Seismic evaluation of a four-story apartment building in Matina, Davao City using non-linear dynamic analysis in accordance with ASCE 41-17

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Abstract. The increasing frequency and intensity of seismic activity in the Philippines posed significant challenges to ensuring urban buildings' safety and structural integrity. This study focused on evaluating the seismic performance of a mid-rise apartment building through nonlinear dynamic analysis, following the guidelines set by the American Society of Civil Engineers (ASCE) 41-17 and the National Structural Code of the Philippines (NSCP) 2015, utilizing ETABS software. Earthquake records from the Pacific Earthquake Engineering Research Center (PEER) database, specifically those exhibiting seismic behavior similar to Davao's, were used to simulate ground motions and determine maximum base shear and displacement. The initial analysis results failed to meet the Life Safety performance level criteria, prompting retrofitting measures. After retrofitting, the base shear increased by 15 times along the x-axis and three times along the y-axis. Additionally, displacement decreased by 92.96% in the x-axis and 81.55% in the y-axis, indicating enhanced structural stiffness and resistance to seismic forces. These results confirmed a substantial improvement in the building's resilience to local earthquake impacts.

1 Introduction

Situated within the Pacific Ring of Fire, the Philippine Archipelago exhibits extreme vulnerability to strong earthquakes [1]. In 2023, a 7.9-magnitude earthquake in Nueva Ecija, alongside a 6.8-magnitude earthquake in Davao Occidental, significantly disrupted standard operations and endangered lives in the respective areas. [2-3]. Locally, Renato Solidum Jr., DOST Undersecretary, and PHIVOLCS OIC also mentioned that a central fault system comprised of several fault lines passing through Metro Davao could generate earthquakes of at least 6.5 magnitude [4]. In other words, given its location, Davao City's environment faces persistent threats from earthquakes, requiring comprehensive analysis of infrastructures, pre-loading it with realistic lateral loads to ensure long-term integrity.

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To address these inherent vulnerabilities, the ASCE 41-17 standard provides performance-based guidelines for the seismic evaluation and retrofitting of existing structures. This standard utilizes a three-tiered methodology. Tier 1 screening phase employs checklists to identify potential seismic deficiencies. For structures requiring more localized analysis, the Tier 2 deficiency-based approach evaluates specific structural components, while the Tier 3 systematic procedure involves a comprehensive, advanced modeling of the entire building to address complex failure mechanisms. Furthermore, these evaluations integrate both linear and nonlinear analysis methods, allowing engineers to simulate the building's capacity through pushover or time-history simulations, ensuring it meets the performance objectives [5]. In evaluating seismic resilience, structural analysis typically follows a progressive approach from simplified linear models toward more complex nonlinear frameworks. This is done to capture realistic material behavior under stress. Linear static analysis represents the foundational approach, assuming a constant load-to-response ratio where the structure remains strictly within the elastic range; however, this is often insufficient for complex tremors. While linear dynamic analysis—such as modal response spectrum methods—advances this by incorporating time-dependent variables, it remains fundamentally limited to elastic behavior. Thus, to better understand actual capacity, engineers must transition to nonlinear static analysis, or pushover analysis, which evaluates lateral resistance by subjecting the model to increasing loads until failure occurs [6-7]. This analytical progression then culminates in Nonlinear Dynamic Analysis (NLDA), currently the most sophisticated tier in the engineering workflow. By integrating recorded ground motions directly with previously identified nonlinear parameters, NLDA accounts for real-time strength degradation and elastoplastic deformations. This iterative advancement across methods allows for a highly accurate simulation of plastic hinge formation and cyclic degradation, providing the granular detail necessary in applying the ASCE 41-17 standards to specific local contexts like the Trinidad Building [8-9].

While substantial research has explored the application of ASCE 41-17 for seismic evaluation, a notable gap still exists in studies focusing on using nonlinear dynamic analysis for retrofitting mid-rise buildings, particularly within Davao City, Philippines. Existing literature emphasizes high-rise structures, with insufficient attention to mid-rise buildings like four-story apartment complexes. Furthermore, there is a lack of consideration for local construction practices and material properties unique to the Philippines. Most studies rely on international case studies, which may not adequately reflect the conditions of buildings in Davao City, such as variations in concrete strength, indigenous construction techniques, and the prevalence of non-engineered structures. Additionally, research often prioritizes linear analysis methods for their simplicity and computational efficiency, neglecting the benefits of nonlinear dynamic analysis in capturing more accurate seismic responses. By addressing these gaps, this study aims to provide a more context-specific understanding of seismic vulnerability and retrofitting effectiveness in local mid-rise structures while also contributing to adapting ASCE 41-17 standards for Philippine construction practices.

The general objective of this study is to assess the seismic performance of the four-story apartment building located in Matina, Davao City, through a nonlinear dynamic analysis, adhering to the guidelines established by the National Structural Code of the Philippines (NSCP) 2015 and ASCE 41-17. Specifically, this research aims to (1) identify the structural performance of the building in terms of its displacement, structural irregularities, and demand-capacity ratio, (2) determine the seismic performance of the structure, and (3) propose retrofitting strategies to achieve Life Safety Structural Performance Level.

Furthermore, this study is significant as it evaluates the seismic performance and retrofitting needs of mid-rise buildings in Davao City using nonlinear dynamic analysis in line with ASCE 41-17 standards. Incorporating local construction practices and materials addresses existing research gaps and provides practical solutions tailored to the Philippine context. The findings will aid engineers and policymakers in improving seismic assessment methods, ultimately enhancing building safety and retrofitting strategies in earthquake-prone areas. Additionally, the study will serve as a reference for future applications of NLDA in similar settings.

The scope of this study involves the seismic evaluation and retrofitting recommendations of deficient structural elements for a four-story apartment building in Matina, Davao City, utilizing nonlinear dynamic analysis by ASCE 41-17 standards. ETABS software will be used to model the structure, perform seismic simulations, and assess its structural performance under various earthquake loading scenarios; the assumptions and capabilities of the ETABS software will constrain the analysis. This study will focus on the primary structural members, namely the beams and columns, while connection details and foundation components will not be analyzed. Furthermore, the study limits a design considering an earthquake 10% in 50 years of seismic hazard or a return period of 500 years.

2 Materials and methods

2.1 Conceptual Framework

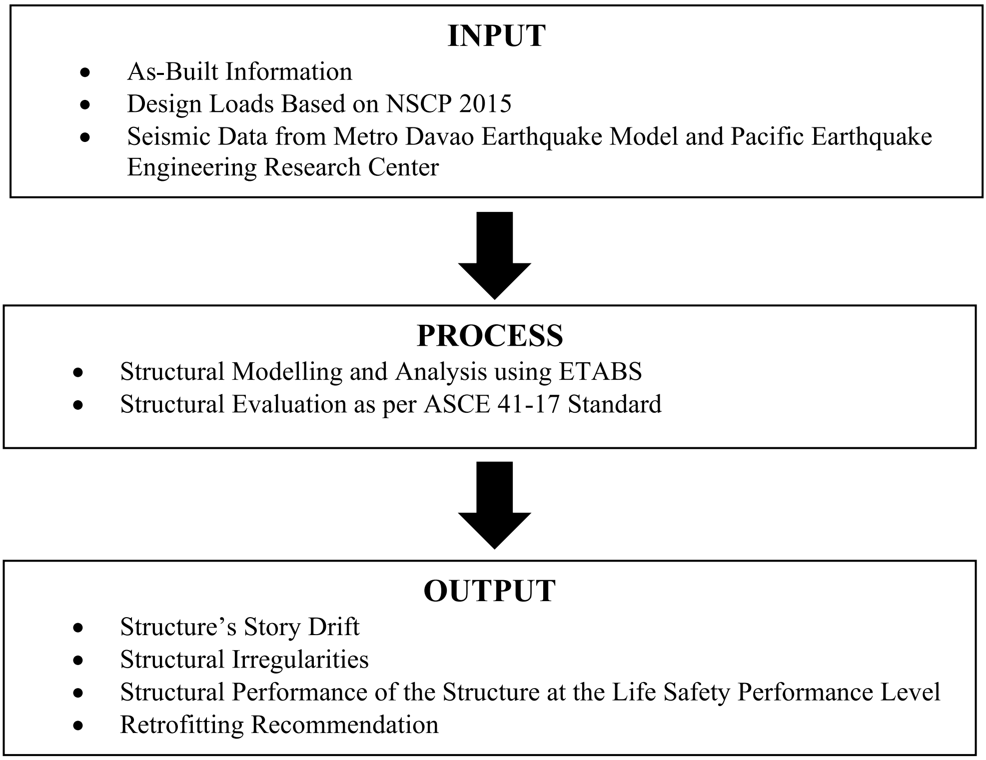

Fig. 1. Conceptual Framework

This study uses the Input-Process-Output (IPO) framework, as illustrated in Figure 1. In the input stage, essential elements were gathered, including As-Built Information, which encompassed the building's architectural and structural plans, loading parameters based on NSCP 2015, and seismic data from the Metro Davao Earthquake Model (MDEM) and the database of the Pacific Earthquake Engineering Research Center (PEER). Then, structural modeling and nonlinear dynamic analysis using ETABS were conducted. Additionally, structural evaluation per ASCE 41-17 was performed. Since needed, retrofitting strategies were also provided.

2.2 Data Collection

The initial step in conducting the seismic evaluation of the four-story building in Matina, Davao City, was gathering the as-built plans. The plans provided essential information about the building design, structural system, configurations, and material properties, including the steel grade for beams and columns used in the structure [5]. In addition, the spectral accelerations generated due to seismic movements were extracted from the 'MDEM,' a database that provides information from various earthquake sources to assess ground motion hazards [10]. The representative earthquake ground motion data for time history analysis is sourced from the PEER database, which had a large Excel file called the 'flat file,' providing data about the ground motion [11]. The data collection then followed ASCE 41-17 guidelines to create an accurate model of the building's behavior.

2.3 Basic Performance Objectives for Existing Buildings (BPOE)

Identifying seismic hazard level (SHL) and target building performance level for structural and non-structural components of the building is included in selecting performance objectives. According to the BPOE table presented in ASCE 41-17, which includes structural and non-structural performance levels, SHL, and their risk category, the target structural performance level of the structure at hand is Life Safety (LS). This behavior is defined as the condition of a structure after an earthquake where, despite sustaining damage to some of its parts, it still retains enough strength to prevent partial or complete collapse [5]. The risk categories are I and II. Also, the SHL Basic Safety Earthquake-1E (BSE-1E) is arrived at considering a 10 percent probability of exceedance in 50 years or 475 years return period with 5 percent damped.

2.4 Structural Modeling

After data collection, the building was modeled in 3D using ETABS, adhering to the NSCP 2015 guidelines for accurately applying vertical loads and earthquake forces. Furthermore, the modeling complied with ASCE 41 standards. The model represented the building's shape, materials, and load distribution. Key material properties, such as steel grade and yield strength, were included to ensure realistic behavior under forces. Nonlinear properties were also added to simulate inelastic behavior during earthquakes, helping to identify potential weaknesses and failure points in the structure.

2.5 Structural Analysis

The modal response spectrum method was used for seismic analysis. The seismic weight included 100% of the dead load and 20% of the unreduced design live load. For seismic drift calculations, 100% of the dead load plus 25% of the unreduced live load was applied. Roof live loads were excluded from the analysis, considering 2% of the story height as the limit for seismic drift [12].

The study applied both linear and nonlinear analysis procedures. Initially, linear methods were used to assess the global and local behavior of the structure. This was followed by nonlinear methods to evaluate the structure's performance, focusing on key indicators such as drift and the demand-capacity ratio. Detailed descriptions of these analysis methods are outlined below:

2.5.1. Linear Analysis

The forces applied to a structure were determined using equivalent static story forces in linear static analysis. The calculation of these forces followed clearly defined formulas specified in the building code. Conversely, the linear dynamic procedure relied on the principle of modal superposition. This analysis utilizes the response spectrum to determine the peak linear response [7].

2.5.2. Nonlinear Analysis

Pushover analysis estimates how a building deforms during an earthquake by applying increasing horizontal forces until failure. As parts of the structure yield, forces shift to other areas, simulating real seismic behavior. This process identifies weak points and checks the building's performance using base shear and displacement graphs. The analysis continues until the overall failure pattern is identified [8]. Conversely, Time history analysis evaluates a structure's seismic response, especially when nonlinear behavior is involved. It requires a representative earthquake time history and analyzes the structure's response step by step to changing loads over time. This approach helps assess how a building reacts to dynamic seismic forces [13].

2.6 Structural Evaluation

The acceptability of the component's performance was assessed based on the criteria stipulated in ASCE 41-17 section 7.5. Moreover, structural members are classified as either primary or secondary. Primary components resist seismic forces and undergo deformation, while secondary members are those that do not provide resistance to seismic forces. In this study, only primary members were considered, and each action was classified as deformation-controlled (ductile).

2.6.1. Linear Procedures

Deformation-controlled actions, QUD, were calculated using the equation in Section 7.5.2.1.1. The requirement for deformation-controlled linear procedures stated that actions in both primary and secondary components adhered to the equation outlined in Section 7.5.2.2.1 [5].

2.6.2. Nonlinear Procedures

Deformation-controlled actions of components that are specified in Nonlinear Procedures need to fulfill the requirements according to section 7.5.3.2.2, which states that at the target displacement levels, the calculated maximum deformation demands should not go beyond what the primary and secondary components are expected to handle in terms of deformation capacity. Additionally, the acceptance criteria concerning the deformation ratios of primary components of the target performance LS building were defined by the deformations associated with specific points on the curves presented in 7-7-Acceptance Criteria Illustration [5].

2.7 Retrofitting

The building was evaluated and analyzed for the Life Safety performance level acceptance criteria as per ASCE41-17 following the structural assessment. It was necessary for the building to have this assessment done to protect the occupants from serious harm in the event of a quake. If the analysis shows that the building does not conform to the above-mentioned standards, retrofitting measures are suggested based on the structure. Due to the structure's strengthened and economical design, various methodologies will be employed to determine the most effective retrofitting measure.

2.8 Post-Retrofit Simulation

Besides evaluating structure states with site-specific seismic hazards, simulations were conducted based on seismic magnitudes from the nearest faults in the region. The approach evaluated the design of the retrofit to withstand expected earthquake magnitudes.

2.9 Data Analysis

Percent change shows how much a value increases or decreases relative to its original amount, expressed as a percentage. It is widely used in finance, statistics, and other fields. A positive percent change means an increase, while a negative percent change indicates a decrease [13].

This is the formula for percentage change used in this study:

$$PC = \frac{(PR - PA)}{PA} \times 100 \quad (1)$$

This equation calculates the percentage change in the performance point (PP) of the as-built structure after retrofitting to determine the extent of improvement. Here, PC represents the percentage change, PR denotes the PP parameter of the retrofitted building, and PA refers to the PP parameter of the as-built structure. The key parameters considered are the base shear and displacement.

3 Results and discussion

3.1 Linear Procedures

After structural modeling in ETABS and application of loads and seismic parameters for structural evaluation, the following results are obtained for linear static and dynamic procedures:

3.1.1. Soft-story

The soft story occurs when "the lateral stiffness is below 70% of that in the floor above or under 80% of the average stiffness of the three floors above" [15]. Table 1 shows the soft-story check of the as-built structure, while Table 2 shows the soft-story check of the retrofitted structure.

Table 1. Soft story check (as-built)

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	8426.895	18353.256	0	0	0	0	None	None
4th	8546.489	23571.84	5898.8265	12847.2792	6741.516	14682.6048	None	None
3rd	8580.956	25169.31	5982.5423	16500.288	6789.3536	16770.0384	None	None
2nd	8066.714	33240.447	6006.6692	17618.517	6814.490667	17891.8416	None	None

Table 2. Soft story check (retrofitted)

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	120304.173	30335.749	0	0	0	0	None	None
4th	413507.127	339513	84212.9211	21235.0243	96243.3384	24268.5992	None	None
3rd	827013.212	669388.89	289454.9889	237659.1	213524.52	147939.4996	None	None
2nd	1751854.932	1081101.7	578909.2484	468572.223	362886.5365	277130.0371	None	None

3.1.2. Mass Irregularity

If one story exceeds 150 percent of the effective mass of an adjacent story, the structure is considered to exhibit mass irregularity [15]. Table 3 shows the mass irregularity of the as-built structure, while Table 4 shows the mass irregularity of the retrofitted structure.

Table 3. Mass irregularity check (as-built)

Story	Story Mass (kg)	150% Above and Below Story Mass (kg)	Mass Irregularity
Roof	52616.24	- 185102.205	None
4th	123401.47	- 185103.705	None
3rd	123402.47	185102.205 185103.705	None
2nd	123402.47	185103.705	None

Table 4. Mass irregularity (retrofitted)

Story	Story Mass (kg)	150% Above and Below Story Mass (kg)	Mass Irregularity
Roof	53802.56	- 192475.41	None
4th	128316.94	- 196854.93	None
3rd	131236.62	192475.41 200804.805	None
2nd	133869.87	196854.93	None

3.1.3. Torsional Irregularity

When the displacement at one end of a structure, considering unintended torsion, exceeds 1.2 times the average displacement of both ends, torsional irregularity is said to be present in the building [15]. Table 5 shows the torsional irregularities of the as-built structure for both X and Y axes. In contrast, Table 6 shows the torsional irregularities of the retrofitted structure for both axes.

Table 5. Torsional irregularities (as-built)

Story	Max. Displacement (mm)	Ave. Displacement (mm)	Ratio	Remarks	Story	Max. Displacement (mm)	Ave. Displacement (mm)	Ratio	Remarks
X+					Y+				
Roof	2.804	2.77	1.012	None	Roof	1.867	1.73	1.079	None
4th	5.837	5.741	1.017	None	4th	3.387	3.227	1.050	None
3rd	7.932	7.79	1.018	None	3rd	4.367	4.209	1.038	None
2nd	8.997	8.918	1.009	None	2nd	3.537	3.435	1.030	None
X-					Y-				
Roof	2.801	2.773	1.010	None	Roof	2.646	1.848	1.432	Irregular
4th	5.758	5.746	1.002	None	4th	4.807	3.444	1.396	Irregular
3rd	7.801	7.795	1.001	None	3rd	6.207	4.489	1.383	Irregular
2nd	8.925	8.918	1.001	None	2nd	4.754	3.517	1.352	Irregular

Table 6. Torsional irregularities (retrofitted)

Story	Max. Displacement (mm)	Ave. Displacement (mm)	Ratio	Remarks	Story	Max. Displacement (mm)	Ave. Displacement (mm)	Ratio	Remarks
X+					Y+				
Roof	2.842	2.565	1.108	None	Roof	7.12	7.017	1.015	None
4th	1.559	1.498	1.041	None	4th	2.947	2.731	1.079	None
3rd	0.846	0.808	1.047	None	3rd	1.553	1.511	1.028	None
2nd	0.411	0.392	1.048	None	2nd	0.65	0.635	1.024	None
X-					Y-				
Roof	3.175	2.696	1.178	None	Roof	8.213	7.095	1.158	None
4th	1.503	1.499	1.003	None	4th	3.123	2.719	1.149	None
3rd	0.812	0.808	1.005	None	3rd	1.751	1.54	1.137	None
2nd	0.395	0.392	1.008	None	2nd	0.678	0.647	1.048	None

3.1.4. Demand Capacity Ratio

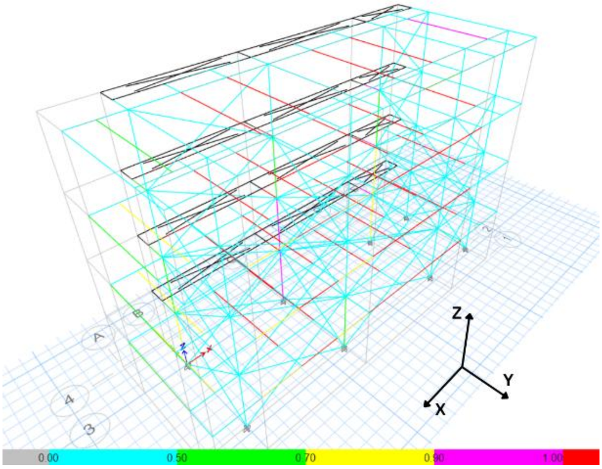

Fig. 2. Demand-Capacity Ratio (as-built)

Figure 2 shows the members' demand-capacity ratios (DCR), with different colors corresponding to varying DCR values. Values less than 1.00 represent adequate members, while values greater than 1.00 indicate inadequate members, implying the need for structural enhancement.

3.1.4.1 Retrofitting measures

Three retrofitting methods were tested for safe and economical design considerations. Method A incorporates the addition of bracings along the critical spans of the X and Y axes across multiple floors. Method B, conversely, incorporates built-up sections for the critical members based on the result shown in Figure 2. Lastly, Method C is the combination of method A and B strategies wherein the addition of bracings and built-up sections were utilized. Method C proved to be the safest and most feasible retrofitting option. The other methods still exhibited structural insufficiencies, with inadequate members and irregularities.

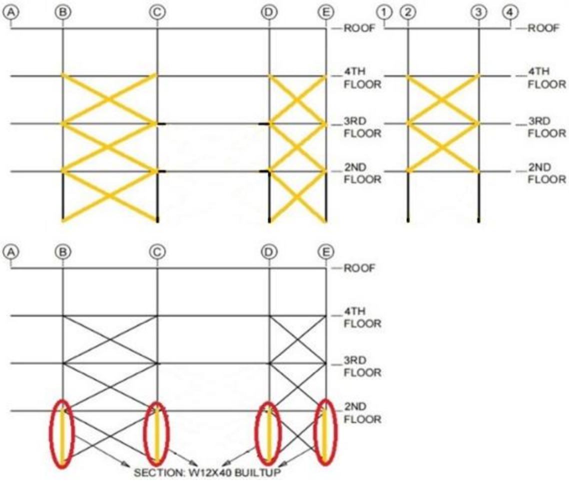

Fig. 3. Retrofitting measures

Figure 3 illustrates the added structural elements based on the weaknesses identified in the analysis of the as-built structure. Specifically, bracings were symmetrically placed along the x- and y-axes to enhance the structure's stiffness, address torsional irregularities, and reinforce failed primary members. Similarly, existing columns at the ground level were converted into built-up sections by adding plates to increase their capacity.

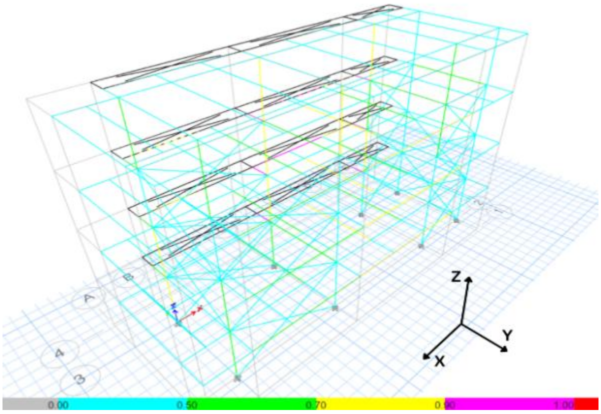

Fig. 4. Demand-Capacity Ratio of Method C (retrofitted)

3.1.5 Response Spectrum Analysis

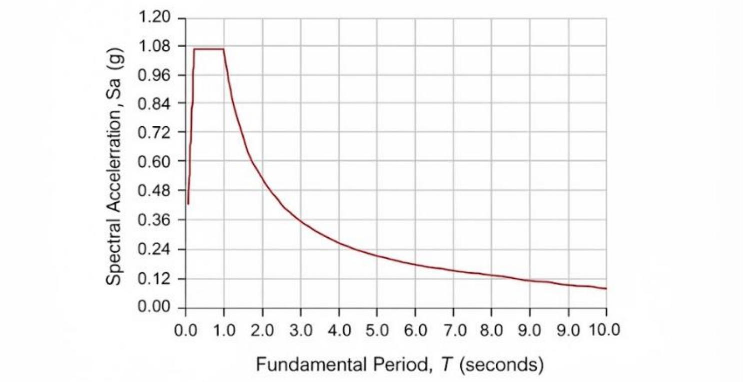

Fig. 5. Response Spectrum Curve

Table 7. Modal period (as-built and retrofitted)

Case	Mode	Period, seconds (as-built)	Period, seconds (retoriffited)
Modal	1	2.188	0.31
Modal	2	1.188	0.256
Modal	3	1.005	0.222
Modal	4	0.705	0.2
Modal	5	0.45	0.198
Modal	6	0.376	0.162
Modal	7	0.366	0.154
Modal	8	0.316	0.133
Modal	9	0.22	0.071
Modal	10	0.193	0.066
Modal	11	0.183	0.069
Modal	12	0.173	0.043

The fundamental period of the structure was 0.584 seconds, while the modal period of the as-built and retrofitted structures was 2.188 seconds and 0.31 seconds, respectively. The higher modal period than the fundamental period indicates that the as-built structure lacks sufficient stiffness. In contrast, the decrease in the modal period shows the effectiveness of the suggested retrofitting measures to improve structural stiffness. The site-specific seismic performance of the structure was evaluated through response spectrum analysis, and the site-specific seismic parameters used were the 0.2-second spectral acceleration (Ss) of 1.6g and the 1.0-second spectral acceleration (S1) of 0.9g. These values were obtained from MDEM, based on a 500-year return period.

3.2 Nonlinear Procedures

After completing the linear procedures, the structure underwent further analysis using nonlinear methods to capture its performance under seismic forces. The following results were obtained:

3.2.1. Structure's Performance Point

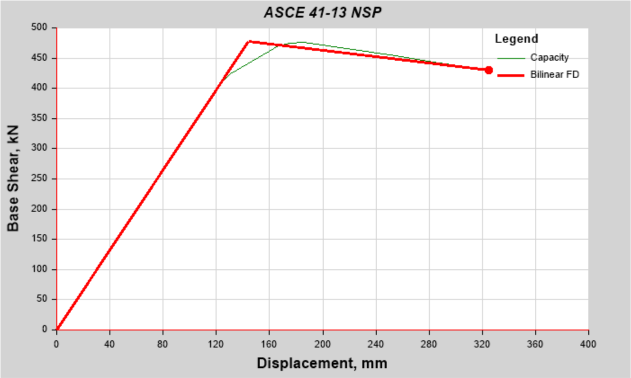

Fig. 6. Pushover x-axis (as-built)

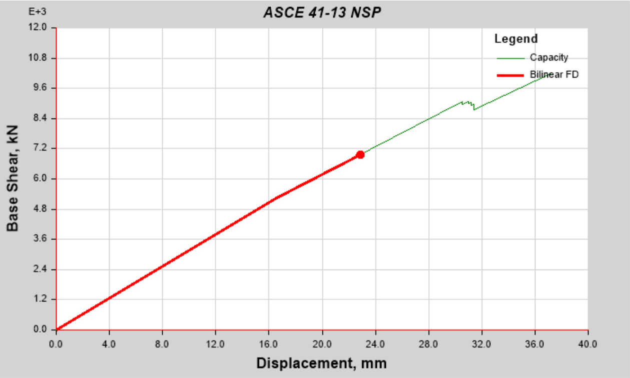

Fig. 7. Pushover x-axis (retrofitted)

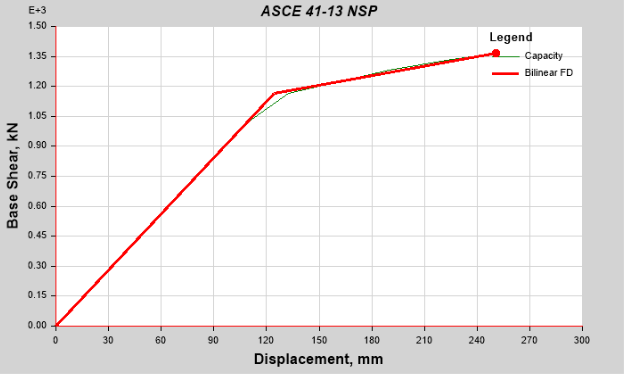

Fig. 8. Pushover y-axis (as-built)

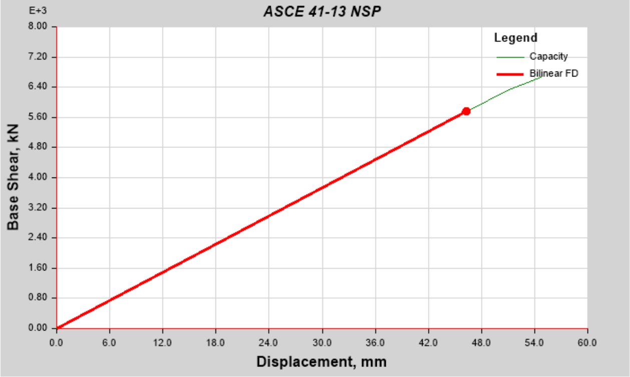

Fig. 9. Pushover y-axis (retrofitted)

3.2.1. Structure's Performance Point

In this method, three seismic events—Tottori, Darfield, and Borrego—were used, each exhibiting characteristics similar to the expected earthquakes at the site. Among them, Tottori produced the highest values.

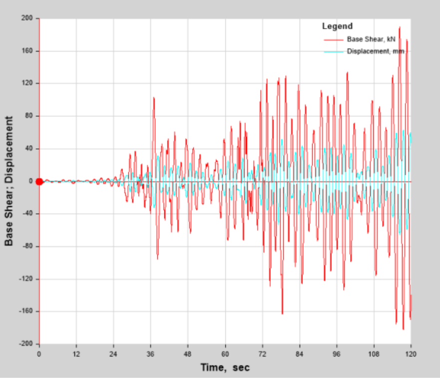

Fig. 10. X-axis time history plot (as-built)

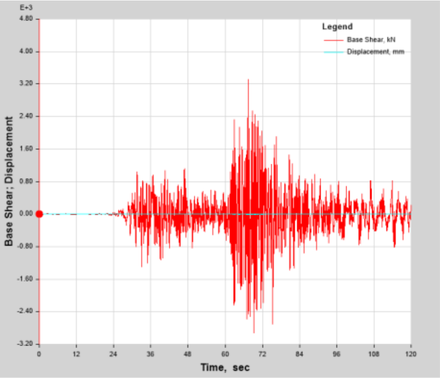

Fig. 11. X-axis time history plot (retrofitted)

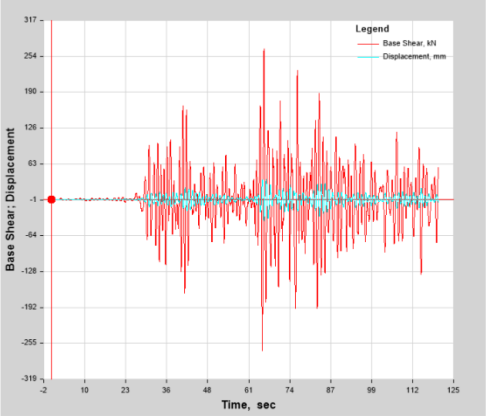

Fig. 12. Y-axis time history plot (as-built)

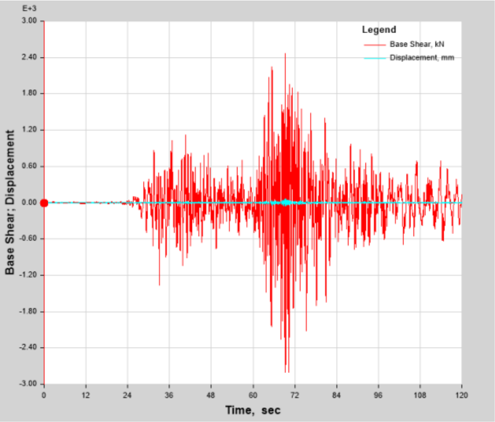

Fig. 13. Y-axis time history plot (retrofitted)

Figure 12 shows that the base shear of the as-built structure reached its peak value of 268.58 kN at 65.35 seconds, with a displacement of 60.415 mm on the x-axis. In contrast, Figure 13 illustrates that the retrofitted structure achieved a maximum base shear of 2,802.537 kN at 69.33 seconds, with a displacement of 38.541 mm.

3.3 Data Analysis

The structural performance of the building was also evaluated by analyzing the percentage change between the as-built and retrofitted states. Performance points from both conditions are computationally examined to quantify improvements and determine the effectiveness of retrofitting in enhancing the building's seismic resistance.

Table 8. Percentage change

X-axis		
PA (Base Shear, KN)	PR (Base Shear, KN)	Percentage Change
430.65	6974.05	1519.42%
Y-axis		
PA (Base Shear, KN)	PR (Base Shear, KN)	Percentage Change
1366.258	5754.324	321.17%
X-axis		
PA (Displacement, mm)	PR (Displacement, mm)	Percentage Change
325	22.882	-92.96%
Y-axis		
PA (Displacement, mm)	PR (Displacement, mm)	Percentage Change
250.799	46.282	-81.55%

Table 8 presents the change in terms of percentage in the performance point of the structure. A positive value in the change of base shear indicates a capacity increase of approximately 15 times along the X-axis and 3 times along the Y-axis. A negative percentage change in displacement indicates reduced displacement, improving structural stiffness, and enhanced resistance to seismic forces.

4 Conclusion and future works

The linear procedure results indicate that the recommended retrofitting measure will effectively resolve the irregularities of the as-built structure, address the failed members, and substantially increase stiffness, as evidenced by the decrease in the modal period from 2.188 seconds in the as-built structure to 0.31 seconds in the retrofitted structure. Moreover, the nonlinear procedure illustrations reveal the as-built structure's insufficient performance, which can be improved through retrofitting, as evidenced by the increased performance point, higher base shear, and reduced displacements. Additionally, the time history analysis results for the retrofitted structure conform with its performance point, indicating that the structure's actual seismic performance is adequate. Furthermore, it is supported by the positive percentage change in base shear and negative percentage change in displacement, indicating an overall structural performance improvement. Overall, the seismic evaluation under ASCE 41-17 and NSCP 2015 found the initial assessment insufficient, highlighting the need for retrofitting. Consequently, retrofitting measures were recommended to enhance the structure's capacity and achieve life safety levels, highlighting a better approach to attaining earthquake-resilient structures.

Considering the results established in this research, it is advisable to implement the proposed retrofitting measures to address the identified structural deficiencies and enhance the building's compliance with the Life Safety performance objective set forth by ASCE 41-17. Further exploration of alternative retrofitting schemes is also encouraged to assess their feasibility and effectiveness in improving the seismic resilience of similar mid-rise structures. Additional structural analysis software beyond ETABS is suggested to support model verification and provide a more comprehensive understanding of the building's nonlinear dynamic response. Lastly, future studies should consider expanding the scope of analysis beyond the primary members by examining the performance of structural connections and foundation elements, as these components contribute to the overall seismic behavior and integrity of the structure.

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