- Technical Paper -

SEISMIC EVALUATION OF AN 8-STORY SRC BUILDING USING PERFORMANCE CURVE IN THE 2011 OFF THE PACIFIC COAST OF TOHOKU EARTHQUAKE

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ABSTRACT

Seismic performance curve ($S_a - S_d$ curve) shows the relationship between the representative displacement (S_d) and the equivalent base-shear force coefficient (S_a); deformation and shear force of the building can be observed straightforwardly through a simple $S_a - S_d$ curve, which can help us to understand the response of the building in strong earthquakes. In this research, $S_a - S_d$ curve was used to evaluate the seismic performance of an 8-story SRC building experiencing the 2011 off the Pacific coast of Tohoku Earthquake (happened in 2011.03.11.14:46). The results confirmed the applicability of $S_a - S_d$ curve to evaluate the seismic performance of real building.

Keywords: Performance curve, Seismic evaluation, SRC building, Wavelet Transform Technology

1. INTRODUCTION

Record of earthquake responses of real buildings contain abundant real-time information about the building’s performance, for example the dynamic characteristics, damage situation and so on. There has been much research about how to use the measurement data to detect structural damage and identify dynamic characteristics [1], which can help engineers to take further steps to retrofit damaged structural elements and avoid more serious damage in the next earthquakes. However, most current available earthquake damage detection methods are based on monitoring the changes in the dynamic characteristics of the structures (vibration frequency and modal shapes). It is difficult to know the changes of seismic response in one specific strong earthquake using the methods mentioned above.

In recent years, a kind of real-time evaluation method of residual seismic performance was brought out to evaluate and predict the seismic capacity of building quickly [2], and the method was designed to judge whether the building can survive or not in the aftershocks, especially after very strong earthquakes. The core of this method is to get $S_a - S_d$ curve (seismic performance curve) through measurement data recorded by limited acceleration meters installed in the building (such as base floor, middle floor and the top floor) [2]. And the $S_a - S_d$ curve is based on two assumptions: (1) Multi-story building can be simplified as an equivalent SDOF model; (2) the fundamental mode is dominant during an earthquake. Wavelet Transform Technology was applied to extract the fundamental mode responses [3]. Effectiveness of the method for large structural deformation has been confirmed through the shaking table test, and the measured performance curve agreed largely with the computed ones calculated through WTT [4].

However, there were rare application cases on how to use the method to evaluate seismic performance of a real SRC building in very strong earthquakes. This paper researched the seismic performance curve of an 8-story SRC building (BRI annex building, local PGA=279.3gal, IJMA=5.3) which experienced 2011 off the Pacific coast of Tohoku Earthquake. In this study, a polygonal line was constructed to simplify $S_a - S_d$ curve. And the evaluation of the observed stiffness degradation in $S_a - S_d$ curve can be made using the slope of secant of points in polygonal line, which shows the changes of fundamental frequency. And the influence of rocking effect on $S_a - S_d$ curve was also discussed.

2. Measurement outline and computation model of the building

2.1 BRI-annex building

The BRI annex building is an eight-story SRC building with a basement floor (B1F), and the building is supported by a gravity foundation and connected with the main building through a nonstructural passageway shown in Figure 1(a). The height of the building (from ground level to the 8th floor) is 28m and the depth of underground part is 8.5m. An instrument cabin made of the steel structure is built on the 8th floor. The building is instrumented with 11 accelerometers, and each of those can record 3-direction accelerations,

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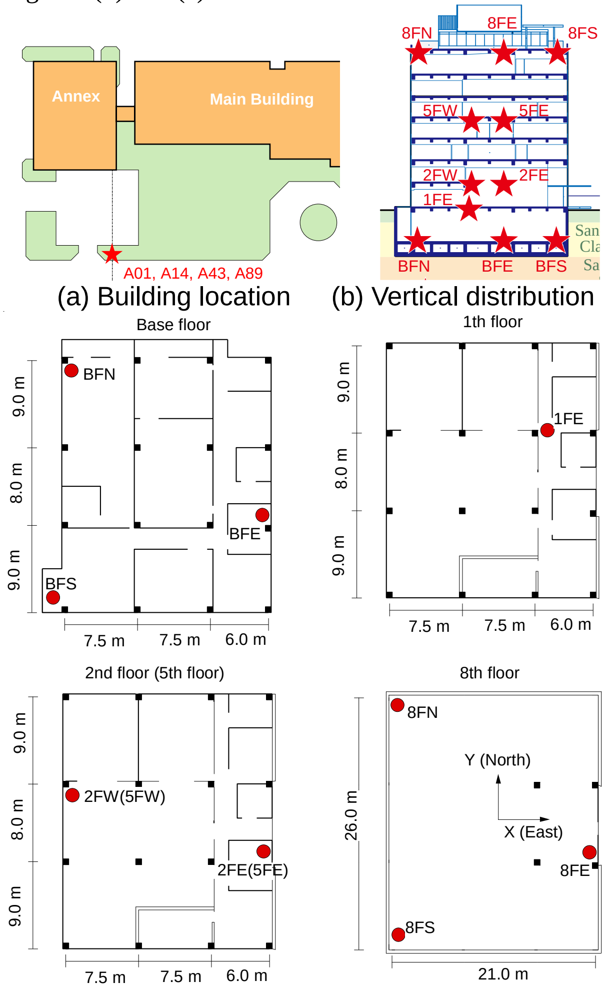
which are East-West motion (X direction), South-North motion (Y direction), Up-Down motion (Z direction). The distribution of the measurement points is shown in Figure 1(b) and (c).



(c) Plane distribution

Figure.1. Measurement outline of the earthquake response

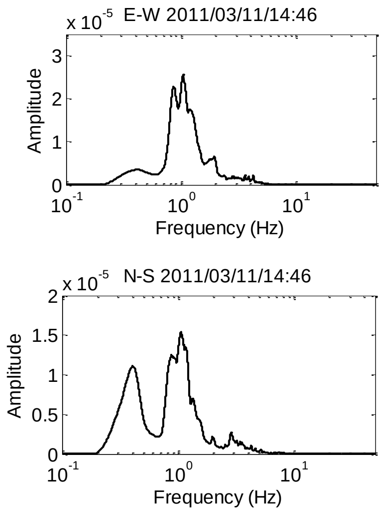


Figure.2. Fourier spectrum of rocking motion calculated through vector method

Since the BRI annex building was built in 1998, observation of seismic responses of the building has been started. Kashima et al. carried out a series of research on the SSI effect, ground motion and dynamic characteristics of the building using the measurement data of the building responses [5, 6, 7]. According to their research, rocking ratio (8~11%) is much larger than the swaying ratio (2~3%). Rocking effect was an important influence factor in the total motion, so it is necessary to evaluate the rocking motion and superstructure deformation separately.

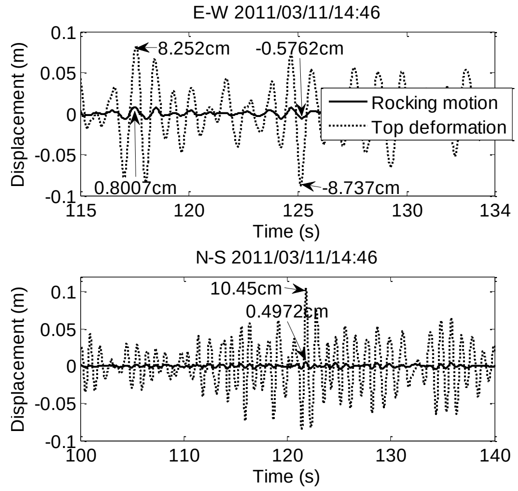


Figure.3. Rocking motion and deformation of the top floor

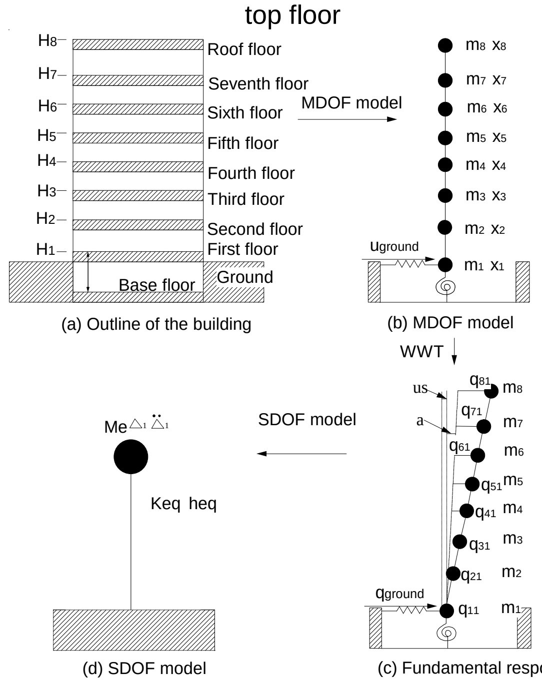


Figure.4. Procedure of simplifying MDOF model to SDOF model

2.2 Earthquake response records

Figure 1(b)(c) shows that only acceleration of specific floors (base floor, 1st floor, 2nd floor, 5th floor and 8th floor) can be accumulated; so in order to calculate the lateral acceleration of other floors, it is assumed that the accelerations of other floors are the linearized values of accelerations of the corresponding neighborhood floors, see Figure 4(c). Generally, vertical motions of two measurement points on the base floor were used to calculate the rocking motion [5, 8]. But in this research three measurement points on the basement are not located on the central axes, so the vector method which makes use of three points is employed to calculate the rocking angle. The Fourier spectrum of rocking motions calculated by the Vector method (3-points) [9] is shown in Figure 2. In this paper, 3-point method is used to calculate the rocking angle. Figure 3 gives the displacements of rocking motion and deformation of the top floor, which shows that the rocking ratio is about 5%~7%. Based on above calculation for the earthquake response records, rocking motion and structural deformation can be separated and these results will be used for the calculation of the seismic performance curve.

Table 1 Property the MDOF system

i	Mass $\boldsymbol{m_i}$ ($\mathbf{10^6}$kg)	$\boldsymbol{x_i}$ (m)	$\boldsymbol{u_i}$ (m)	$\boldsymbol{q_{i1}}$ (m)	$\boldsymbol{H_i}$ (m)
8	0.30	x_8	u_8	q_{81}	34
7	0.82	x_7	u_7	q_{71}	28.9
6	0.74	x_6	u_6	q_{61}	25.2
5	0.77	x_5	u_5	q_{51}	21.5
4	0.93	x_4	u_4	q_{41}	17.8
3	0.78	x_3	u_3	q_{31}	14.1
2	0.78	x_2	u_2	q_{21}	10.3
1	0.84	x_1	u_1	q_{11}	6

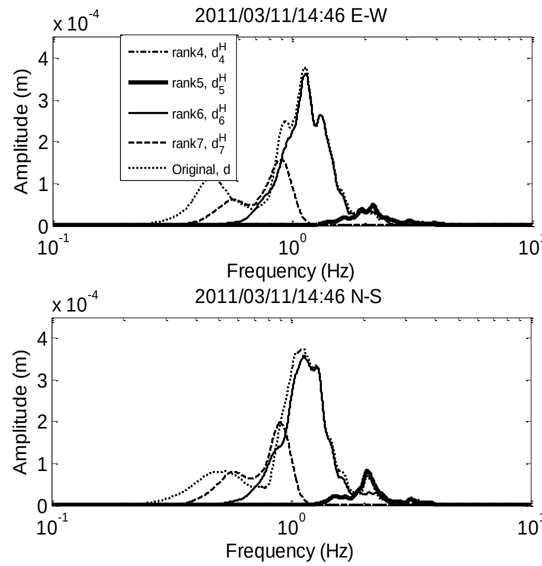


Figure.5. Fourier spectrum of responses of major ranks for roof deformation d

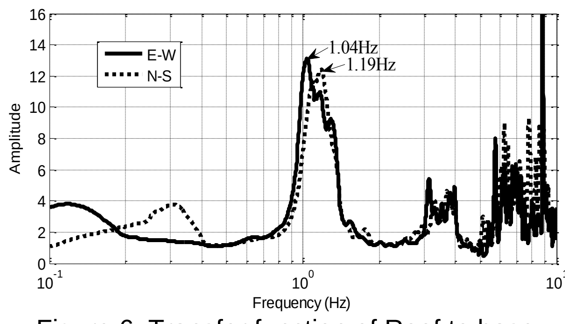


Figure.6. Transfer function of Roof to base

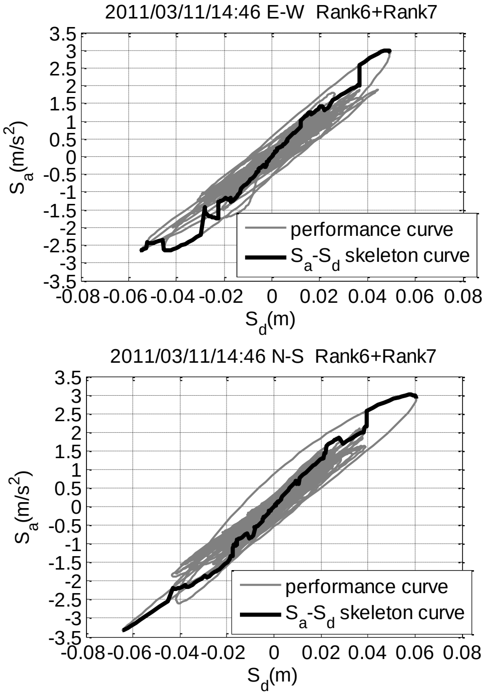


Figure.7. Seismic performance curve

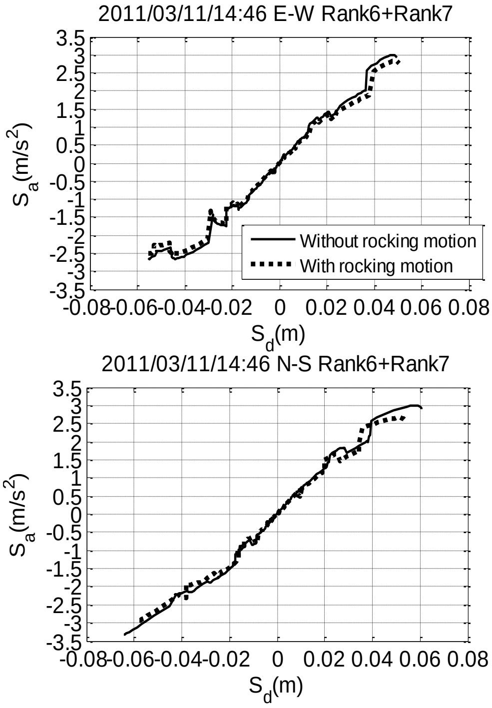


Figure.8. Influence of the rocking motion

3. Introduce of seismic performance curve

The method of simplifying the MDOF model to SDOF model is the foundation of the seismic performance curve. The method based on rigid-foundation has been given out [2]. While for BRI annex building, the influence of rocking effect was quite large. In this paper, in order to evaluate the influence of rocking motion on the performance curve, representative displacement S_d was calculated based on two cases: case 1, S_d was calculated only using the deformation of the superstructure; case 2, S_d was calculated using the displacement including rocking motion.

Case 1: deformation of the superstructure:

$$\Delta_1 = \frac{\sum m_i \cdot q_{i1}}{\sum m_i} \quad (1)$$

Case 2: displacement including rocking motion:

$$\Delta_1 = \frac{\sum m_i \cdot (q_{i1} + u_{ri})}{\sum m_i} \quad (2)$$

Calculation of base-shear force Q_B is as follows,

$$Q_B = \sum m_i \cdot \ddot{x}_i \quad (3)$$

The equivalent base-shear coefficient S_a will be calculated by equation (4a); the equivalent representative displacement S_d can be calculated by equation (4b).

$$S_a = \frac{Q_B}{M_e} \quad (4a)$$

$$S_d = \Delta_1 \cdot \frac{\sum m_i}{M_e} \quad (4b)$$

Where $\ddot{x}_i$ is the measurement acceleration of i th floor, M_e is the equivalent mass of the superstructure; Δ_1 is the equivalent deformation of the superstructure, $\{q_1\}$ is the fundamental mode response of the superstructure, u_{ri} is the rocking motion of the ith floor, see Figure 4. Table 1 shows the motion property of the MDOF model of real building, which can be used for the above equations.

The relationship between S_a and S_d can be expressed as follows, and ω_f is fundamental circular frequency of the superstructure.

$$S_a = \omega_f{}^2 \cdot S_d \quad (5)$$

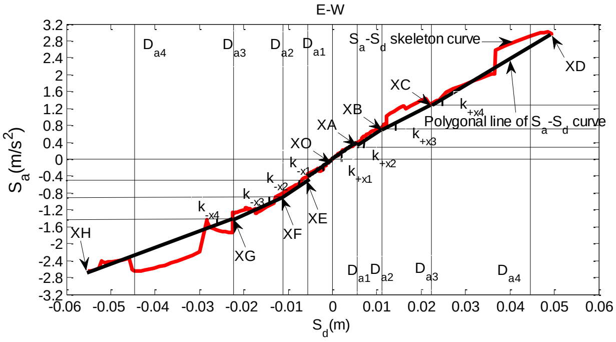
It is necessary to extract the fundamental response through the WTT technique. KOICHI KUSUNOKI & MASAOMI TESHIGAWARA [3] has presented the method on how to use WTT to get fundamental response. Figure 5 shows the Fourier spectrum of roof's response of the major ranks separated through the WWT technique, then the signals of Rank6 and Rank7 are considered as fundamental responses. Figure 7 shows the seismic performance curve of the researched earthquake (2011 off the Pacific coast of Tohoku Earthquake).

4. Evaluation of $S_a - S_d$ curve

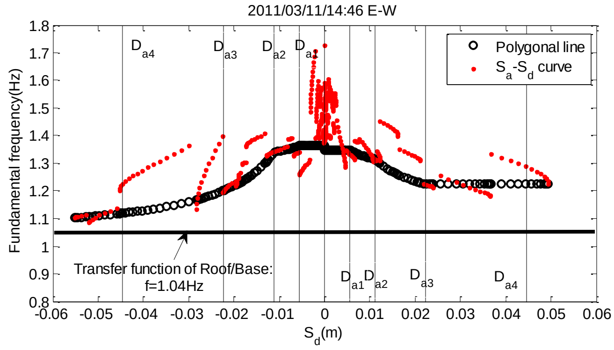
4.1 Polygonal line corresponding to $S_a - S_d$ curve

The object of this paper is to evaluate seismic performance of the building experiencing strong Earthquake through $S_a - S_d$ curve. The $S_a - S_d$ curve has been calculated through the WWT technique and SDOF model theory, and the peak response points distributed in $S_a - S_d$ curve told us real-time seismic capacity of the building, see Figure7. A simple method of using Polygonal line to evaluate $S_a - S_d$ curve is brought out in this section, see Figure 9(a) and Figure 10(a).

The basic problem of polygonal line is how to calculate the tangent slope of each segment. Generally, cracks generally happen when the drift angle of SRC members is about 1/3000. In this paper, drift angle D_a equal with the values of 1/3200, 1/1600, 1/800, 1/400, 1/200 and 1/120 are selected as the deformation level, and the corresponding representative displacements S_d for the drift angle D_a are shown in Table 2. Polygonal line of performance curve is made up with several segments, each of which is decided by tangent slope (for example k_{+xi}) and end points (for example XA in Table 3). The tangent slope and end points (for E-W direction) are determined by the following rules:

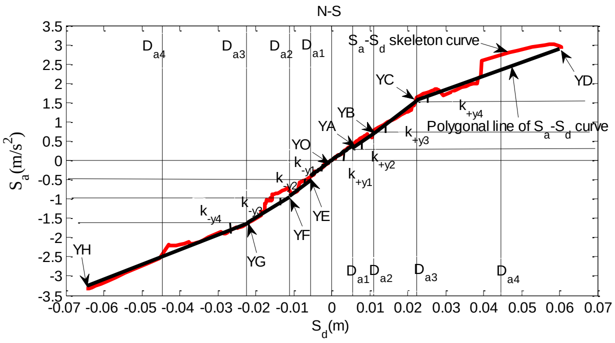


(a) Polygonal line and $S_a - S_d$ curve

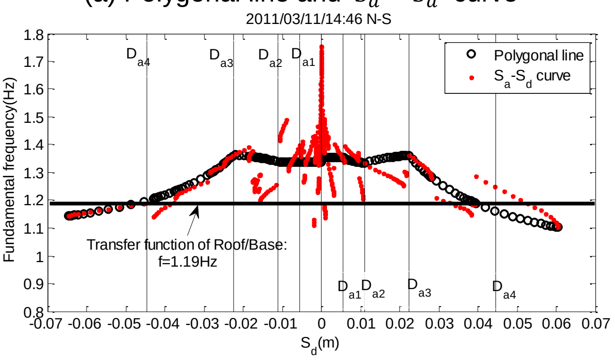


(b) Changes of fundamental frequency

Figure.9. Evaluation of $S_a - S_d$ curve in E-W direction



(a) Polygonal line and $S_a - S_d$ curve



(b) Changes of fundamental frequency

Figure.10. Evaluation of $S_a - S_d$ curve in N-S direction.

Table 2 Evaluation level for the performance curve

Case (i)	1	2	3	4	5	6
D_{ai} (rad)	$\frac{1}{3200}$	$\frac{1}{1600}$	$\frac{1}{800}$	$\frac{1}{400}$	$\frac{1}{200}$	$\frac{1}{120}$
Height of the building (m)						28
S_{di} (10^{-3}m)	5.6	11.1	22.3	44.6	89.1	148.5

Table 3(a) Property of Polygonal line for performance curve in E-W direction

E-W direction				
	Intersection point (S_d(m), $S_a(m/s^2)$)		Tangent slope ($1/s^2$)	
Positive direction	XA($D_{a1}=\frac{1}{3200}$)	(0.0056, 0.4020)	k_{+x1}	71.79
	XB($D_{a2}=\frac{1}{1600}$)	(0.0111,0.7591)	k_{+x2}	64.93
	XC($D_{a3}=\frac{1}{800}$)	(0.0223,1.3200)	k_{+x3}	50.08
	XD($D_{am}=\frac{1}{363}$)	(0.0494,2.9356)	k_{+x4}	59.55
Negative direction	XE($D_{a1}=\frac{1}{3200}$)	(-0.0056,-0.4113)	k_{-x1}	73.45
	XF($D_{a2}=\frac{1}{1600}$)	(-0.0111,-0.789)	k_{-x2}	68.67
	XG($D_{a3}=\frac{1}{800}$)	(-0.0223, -1.271)	k_{-x3}	43.04
	XH($D_{am}=\frac{1}{325}$)	(-0.05514,-2.649)	k_{-x4}	41.96

Table 3(b) Property of Polygonal line for performance curve in N-S direction

N-S direction				
	Intersection point (S_d(m), $S_a(m/s^2)$)		Tangent slope ($1/s^2$)	
Positive direction	YA($D_{a1}=\frac{1}{3200}$)	(0.0056, 0.4050)	k_{+y1}	72.32
	YB($D_{a2}=\frac{1}{1600}$)	(0.0111,0.7794)	k_{+y2}	68.07
	YC($D_{a3}=\frac{1}{800}$)	(0.0223,1.633)	k_{+y3}	76.21
	YD($D_{am}=\frac{1}{296}$)	(0.06055,2.903)	k_{+y4}	33.20
Negative direction	YE($D_{a1}=\frac{1}{3200}$)	(-0.0056,-0.3951)	k_{-y1}	70.55
	YF($D_{a2}=\frac{1}{1600}$)	(-0.0111,-0.7844)	k_{-y2}	70.78
	YG($D_{a3}=\frac{1}{800}$)	(-0.0223,-1.639)	k_{-y3}	76.36
	YH($D_{am}=\frac{1}{278}$)	(-0.06452,-3.33)	k_{-y4}	40.05

(1) Initial tangent slope $k_{+x1}(k_{-x1})$ of segments XO−XA (XO−XE): drift angle D_a is in the range [0, 1/3200], and the tangent slope of the S_a-S_d curve in the range can be calculated using the least-square method. Then the end points XA (XE) can be calculated through the linear equation of the segments in the range.

(2) Tangent slope k_{+x2} (k_{-x2}) of segments XA−XB (XE−XF), drift angle D_a is in the ranges [1/3200, 1/1600]. The intersection points XB (XF) can be decided. Then the tangent slope k_{+x2} between the points XA and XB can be calculated.

(3) Tangent slope k_{+x3} (k_{-x3}) of segments XB−XC (XF−XG), drift angle D_a is in the ranges [1/1600, 1/800], and the procedure is similar with (2).

(4) Tangent slope k_{+x4} (k_{-x4}) of segments XC−XD (XG−XH), drift angle D_a is in the ranges [1/800, 1/400], and the procedure is similar with (2); But for the S_a-S_d curve around the drift angle 1/400, the velocity effect is large; and the maximum drift angle is much less than 1/200 (1/363 and 1/325, see Table 3(a)). As a result, the final segments are constructed by the maximum response points XD and the previous intersection point XC (for negative direction, XG to XH).

For the N-S direction, the calculation procedure is same with E-W direction mentioned above.

Table 3 gives the property of polygonal line. From Figure 9 (a) and Figure 10 (a), the polygonal line agrees with the S_a-S_d curve well and can evaluate the stiffness degradation simply and clearly. On the one hand, there are some fluctuations in the S_a-S_d curve, which is difficult for us to understand the changes of the stiffness of superstructure; on the other hand, polygonal line is more smoothed and has the same variation trend of S_a-S_d curve. According to the Figure 9(b) and Figure 10 (b), we can see that the stiffness calculated through S_a-S_d curve has much more fluctuations than the ones calculated through polygonal line. The fundamental frequency (calculated through equation (5)) fell from about 1.36Hz (E-W, 1.37 Hz for N-S) to about 1.10Hz, which means the stiffness of superstructure decreased about 34.58% (35.54%) in the 2011 off the Pacific coast of Tohoku Earthquake. Actually, the field investigation of the earthquake damage showed that visible clear cracks (crack width is about 0.2-0.8mm) on structural elements and element joints had been found in each floor. We thought that those cracks were the reason of the decrease of fundamental frequency.

4.2 Influence of the rocking motion

In this paper, rocking motion and superstructure deformation were separated through the simple calculation [10]. Based on previous calculation, it is necessary to evaluate the influence of rocking motion on the S_a-S_d curve, especially when the rocking motion was not small which is shown in Figure 3. The comparison results show that influence of rocking motion on S_a-S_d curve is not small, see Figure 8.

According to Figure 8, S_a-S_d curve with rocking motion shows the similar stiffness degradation trend with that of without rocking motion. Therefore it is necessary to use S_a-S_d curve without rocking motion to evaluate the seismic capacity of the superstructure.

4.3 Discussion

Generally, transfer function (see Figure 6) is used to identify the fundamental frequency of the building [11]. However, the traditional transfer function method only gives one dominant fundamental frequency and we cannot judge whether the building's stiffness changes or not during earthquake. But S_a-S_d curve can show the changes of the stiffness (fundamental frequency) from the smaller response to the maximum response in one specific strong earthquake, see Figure 9 and Figure 10.

Major influence factors on the S_a-S_d curve are the quality of the measurement data (noise), higher mode effect, SSI effect etc. Now we can use WWT to delete the higher mode effect and even most noise effect, and the effectiveness of the method has been confirmed for very large deformation. While the WWT may not delete the noise effect completely especially in the smaller deformation, and calculation error of WWT have not been evaluated under that condition. As a result, it is difficult to judge whether the stiffness changes was caused by the calculation errors, noise effect or the smaller damage. Therefore, it is necessary to evaluate these effects in the future research.

5. Conclusion

This paper used seismic performance curve ($S_a - S_d$ curve) to evaluate the seismic response of an 8-story SRC building in the 2011 off the Pacific Coast of Tohoku Earthquake. A method using polygonal line was brought out to simplify $S_a - S_d$ curve, and the changes of the fundamental frequency were evaluated through the polygonal line. Besides, the influence of rocking effect on $S_a - S_d$ curve was also evaluated. Several conclusions can be summarized as follows:

(1) The $S_a - S_d$ curve is practicable to evaluate the seismic performance of the real building in strong earthquakes. Compared with traditional FFT method, $S_a - S_d$ curve can show the changes of the building stiffness from small response to maximum response; and stiffness degradation (fundamental frequency) can be evaluated through the slope of secant of the points in polygonal line.

(2) Stiffness of the building decreased about 34.58% (E-W, 35.54% for N-S) during the 2011 off the Pacific coast of Tohoku Earthquake.

(3) The $S_a - S_d$ curve without rocking motion will be clearer and more accurate than the one with rocking motion when analyze the changes of stiffness of superstructure.

(4) The polygonal line for corresponding $S_a - S_d$ curve has the potential to be used for the damage evaluation. However, the method is only effective for large drift angle, for example $D_a \geq$1/3200. For smaller drift angle, it is difficult to judge whether stiffness changes are caused by the smaller, hidden damage or calculation errors. The calculation error of WWT will be evaluated in further research.

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