Civil and Environmental Engineering for Resilient, Smart and Sustainable Solutions

Edited by
Tahar Ayadat

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Description

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The book focusses on recent developments in the area of infrastructures that are resilient, smart, and sustainable. It presents an important guideline for policy makers, engineers and researchers interested in various infrastructure issues faced by societies.

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A study case: Seismic evaluation of existing six-story office building with flat plate structural system

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Keywords: Seismic Evaluation, ASCE 41-17, Performance Levels, Flat Plate, Pushover

Abstract. Indonesia is one of the countries with a relatively high frequency of earthquakes, which can impact buildings and infrastructure. With the ongoing updates to regulatory codes, there will be an elevation in the level of safety factors in building design. Concurrently, there will be an increased prevalence of incorporating seismic hazards into the design of new buildings. Apart from that, earthquake loads can cause the performance of flat-plate structures to decrease until they collapse. Therefore, in this research, a case study of the existing office building with a flat plate structural system built in 1998 will undergo a seismic evaluation based on ASCE 41-17 to determine whether the building's performance is still safe. The office building was evaluated at the Collapse Prevention performance level for the BSE-2E seismic hazard (975-year period) according to ASCE 41-17. The evaluation occurred in three stages: tier 1, tier 2, and tier 3. The pushover analysis demonstrates the use of linear and nonlinear static procedures in structural analysis. The evaluation indicated that the current office building could meet the specified performance level; however, several beam and column structural components still required fixing.

Introduction

Indonesia lies at the convergence of three tectonic plates, resulting in a high frequency of earthquakes. As a result, buildings and infrastructure can be damaged and endanger their occupants if a collapse occurs. Several earthquakes have occurred in Indonesia, causing significant casualties, namely in Aceh in 2004, Yogyakarta in 2006, Padang in 2009, and Palu in 2018. With the risk of earthquake hazards to buildings, this research will conduct a seismic evaluation of a building that functions as an office located in Jakarta. The office building was constructed in 1998 and still adheres to outdated building codes. The structure is composed of a reinforced concrete construction with a seismic moment-resisting frame. The horizontal structural system in this building consists of flat plates with perimeter beams.

The evolving seismic hazard considerations in the SNI 1726: 2019 office building design code compared to the SNI 1726:1987 code emphasize the importance of reevaluating and updating safety standards for office buildings. In an earthquake, a flat plate structural system is vulnerable and may compromise the building's performance, potentially leading to collapse. Therefore, it is essential to thoroughly assess seismic risks based on ASCE 41-17 to determine whether the building's performance is still safe. Based on the analysis of office buildings, this study evaluated the buildings performance and assessed their compliance with ASCE 41-17 performance standards.

Literature Review

Seismic evaluation is defined as an approved process or methodology of evaluating deficiencies in a building that prevent the building from achieving a selected Performance Objective [1]. Seismic evaluation based on ASCE 41-17 can follow three procedures: tier 1, tier 2, and tier 3.

Tier 1 is a screening stage in the form of a checklist. Tier 2 is a deficiency-based procedure based on tier 1 screening. Tier 3 is a systematic evaluation procedure based on building performance. In tier 2 and tier 3, it can be analyzed using static or dynamic procedures, and the analysis can be carried out linearly or nonlinearly.

Performance level is one factor determining the strength limits of a building that needs to be reviewed for evaluation or rehabilitation. Based on ASCE 41-17, structural performance levels are defined into six sequential levels: immediate occupancy (IO), damage control (DC), life safety (LS), limited safety (LdS), collapse prevention (CP) and Not considered structural performance levels (NC).

The seismic hazard level used in ASCE 41-17 is the seismic hazard for existing buildings with a probability of exceeding 20% in 50 years (return period 225 years), which is called Basic Safety Earthquake 1-Existing (BSE-1E) and a probability of exceeding 5% in 50 years (return period 975 years) which is called Basic Safety Earthquake 2-Existing (BSE-2E). This seismic hazard differs from those used for new building designs known as BSE-1N and BSE-2N. Figure. 1 compares the Jakarta soft soil response spectrum for new and existing buildings.

In determining the actions in buildings, ASCE 41-17 classified actions into deformation-controlled and force-controlled actions. The action classified as deformation controlled in the column is a combined axial and bending action, and in the beam is a bending action. The force-controlled action in the column is axial and shear action, while in beam and column flat plate joint connections, it is shear forces.

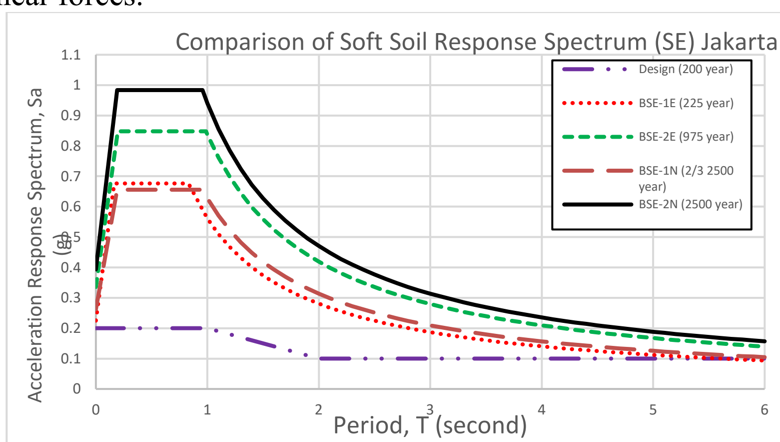

Fig. 1 Comparison of Jakarta's Soft Soil Spectrum Response

The acceptance criteria for each structural element are determined based on the building's performance level and limits in ASCE 41-17. For linear analysis, the acceptance criteria for deformation-controlled action must satisfy Eq. 1, while for force-controlled action, it must satisfy Eq. 2. In nonlinear analysis, the acceptance criteria for deformation-controlled action involve comparing the deformation curve of each element with the acceptance points, shown in Figure 2. For force-controlled action in nonlinear analysis, it must satisfy Eq. 3.

$$mkQ_{CE} > Q_{UD} \qquad \text{(Eq. 1)}$$

where

Period T (seconds)

m	=	component capacity modification factor to account for expected ductility associated with this action at the selected Structural Performance Level
Q_{UD}	=	deformation-controlled action caused by gravity loads and earthquake forces
Q_{CE}	=	expected strength of component deformation-controlled action of an element at the deformation level under consideration
k	=	knowledge factor

$kQ_{CL} > Q_{UF}$ (Eq. 2)

where

Q_{CL}	=	lower-bound strength of a force-controlled action of an element at the deformation level under consideration
Q_{UF}	=	force-controlled action caused by gravity loads in combination with earthquake forces.

$YX\,(Q_{UF} - Q_G) + Q_G \leq Q_{CL}$ (Eq. 3)

where

Q_{UF}	=	the force-controlled demand determined.
Q_G	=	gravity load demand
Q_{CL}	=	lower-bound component strength
Y	=	Load factor
X	=	is taken as 1.0 for Collapse Prevention or 1.3 for Life Safety and Immediate Occupancy

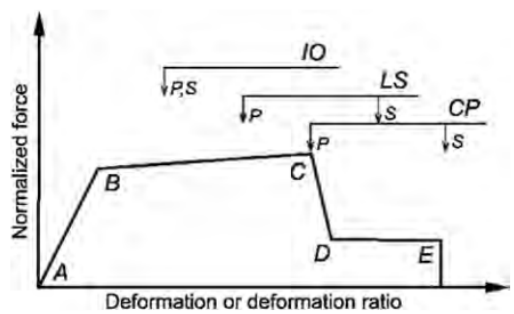

Fig. 2 Illustration of Acceptance Criteria

(Source : ASCE 41-17)

Research Method

The codes used in this research are ASCE 41-17, SNI 1726:2019, SNI 2847:2019, and SKBI-1.3.53 1987. The location of the existing office building is in North Jakarta. It consists of 6 story with a height of 4.2m between levels, making the total height of the building 25.2m. The building utilizes a flat plate system with shear stud rails at the interior column plate connections and edges.

According to ASCE 41-17, with the risk category II, the office buildings will be evaluated with BSE-2E seismic hazards, with the target performance level set being collapse prevention. In the tier 1 evaluation, screening is conducted based on building criteria and collapse prevention performance levels. The screening will according to list from the Tables from ASCE 41-17 with the base shear determined only for tier 1. In tier 2, a linear static analysis is carried out based on the deficiencies identified in tier 1. The tier 2 will be analyzed with different base shear accordance to ASCE 41-17, and will be evaluated for each member to know the performance member on the building.

As a part of the comparison from tier 2 evaluation result in this study, the existing office building will be assessed in tier 3 using nonlinear static (pushover) analysis. For the tier 3, the base shear that applied to the building also different from previous tier. Base shear on tier 3 is obtained from pushover curve of the building. In this tier, the performance of the building can be directly obtained through pushover curve in accordance with the requirements in ASCE 41-17. However, every member must be checked with the acceptance criteria from ASCE 41-17 based on the performance level.

The ETABS 21.1.0 program facilitates office building modeling and analysis in each tier. According to a study conducted by Wijanto & Rastandi, 1998, flat plate modeling in the ETABS program without including the stiffness of the horizontal connecting elements will result in distorted results of vibration time, level translation, and shear force distribution [8]. Therefore, the flat plate in this office building is modeled using the two-beam method. In ETABS modeling, structural components consist of 8 beam configurations, 2 column configurations, and one plate configuration. The total member on the building is 414 columns, 264 beams, and 306 joint points. Plastic hinge modeling on beams and columns is for analysis nonlinear on tier 3. The plan view and model of the office building in ETABS are shown in Figure 3 and Figure 4 respectively.

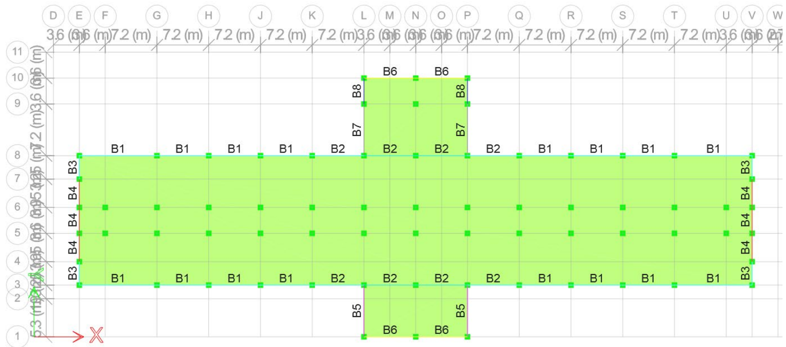

Fig. 3 Plan View Office Building model

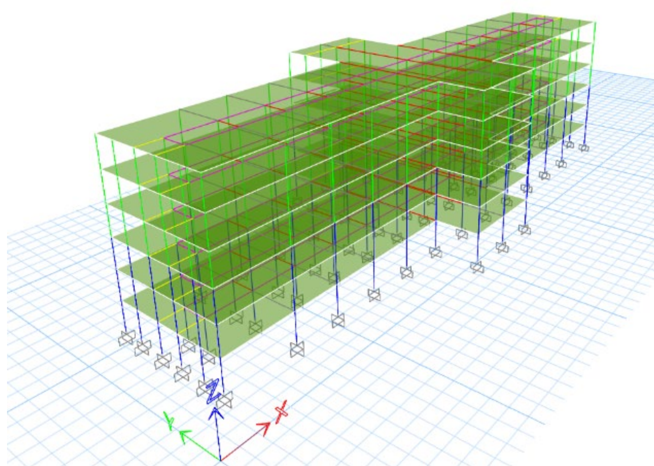

Fig. 4 Existing Office Building 3-D model

Results and Discussion

The results of the tier 1 evaluation of existing office buildings were obtained by screening the list item from tables determined by ASCE 41-17 for visual checking and quick calculations. Base shear used in tier 1 is 135,191kN. The tier 1 evaluation results found deficiencies in the shear stress of columns, beams, and plates. Therefore, evaluation continues to tier 2 evaluation using linear static analysis on columns, beams, and column flat plate joints with predetermined action classifications. The base shear force in the linear analysis used for assessment is 73,406kN. The results from column evaluation showed that the column was still adequate for axial and shear action, but failure was found to be 50.48% due to the combined axial and bending action. When checking the beam components, it was found that failure was 7.25% due to bending action, and 43.96% failure was due to shear action. Meanwhile, checking each column flat plate joint for shear action, both interior and edge, is still capable of serving the action that occurs in the BSE-2E seismic hazard. Based on the result, the building did not achieve the target performance level.

A tier 3 evaluation used nonlinear static analysis (pushover) to assess the building's nonlinear performance. The base shear force in the nonlinear analysis used for assessment is 48,294kN. The results of the pushover curve for the existing office building are depicted in Figure 5 and Figure 6 respectively. In the X direction, the target displacement (performance level point) from the curve is 466mm, indicating a life safety performance. Meanwhile in the Y direction, the target displacement is 451mm, signifying collapse prevention performance. Consequently, the office building has attained the target performance level as per ASCE 41-17.

The nonlinear static analysis (pushover) results reveal that plastic joint formation initially occurred in the beam due to bending forces. Certain plastic joints met the required safety standards with no bending-related failures in the beam. Nonetheless, examination of the beam against shear action yielded a failure rate of 19.57%. Meanwhile, the column evaluation noted that several columns failed due to plastic hinge formation, resulting from increased collapse prevention performance under axial bending forces. Notably, no failures were observed when assessing the columns against shear action. Similarly, the column flat plate joints exhibited no failures under shear action.

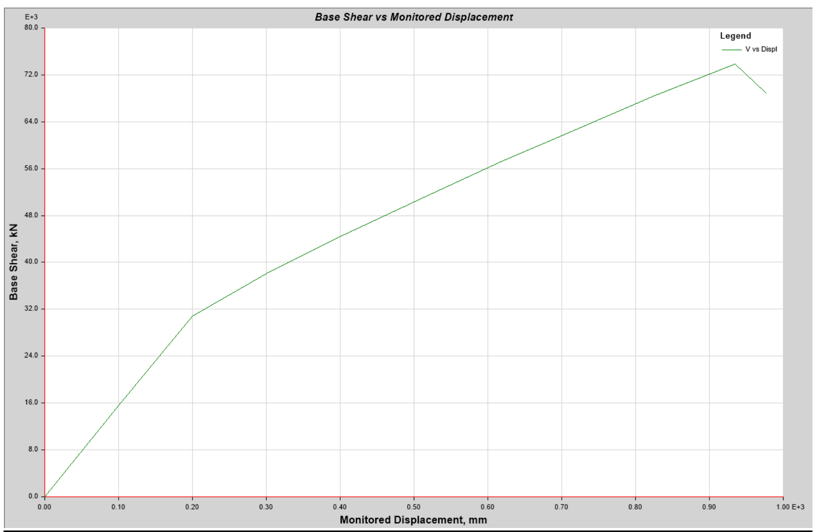

Fig. 5 Base Shear Force Versus Nodal Displacement in X Direction

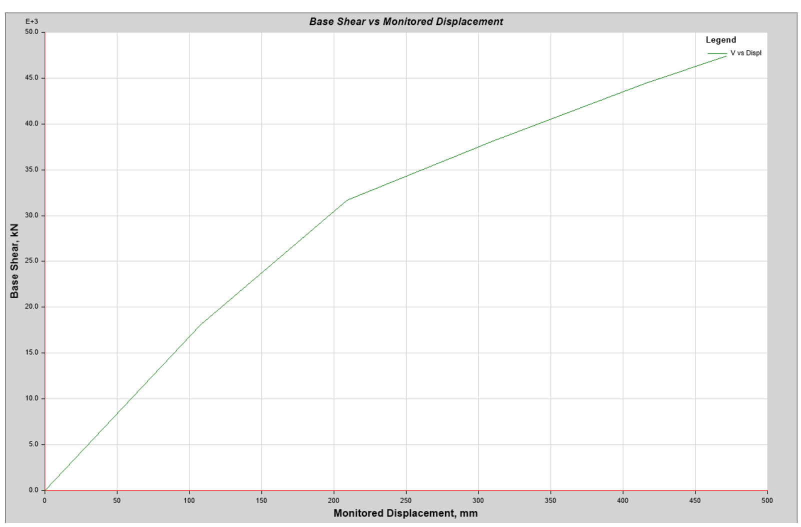

Fig. 6 Base Shear Force Versus Nodal Displacement in Y Direction

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Tables 1 to Table 5 shows a comparison of the number of element failure percentages evaluated at tier 2 with linear static procedure analysis (LSP) and tier 3 with nonlinear static procedure analysis (NSP). In linear static, there are more failures because linear analysis evaluates component performance up to the maximum elastic point without considering the inelastic properties of the component. Therefore, the results of the nonlinear analysis are the actual building performance conditions. Based on the results of the nonlinear analysis, It has determined that the maximum base shear force is lower than the linear base shear force.

Table 1 Comparison of Column Evaluations for Deformation Controlled Actions

Story	Total Column	Percentage of Column Failure Due to Combined of Axial Bending Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	69	0	0.00	0	0.00
5	69	0	0.00	0	0.00
4	69	8	11.59	0	0.00
3	69	63	91.30	0	0.00
2	69	69	100.00	0	0.00
1	69	69	100.00	15	21.74
Total	414	209	50.48	15	3.62

Table 2 Comparison of Column Evaluations for Force Controlled Actions

Story	Total Column	Percentage of Column Failure Due to Axial and Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	69	0	0.00	0	0.00
5	69	0	0.00	0	0.00
4	69	0	0.00	0	0.00
3	69	0	0.00	0	0.00
2	69	0	0.00	0	0.00
1	69	0	0.00	0	0.00
Total	414	0	0.00	0	0.00

Table 3 Comparison of Beam Evaluations for Deformation Controlled Actions

Story	Total Beam	Percentage of Beam Failure Due to Bending Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	44	0	0.00	0	0.00
5	44	3	4.35	0	0.00
4	44	8	11.59	0	0.00
3	44	8	11.59	0	0.00
2	44	8	11.59	0	0.00
1	44	3	4.35	0	0.00
Total	264	30	7.25	0	0.00

Table 4 Comparison of Beam Evaluations for Force Controlled Actions

Story	Total Beam	Percentage of Beam Failure Due to Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	44	12	17.39	5	7.25
5	44	34	49.28	16	23.19
4	44	39	56.52	16	23.19
3	44	41	59.42	16	23.19
2	44	40	57.97	16	23.19
1	44	16	23.19	12	17.39
Total	264	182	43.96	81	19.57

Table 5 Comparison of Plate Column Joint Evaluations for Force Controlled Actions

Story	Total Joint	Percentage of Flat Plate Column Joint Due to Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	51	0	0,00	0	0.00
5	51	0	0.00	0	0.00
4	51	0	0.00	0	0.00
3	51	0	0.00	0	0.00
2	51	0	0.00	0	0.00
1	51	0	0.00	0	0.00
Total	306	0	0.00	0	0.00

Conclusion

We can derive several significant conclusions based on the detailed explanation in the previous discussion:

1. Based on the results of the linear static evaluation, 50.48% of the columns failed due to the combined of axial and bending action. As a result of the same action, the results of the nonlinear static evaluation (pushover) only resulted in 3.62% failure in the column.
2. Based on the results of the linear static evaluation, failure occurred 7.25% due to bending action and 43.96% due to shear action. Meanwhile, in nonlinear static (pushover) failure only occurred in 19.57% of the beams due to shear action.
3. The connection joint between the flat plate and column in the current office building still has enough capacity to resist the shear forces generated by seismic load.
4. According to ASCE 41-17, the existing office buildings have the capacity to meet the specified level of collapse prevention in both the X and Y directions.
5. The results of the nonlinear static analysis indicate a lower incidence of failures than the linear static analysis. Therefore, it is advisable to consider the nonlinear static analysis results when rehabilitating an existing building.

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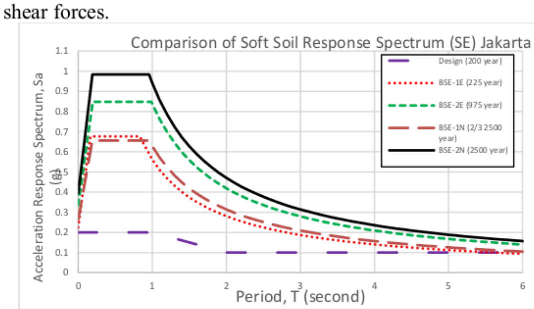

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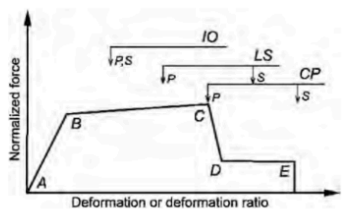

Fig. 2 Illustration of Acceptance Criteria

(Source : ASCE 41-17)

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As a part of the comparison from tier 2 evaluation result in this study, the existing office building will be assessed in tier 3 using nonlinear static (pushover) analysis. For the tier 3, the base shear that applied to the building also different from previous tier. Base shear on tier 3 is obtained from pushover curve of the building. In this tier, the performance of the building can be directly obtained through pushover curve in accordance with the requirements in ASCE 41-17. However, every member must be checked with the acceptance criteria from ASCE 41-17 based on the performance level.

The ETABS 21.1.0 program facilitates office building modeling and analysis in each tier. According to a study conducted by Wijanto & Rastandi, 1998, flat plate modeling in the ETABS program without including the stiffness of the horizontal connecting elements will result in distorted results of vibration time, level translation, and shear force distribution [8]. Therefore, the flat plate in this office building is modeled using the two-beam method. In ETABS modeling, structural components consist of 8 beam configurations, 2 column configurations, and one plate configuration. The total member on the building is 414 columns, 264 beams, and 306 joint points. Plastic hinge modeling on beams and columns is for analysis nonlinear on tier 3. The plan view and model of the office building in ETABS are shown in Figure 3 and Figure 4 respectively.

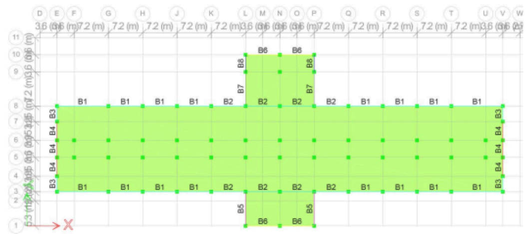

Fig. 3 Plan View Office Building model

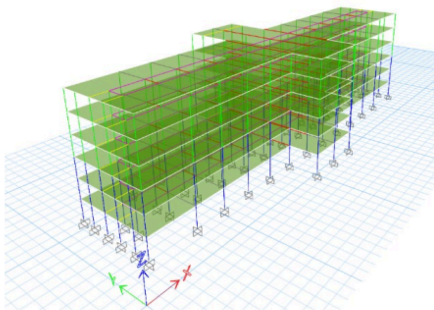

Fig. 4 Existing Office Building 3-D model

Results and Discussion

The results of the tier 1 evaluation of existing office buildings were obtained by screening the list item from tables determined by ASCE 41-17 for visual checking and quick calculations. Base shear used in tier 1 is 135,191kN. The tier 1 evaluation results found deficiencies in the shear stress of columns, beams, and plates. Therefore, evaluation continues to tier 2 evaluation using linear static analysis on columns, beams, and column flat plate joints with predetermined action classifications. The base shear force in the linear analysis used for assessment is 73,406kN. The results from column evaluation showed that the column was still adequate for axial and shear action, but failure was found to be 50.48% due to the combined axial and bending action. When checking the beam components, it was found that failure was 7.25% due to bending action, and 43.96% failure was due to shear action. Meanwhile, checking each column flat plate joint for shear

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action, both interior and edge, is still capable of serving the action that occurs in the BSE-2E seismic hazard. Based on the result, the building did not achieve the target performance level.

A tier 3 evaluation used nonlinear static analysis (pushover) to assess the building's nonlinear performance. The base shear force in the nonlinear analysis used for assessment is 48,294kN. The results of the pushover curve for the existing office building are depicted in Figure 5 and Figure 6 respectively. In the X direction, the target displacement (performance level point) from the curve is 466mm, indicating a life safety performance. Meanwhile in the Y direction, the target displacement is 451mm, signifying collapse prevention performance. Consequently, the office building has attained the target performance level as per ASCE 41-17.

The nonlinear static analysis (pushover) results reveal that plastic joint formation initially occurred in the beam due to bending forces. Certain plastic joints met the required safety standards with no bending-related failures in the beam. Nonetheless, examination of the beam against shear action yielded a failure rate of 19.57%. Meanwhile, the column evaluation noted that several columns failed due to plastic hinge formation, resulting from increased collapse prevention performance under axial bending forces. Notably, no failures were observed when assessing the columns against shear action. Similarly, the column flat plate joints exhibited no failures under shear action.

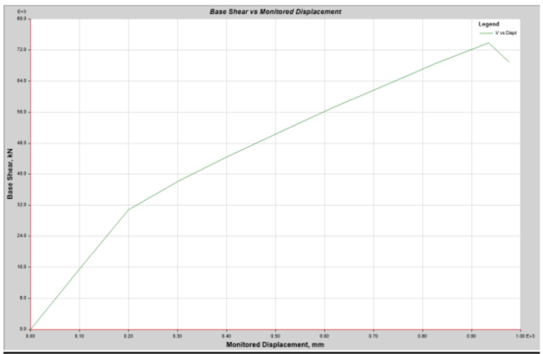

Fig. 5 Base Shear Force Versus Nodal Displacement in X Direction

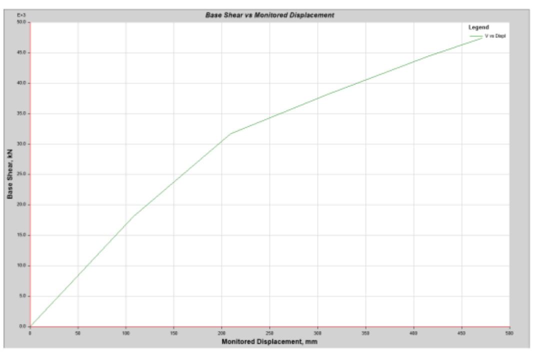

Fig. 6 Base Shear Force Versus Nodal Displacement in Y Direction

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Tables 1 to Table 5 shows a comparison of the number of element failure percentages evaluated at tier 2 with linear static procedure analysis (LSP) and tier 3 with nonlinear static procedure analysis (NSP). In linear static, there are more failures because linear analysis evaluates component performance up to the maximum elastic point without considering the inelastic properties of the component. Therefore, the results of the nonlinear analysis are the actual building performance conditions. Based on the results of the nonlinear analysis, It has determined that the maximum base shear force is lower than the linear base shear force.

Table 1 Comparison of Column Evaluations for Deformation Controlled Actions

Story	Total Column	Percentage of Column Failure Due to Combined of Axial Bending Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	69	0	0.00	0	0.00
5	69	0	0.00	0	0.00
4	69	8	11.59	0	0.00
3	69	63	91.30	0	0.00
2	69	69	100.00	0	0.00
1	69	69	100.00	15	21.74
Total	414	209	50.48	15	3.62

Table 2 Comparison of Column Evaluations for Force Controlled Actions

Story	Total Column	Percentage of Column Failure Due to Axial and Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	69	0	0.00	0	0.00
5	69	0	0.00	0	0.00
4	69	0	0.00	0	0.00
3	69	0	0.00	0	0.00
2	69	0	0.00	0	0.00
1	69	0	0.00	0	0.00
Total	414	0	0.00	0	0.00

Table 3 Comparison of Beam Evaluations for Deformation Controlled Actions

Story	Total Beam	Percentage of Beam Failure Due to Bending Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	44	0	0.00	0	0.00
5	44	3	4.35	0	0.00
4	44	8	11.59	0	0.00
3	44	8	11.59	0	0.00
2	44	8	11.59	0	0.00
1	44	3	4.35	0	0.00
Total	264	30	7.25	0	0.00

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Table 4 Comparison of Beam Evaluations for Force Controlled Actions

Story	Total Beam	Percentage of Beam Failure Due to Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	44	12	17.39	5	7.25
5	44	34	49.28	16	23.19
4	44	39	56.52	16	23.19
3	44	41	59.42	16	23.19
2	44	40	57.97	16	23.19
1	44	16	23.19	12	17.39
Total	264	182	43.96	81	19.57

Table 5 Comparison of Plate Column Joint Evaluations for Force Controlled Actions

Story	Total Joint	Percentage of Flat Plate Column Joint Due to Shear Action			
		Tier 2 PSL	Percentage (%)	Tier 3 PSN	Percentage (%)
6	51	0	0,00	0	0.00
5	51	0	0.00	0	0.00
4	51	0	0.00	0	0.00
3	51	0	0.00	0	0.00
2	51	0	0.00	0	0.00
1	51	0	0.00	0	0.00
Total	306	0	0.00	0	0.00

Conclusion

We can derive several significant conclusions based on the detailed explanation in the previous discussion:

1. Based on the results of the linear static evaluation, 50.48% of the columns failed due to the combined of axial and bending action. As a result of the same action, the results of the nonlinear static evaluation (pushover) only resulted in 3.62% failure in the column.
2. Based on the results of the linear static evaluation, failure occurred 7.25% due to bending action and 43.96% due to shear action. Meanwhile, in nonlinear static (pushover) failure only occurred in 19.57% of the beams due to shear action.
3. The connection joint between the flat plate and column in the current office building still has enough capacity to resist the shear forces generated by seismic load.
4. According to ASCE 41-17, the existing office buildings have the capacity to meet the specified level of collapse prevention in both the X and Y directions.
5. The results of the nonlinear static analysis indicate a lower incidence of failures than the linear static analysis. Therefore, it is advisable to consider the nonlinear static analysis results when rehabilitating an existing building.

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