

BEHAVIOR OF INDUSTRIAL BUILDING UNDER SEISMIC LOADING

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ABSTRACT: Every year, earthquakes cause injuries, deaths, severe structural damage to buildings and destruction of property in many countries. In developing countries, economic growth depends on industrial development. Therefore, if an earthquake occurs, it may cause severe damage to large industrial factories. This present study aims to examine the structural behavior of industrial buildings under the earthquake force which is a reinforced concrete building. The structure of an industrial building is different from a general building. In this study, the factory is a four-story building with the dimensions of 34.4 meters in width, 59.2 meters in length and 16.2 meters in height. In the analysis, the nonlinear dynamic procedure is applied to analyze the building behaviors. The 20 seismic waves are selected and adjusted with the ASCE41-13. LMSR wave are considered in x-direction and y-direction. From the results, the responses and damage of the industrial structure are analyzed. The building has performed the soft story irregularity. The performance level for the acceptance criteria, according to ASCE41-13 and FEMA365 is life safety performance level. Therefore, the industrial factory building is needed to enhance the seismic capacity for damage prevention.

Keywords: Seismic behavior, Reinforced concrete, Industrial factory, Nonlinear time history procedure

1. INTRODUCTION

The industrial sector has had an important role in the economic growth in developing countries. Pricing instruments with technological innovation are installed in factories. Therefore, if an earthquake occurs, it may cause severe damage to industrial instruments and building structures. To prevent and reduce this potential damage, an industrial factory is analyzed under seismic loading in this present study. A four-story reinforced concrete building located in the Northeastern region of Thailand is analyzed. The building model comprises a linear elastic element, a fiber element and a rigid joint. The fiber element is located at both ends of structural members to represent the nonlinear behavior of them. This analysis applies a nonlinear time history procedure subjected to 20 seismic waves using PERFORM3D program [1]. A three-dimensional fiber model is used to model plastic hinges for columns and beams. The seismic waves are appropriately scaled with a design response spectrum of the Northeastern region according to the Earthquake Resistant Design code 1303 [2] of Thailand. The analysis results are reported in terms of maximum inter-story drift and rotation of fiber elements, which are used to specify the damage level related to the acceptance criteria of ASCE41-13 [3] and FEMA356 [4].

2. ANALYZED BUILDING

The analyzed industrial factory is a 4-story reinforced concrete building which is used as a cooling tower. The structural type is a moment-resisting frame with beams and columns. The first-floor plan with beam section is shown in Fig. 1. The dimensions of this factory building are 34.4 meters in width, 59.2 meters in length and 16.2 meters in height. There are eight spans of columns in length and four spans of columns in width with a span of 7.4 meters and 5.6 meters, respectively. As illustrated in Fig. 2, the height of each story from the first floor to the fourth floor is 1.80 meters, 7.45 meters, 3.82 meters and 3.11 meters, respectively. This building has a symmetrical appearance in the plan, but the structural configuration is an irregularity in the vertical. There are two rectangular column sections in the building as shown in Table 1. The 650x650 mm column section consists of 20-DB32mm longitudinal reinforcement bars and 5-DB12@200mm crossties stirrup. The 700x700 cm column section includes of 24-DB32mm longitudinal reinforcement bars and 7-DB12@200mm crossties stirrup. There are seventeen rectangular beam sections in the building. The section and reinforcement of beams are demonstrated in Table 2. Rotors and gearboxes are placed at the roof level, with the weights of 1,843

kilograms and 1,937 kilograms, respectively. In the construction drawing, the compressive strength of concrete is 23.54 MPa and the specified yield strength of reinforcement is 490.33 MPa.

Table. 1 Rectangular column sections and reinforcement details.

No	Section (cm.)	Reinforcement	Stirrup
C1	650x650	20DB32	5DB12@200
C2	700x700	24DB32	7DB12@200

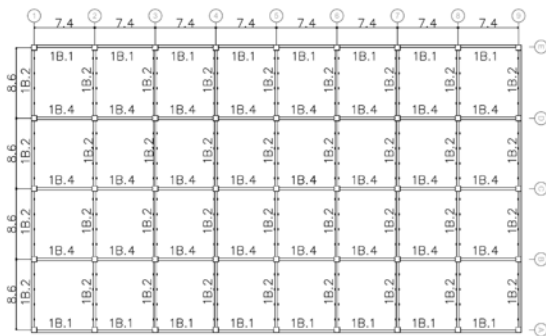


Fig. 1 First floor plan at an elevation of 1.80 meters.

Table. 2 Beam sections and reinforcement details.

No.	Section (mm.)	Upper Reinf.	Lower Reinf.	Stirrup
1B.1	300x750	4DB25	4DB25	DB12@125
1B.2	300x750	5DB25	5DB25	DB12@125
1B.4	300x750	6DB25	6DB25	DB12@200
2B.1	300x750	2DB25	2DB25	DB12@150
2B.2	300x750	4DB32	6DB25	DB12@150
		2DB16		
2B.4	300x750	4DB20	4DB20	DB12@150
2B.5	350x750	4DB16	4DB16	DB12@200
3B.1	300x750	4DB20	4DB20	DB12@200
3B.2	300x750	4DB32	4DB25	DB12@125
		2DB16		
RB1	300x700	2DB20	2DB20	DB12@200
RB2	250x600	4DB25	4DB25	DB12@200
RB3	300x800	5DB25	5DB25	DB12@150
RB4	300x700	2DB16	2DB16	DB12@200
RB5	300x700	2DB20	2DB20	DB12@150
RB6	300x700	2DB20	2DB20	DB12@150
RB7	250x600	2DB25	2DB25	DB12@150
RB8	500x800	8DB25	8DB25	DB12@150

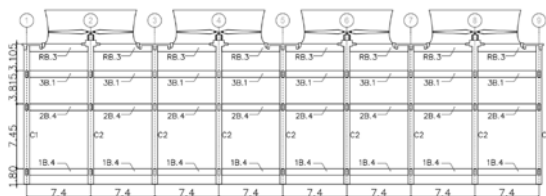


Fig. 2 Side view at gridline B.

3. SEISMIC HAZARD

Seismic behaviors under the seismic hazard of the factory building in the Northeast region of Thailand is analyzed by using the nonlinear time history procedure. The seismic waves are appropriately scaled with the design response spectrum constructed from the seismic hazard. The new seismic hazard for this area was proposed by Janpila [5], which is approximately twice as high as the Earthquake Resistant Design code 1303 of Thailand [2]. The highest seismic hazard location is selected, which is in Nongkai province. According to the Earthquake Resistant Design code 1303 [2], the seismic hazard with the probability of exceedance of 10% in 50 years is used to evaluate the seismic behavior of an existing building structure. The seismic hazard map in the term of spectral acceleration (SA) at the structural periods of 0.2 and 1.0 second at base rock level with 5% critical damping ratio for reference return periods of 10% POE in 50 years are shown in Fig. 3 and 4, respectively. The spectral acceleration at the structural periods of 0.2 and 1.0 second at Nongkai province are 0.567 m/s² and 0.204 m/s², respectively. The target design response spectrum used to analyze the factory building is shown in Fig. 5.

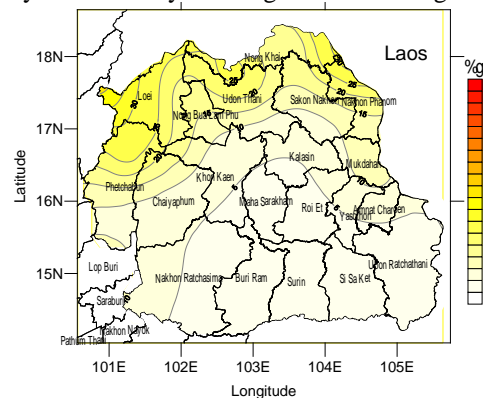


Fig. 3 Seismic hazard maps in the Northeast region of Thailand corresponding to a probability of exceedance of 10% in 50 years, SA0.2sec.

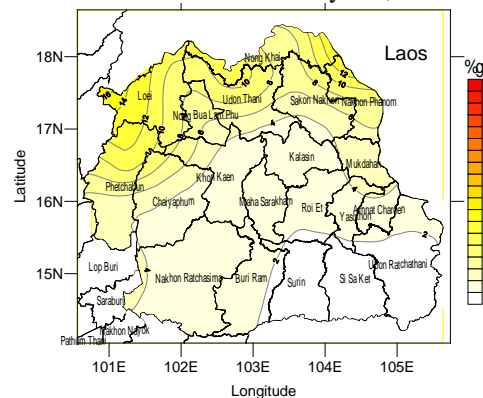


Fig. 4 Seismic hazard maps in the Northeastern Thailand corresponding to a probability of exceedance of 10% in 50 years, SA1.0sec.

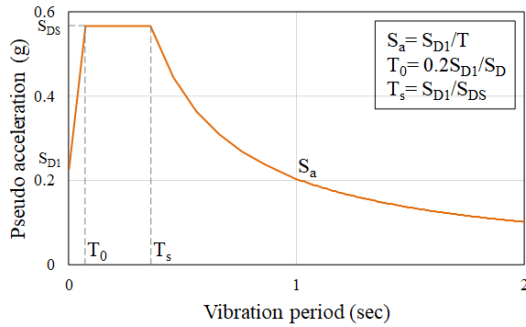


Fig. 5 Target design response spectrum at Nongkai province, Thailand at base rock level with 5% critical damping ratio for 10% POE in 50 years

4. BUILDING MODEL

4.1 Model Calibration

The building model is analyzed with the nonlinear time-history procedure under 20 seismic waves by using PERFORM3D [1] program. The nonlinear behaviors of the structure are represented by fiber elements located at both ends of structural members. The fiber element is separately modelled by considering the behavior of each material, which primarily consists of unconfined concrete models, confined concrete models and longitudinal reinforcement models. The stress-strain relationships of unconfined concrete are modeled using the equation proposed by Kent and park [6]. The confined concrete behavior is modeled using the equation proposed by Hoshikuma et al. [7]. The longitudinal reinforcement is modeled using the equation proposed by Menegotto and Pinto [8]. When conducting a structural model validation, the results of RC columns experiment obtained from the study by Wehbe et al. [9] and RC frames experiment results received from Anil and Altin [10] are compared to analytical results. The plastic hinge lengths of beams and columns are evaluated by using the equation proposed by Paulay and Priestley [11] as shown in Eq. 1

$$L_p = 0.08L + 0.022d_b f_y \quad (1)$$

where L is the distance from a critical section to the point of contraflexure (meters), d_b is the diameter of longitudinal reinforcement (meters) and f_y is the yield stress of longitudinal reinforcement (MPa).

RC columns experiment conducted by Wehbe et al. [9] yielded results of a rectangular column section with the dimensions of 610mm x 380mm and 2.050 m in height. The longitudinal reinforcements were 18-DB19mm. The transverse

reinforcements were 2-RB6mm crossties and 2-RB10mm crossties with an equal space of 110mm interval along with the column height. The RC column was tested under cyclic loading with an axial force of 615 kN. The compressive strength of concrete was 27.2 MPa. The yield strengths of reinforcements were 445 MPa, 428 MPa and 448 MPa for DB19, RB10 and RB6, respectively. The column model consists of the fiber element and elastic element is shown in Fig 6. The plastic hinge is 0.352 m in length. The comparison of force and deformation obtained from the analytical results versus the experimental results is shown in Fig 7. The analytical results can also capture experimental behaviors. The analytical results give a slightly lesser amount of the maximum load and slightly greater estimates of the initial stiffness than the experimental results.

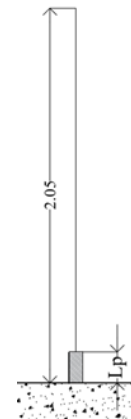


Fig. 6 Model of RC columns experiment results conducted by Wehbe et al. (1999).

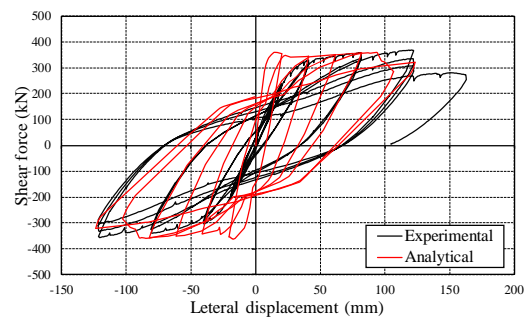


Fig. 7 The Comparison of analytical results versus experimental results by Wehbe et al. (1999).

For RC bare frame experiment results of the study by Anil and Altin [10], the rectangular columns were the 100x150mm section with 4-DB10mm for the longitudinal reinforcement and RB6 crossties with an equal space of 40mm interval along with the column height. The rectangular beam was 150x300mm section with 4-DB8mm for both top and bottom reinforcement and RB4 crossties with an equal space of 40mm interval along the

beam length. The compressive strength of concrete was 21.8 MPa. The yield strengths of reinforcements for DB10, DB8, RB6 and RB4 were 475 MPa, 592 MPa, 427 MPa and 326 MPa, respectively. The bare frame model which comprises the fiber element, elastic element and rigid joint connection is shown in Fig. 8. The plastic hinge lengths of beam and column are 0.174 m and 0.150 m, respectively. The comparison of the analytical results versus the experimental results is presented in Fig. 9. Experimental behaviors can be captured by analytical results.

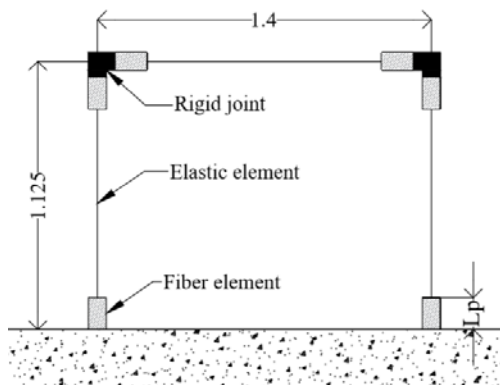


Fig. 8 Model of RC frame experiment results of the study by Anil and Altin (2007).

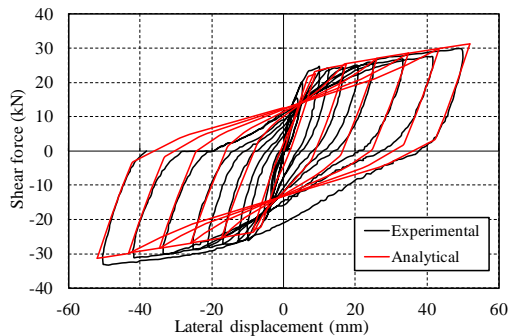
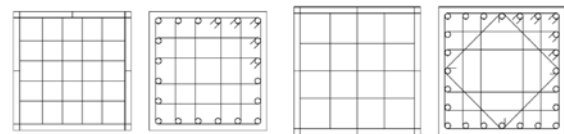


Fig. 9 The Comparison of analytical results vs. experimental results of the study by Anil and Altin (2007).

4.2 Analyzed Model

An analysis of seismic behavior under seismic hazard of the factory building located in Northeastern Thailand applies the nonlinear time history procedure. The building model consists of the elastic elements in the middle of members, the fiber elements at both ends of members and the beam-column connection which is assumed to be rigid. The foundations are modelled as fixed support. RC slab in each floor is considered as a rigid floor. The fiber element is modelled by dividing the cross-section into the properties of each material, which are confined concrete, unconfined concrete and longitudinal reinforcement. Fig. 10 describes the fiber section of columns C1 and C2.

For column C1, the fiber section is divided into 18 sub-elements for unconfined concrete, 8 sub-elements for confined concrete and 20 sub-elements for longitudinal reinforcement. For column C2, the fiber section is divided into 18 sub-elements for unconfined concrete, 8 sub-elements for confined concrete and 24 sub-elements for longitudinal reinforcement. The 3D building model is shown in Fig. 11. The Preliminary analysis of the building model is performed by determining the natural period in X and Y directions, which are used to scale the seismic waves. The natural periods of building model are 0.758 sec for X direction and 0.733 sec for Y direction.



a) Column C1 b) Column C2
Fig. 10 Fiber section of column C1 and column C2.

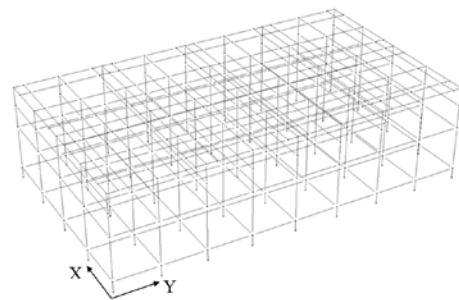


Fig. 11 Analyzed building

5. SEISMIC WAVE

The seismic waves, collected by the Pacific Earthquake Engineering Research Center (PEER) [12] database, are selected to analyze the building model. As mentioned before, although the Northeast region of Thailand is classified as a low seismic hazard region, there are two active faults. Therefore, the large-magnitude small distance (LMSR) seismic wave type is considered in this analysis. The wave selection criteria are as follows:

- 1 Distance from the earthquake epicenter to the considering site is in the range of 30 km to 50 km.
- 2 Earthquake magnitudes are in the range of 6.5 Mw to 6.9 Mw, which is the possibility maximum magnitude of the faults in this area.
- 3 The fault of earthquake events is a crustal fault and the epicenter is shallow.
- 4 The soil type in Northeastern Thailand is soil type D with the shear wave velocity (V_s30) of about 180-360 m/s.

Table 3 The appropriate selection of seismic waves for the Northeast region and scale factor.

No.	Earthquake Name	Year	Station Name	Magnitude	Scale factor x dir.	Scale factor y dir.
W1	San Fernando	1971	LA - Hollywood Stor FF	6.6	1.381	1.381
W2	Superstition Hills-02	1987	Brawley Airport	6.5	2.029	2.029
W3	Superstition Hills-02	1987	El Centro Imp. Co. Cent	6.5	1.17	1.17
W4	Superstition Hills-02	1987	Plaster City	6.5	1.506	1.506
W5	Superstition Hills-02	1987	Westmorland Fire Sta	6.5	1.174	1.174
W6	Loma Prieta	1989	Agnews State Hospital	6.9	1.439	1.439
W7	Loma Prieta	1989	Capitola	6.9	1.17	1.17
W8	Loma Prieta	1989	Gilroy Array #3	6.9	1.17	1.17
W9	Loma Prieta	1989	Gilroy Array #4	6.9	1.17	1.17
W10	Loma Prieta	1989	Gilroy Array #7	6.9	1.811	2.282
W11	Loma Prieta	1989	Hollister City Hall	6.9	1.557	1.475
W12	Loma Prieta	1989	Hollister Differential Array	6.9	1.29	1.17
W13	Loma Prieta	1989	Sunnyvale - Colton Ave.	6.9	1.153	1.153
W14	Northridge-01	1994	Canoga Park - Topanga Can	6.7	1.17	1.17
W15	Northridge-01	1994	LA - Fletcher Dr	6.7	1.233	1.268
W16	Northridge-01	1994	LA - Hollywood Stor FF	6.7	1.17	1.17
W17	Northridge-01	1994	LA - N Faring Rd	6.7	1.17	1.17
W18	Northridge-01	1994	LA - N Westmoreland	6.7	1.17	1.17
W19	Northridge-01	1994	Northridge - 17645 Saticoy St	6.7	1.17	1.17
W20	Northridge-01	1994	Pardee - SCE	6.7	1.17	1.17

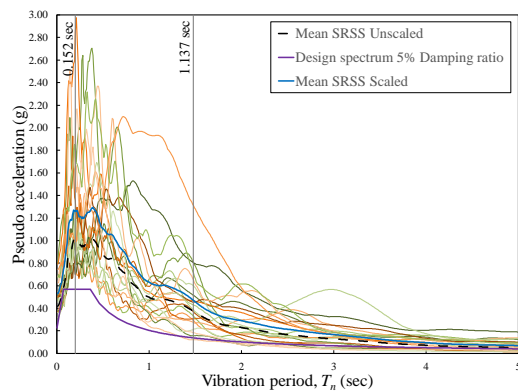


Fig. 12 Response spectrum and scaled SRSS spectrum LMSR for X- direction

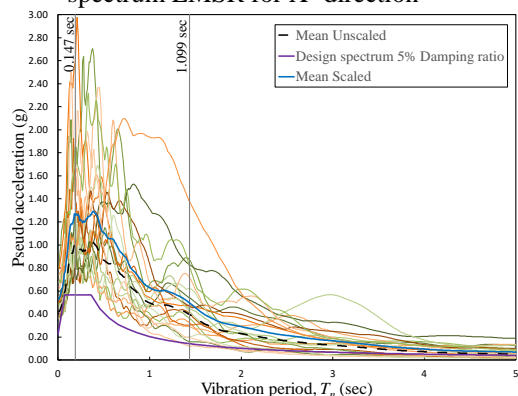


Fig. 13 Response spectrum and scaled SRSS spectrum LMSR for Y- direction

Twenty seismic waves that are considered to be appropriate for the Northeast region are shown in Table 3. According to the Earthquake Resistance Design Code.1302 of Thailand, the response spectrums of seismic waves are analyzed and compare with the target design response spectrum

(Fig. 5). All seismic wave response spectrums have to be higher than the target design spectrum for the natural period in the range of 0.2T to 1.5T, where T is the natural period of the analyzed building model. The response spectrums of seismic wave are scaled at least 1.17 times. The scale factors of each seismic wave in X-direction and Y-direction are demonstrated in Table 3. The scaled response spectrum of twenty seismic waves as compared with the target design spectrum for X-direction and Y-direction are shown in Fig. 12 and Fig. 13, respectively.

6. ANALYSIS AND RESULTS

The building model is analyzed under twenty seismic waves in both X-direction and Y-direction. According to the Earthquake Resistance Design Code 1303 of Thailand [2], the analyzed load combinations for the 3-dimensional model are defined into two cases,

- 1) $E = 1.00X + 0.30Y$ (2)
- 2) $E = 0.30X + 1.00Y$ (3)

where E is the earthquake load, X is the load in X-direction and Y is the load in Y-direction. For conservative, the seismic waves in X-direction and Y-direction are switched to evaluate the maximum building responses. Therefore, four cases are considered in the analysis. From [3] and [4], the acceptance criteria performance level for the plastic hinge rotation angle and the maximum inter-story drift are shown in Table 4 and Table 5, respectively. The acceptance criteria performance level is classified into 3 levels, which are immediate

occupancy (IO), life safety (LS) and collapse prevention (CP).

Table 4 Acceptance criteria for the plastic rotation (ASCE41-13).

Performance Level	IO	LS	CP
Rotation Angle (radians)	0.005	0.045	0.060

Table 5 Acceptance criteria for the maximum inter-story drift (FEMA356).

Performance Level	IO	LS	CP
Maximum Inter Story Drift	<1%	<2%	<4%

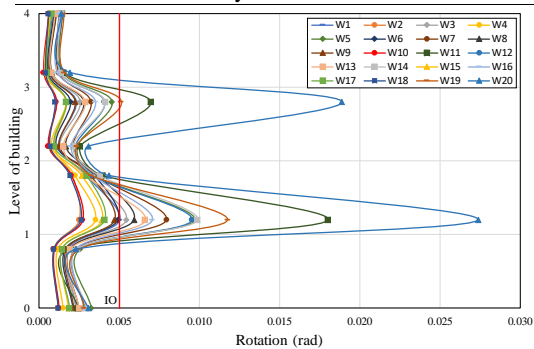


Fig. 14 Plastic rotation angle of the column

From the analysis result, the maximum plastic rotation of columns at all levels under each seismic wave are shown in Fig. 14. The top of columns under the second floor at an elevation of 9.25m has the highest rotation angle due to the long column. The maximum rotation angle is 0.0274 rad due to the W20 Northridge-01 seismic waveform which occurs the immediate occupancy performance level and is reached about 61% of life safety performance level. The building model has performed the immediate occupancy performance level under eleven seismic waveforms.

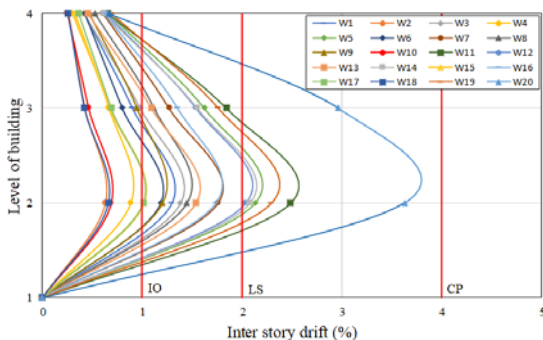


Fig. 15 Maximum inter-story drift

The maximum inter-story drift has occurred into the weak direction of the structure as shown in Fig. 15. The maximum inter-story drift of column is on the second floor that has the highest column. The column height of this level is 7.45 meters. The performance level of the structure is life safety,

which has the maximum inter-story drift more than two percentage, under the seismic wave number W12, W14, W5, W19, W11, and W20. The maximum inter-story drift under the seismic waveform W20 is closely reached the collapse prevention performance level.

7. CONCLUSION

The industrial factory building is analyzed the seismic behavior under seismic hazard in Northeastern Thailand according to the Earthquake Resistant Design code 1303 [2]. Twenty seismic waveforms are selected and scaled for this area. The nonlinear time history procedure is applied to capture the building responses. The building model consists of the elastic elements in the middle of members, the fiber elements at both ends of members and the beam-column connection, which is assumed to be rigid. From the results, the maximum damage has occurred in the second-floor column with a height of 7.45 m. The columns in this floor perform the soft story irregularity. The building is severe damage due to the W20 Northridge-01 seismic waveform. The performance level for the acceptance criteria for the plastic rotation is immediate occupancy with the rotation angle of 0.0274 rad, and for the maximum inter-story drift is life safety with the inter-story drift of 3.63 percentage. Therefore, the industrial factory building is needed to enhance the seismic capacity for damage prevention.

8. ACKNOWLEDGMENTS

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