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SEISMIC DESIGN FORCE FOR CEILINGS IN JAPAN BASED ON A DIRECT METHOD FOR FLOOR RESPONSE SPECTRUM

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ABSTRACT

In the Great East Japan Earthquake, many suspended ceilings suffered damage and collapsed. Following the heavy damage, a new seismic design code for specified ceilings was established and came into force in 2014 in Japan.
In this paper, the technical background of seismic forces on specified ceilings in Japan is reported.
At first, an empirical direct method is introduced. It is utilized to calculate approximate floor response spectrum (FRS) used for determining the design forces on specified ceilings. The method uses a new amplification function proposed to represent the degree of resonance with structural frames. Approximate FRS can be obtained using the amplification function and participation vectors of a structural frame by SRSS combination rule. Validation of the method is confirmed by comparing with results of time history analysis.
Next, the background of compiling the seismic forces into a tabular form in the code is described. To omit the eigenvalue analysis for each main frame, representative values for participation vectors of structural frames are utilized for calculating FRS. The regions of natural periods and stories attached by ceilings are roughly divided into a few parts respectively. The representative design forces have been assigned to each part.

Keywords: resonance; floor response spectrum; suspended ceiling system; modal analysis; design seismic force

1. INTRODUCTION

In the Great East Japan Earthquake, many suspended ceilings suffered damage and collapsed. Of those, there were some cases where a response of the suspended ceilings was considered to be amplified by resonance with the structural frame.
For aseismic design of nonstructural components and systems (NSCS) where the amplification ratio can be raised, resonance with a structural frame which amplifies inertial force and deformation should be taken into account. The degree of resonance can be evaluated with the floor response spectrum (FRS). Even in the general building structures where any time history analyses are not carried out, it is desirable to set a seismic force with considering characteristics of FRS. However, the characteristics of FRS are not always sufficiently reflected in a seismic force for design for NSCS. In many cases (except for special ones) in Japan, NSCS have been practically designed with taking into account for a seismic force of about 1 g.
Following the above-mentioned damage, the new seismic design code for specified ceilings (refer to ceilings that the Minister of Land, Infrastructure, Transport and Tourism has specified as one in danger of causing serious harm by falling) was established as a notification of Ministry of Land, Infrastructure, Transport and Tourism (MLIT, 2013) and came into force in 2014 in Japan. According to the code, seismic design forces on ceilings are determined considering representative FRS by an empirical direct method.
In this paper, the technical background of seismic forces on specified ceilings in Japan is reported.
At first, the empirical direct method is introduced. It is utilized to calculate approximate FRS used for

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determining the design forces on specified ceilings. The method uses a new amplification function proposed to represent the degree of resonance with structural frames. Approximate FRS can be obtained by the amplification function and participation vectors (i.e. participation factors and eigenvectors) of a structural frame by SRSS combination rule. Validation of the method is confirmed by comparing with results of time history analysis (THA).

Next, the background of compiling the seismic forces into a tabular form in the code is described. To omit the eigenvalue analysis for each main frame, representative values for participation vectors of structural frames are utilized for calculating FRS. The regions of natural periods and stories attached by ceilings are roughly divided into a few parts respectively. The representative design forces have been assigned to each part.

Although the empirical direct method for FRS presented in this paper was developed for ceilings, it is also suitable for other types of NSCS.

Similar research works for estimation methods for FRS can be found in the literature before and after our investigation reported in this paper. Peak floor accelerations, which correspond to FRS for rigid NSCS, have been investigated for linear responses (e.g. Miranda and Taghavi 2005, Taghavi and Miranda 2005, Pozzi and Der Kiureghian 2015) and nonlinear responses (e.g. Rodriguez et al.2002, Wieser et al. 2013). Some methods for FRS have been proposed for linear and nonlinear seismic responses in single-degree-of-freedom (SDOF) systems and multi-degree-of-freedom (MDOF) systems (e.g. Yasui et al. 1993, Sullivan et al. 2013, Calvi and Sullivan 2014, Jiang et al. 2015, Vukobratović and Fajfar 2016).

2. A DIRECT METHOD FOR FLOOR RESPONSE SPECTRUM

This paper presupposes that seismic forces for NSCS are investigated for allowable stress design against the lower level of seismic intensity in Building Standard Law of Japan.

2.1 Assumptions

In order to deliberate a simple method for FRS, we provide several assumptions.

[1] Super high-rise buildings and buildings with dampers shall not be targeted.
[2] Structural frame and NSCS shall be linear systems; the damping ratio shall be 5%.
[3] NSCS is much more lightweight than the structural frame; vibration of structural frame shall be free from motions of NSCS.
[4] NSCS shall be modeled as a SDOF system.
[5] Torsional vibrations of structural frame and particular individual members' vibrations or the like can be ignored.
[6] NSCS are attached to floors or roofs, free of any impact of enforced deformation caused by story drifts of the structural frame.

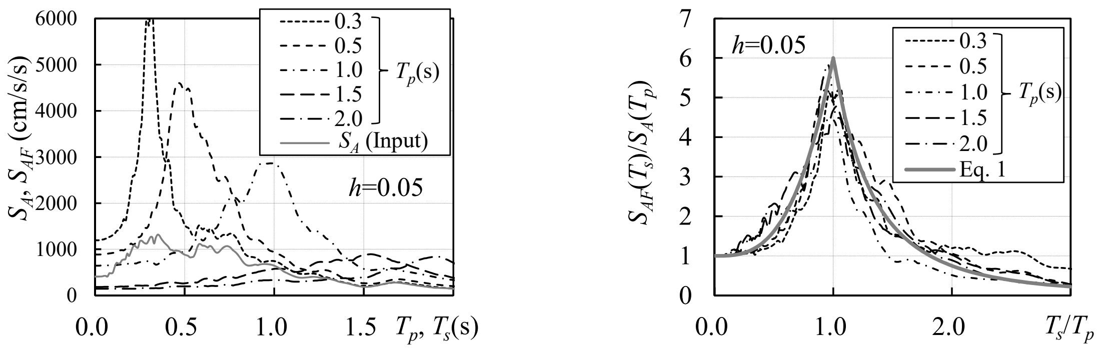
With respect to the damping ratio of assumption [2], the value of damping for structural frame is applied according to the design spectrum in Japan. Taking a suspended ceiling for an example of NSCS, it has been reported to be usually from in the order of 3% to 8% in some technical reports in Japan. In view of the above, this paper makes an examination under assumption [2].

2.2 Floor Response Spectrum in SDOF System

First, we consider a case where the structural frame is modeled by a SDOF system. The input seismic motion is NS component recorded at Japan Meteorological Agency (JMA) Sendai station during the Tohoku earthquake in 2011. Figure 1(a) illustrates FRSs S_{AF} obtained by THA. Horizontal axis T_p is a natural period of the structural frame (primary system), and T_s is of NSCS (secondary system). The solid line in the figure is the absolute acceleration response spectrum S_A, the dotted lines, etc. are FRSs S_{AF} for primary system with various T_p shown in the figure. Naturally, S_{AF} differs according to T_p. But as shown in Figure 1(b), the relations between $R(T_p, T_s) \equiv S_{AF}(T_s)/S_A(T_p)$ (Sign [≡] indicates definition) and T_s/T_p are similar irrespective of T_p. The solid gray line by Equation 1 agrees with the tendency of numerical results. We apply Equation 1 to approximate evaluation of FRS for seismic forces on NSCS.

$$R(T_p, T_s) \equiv \frac{S_{AF}(T_s)}{S_A(T_p)} = \begin{cases} 1+5\left(T_s/T_p\right)^3 & (T_s \le T_p) \\ 6\left(T_p/T_s\right)^3 & (T_p < T_s) \end{cases} \tag{1}$$

Although omitted in this paper, it is confirmed that the same approximation is applicable in other earthquake motions. As was pointed out in Sullivan et al (2013), it is confirmed that the relation R (in other words, amplification factors) for long-duration seismic motions are similar to those for normal duration ones.



(a) Acceleration response spectrum S_A(solid line) and floor response spectra S_{AF}(dotted lines, etc.)

(b) $S_{AF}(T_s)/S_A(T_p)$-T_s/T_p relations

Figure 1. Examples of floor response spectra (NS component recorded at JMA Sendai)

2.3 Expansion to MDOF System – Response Spectrum Method –

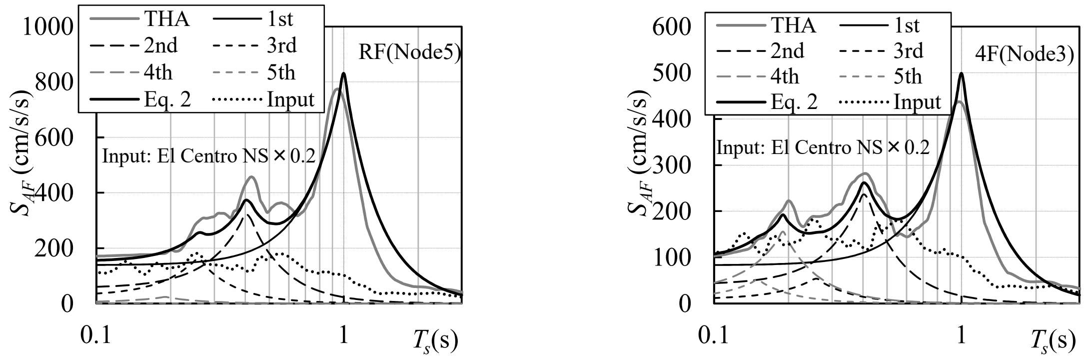
Although the approximate evaluation in Equation 1 shown in Figure 1(b) is obtained by using the primary SDOF systems, we expand it to MDOF systems in accordance with the concept of the modal analysis (e.g. Yasui et al. 1993). This is a method of synthesizing modal responses in accordance with SRSS combination rule by utilizing a participation vector. FRS at floor I can be estimated as follows:

$$S_{AF}(T_s) \approx \sqrt{\sum_j \left\{ R(T_j, T_s) \cdot \beta_j U_{Ij} \cdot S_A(T_j) \right\}^2} \tag{2}$$

where, subscript I is the number of installation floor for NSCS; $\beta_j U_{Ij}$ is a participation vector of j-th mode of primary system at floor I; β_j is a participation factor of j-th mode of primary system; U_{Ij} is a component of j-th mode at floor I; T_j is a natural period of j-th mode of primary system; T_s is a natural period of NSCS (secondary system); $R(T_j, T_s)$ is a value to set T_p of Equation 1 to T_j; and S_A is acceleration response spectra of input seismic motion.

An example is shown to confirm the validity of Equation 2.

A building is supposed to be a five-story shear building (five-degree-of-freedom system), having uniform mass, inverted triangular first mode, and primary natural period T_1 = 1.0 s. The damping ratio is 5% for all modes. An input wave is defined as multiplying the El Centro NS wave by 0.2. The result is shown in Figure 2. Although the FRS S_{AF} (thick gray lines) by THA and S_{AF} (thick black lines) by Equation 2 differ a little bit on the short period side from each other, it is observed that Equation 2 gives acceptable estimates that are close to the THA results.



(a) RF (Roof), $I = 5$

(b) 4F, $I = 3$

Figure 2. Comparison of S_{AF} by THA with S_{AF} by Equation 2

2.4 Comparison with other proposed equations

As a simple direct method for FRS, there is already a proposal by Yasui et al. (1993), which is the base of recent research extended to inelastic MDOF systems by Vukobratović and Fajfar (2016). In Yasui's method, responses by each mode are obtained by Equation 3 and FRS is obtained as SRSS according to Equation 4 (the symbols have been changed appropriately corresponding to the preceding section).

$$S_{AFj}(T_s, h_s, T_j, h_j) = \sqrt{\frac{\left\{(\omega_s/\omega_j)^2 S_A(T_j, h_j)\right\}^2 + \left\{S_A(T_s, h_s)\right\}^2}{\left\{1-(\omega_s/\omega_j)^2\right\}^2 + 4(h_s + h_j)^2(\omega_s/\omega_j)^2}} \tag{3}$$

$$S_{AF}(T_s, h_s) = \sqrt{\sum_j \left(\beta_j U_j \cdot S_{AF\,j}\right)^2} \tag{4}$$

where, ω_s is the natural circular frequency of NSCS (= $2\pi/T_s$); ω_j is j-th natural circular frequency of structural frame (= $2\pi/T_j$); h_s is the damping ratio of NSCS; and h_j is the j-th damping ratio of structural frame.

The method proposed by Yasui et al. (1993) is characterized as the possibility to take account of the level of damping ratio of structural frame and NSCS. Another feature is the formulation where S_{AFj} does not fall below S_A even within the range of $T_j < T_s$ based on the theory. It is a useful method when the damping ratios are known. This paper proposes Equation 1, intending simplicity for design, in view of difficulties in evaluating damping ratios in designing; taking into account that it is rare when the natural period of NSCS becomes longer than the first natural period of structural frame.

In order to compare with Equation 1, assuming that $h_s = h_j = 0.05$ in Equation 3, and provided $S_A(T_s, h_s) = S_A(T_j, h_j)$ as in a constant-acceleration region of S_A, it becomes as follows:

$$R(T_j, T_s) = \frac{S_{AFj}(T_s, 0.05, T_j, 0.05)}{S_A(T_j, 0.05)} = \sqrt{\frac{(T_j/T_s)^4 + 1}{\left\{1-(T_j/T_s)^2\right\}^2 + 0.04(T_j/T_s)^2}} \tag{5}$$

In Figure 3, Equations 1 and 5 are shown by comparison. It is confirmed that both equations give approximate values.

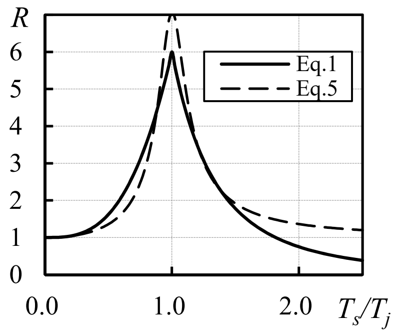


Figure 3. Proposed Equations by Yasui et al. (Equation 5) and of this paper (Equation 1)

Sullivan et al. (2013) proposed the peak value of R (dynamic amplification factor, *DAF*) for linear and nonlinear SDOF systems as,

$$DAF = R_{peak} = 1\big/\sqrt{\xi} \tag{6}$$

where ξ is the damping ratio of NSCS. When ξ is 0.05 according to the assumption [2], *DAF* is 4.47. The peak value given by Sullivan et al. (2013) is a little bit smaller than that of Equation 1.
Vukobratović and Fajfar (2016) proposed the peak value of R (amplification factor, *AMP*) in a short period range for elastic and elasto-plastic SDOF systems as,

$$AMP = R_{peak} = 18\left(1+\xi\right)^{-0.60} \tag{7}$$

where ξ is given in %. When ξ is 5%, *AMP* is 6.14. The peak value given by Vukobratović and Fajfar (2016) is almost the same as Equation 1.

3. DETERMINATION OF SEISMIC FORCE FOR NSCS

For a simple form in practice, it is considered better to arrange the seismic forces for design in a tabular form, in light of the consideration in the preceding chapter.

3.1 Input Seismic Motion

The spectrum S_A of input seismic motion is considered to be such a design spectrum as shown in Figure 4(a). S_{DN} is the constant value of S_A in a short period, T_G is the period at the end of the constant-acceleration region. Except for an extremely short period region, it is expressed as follows:

$$S_A(T) = \begin{cases} S_{DN} & (T \le T_G) \\ \left(T_G/T\right)S_{DN} & (T_G < T) \end{cases} \tag{8}$$

where T is a natural period.
Further, the acceleration when period T is zero (= peak ground acceleration) is defined as $S_A(0)$ = $0.4S_{DN}$. The lower level of seismic intensity in the Building Standard Law of Japan is used, where S_{DN} = 240 cm/s/s as shown in Figure 4(b).

(a) Standard acceleration response spectrum (b) Building Standard Law of Japan

Figure 4. Acceleration response spectrum of input seismic motion

3.2 Evaluation of Resonance According to Representative Values of Participation Vectors

Suppose multistory buildings are roughly separated into upper layer stories, middle layer stories and lower layer stories in a height direction. Assuming the lower layer stories as equivalent to ground seismic motion, the remaining two stories will be considered based on Equation 2. In view of increasing S_{AF} in resonances, the first mode or second mode of the structural frame and resonance conditions of NSCS are considered.

3.2.1 Representative Values of Participation Vectors and Three Layers of Stories

Determine representative values for participation vectors. The first participation vector of discrete shear-type model, whose mass is uniformly distributed and which has an inverted-triangular first mode, will be expressed as follows:

$$\beta_1 U_{I1} = 3I/(2N+1) \tag{9}$$

where, N is the total number of stories; and I is the floor number ($1 \leq I \leq N$, $I = N$ at the roof). The participation vectors are illustrated in Figures 5 and 6, including the second and third modes. In consideration of the above, representative values are determined as shown in Table 1.

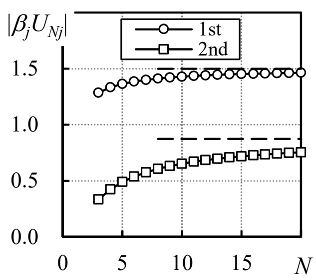


Figure 5. Absolute values of participation vectors at the top (roof)

(Inverted-triangular first-mode model. Broken lines indicate the corresponding values of continuous shear-beam model, the first mode is 3/2 = 1.5, second mode is 7/8 = 0.88)

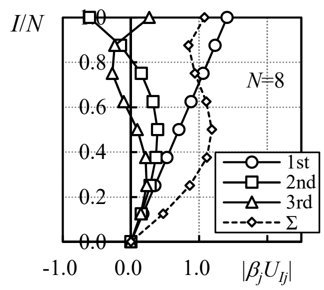


Figure 6. Examples of participation vectors (N = 8)

(Inverted-triangular first-mode model. Σ is a sum from the first to the third.)

Table 1. Representative values of participation vectors

Layer	**Representative values of participation vectors $\beta_j U_{Ij}$**	
	First	**Second**
Upper layer stories	1.5	0.7
Middle layer stories	0.9	0.4

Here, the region of the upper layer stories is considered. Taking account of resonance conditions with the first mode of structural frame, the effect of the first mode is dominant (see Figure 2). In this regard, a story whose absolute value of the first participation vector is greater than the representative value 0.9 of middle layer stories will be regarded as upper layer stories. That is, the region of I which satisfies $\beta_1 U_{I1} > 0.9$ is upper layer stories. Substitute Equation 9, it leads to as follows:

$$I > 0.3(2N+1) \tag{10}$$

This roughly occupies a third from the top.

Next, we consider the region of the lower layer stories. Assuming seismic forces for NSCS in the lower layer stories as equivalent to ground seismic motion and little amplification by structural frame, suppose a case with response acceleration A_l. Similarly to the upper layer stories, in view of resonance with the first mode, we propose an equation as follows:

$$S_{AF} = 6 \cdot \beta_1 U_{I1} \cdot S_{DN} < A_l \tag{11}$$

Here, the value 6 is the maximum of Equation 1. When we substitute Equation 9, the region of the following equation will be the lower layer stories.

$$I < \{(2N+1)/18\}\left(A_l / S_{DN}\right) \tag{12}$$

The design code for specified ceilings (MLIT, 2013) sets forth that lower layer stories are determined as the region of $I < 0.11(2N + 1)$ by Equation 12, where $A_l = 0.5$ g = 490 cm/s/s and $S_{DN} = 240$ cm/s/s.

3.2.2 Resonance with the First Mode of Structural Frame (First Resonance)

As mentioned above, since S_{AF} in the first resonance ($T_s = T_1$) is predominated by the first mode, an approximation of Equation 2 will be as follows:

$$S_{AF}(T_1) \approx R(T_1, T_1) \cdot \beta_1 U_{I1} \cdot S_A(T_1) = 6 \cdot \beta_1 U_{I1} \cdot S_A(T_1) \tag{13}$$

Substituting the values of the participation vector in Table 1 and Equation 8 into the above Equation, we will find as follows:

(i) When $T_1 \leq T_G$,

Upper layer stories: $S_{AF}(T_1) = 9.0 S_{DN}$, Middle layer stories: $S_{AF}(T_1) = 5.4 S_{DN}$ (14)

(ii) When $T_G < T_1$,

Upper layer stories: $S_{AF}(T_1) = 9.0(T_G/T_1) S_{DN}$, Middle layer stories: $S_{AF}(T_1) = 5.4(T_G/T_1) S_{DN}$ (15)

3.2.3 Resonance with the Second Mode of Structural Frame (Second Resonance)

S_{AF} at the second resonance ($T_s = T_2$), ignoring the third mode or higher in Equation 2, is:

$$S_{AF}(T_2) \approx \sqrt{\{R(T_1, T_2) \cdot \beta_1 U_{I1} \cdot S_A(T_1)\}^2 + \{R(T_2, T_2) \cdot \beta_2 U_{I2} \cdot S_A(T_2)\}^2} \tag{16}$$

$R(T_1, T_2)$ in Equation 16 is determined by the ratio of T_2 to T_1. For example, in the case of the inverted-triangular first-mode model (see Figure 6), since the j-th period ratio to the first period is $T_j/T_1 = 1/\sqrt{j(2j-1)}$ irrespective of the total number of stories N, the second period ratio is $T_2/T_1 = 1/\sqrt{6} = 0.41$. In addition, in the case of a uniform shear-beam model, $T_2/T_1 = 1/3 = 0.33$. With reference to the above values, when we put $T_2/T_1 = 0.4$ so as for R to take larger values as an approximation of the safe side, $R(T_1, T_2) = 1 + 5 \times 0.4^3 = 1.32$ is derived from Equation 1. Further, when $T_1/T_G \leq 2.5$, $T_2 = 0.4T_1 \leq T_G$ and it becomes $S_A(T_2) = S_{DN}$.

From these values, FRSs at $T_s = T_2$ can be approximated as follows:

(i) When $T_1 \le T_G$,

Upper layer stories: $S_{AF}(T_2) = 4.6S_{DN}$, Middle layer stories: $S_{AF}(T_2) = 2.7S_{DN}$ (17)

(ii) When $T_G < T_1 \le 2.5T_G$,

$$\text{Upper layer stories: } 4.6S_{DN} \ge S_{AF}(T_2) \ge 4.3S_{DN}, \quad \text{Middle layer stories: } 2.7S_{DN} \ge S_{AF}(T_2) \ge 2.4S_{DN} \tag{18}$$

In case of $T_G < T_1$, $S_{AF}(T_2)$ of second resonance, although the first mode's contributions reduce to fall down, by avoiding significant reduction and by prioritizing simplicity in design, we adopt Equation 17 irrespective of T_1.

3.2.4 Case of stiff NSCS

When NSCS are sufficiently stiff, response acceleration is identical with the position of installation. Taking account of up to the third mode of inverted-triangular first-mode model, with regard to the case where S_A in Figure 4(b) is set to input, Figure 7 illustrates the result of the peak floor acceleration, S_{AF} (0) obtained by SRSS. The horizontal axis indicates the peak acceleration $S_{AF}(0)$ normalized by $0.4S_{DN}$ equivalent to peak ground acceleration. We set the first natural period to $T_1 = 0.1N$(s). At the lower portion of about a third of the whole height, since the sum of participation vectors is less than one (see Figure 6), it is not shown in the figure. When the number of stories N is up to 9 (the first period is about 0.9 s), the distribution is linear; when the number of stories is large (the period is longer), the distribution declines at the middle part.

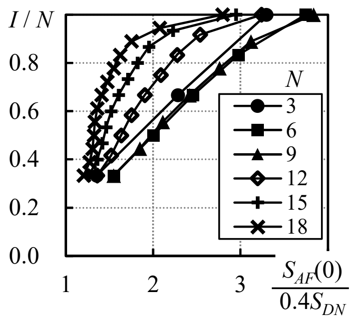


Figure 7. Distribution of peak floor acceleration $S_{AF}(0)$ along the height

According to Figure 7, an approximation of $S_{AF}(0)$ for sufficiently stiff NSCS is obtained by the following equations;

Upper layer stories: $S_{AF}(0) = 1.5S_{DN}$, Middle layer stories: $S_{AF}(0) = 1.0S_{DN}$ (19)

3.3 Seismic Force for Design of NSCS

Table 2 lists the results of the previous section. Since the acceleration is directly reflected on the inertial force during an earthquake according to the assumption [4], a seismic force for design can be calculated from the acceleration in Table 2 and the mass of NSCS. In this regard, since the natural period of structural frame or NSCS cannot necessarily be obtained precisely, the first and second resonance shall have some allowances in periods; in other words, FRSs shall have some plateaus. The period regions not prescribed in Table 2 can be supplemented by linear interpolation.

Table 2. Acceleration used in seismic force for design of NSCS

Layer	Period	Resonance		Stiff *3)
		First *1)	Second *2)	
Upper layer stories	$T_1 \le T_G$ *4)	$9.0S_{DN}$	$4.6S_{DN}$	$1.5S_{DN}$
	$T_G < T_1$	$9.0(T_G/T_1)S_{DN}$		
Middle layer stories	$T_1 \le T_G$	$5.4S_{DN}$	$2.7S_{DN}$	$1.0S_{DN}$
	$T_G < T_1$	$5.4(T_G/T_1)S_{DN}$		

*1) The first resonance region is set to $T_1 - 0.1\text{ s} \le T_s \le T_1 + 0.1\text{ s}$.

*2) The second resonance region is set to $\max[T_2 - 0.1\text{ s}, 0.1\text{ s}] \le T_s \le T_2 + 0.1\text{ s}$.

*3) "Stiff" indicates a case of $T_s \le 0.1$ s.

*4) T_G is a period at the end of the constant-acceleration region.

The level of seismic motion is set to S_{DN} = 240 cm/s/s , corresponding to the lower one in the Building Standard Law of Japan as shown in Figure 4(b). The result of comparing Table 2 with the calculations according to Equation 2 is shown in Figure 8. The used structural models are inverted-triangular first-mode ones. With respect to the total number of stories N, we set the first natural period to $T_1 = 0.1N$(s), and set to $T_2 = T_1/3$ in Table 2. The thick black and gray lines in the figure indicate the upper layer stories and middle layer stories in Table 2, respectively. In Equation 2, we took account up to the third mode. The vertical axis of the figure is acceleration normalized by gravity (i.e. seismic coefficient); the values in the remarks are floor number I. From the figure, it is understood Table 2 shows a substantially favorable correspondent relations to the results according to Equation 2.

(a) $N = 8$ (b) $N = 15$

Figure 8. Comparison between FRSs according to Equation 2 and Table 2 (S_{DN} = 240 cm/s/s)

We substitute the value S_{DN} = 240 cm/s/s to Table 2 and simplify even further for design. The result is shown in Table 3 with modification of 0.5g at the minimum. In Table 2, the linear interpolation is used; in Table 3, any value of seismic coefficient is taken up. Even for the lower level of seismic intensity in Building Standard Law of Japan, seismic force for NSCS can be amplified to 2.2 g at upper layer stories by resonating with the structural frame.

Table 3. Seismic force (acceleration) for design of NSCS

Layer	Classified by the level of resonance		
	$T_1/3 < T_s$ or T_s is unknown	0.1(s)< $T_s \le T_1/3$	$T_s \le 0.1$(s)
Upper layer stories	2.2 g	1.1 g	0.5 g
Middle layer stories	1.3 g	0.66 g	0.5 g
Lower layer stories	0.5 g	0.5 g	0.5 g

4. CONCLUSIONS

This paper proposes a simple method for calculating the FRS, carries out comparisons with the THA to confirm its validity. Further, seismic forces for design of NSCS are determined and compiled into a tabular form by setting typical values of participation vectors of structural frames. Although seismic design of most NSCS has been carried out with taking account of a seismic force of about 1 g in Japan, it was indicated that a seismic force as much as 2.2 g may be needed to be taken account of resonance with the structural frame in some cases. The results of this study were appropriately modified and adopted for the design code for specified ceilings (MLIT, 2013).
In this paper, we considered under the several assumptions. For example, we set the damping ratios for structural frame and NSCS to 5% and assumed regularly-shaped buildings, etc. (see Section 2.1). In cases where the damping ratio is small and when coupling of the mode responses may be generated when natural periods are not well-separated, please keep in mind that there is a possibility that it will not necessarily be a sufficient seismic force.

5. ACKNOWLEDGMENTS

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