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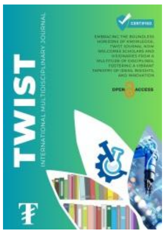

Seismic Performance of Four-Story Steel Building using ASCE 41-17 and Metro Davao Earthquake Model Atlas

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Abstract

Earthquakes are natural phenomena that occur when there is a sudden release of energy, resulting in seismic waves that can cause devastating events, causing widespread destruction and loss of life. The study evaluates the seismic performance of the 15-year-old Steel Building based on the latest Metro Davao Earthquake Model Atlas, National Structural Code of the Philippines (NSCP) 2015, and American Society of Civil Engineering (ASCE) 41-17. Analyzing the structure through Nonlinear Static Procedures and using the Demand Considered Earthquake (DCE) or 500-year-return period, the assessment reveals structural adequacy in terms of demand-capacity ratio, story drift, and various irregularities, except for a re-entrant corner irregularity. Pushover analysis was used to determine the structure's performance level, and the building's level was at the immediate occupancy to life safety performance level. The building is projected to remain functional and safe after seismic events, contributing valuable knowledge for earthquake-resistant construction in seismic-prone regions.

Keywords

Performance Based, Pushover Analysis, ASCE 41-17, Demand Considered Earthquake

INTRODUCTION

Earthquakes do not kill people, but poor buildings do. Earthquakes are one of the natural phenomena that exist in the world. The Philippines hits 100 to 150 earthquakes yearly, per the Philippine Institute of Volcanology and Seismology or PHIVOLCS. Also, the Philippines is the vulnerable country in terms of natural phenomena and disaster (Plazos et al., 2023). Last 2019, Davao City experienced strong earthquakes ranging from magnitude 6.1-6.9 from the Tangbulan Fault, Central Digos Fault, and Cotabato Fault System (CFS) that caused partially collapsed buildings in the city. The same year, the agency released the Metro Davao Earthquake Model Atlas to help engineers build earthquake-resilient and safe buildings to decrease the impact of destructive ground shaking and prevent casualties. Atlas introduced the Central Davao Fault System, which was found based on their study. The fault system comprises the Tamugan Fault, Lacson Fault, Dacudao Fault, Pangyan-Biao Escuela Fault, and New Carmen Fault. It can generate at least a magnitude of 6.5 to 6.9 (Cabotaje & Bernardo, 2024). The Four-Story Steel Building is located at Matina, Davao City, 6km from the Dacudao Fault. It can generate ground shaking of intensity VIII and is highly susceptible to liquefaction.

The recent earthquakes that affected the operations of existing structures helped strengthen the need to evaluate the seismic performance of the existing structures such as, the development of Performance-Based Design (PBD) in the current structural engineering practice is getting more ground nowadays because of its capability to assess the building’s structural behavior during strong earthquakes (Harris & Speicher, 2020). ASCE 41-17 is one of the most accepted performance-based seismic evaluations for existing building standards, also known as ASCE 41. It is developed by the American Society of Civil Engineers to assess the existing structure (Kiland, 2020).

The main objective of this study is to determine the current structural integrity and seismic performance of the Steel Building during the Design Considered Event (DCE) or 500-year return period of earthquakes in the future based on the Metro Davao Earthquake Model. Specifically, to identify the storey drift and structural irregularities, to check the behavior of local members by using the demand-capacity ratio, and to determine the performance level of the building.

MATERIALS AND METHODS

Conceptual Framework

As shown in Figure 1, As Built plans were first acquired for data collection, followed by the corresponding loads from NSCP 2015 and Metro Davao Earthquake Model Atlas. The structure was then analyzed using ETABS 21 software. Perform seismic evaluation using them according to ASCE 41-17 standards. If necessary, seismic mitigation measures for the structure should be provided.

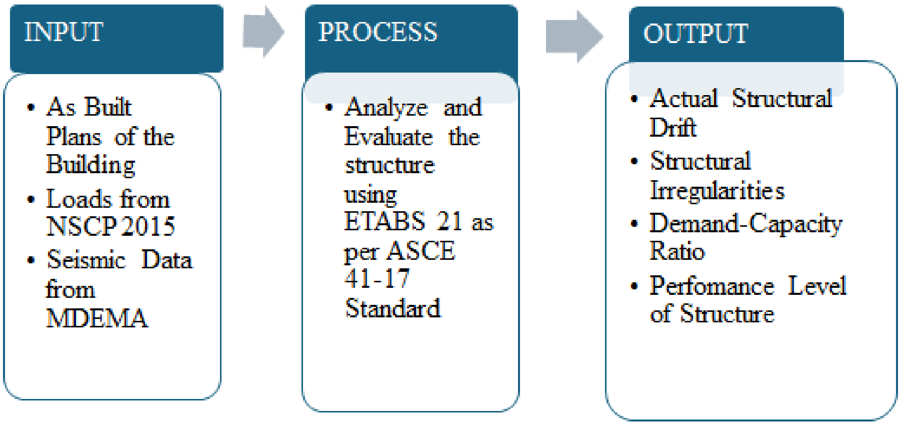


Fig. 1 Conceptual Framework of the Study

Materials and Resources

ETABS 21 Software was used for evaluating the steel building. A flexible finite element program, ETABS 21 may analyze structural problems in a static, dynamic, linear, or nonlinear fashion. It also serves as a solid structural design tool that complies with NSCP building codes and other standards like ASCE 41 for assessing pre-existing structures. The Metro Davao Earthquake Model Atlas (MDEMA) is a map set that shows assessments of seismic ground motion hazards based on various earthquake sources. These maps include Spectral Acceleration and Peak Ground Acceleration, which are produced using Probabilistic Seismic Hazard Analysis. These results are the product of the combined efforts and knowledge of seismologists, geologists, engineers, and researchers connected to PHIVOLCS. Numerous designs for new structures and assessing existing ones are based on this modeling (Reddy, 2020).

Methods and Procedures

This study was made to evaluate steel building. It begins by analyzing the seismic performance of the said structure, close to the earthquake-prone Central Davao Fault System. All loads, such as Dead, Live, and Seismic loadings, shall conform with the NSCP 2015 and MDEMA. Minimum Design Loads were used per the code for dead, live, and roof live loads. The assessment might start straight with the Tier 3 systematic examination. Basic Performance Objective for Existing Structure were the basis for this study as per ASCE 41-17. Life Safety was the basis of the performance level of the building. Figure 2 shows the isometric view of the steel building.

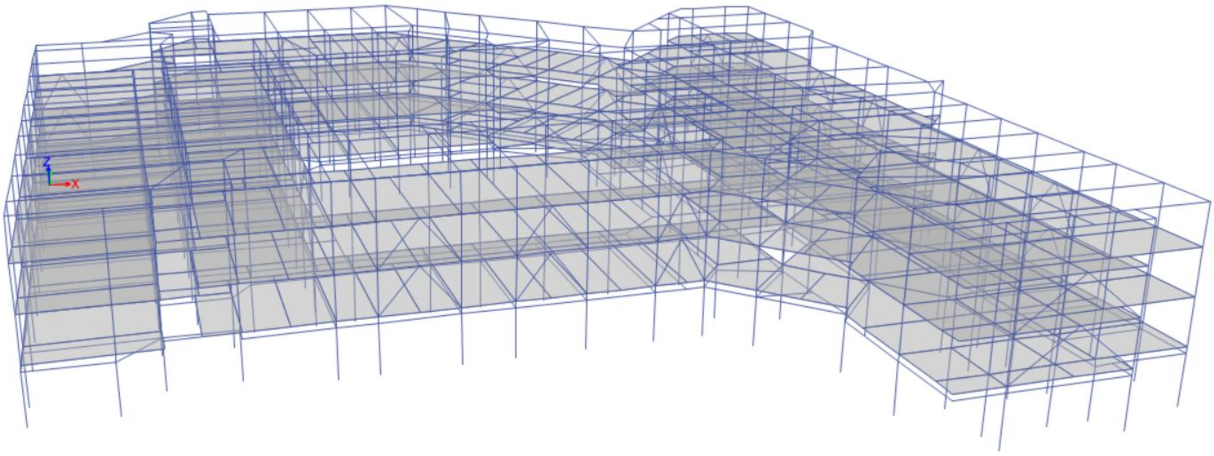


Fig. 2 Isometric View of the Building

Pushover analysis procedure was applied. A combination of 100% dead and 25% live load, incremental horizontal loads are sequentially applied to the structure until failure occurs. These loads represent the seismic forces in each direction (global x and y directions), causing the structure to deform until it reaches its failure threshold. The primary objective of this method is to assess the building's performance by analyzing the pushover curve under lateral loads, considering the nonlinear behavior of structural properties (Gupta et al., 2017). The Acceptance Criteria must follow ASCE 41-17 guidelines. There are two types of structural elements: primary and secondary members. Members classified as primary can withstand lateral forces, while members classified as secondary cannot. During this process, every member is scrutinized to ensure its demand meets the acceptance standards. In this study, only primary members were assessed. Every component is categorized as controlled deformation. The global drift for both axes in the approval criteria of the global nonlinear method should be at most 2% of the tale height. Determine the most critical performance level attained at the plastic hinges by evaluating the global structure in light of the identification step (Harrington & Liel, 2020).

RESULTS AND DISCUSSIONS

Story drift is the displacement of a single story relative to the previous story. Based on Table 1, the actual story drifts of all stories were less than the allowable story drifts, and the structure is adequate in terms of story drift. The 3rd floor along the X and Y axis had the highest drift value, while the 2nd floor along the X and Y axis had the lowest drift value. NSCP 2015 shows that the allowable story drift is 0.010h, where h is the story level height for risk category IV. The damping ratio is 5%.

Table 1 Story Drifts

Story	Height (m)	Story Drift at X+ (mm)	Story Drift at X- (mm)	Story Drift at Y+ (mm)	Story Drift at Y- (mm)	Allowable Drift (mm)
Roof	14.93	2.269	2.262	3.478	3.476	35
4th	11.43	0.653	0.658	0.451	0.535	35
3rd	7.93	1.052	1.062	0.605	0.714	35
2nd	4.43	1.475	1.544	1.589	1.672	44.3

Structural irregularities refer to deviations from an ideal or regular building configuration in terms of its shape, stiffness, or mass distribution. These irregularities can make structures more vulnerable to seismic forces or other types of loads, as they may respond unevenly during such events. Structural irregularities are often classified into two main categories: plan irregularities and vertical irregularities (Sardari et al., 2020). The soft story is a situation when the upper levels of a building are stiffer than the lower story. This can result in undesirable building performance. According to NSCP 2015, a soft story is one in which the lateral stiffness is less than 70% of that in the story above or less than 80% of the average stiffness of the three stories above. Table 2 shows that the steel building has no soft storey on all axis.

Table 2 Soft Storey Check

Story	Lateral Stiffness X (kN/m)	Lateral Stiffness Y (kN/m)	70% Lateral Stiffness Above X (kN/m)	70% Lateral Stiffness Above Y (kN/m)	80% Lateral Stiffness Three Stories Above X (kN/m)	80% Lateral Stiffness Three Stories Above Y (kN/m)	Soft Storey X	Soft Storey Y
Roof	243804.9	258993.8	170663.4	181295.7	-	-	NONE	NONE
4th	2133565.8	2769717.7	1493496.1	1938802.4	195044	207195	NONE	NONE
3rd	2633339.2	3473214.8	1843337.5	2431250	950948	1211484	NONE	NONE
2nd	23398429	32418659	-	-	1336189	1733847	NONE	NONE

Mass irregularity shall be considered to exist where the effective mass of any story is more than 150% of the effective mass of an adjacent story. A roof that is lighter than the floor below need not be considered. Table 3 shows that there were no mass irregularities on the structure.

Table 3 Mass Irregularity Check

Story	Story Mass (kg)	150% Story Mass Above (kg)	Mass Irregularity
4th	1954492.9	2931739	NONE
3rd	1977293.68	2965940	NONE
2nd	1927921.6	-	NONE

Re-entrant corner irregularity exists when both projections of the structure beyond a re-entrant corner are greater than 15% of the plan dimension of the structure in the given direction. Buildings with re-entrant corners are considered more susceptible to torsional response and may experience amplified forces and displacements during an earthquake. A re-entrant corner alters the distribution of mass and stiffness in the structure. The building has re-entrant corner irregularity, as shown in Table 4, since both axes of the structure exceed the maximum allowable percentage as per the code. Along the x-axis, the re-entrant percentage was 28.13%; on the y-axis, it was 20.89%, greater than the allowable re-entrant value of 15%.

Table 4 Re-entrant Corner Irregularity of the Building

	Distance (m)	Percentage	Status
Length of the Building along X-axis	67.59 m	28.13%	Re-entrant
Re-entrant along X-axis	19.01 m		
Length of the Building along Y-axis	82.09 m	20.89%	Re-entrant
Re-entrant along Y-axis	17.15 m		

Torsional Irregularity of the building exists when the maximum story drift, including the accidental torsion at one end of the structure, are more than 1.2 times the average of the story drift of the two ends. Table 5 shows the maximum displacements and average displacements of the building on X axis at different stories. The ratios were less than 1.2 which means that the building has no torsional irregularity.

Table 5 Torsional Irregularity on X axis of the building

Story	Maximum Drift	Average Drift	Ratio	Remarks
4th	7.747	6.749	1.149	PASSED
3rd	5.944	5.152	1.154	PASSED
2nd	3.39	2.853	1.188	PASSED

There was no torsional irregularity on different stories of the building along Y axis. It shows on Table 6 that the ratios of maximum to average displacements is less than 1.2.

Table 6 Torsional Irregularity on Y axis of the building

Story	Maximum Drift	Average Drift	Ratio	Remarks
4th	7.899	6.698	1.179	PASSED
3rd	6.061	5.132	1.181	PASSED
2nd	3.558	3.004	1.184	PASSED

The interaction ratio is typically defined as the sum of the ratios of the actual stress or load in a member to its allowable or design capacity for different loading conditions. It is a parameter used to evaluate whether a structural member is adequately designed to resist combined loading conditions. This ratio is commonly used in the design of structural elements subjected to multiple types of stresses or loads simultaneously, such as axial forces, bending moments, shear forces, and torsional moments. the interaction ratio helps ensure that a structural member does not exceed its combined stress limits under the various loading conditions it might encounter. **IR ≤ 1:** The member is considered safe, meaning that the combined loading does not exceed the member's capacity. **IR > 1:** The member is overstressed, indicating that it does not have sufficient capacity to resist the combined loading conditions, and it may require redesign or strengthening (Zhang and Tian, 2019). Table 7 shows the three highest ratios for steel beams per story using the ASCE 41-17 Load Combinations. It shows that all members were adequate because the ratios were less than 1.0.

Table 7 Demand Capacity Ratio for Steel Beams

Story	Section	Demand Value (Q_u)	Capacity Value (mkQ_{CE})	Demand Capacity Ratio	Remarks
Roof	W8x24	102.1	117.5	0.869	PASSED
Roof	W8x24	93.18	117.5	0.793	PASSED
Roof	W8x24	92.94	117.5	0.791	PASSED
4th Floor	W16x45	163.02	311.10	0.524	PASSED
4th Floor	W16x45	139.07	273.76	0.508	PASSED
4th Floor	W16x45	138.01	272.21	0.507	PASSED
3rd Floor	W16x45	132.80	296.43	0.448	PASSED
3rd Floor	W18x60	155.28	347.39	0.447	PASSED
3rd Floor	W16x45	180.77	418.44	0.431	PASSED
2nd Floor	W16x45	139.73	305.76	0.457	PASSED
2nd Floor	W16x45	136.28	309.73	0.440	PASSED
2nd Floor	W16x45	127.30	301.66	0.422	PASSED

Table 8 shows the top three highest demand capacity ratios for steel columns using linear static procedure. Columns were subjected to combined axial and bending. steel columns are safe because the ratios were less than 1.0.

Table 8 Demand Capacity Ratio for Steel Columns

Story	Section	Demand Value (Q_u)			Capacity Value (mkQ_{CE})			Demand Capacity Ratio	Remarks
		P_u	M_{ux}	M_{uy}	$\emptyset P_n$	$\emptyset M_{nx}$	$\emptyset M_{ny}$		
Roof	W12x120	49.8	12.2	94.6	6570	945.7	434.2	0.235	PASSED
Roof	W12x120	57.8	34.6	83.6	6570	945.7	434.2	0.234	PASSED
Roof	W12x120	75	43.1	73.8	6570	945.7	434.2	0.221	PASSED

4th	W12x120	374	45.9	136	6577	945.7	434.2	0.390	PASSED
4th	W14x120	500	190	54.5	6733	1078	518.6	0.319	PASSED
4th	W12x120	262	6.04	123	6577	945.7	434.2	0.311	PASSED
3rd	W12x120	673	34.6	115	6577	945.7	434.2	0.353	PASSED
3rd	W14x120	796	200	54.9	6733	1078	518.6	0.351	PASSED
3rd	W14x120	601	276	12.1	6733	1078	518.6	0.324	PASSED
2nd	W12x120	2173	10.1	9.25	7046	945.7	434.2	0.439	PASSED
2nd	W12x120	2201	12.5	8.23	7046	945.7	434.2	0.423	PASSED
2nd	W12x120	1987	15.6	9.67	7046	945.7	434.2	0.40	PASSED

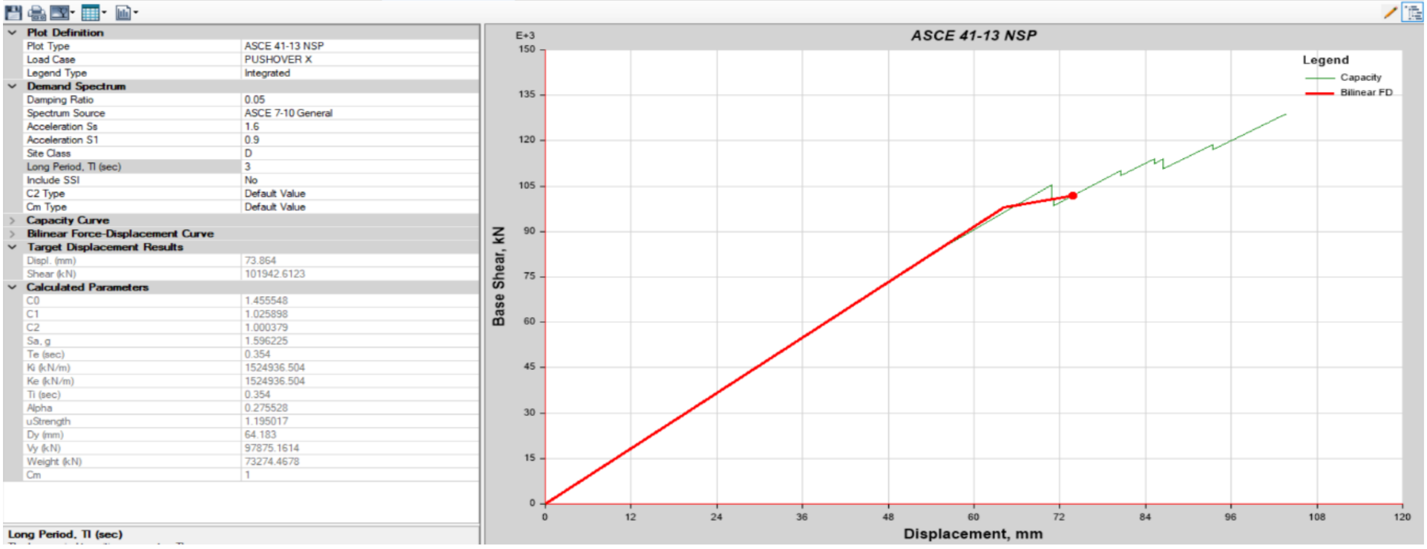
The top three highest demand capacity ratio per floor story for steel bracing using is shown in Table 9. All bracing of the structure were adequate since the ratios were less than 1.0.

Table 9 Demand Capacity Ratio for Steel Bracings

Story	**Section**	**Demand Value (Q_u)**	**Capacity Value (mkQ_{CE})**	**Demand Capacity Ratio**	**Remarks**
3rd to 4th	12” PIPE Gr. 50	185.991	3263	0.057	PASSED
3rd to 4th	12” PIPE Gr. 50	221.21	4022.06	0.055	PASSED
3rd to 4th	12” PIPE Gr. 50	182.411	3316.57	0.055	PASSED
2nd to 3rd	12” PIPE Gr. 50	313.25	3262.99	0.096	PASSED
2nd to 3rd	12” PIPE Gr. 50	301.81	3316.57	0.091	PASSED
2nd to 3rd	12” PIPE Gr. 50	283.34	3294.66	0.086	PASSED

The purpose of pushover analysis is to evaluate the capacity of a structure to withstand seismic forces and to identify potential weak points or failure modes. It is beneficial for assessing the behavior of structures under nonlinear conditions, which is common during earthquakes. The displacement for Life Safety is 2% percent of the total building height or 286 mm. The corresponding load combination assigned for analysis is Dead Load plus 25% of Live Load. Plastic hinges were assigned to all members of the structure. For beam members, the M3 hinge was used for the hinges, the P-M2-M3 hinge was used for column member hinges, and the P hinge was used for braces member hinges (El-batar, 2020).

Performance Point is the point where the demand curve meets the capacity curve. It is also the basis for determining the performance level of the structure. Refer to Figure 3 or the Pushover along the X-axis; the demand curve (red curve) meets the capacity curve (green curve) at the displacement of 73.864 mm and base shear of 101,943 kN.

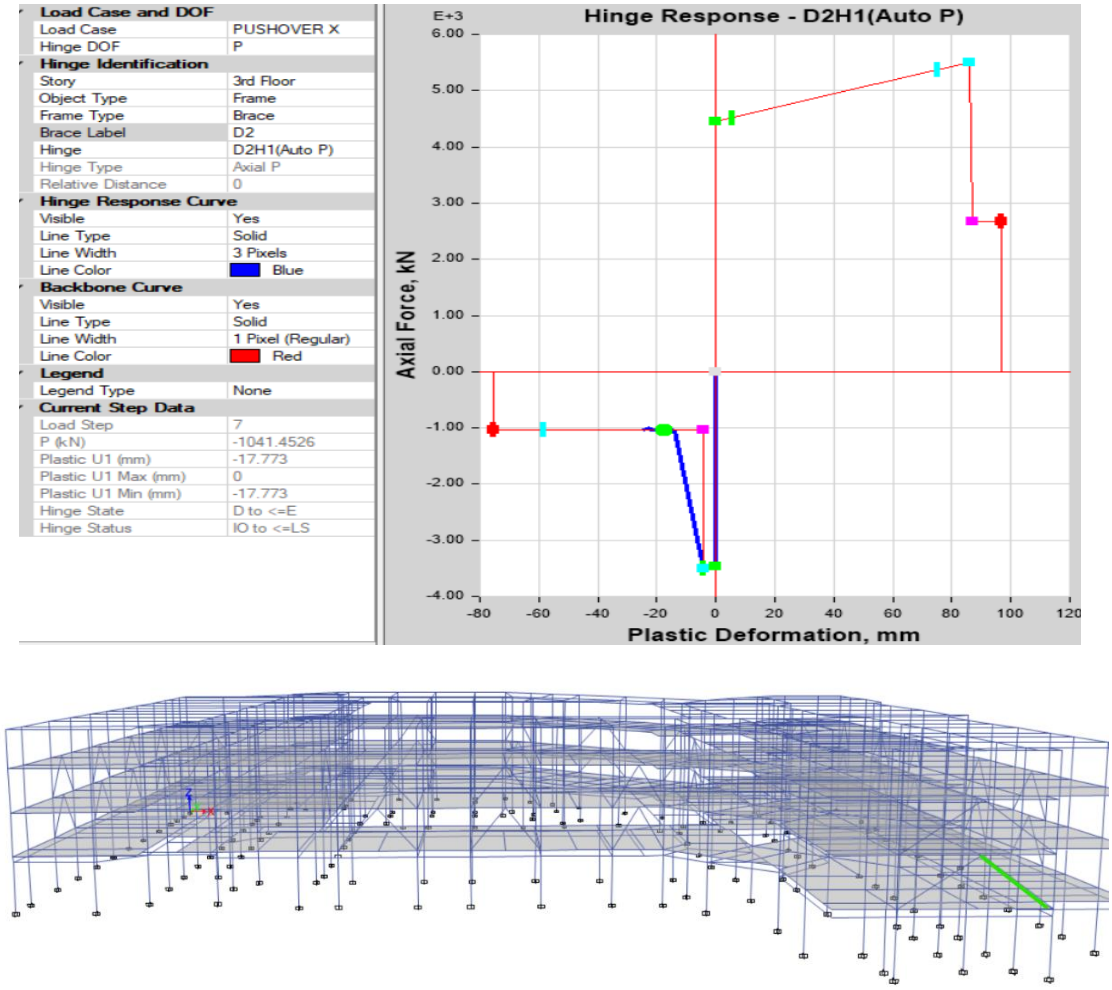


Plot Definition	
Plot Type	ASCE 41-13 NSP
Load Case	PUSHOVER X
Legend Type	Integrated
Demand Spectrum	
Damping Ratio	0.05
Spectrum Source	ASCE 7-10 General
Acceleration Ss	1.6
Acceleration S1	0.9
Site Class	D
Long Period, Tl (sec)	3
Include SSI	No
C2 Type	Default Value
Cm Type	Default Value
Capacity Curve	
Bilinear Force-Displacement Curve	
Target Displacement Results	
Displ. (mm)	73.864
Shear (kN)	101942.6123
Calculated Parameters	
C0	1.455548
C1	1.025898
C2	1.000379
Sa, g	1.596225
Te (sec)	0.354
Ki (kN/m)	1524936.504
Ke (kN/m)	1524936.504
Ti (sec)	0.354
Alpha	0.275528
uStrength	1.195017
Dy (mm)	64.183
Vy (kN)	97875.1614
Weight (kN)	73274.4678
Cm	1

Long Period, Tl (sec)

Fig. 3 Pushover Curve on X-Axis of the Building

Along x-axis, there is only one member that develop plastic yielding. Figure 4 shows the plastic hinge of the D2 brace of the building. The immediate occupancy starting plastic deformation was 4.18 mm, life safety plastic deformation was 59.38 mm, and plastic deformation was 75.31 mm for collapse prevention. The D2 brace has a plastic rotation of 17.773 mm, which means the hinge status is from immediate occupancy to life safety.

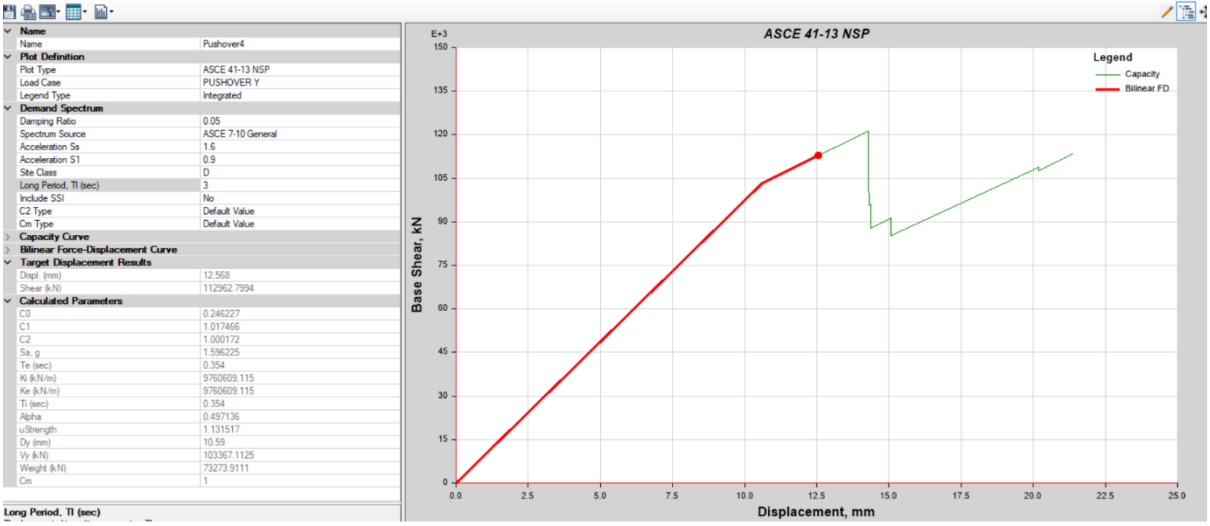


Load Case and DOF	
Load Case	PUSHOVER X
Hinge DOF	P
Hinge Identification	
Story	3rd Floor
Object Type	Frame
Frame Type	Brace
Brace Label	D2
Hinge	D2H1(Auto P)
Hinge Type	Axial P
Relative Distance	0
Hinge Response Curve	
Visible	Yes
Line Type	Solid
Line Width	3 Pixels
Line Color	🟦 Blue
Backbone Curve	
Visible	Yes
Line Type	Solid
Line Width	1 Pixel (Regular)
Line Color	🟥 Red
Legend	
Legend Type	None
Current Step Data	
Load Step	7
P (kN)	-1041.4526
Plastic U1 (mm)	-17.773
Plastic U1 Max (mm)	0
Plastic U1 Min (mm)	-17.773
Hinge State	D to <=E
Hinge Status	IO to <=LS

Fig. 4 Bracing D2 Hinge Response

Since the plastic hinges form in a controlled manner, typically away from load-carrying parts like columns, braces will develop yield first in pushover analysis. Energy dissipation during seismic events is possible by creating plastic hinges in bracing elements. Seismic energy is absorbed and dispersed by yielding the bracing elements' materials, preventing severe deformations and damage to other structural components. It guarantees that if any components experience plastic deformation, the structure will still withstand lateral stresses (Lago et al., 2019).

For Pushover along the Y-axis given in Figure 5, the capacity and demand curves meet on the performance point of 12.568 mm with the corresponding base shear of 112,962 kN.



Name	
Name	Pushover4
Plot Definition	
Plot Type	ASCE 41-13 NSP
Load Case	PUSHOVER Y
Legend Type	Integrated
Demand Spectrum	
Damping Ratio	0.05
Spectrum Source	ASCE 7-10 General
Acceleration Ss	1.6
Acceleration S1	0.9
Site Class	D
Long Period, Tl (sec)	3
Include SSI	No
C2 Type	Default Value
Cm Type	Default Value
Capacity Curve	
Bilinear Force-Displacement Curve	
Target Displacement Results	
Displ. (mm)	12.568
Shear (kN)	112962.7994
Calculated Parameters	
C0	0.246227
C1	1.017466
C2	1.000172
Sa, g	1.596225
Te (sec)	0.354
Ki (kN/m)	9760609.115
Ke (kN/m)	9760609.115
Ti (sec)	0.354
Alpha	0.497136
uStrength	1.131517
Dy (mm)	10.59
Vy (kN)	103367.1125
Weight (kN)	73273.9111
Cm	1

Long Period, Tl (sec)

Fig. 5 Pushover Curve on Y-Axis on the Building

Figure 6 shows the behavior of structure using pushover analysis at y-axis. No hinges were yielded; therefore, the performance level of the BE building was immediate occupancy level.

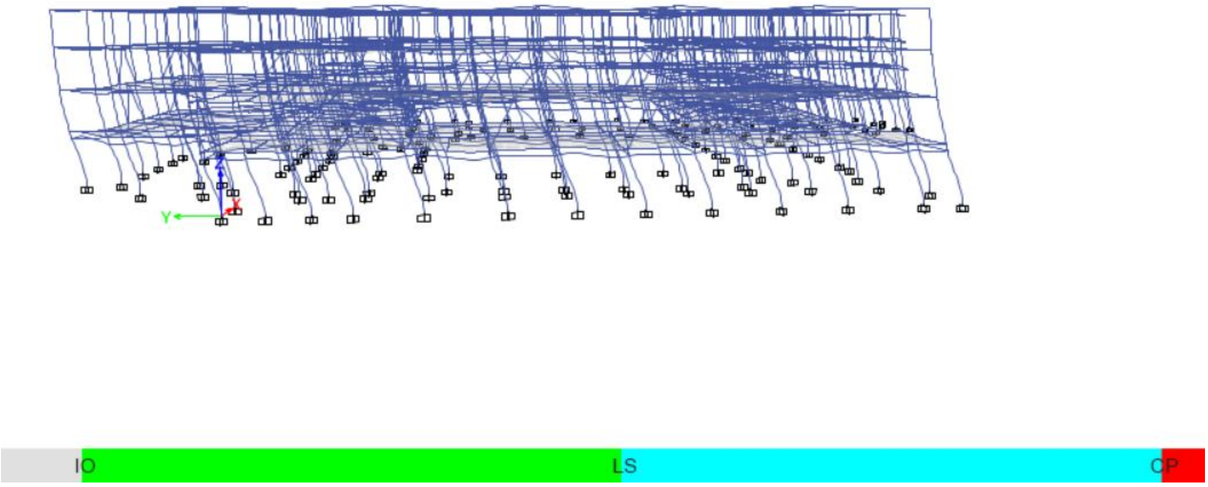


Fig. 6 Pushover Analysis on Y-axis on the Building

CONCLUSIONS

The series of earthquakes happened from 2019 to 2024, and the discovery of the Central Davao Earthquake Fault Line motivated the proponent to study the 15-year-old Steel Building. The structure was evaluated using ASCE 41-17 Tier 3 Systematic Evaluation Procedure, NSCP 2015, and Metro Davao Earthquake Model Atlas Demand Considered Earthquake to determine the structural safety based on drifts, structural irregularities, demand-capacity ratio, and seismic performance. The building undergoes on Nonlinear Static Procedure. All structural members were analyzed using demand-capacity ratio criteria, and the results show that all members were adequate.

The structure was also safe based on story drift and structural irregularities like the soft story, mass irregularities, torsional irregularities, and torsion. However, the structure has that irregularity on the re-entrant corner. The building's performance, evaluated according to ASCE 41-17, NSCP 2015, and using ETABS 21, falls within the range between immediate occupancy and life safety levels. Since the target performance level is life safety, we can conclude that the building meets the required performance standards and is considered adequate for the intended safety goals.

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DECLARATION OF CONFLICT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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