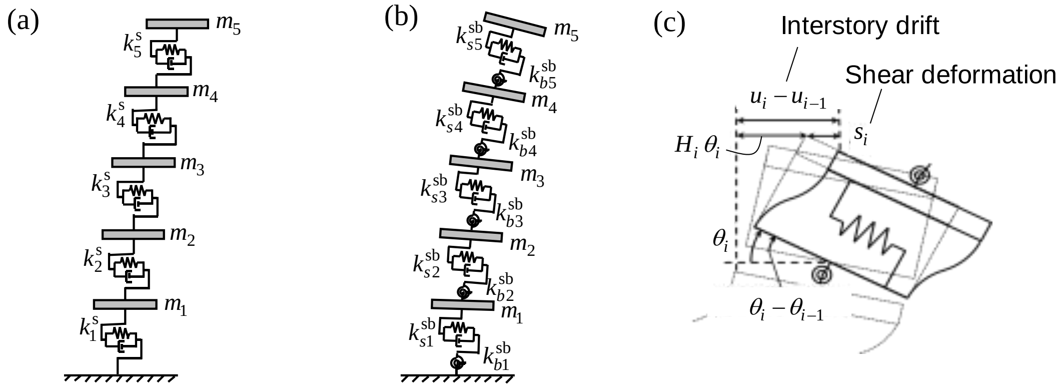


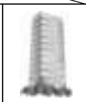
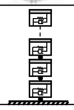
Fig.1 Shear model and shear-bending model

2. Measurement and analytical model of target building

First, it should be clarified what measurement data of the target objective building can be used in the proposed identification method shown in a later section considering the measurement capability. In this paper, the target objective building to be identified is referred to as the identification target. Since the identification target is an actual building, there is no true structural model to represent the identification target. Therefore, the validity or accuracy of the identified model should be discussed by comparing the observed records with estimated responses obtained from the identified model.

In the previous works, a fundamental natural mode shape of both horizontal displacement and rotational angle has been used in the inverse-problem formulation to identify the stiffness of the SB model, [7, 8]. However, since it is difficult to measure the floor rotational response directly, the identification of the rotational fundamental natural mode shape is hard to be achieved. In this paper, instead of the identification of the rotational fundamental natural mode shape, pre-analysis using an analytical model of the identification target is also utilized in the SI. For this purpose, push-over analysis is conducted by using a three-dimensional frame model that can be constructed from design specifications. This analytical model is referred to as the design model. The SB model obtained as the result of identification is referred to as the identified model. Table 1 shows the relationship among the identification target, the design model and the identified model.

Table 1 Relationship among identification target, design model and identified model

		Natural frequency & mode shapes	**Mass**	**Story stiffness**
Identification target (Actual building)		Unknown but possible to observe	Unknown and impossible to measure	Unknown
Design model (Frame model)		Possible to calculate but including modelling errors	Estimate	Possible to extract stiffness ratio from equivalent shear-bending model derived by static analysis ⬇
Identified model (Shear-bending model)		Consistent with observation (fundamental natural frequency and mode shape)	Consistent with estimation (same with design model) ➡	Finally identified

Used for model tuning in optimization

3. System identification of high-rise building under seismic response at limited stories

3.1 Overview of proposed identification method

This paper presents a new SI method for high-rise buildings using a shear-bending model which is based on seismic responses observed at limited stories. The shear-bending model can be derived from the fundamental natural frequency and mode shape. However, it is difficult to estimate the rotational component of the fundamental natural mode shape from observed data. Compared with previously proposed methods, the SI method proposed in this paper does not intend to estimate the rotational component of the fundamental natural mode shape. Alternatively, the bending stiffness of the identified shear-bending model is estimated by using the stiffness ratio of bending stiffness to shear stiffness derived from the static analysis of the design model. In the proposed method, the seismic horizontal floor acceleration response and the acceleration on the ground are used as observation records obtained from the identification target. Simultaneous observation of these records is necessary to evaluate the transfer function. The detailed flow of the proposed SI method will be explained in the following sub-sections.

3.2 Estimation of fundamental natural period and mode shape of identification target

The subspace method is often used in SI. By applying the subspace method to the input and output data, the parametric transfer function can be derived that is useful to estimate the characteristics of building vibration [9-11]. In the subspace method, state equations are described as

$$\begin{aligned} \boldsymbol{x}(k+1) &= \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) \\ \boldsymbol{y}(k) &= \boldsymbol{C}\boldsymbol{x}(k) + \boldsymbol{D}\boldsymbol{u}(k) \end{aligned} \tag{1a,b}$$

where $\boldsymbol{x}$, $\boldsymbol{y}$ and $\boldsymbol{u}$ represent an input vector, an output vector, and a state vector. $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, and $\mathbf{D}$ are parameter matrices. The N4sid method (Numerical algorithm for Subspace based State Space System Identification method) is used to estimate these parameter matrices. The input data is observed ground acceleration, and the output data is observed floor horizontal accelerations. Laplace transform of Eqs.(1) provides the transfer function of the output to the input as

$$\mathbf{G}(z) = \mathbf{C}(z\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D} \tag{2}$$

where, T_0 is the time step of the input/ output data. z in Eq.(2) is given by $e^{i\omega T_0}$ where ω is a circular frequency. It is well known that the fundamental natural frequency ω_1 can be derived by the minimum frequency that gives the extremum value of the transfer function. The fundamental natural mode shape $\boldsymbol{U}_1$ is identified by the following equation, where transfer function values of $z_{\omega 1} = e^{i\omega_1 T_0}$ are reffered. Using all floor records, it has been demonstrated that $\boldsymbol{U}_1$ can be identified within allowable accuracy [5].

$$\boldsymbol{U}_1 = \left|\frac{\boldsymbol{U}}{\boldsymbol{U}_g}\right| \approx \left|\frac{\ddot{\boldsymbol{U}}}{\ddot{\boldsymbol{U}}_g}\right| = \left|\frac{\ddot{\boldsymbol{U}} + \ddot{\boldsymbol{U}}_g}{\ddot{\boldsymbol{U}}_g} - \mathbf{1}\right| = \left|\mathbf{G}\left(z_{\omega 1}\right) - \mathbf{1}\right| \tag{3}$$

where $\mathbf{1}$ is a vector consisting of 1 only. In Eq. (3), observed ground acceleration is eliminated from observed floor horizontal absolute acceleration in order to obtain the relative horizontal displacement mode.

3.3 Estimation of fundamental natural mode by cubic spline interpolation

In order to identify an N-degree-of-freedom (DOF) shear model for the N-story building, the horizontal fundamental natural mode shape of all stories is needed. A method using cubic spline interpolation is proposed that interpolates between amplitude values of $\boldsymbol{U}_1$ with independent cubic functions. When accelerometers are installed at the base and in $z_1, z_2, \cdots, z_j$ stories, conditional expressions for 4j unknown quantities are required. The cubic spline interpolation in the non-observed stories is described as

$$P_k(x) = a_k x^3 + b_k x^2 + c_k x + d_k \quad (z_{k-1} \le x \le z_k) \tag{4}$$

Conditional equations for determining coefficients in Eq. (4) are shown below

[Condition 1] Known value of the fundamental natural mode shape at the observed story
[Condition 2] First derivatives of the adjacent cubic functions are continuous at each point
[Condition 3] Second derivatives of the adjacent cubic functions are continuous at each point

Two more conditional equations for 4j unknown quantities are needed in addition to Condition 1 to Condition 3. In this paper, the third derivatives of the adjacent cubic functions at the point next to the end point are considered to be continuous. This condition is called not-a-knot condition and equal to the condition that the boundary conditions at both end points are pin-supported. J cubic functions is obtained by solving j conditional equations and the fundamental natural mode of all stories is obtained. Conditional equations are described as

$$P_k\left(z_k\right) = u_{z_k},\ P_k'\left(z_k\right) = P_{k+1}'\left(z_k\right),\ P_k''\left(z_k\right) = P_{k+1}''\left(z_k\right),\ P_0'''\left(z_1\right) = P_1'''\left(z_1\right),\ P_{j-1}'''\left(z_{j-1}\right) = P_j'''\left(z_{j-1}\right) \tag{5a-e}$$

Figs. 2 (a) and (b) show an example of linear interpolation and cubic spline interpolation of the fundamental natual mode shape for a 20 story building where base, 5th, 10th, 15th and 20th story acclerations are observed. As shown in Fig.3(b), the fundamental interstory drift mode shape can be estimated within allowable accuracy by applying cubic spline interpolation.

3.4 Identification of shear model equivalent to identification target

The shear stiffness $\mathbf{k}^s = \{k_1^s, k_2^s, \cdots, k_N^s\}$ of a shear model can be obtained from ω_1 and $\mathbf{U}_1 = \{U_1(1), U_1(2), \cdots, U_1(N)\}$. By applying static force distribution $F_i = \omega_1^2 U_1(i)$ equivalent to the fundamental natural mode shape and assuming the interstory deformation given by the difference of fundamental natural mode shape, k^s can be derived by the inverse problem formulation as

$$k_i^s = \frac{\omega_1^2 \sum_{j=1}^{N} m_j U_1(j)}{U_1(j) - U_1(j-1)} \quad (i = 1, \cdots, N) \tag{6}$$

where, m_i is the mass given by the design model, and $U_1(0) = 0$.

3.5 Push-over analysis of design model

Push-over analysis is known as the method to derive the restoring force charactersitic of the frame model where the sequential analysis for gradually increasing horizontal load is performed. The floor rotation angle θ_i as shown in Fig.4 can be evaluated from the vertical displacements v_i of columns as

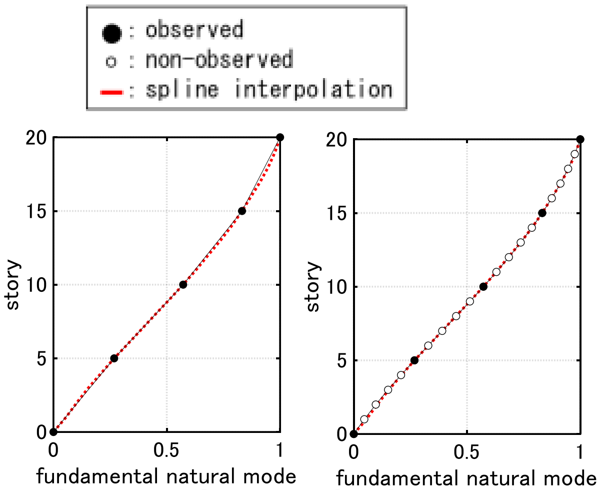
$$\theta_i = \frac{v_i^{x,1} - v_i^{x,n_y}}{\sum_{i=1}^{n_y} l_i} \qquad (i = 1, \cdots N) \tag{7}$$

where the superscript on v_i represents the position of column in x or y direction. n_y and l_i in Eq. (7) are the number of spans in *y* direction and the span length, respectively.

From the push-over analysis, the story shear force-shear deformation relation can be obtained by removing rotational component from interstory drift. Focusing on the elastic range from the restoring force characteristics obtained as shown in Fig.5, the design model can be replaced with the equivalent shear-bending model. The shear stiffness and the rotational stiffness of the equivalent shear-bending model of the design model are described as

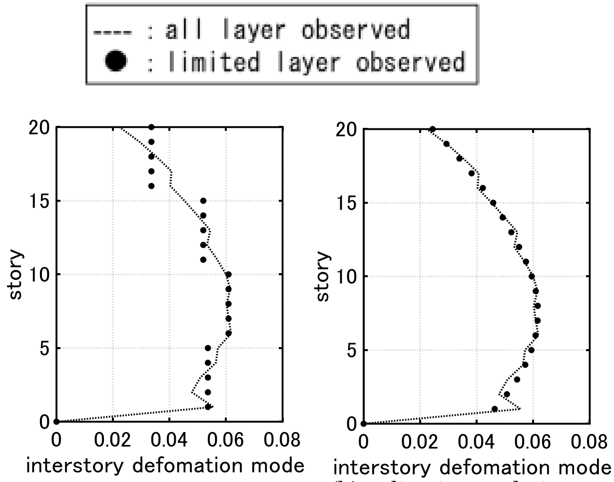
$$k_{si}^{\mathrm{sb}*} = \frac{\sum_{j=i}^{N} F_j}{u_i - u_{i-1} - H_i \theta_i}, \quad k_{bi}^{\mathrm{sb}*} = \frac{\sum_{j=i}^{N}\left(F_j \sum_{k=N+i-j}^{N} H_{N+i-k}\right)}{\theta_i - \theta_{i-1}} \qquad (i = 1, \cdots N) \tag{8a, b}$$

where, F_i and H_i are the horizontal force at the *i*-th floor and story height of the *i*-th story. In Eq. (8b), the numerator is the overturning moment and the denominator is the inter-floor rotational angle. For estimating the elasoplastic properties of the shear-bending model, the yield displacement is determined so that the hysteresis area up to the maximum shear force of the design model is equivalent to that of the identified model. The stiffness ratio after yielding is determined so that the maximum shear force is equivalent.



(a) linear interpolation (b) spline interpolation

Fig. 2 Estimation of fundamental natural mode shape



(a) linear interpolation (b) spline interpolation

Fig. 3 Estimation of fundamental interstory deformation mode

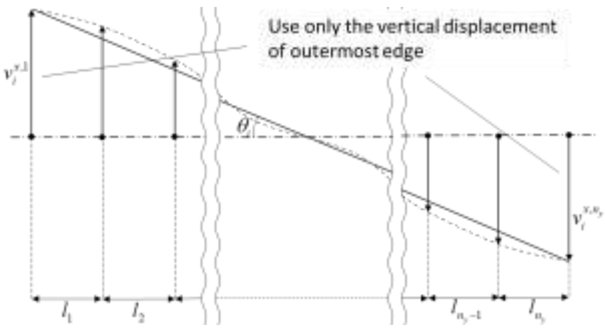


Fig. 4 Definition of floor rotation angle

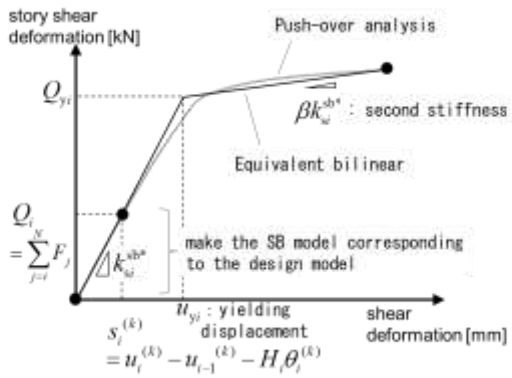


Fig. 5 Restoring-force characteristics of design frame model by push-over analysis

3.6 Identification of shear-bending model by non-linear least-squares method

The shear-bending model of the design frame model can be derived from the push-over analysis by using Eq. (7). However, since modeling error exists between the identification target and the design model, the shear-bending model to be identified is obtained by non-linear least-square method. The initial model is given by multiplying the stiffness ratio $k_{bi}^{sb*} / k_{si}^{sb*}$ of the design model obtained in Eq. (8) to the shear stiffness $\mathbf{k}^{s}$ identified from the actual observation derived in Eq. (6).

The shear stiffness of the shear-bending model is slightly larger than the shear stiffness of the shear model in the upper story. This is because the rotational displacement due to the floor rotation is dominant in the interstory drift in the upper stories. In order to modify the shear stiffness of the initial shear-bending model, the shear stiffness $\mathbf{k}_{s}^{sb}$ of the shear-bending model is updated by multiplying the undetermined coefficient $\boldsymbol{\alpha} = \{\alpha_1, \alpha_2, \cdots, \alpha_N\}^T$ by $\mathbf{k}^{s}$. The rotational stiffness $\mathbf{k}_{b}^{sb}$ of the shear-bending model is determined by multiplying the stiffness ratio depending on the updated values $\boldsymbol{\alpha}$. The fundamental natural frequency and fundamental natural mode shape are calculated by using eigenvalue analysis. The objective function in the non-linear least-square method is described as

$$F(\boldsymbol{\alpha}) = \left(T_1^{\mathrm{ide}} - T_1^{\mathrm{obs}}\right)^2 + \sum_{k=1}^{N}\left(U_1^{\mathrm{ide}}(k) - U_1^{\mathrm{obs}}(k)\right)^2 \qquad (9)$$

4. Numerical examples

In this section, the proposed method is applied to a 20-story building model. Accuracy of the maximum seismic response estimated by the identified model is investigated. In this paper, the observation of the target building is assumed to be given by the time history response analysis of the three-dimensional frame. Although it is difficult to measure the exact values of interstory drifts and shear deformations of the actual building, simulated observations are useful for the verification of the proposed method.

4.1 Overview of design model and identification target

A 20-story steel frame as shown in Fig.6 is used for verification. The mass of the design model is an integrated value, and the stiffness increase by the influence of composite beams and the rigid-connection condition of the beam-column joint are set as commonly used. The design model contains modeling errors, i.e. difference of natural frequencies from the identification target. To consider modelling error, the identification target is provided by changing several parameters of the design model, e.g. the coefficient of composite beams is randomly increased by 100-150%, and each story mass varies randomly by 90-110%. The ground motion input is given only in *y* direction, and the horizontal acceleration responses at several floors in *y* direction are used for identification instead of actual measurement.

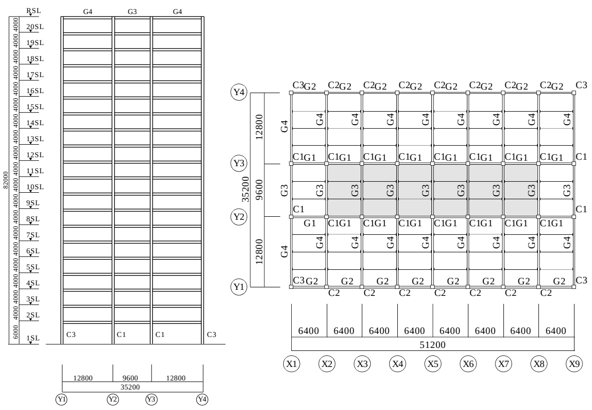


Fig.6 Elevation and plan of objective building

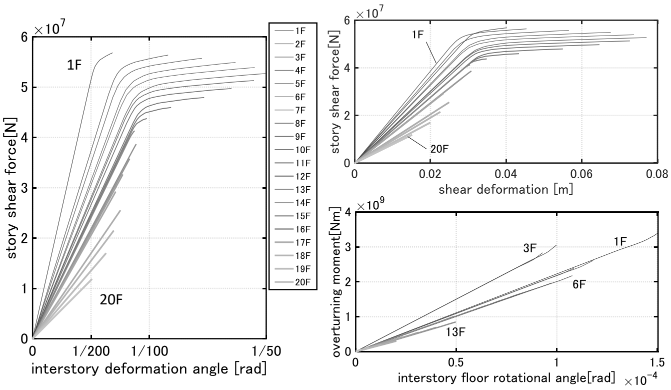


Fig.7 Push-over analysis of design frame

Table2 Equivalent shear-bending model of design frame

F	mass [×10^6kg]	rotational inertia [×10^9kgm^2]	shear stiffness [×10^8N/m]	yielding displacement [mm]	second stiffness ratio	rotational stiffness [×10^13Nm]	SR stiffness ratio [×10^4m^2]
1	1.51	1.56	17.7	30.8	0.14	2.23	1.25
2	1.47	1.52	19.3	27.8	0.08	3.01	1.55
3	1.46	1.50	18.3	29.3	0.05	3.00	1.64
4	1.45	1.49	16.6	31.4	0.05	2.19	1.36
5	1.44	1.48	16.3	33.3	0.04	2.19	1.39
6	1.43	1.48	15.1	32.5	0.04	2.02	1.35
7	1.43	1.48	15.0	32.6	0.04	2.02	1.37
8	1.43	1.48	14.7	33.4	0.04	2.03	1.42
9	1.43	1.48	13.8	32.4	0.06	2.03	1.42
10	1.43	1.49	13.8	31.0	0.10	2.03	1.46
11	1.44	1.48	13.8	-	-	2.03	1.46
12	1.43	1.48	13.8	-	-	2.06	1.47
13	1.43	1.48	12.6	-	-	1.70	1.32
14	1.42	1.47	12.6	-	-	1.72	1.36
15	1.42	1.47	12.6	-	-	1.75	1.38
16	1.42	1.47	12.5	-	-	1.79	1.42
17	1.40	1.44	10.2	-	-	1.50	1.55
18	1.40	1.44	9.51	-	-	1.57	1.69
19	1.38	1.42	8.53	-	-	1.81	2.14
20	1.84	1.90	7.84	-	-	2.07	2.68

Table 3 Natural periods [s]

degree	identification target	design model
1	2.500	2.654
2	-	0.927
3	-	0.552

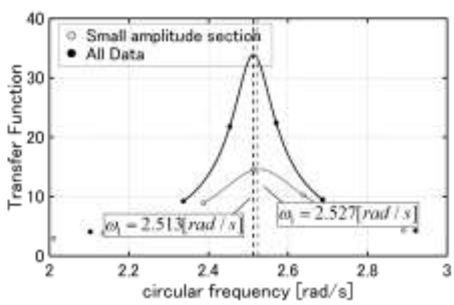


Fig.8 Estimation of fundamental natural frequency from transfer function of top story acceleration

Fig.7 shows the results of push-over analysis of the design model. By evaluating floor rotation angle in the push-over analysis, the relation between the story shear force and the shear deformation and the relation between the overturning moment and the interstory floor rotational angle can be obtained as shown in Fig.7. From these figures, the shear and rotational stiffnesses of the shear-bending model can be derived from Eq. (8). The structural properties of the design model are summarized in Table 2. Table 3 shows that there is an error of 6% in the fundamental natural period between the design model and the identification target.

4.2 Analysis case

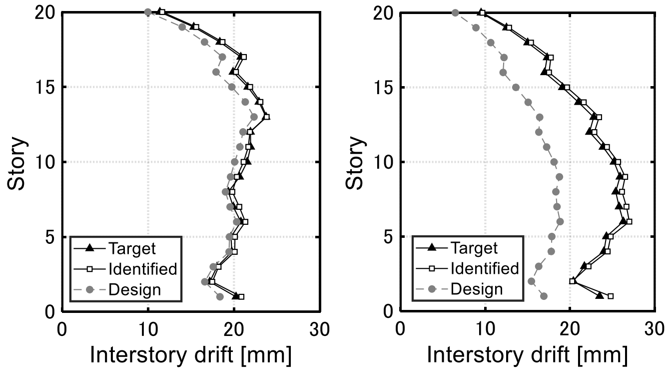
The ground motions used in this study are El Centro NS (1940), Taft EW (1952), Hachinohe NS (1968), JMA Kobe NS (1995), Tomakomai EW (2003). Design standard earthquake ground motions in Japan, i.e. El Centro NS (1940), Taft EW (1952) and Hachinohe NS (1968), are normalized so that each maximum velocity corresponds to 25[cm/s] at level 1 and 50[cm/s] at level 2. We also compare the difference of number of sensors located in the building, i.e. 5 accelerometers at base, 5, 10, 15, 20th stories and 4 accelerometers at base, 6, 15, 20th stories. To clarify the influence of cubic spline interpolation for the estimation of fundamental natural frequency and parameter determination using non-linear least-square method, the identification using floor accelerations at all stories is also investigated. When we can use all floor accelerations for identification, no interpolation is needed.

4.3 Extraction of small amplitude part of horizontal acceleration response during an earthquake

The specific time range is extracted from the time history response data to identify the transfer function. This is because the fundamental natural period of the identification target can be identified more accurately from the elastic response. In this paper, the moving average of the observed acceleration response at the top floor is obtained by multiplying a rectangular window whose length is 100, i.e. 1[s] for $dt = 0.01$. From the variation of normalized root-mean-square value of the moving average, the time range to be used for identification is determined by the decrease below 0.3 after peak location. Fig. 8 shows the transfer function and the fundamental natural frequency obtained by applying the subspace method to the horizontal floor acceleration response for level 2 input of JMA Kobe NS, where plastic deformations were observed in the upper stories. When we use only the data in the small amplitude part, ω_1 is estimated as 2.513[s]. The fundamental natural period T_1 is culculated as 2.500 [s] (the error is 0.02% or less).

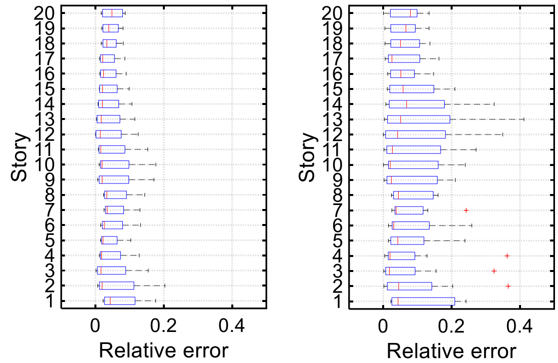
4.4 Identification using simultaneously recorded seismic responses at all stories

In this section, the proposed SI method is verified by using all floor accelerations, i.e. the stiffness ratio of the identified model is compared with the design model. There is no need to interpolate the fundamental natural mode shape shown in Section 3.2. Fig.9 shows the distribution of the maximum interstory drift for El Centro NS (1940) of level 1 and Tomakomai EW (2003). In Fig. 9, the maximum interstory drift distribution of the identification target and the design model are compared. Since the design model has different natural frequencies compared with the identification target as shown in Table 3, it can be confirmed that the maximum interstory dritf of the identification model almost corresponds to that of the identification target as the correct value. Fig.10 shows the boxplot of the relative error ratio of interstory drifts of the identified model for various input ground motions from the correct value of the identification target. In the boxplot, various statistical indices can be expressed in the same plot, where the box represents quartiles, the middle bar means median and outliers are depicted as individual points. Fig.10(a) is a boxplot for a group of earthquakes where the identification target response is elastic. On the other hand, Fig.10(b) is a boxplot for all earthquakes. It has been confirmed that the stiffness ratio of bending to shear derived by pushover analysis of the design model is useful to identify the shear-bending model even in case of including modelling errors.



(a) El Centro NS (Level1) (b) Tomakomai EW

Fig.9 Maximum interstory drift



(a) elastic range (b) elastoplastic range

Fig.10 Boxplot of relative error of maximum interstory drift

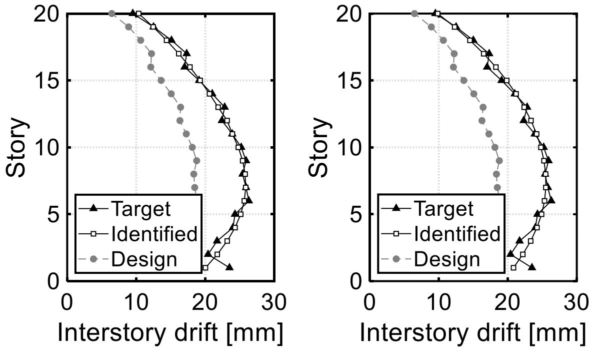
4.5 Identification using simultaneously recorded seismic responses at limited stories

Consider the case where observed records are available only at limited stories. It is necessary to estimate the fundamental natural mode shape as shown in Section 3.3. Validity of the proposed method is investigated by comparing the maximum interstory drift for various ground motions.

Fig.11 shows a comparison of influence of number of sensors installed to the identification target on estimation of the maximum interstory dirft under Tomakomai EW. Four stories' records and base record are used in Fig.11(a), while three stories in Fig.11(b). As in Fig.10, Fig.12 shows the boxplot of relative error ratio of the maximum interstory drifts for different number of sensors installed to the identification target. Although the variation of estimation error is slightly large compared with Fig.10, there is no significant difference depending on the number of installed sensors. Therefore, following simulations are examined for observation records by four accelerometers.

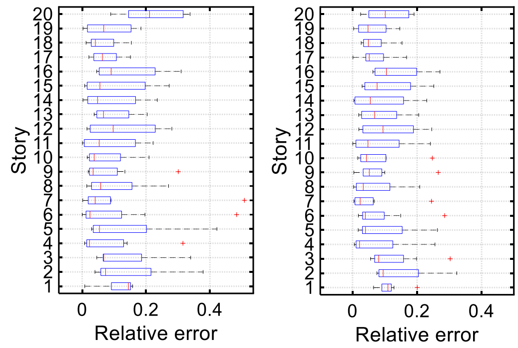
Although it is difficult to measure the floor seismic rotation angle in actual buildings, we can evaluate the time history of floor rotation angles in Eq.(7) by extracting vertical deformations of outmost columns in the numerical simulation. To validate the proposed SI method using the shear-bending model, the maximum shear deformation of the identified shear-bending model, that can be derived by removing the deformation due to the floor rotation from interstory drift, is compared with that of the identification target in Fig.13. It can be confirmed that the shear deformation of the identification target, i.e. the three-dimensional frame, can be estimated by time history response analysis of the identifed model subjected to the same ground motion. It is desired to assess the structural safety of the identification target by using the actual seismic shear deformation in future works.

Fig.14 shows the comparison of time history acclerations at the top floor and 10th floor of the identification target with those estimated by using the identified shear-bending model. The input ground motion is JMA Kobe NS. It can be concluded that floor accelrations including non-observed floor can be evaluated within allowable accuracy by using the identified model in addition to the estimation of the interstory drift. The evaluated floor accelerations can be used for assessment of nonstructural elements in the building.



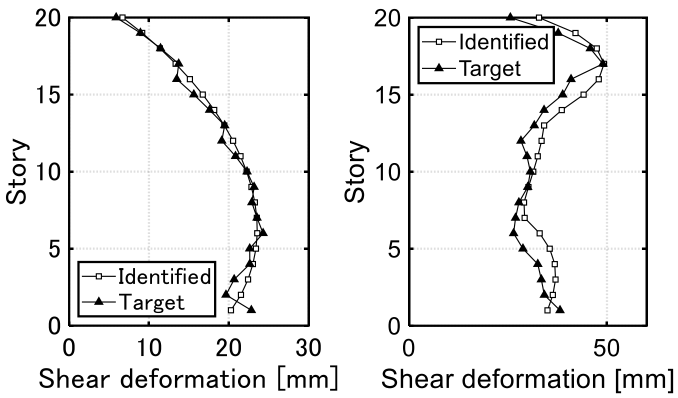
(a) GL,5,10,15,20F (b) GL,6,15,20F

Fig.11 Maximum interstory drift (Tomakomai EW) for different sensor location



(a) GL,5,10,15,20F (b) GL,6,15,20F

Fig.12 Relative error of maximum interstory drifts under various earthquakes for different sensor location



(a) Tomakomai EW (b) JMA Kobe NS

Fig.13 Maximum shear deformation

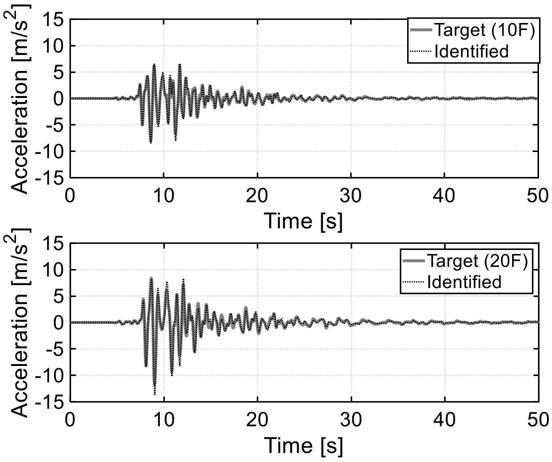


Fig.14 Acceleration response (10F, 20F)

5. Conclusion

In this paper, a new system identification method for high-rise buildings based on limited floor seismic observation has been proposed, where the push-over analysis of the design model is used. The algorithm of the proposed method can be summarized as follows.

- A fundamental natural mode shape at all stories including stories without sensor has been estimated from the observed transfer function derived by the subspace method and the cubic spline interpolation method. To apply cubic spline interpolation, it is necessary to install more than two accelerometers in addition to the ground surface and the top floor.
- From push-over analysis of the design model including modeling errors, the ratio of the bending stiffness to the shear stiffness and restoring force characteristics, i.e. yield displacement and stiffness ratio after yielding to initial, of the shear-bending model have been derived. The stiffness ratio of the shear-bending model is updated through optimization to adjust the fundamental natural frequency and the fundamental natural mode shape.

Numerical examples of the proposed method are shown for a 20-story steel frame. For verification of the proposed method, masses and stiffnesses of beams are unknown in the identification target. The fundamental natural frequency of the design model is about 6% different from the identification target. Results obtained from the application examples are as follows.

- When we can use all floor horizontal accelerations for identification, the maximum interstory drifts estimated by using the identified model almost correspond to that of the identification target for various ground motions.
- Considering the case where observation records at only limited stories are available, the influence of number of sensors installed to the identification target on accuracy of estimation of the maximum interstory drift has been investigated for five accelerometers, i.e. ground surface, 5, 10, 15, 20th stories, or four accelerometers, i.e. ground surface, 6, 15, 20th stories. There is no difference in estimation accuracy. In particular, when using the response to a long-period ground motion, i.e. Tomakomai EW, the response can be evaluated within allowable accuracy compared with that derived by the design model. This may be because the fundamental natural frequency is dominant in seismic responses for long-period ground motions.
- The seismic shear deformation obtained by removing overall bending deformation of the identified model was compared with that of the identification target. It has been confirmed that the seismic shear deformation can be estimated by the identified model within allowable accuracy. The evaluation of shear deformation of the identification target through the proposed system identification method using shear-bending model is expected to be useful for structural safety assessment.

6. References

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