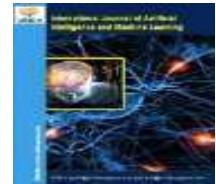


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Evaluation of Seismic Vulnerability and Rehabilitation of an Abandoned Two-Storey Building

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Structural Deterioration is the results of both gradual and unexpected damaging events. The modelling of structural deterioration has been shown to be great importance for decisions about maintenance and reconstruction of critical infrastructure. Ensuring structures undergo regular inspection and maintenance is crucial to avoid deterioration. The purpose of this study was to determine the effectiveness of the concrete jacketing method for fortifying a deteriorating two-storey reinforced concrete building that had been left unattended for over seven years. This building showed significant degradation, including reinforcement corrosion and concrete spalling. Also, it offers insights into the effectiveness of concrete jacketing for evaluating and retrofitting structures through a comprehensive analysis of critical structural components such as columns, beams, slabs, and footings. Additionally, pertinent documents including existing plans, geotechnical reports, and hazard assessments reports were gathered for a thorough assessment. The findings of the Rebound Hammer, Tensile, and Concrete Core Tests revealed inadequate material strength. The structural elements were also inspected by the researcher, revealing insufficient reinforcement and deviations from the approved plans. All test results were used in the building analysis using Non-Linear Static Analysis with Seismobuild Software. Based on the prepared retrofitting plans and cost estimates, the total retrofitting cost is Php1,122,607.50.

KEYWORDS: Non – Linear Static Analysis, Concrete jacketing Method, Rebound Hammer Test, Concrete Core Test, Retrofitting Techniques

1) Introduction

^[1] Earthquakes are any sudden shaking of the ground and their impact can be extensive, triggering other hazards and producing great damage to structures, loss of lives, and natural resources. ^[2] The construction industry is one of the most established and prominent worldwide, and ^[3] the reinforced concrete is a commonly used construction material in the Philippines. It has greater durability compared to wood. However, the lifespan and durability of concrete structures are key issues in civil engineering as these structures get older and face various environmental pressures. Swelling, spalling, galling, and seizure are also potential results of the deterioration. ^[4] Though engineers design concrete structures to last 50 years, they often begin to exhibit cracks and deterioration relatively early due to environmental factors such as chemical attacks and freeze-thaw cycles. ^[5] Moreover, abandoned buildings are usually left unattended without proper maintenance or protective finishes safeguarding the exposed materials. There is an alarming deterioration in the durability and structural integrity of these facilities over time. The compressive and tensile strengths of concrete and steel, respectively were reported to decline due to long term exposure. The exposure to harsh weather conditions, fluctuating temperatures, and aggressive soil agents accelerates the rate of degradation, weakening the concrete and threatening both steel reinforcements and building safety. ^[6] Retrofitting is a priority due to design deficiencies and additional loads on existing buildings. Techniques such as RC jacketing—focusing on surface preparation, reinforcement addition, and shear stirrup spacing—have been shown to significantly improve structural resilience. Various RC jacketing techniques have notably improved the axial capacity of RC columns under compressive force, thus enhancing their overall strength.

^[7] A review of methods for jacketing RC elements highlighted the advantages of utilizing extra reinforcement and Z bars as connector rods between old and new reinforcements in beams that have been slightly damaged or lost mechanical performance. These include effective surface preparation and dowel connectors/micro-concrete. ^[8] Several non-destructive tests, such as the rebound hammer test, are used before rehabilitation to assess the conditions of existing structures. These NDT's will ensure that structures

meet current standards and improve earthquake resistance. ^[9] The effectiveness of retrofitting techniques was evaluated using the finite element modeling and numerical simulations to examine how retrofitting affects structural behavior. These analyses explained the improvements in stiffness and reduced displacements. Also, determined the critical shear failing conditions.

^[10] In a study of 2-storey RC building prone to seismic hazards, SeismoBuild was utilized. As the results of using RC jackets, there was a significant increase in building stiffness as well as load carrying capabilities with target displacement decreasing. ^[11] SeismoBuild, a specialized Finite Element program, has a key role in this area. Engineers created it to assess and strengthen reinforced concrete structures against earthquakes. It supports many code-defined assessment methods, including Linear Static, Linear Dynamic, Nonlinear Static, and Nonlinear Dynamic Analyses.

Thus, this study aims to evaluate the seismic performance and retrofitting strategies for an abandoned two-storey reinforced concrete building, integrating insights from these studies and utilizing advanced analytical tools to enhance structural safety and longevity.

2) Methods and Methodology

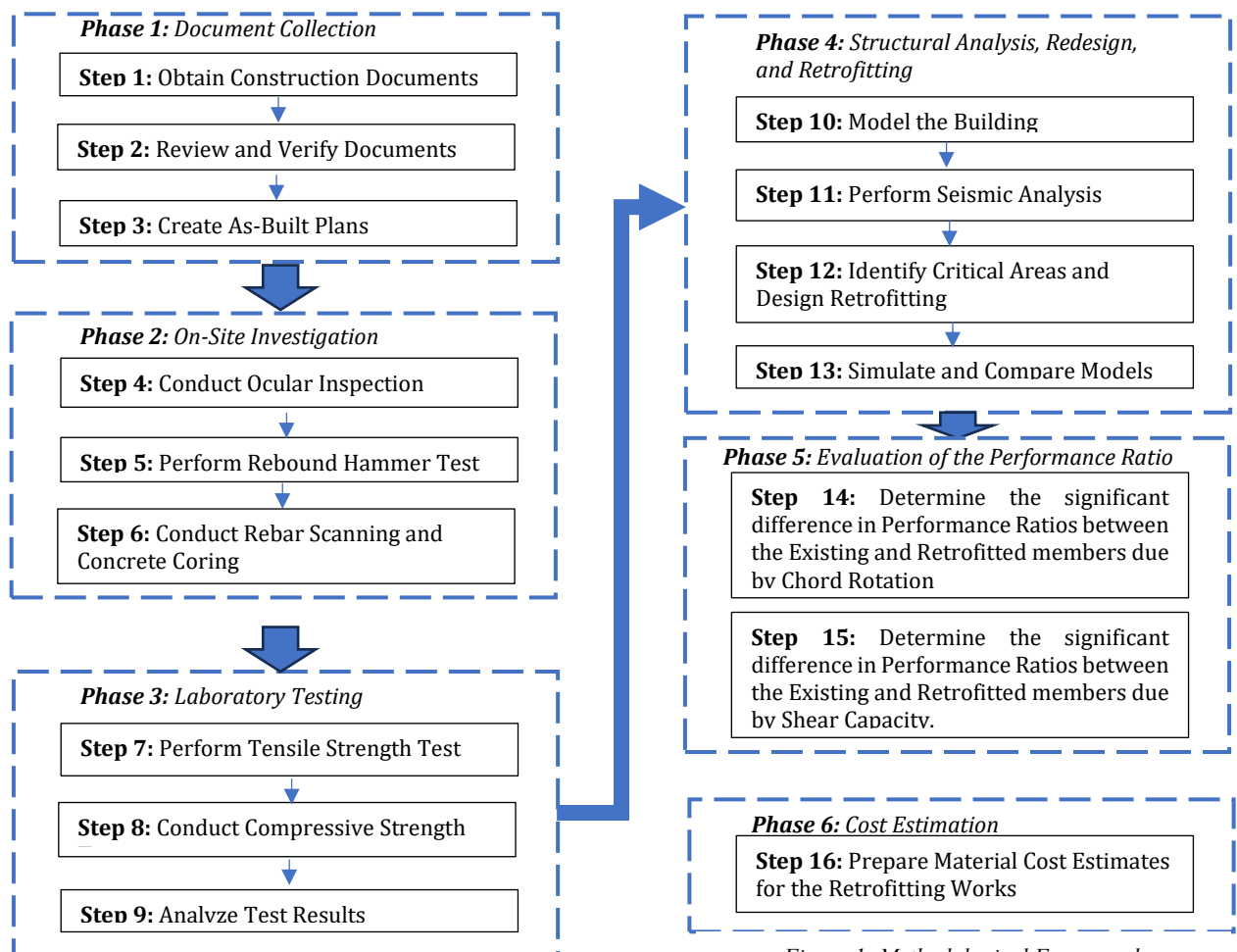


Figure 1: Methodological Framework

3] Results and Discussion

3.1 Existing Building

The building is a two-storey reinforced concrete structure with a footprint of 52.5 m². After being left unattended for almost seven years, the structure shows considerable deterioration, including visible corrosion of the reinforcement and localized concrete spalling. Additionally, some structural components lack adequate longitudinal and transverse reinforcement. Column dimensions vary between 150 mm x 400 mm and 300 mm x 300 mm, with consistent longitudinal and transverse reinforcement along their height, and stirrups spaced at 200 mm. The beams generally have dimensions of 200 mm x 400 mm, with differing

longitudinal reinforcement at the mid-span and ends. The slab's top and bottom reinforcement consist of 10 mm rebar, spaced at 200 mm, but the slab thickness varies from 89 mm to 150 mm, raising concerns about corrosion risk due to insufficient steel cover.

3.2 Tensile Strength and Yield Strength of Reinforcing Steel Bars

Based on the results, the tensile strength and yield strength of the extracted steel from the beams and columns are as follows: 521.67 MPa and 365.33 MPa for the beams, and 545 MPa and 379.67 MPa for the columns.

3.3 Concrete Compressive Strength

The correlation between concrete core compressive strength and rebound hammer readings are determined, the corrected compressive strength equation, derived using SPSS software, is given by:

$$Y = (0.001x^3) - (0.074x^2) + 2.528x - 0.605 \quad \text{Equation 1}$$

The compressive strength values for the structural members used in the model simulations are as follows: for columns on the ground floor, the range is 17.38 MPa to 19.11 MPa, while on the second floor it ranges from 14.15 MPa to 17.97 MPa. Beams on the second floor have a compressive strength ranging from 9.99 MPa to 18.26 MPa, while slabs on the second floor range from 9 MPa to 11 MPa. The compressive strength of the footings is between 9 MPa and 11 MPa, and the tie beams have a compressive strength ranging from 16 MPa to 16.28 MPa.

3.4 Compliance Criteria

Seismic compliance is ensured by implementing suitable seismic actions, analysis methods, and verification procedures intended to structural materials. This compliance is assessed using the full seismic action defined in UBC 1997, with reference to NSCP 2015 for the required return period. A distinction is made between deformation-controlled and force-controlled elements, as well as between primary and secondary seismic components. Secondary components are verified using the same seismic criteria but with less conservative capacity estimates. Mean value properties are applied for deformation-controlled elements, while lower-bound properties are used for force-controlled elements when comparing capacities to demands for safety verification.

3.5 Concrete Jacketing Method

The concrete jacketing method is the process of adding a new layer of reinforced concrete to existing structural elements, along with considerations for material selection, design specifications, and construction techniques. The following table outlines the material properties of the newly introduced structural elements intended for concrete jacketing.

Table 1: New Material Strength for Concrete and Steel	
Concrete Strength	28 MPa
Steel Strength (Longitudinal Reinforcement)	414 MPa
Steel Strength (Transverse Reinforcement)	276 MPa

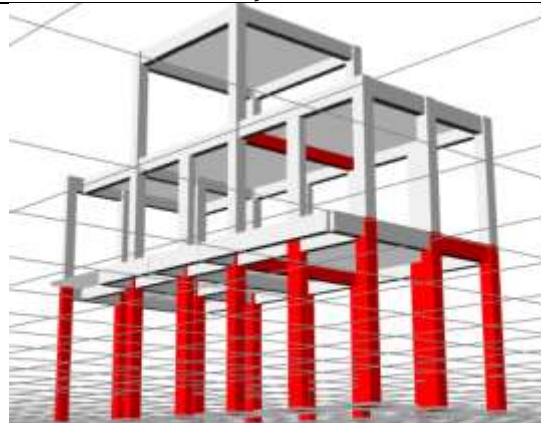


Figure 2: Failed Column Members caused by Chord Rotation (Deformation Capacity)

3.5.1 Column Concrete Jacketing

Column concrete jacketing is the process of reinforcing existing columns by adding extra layers of concrete to enhance their structural resilience and longevity. The assessment results reveal that all existing columns on the ground floor fail to meet the required flexural stress criteria, indicating a critical need for concrete jacketing to reinforce these columns, as presented in Figure 2.

However, upon analysis, it is determined that only six columns can feasibly undergo the concrete jacketing method, allowing for the encasement with new concrete and reinforcements, as presented in Figure 4. This strategic approach ensures that the structural integrity of the building is significantly enhanced, addressing the deficiencies identified in the columns while optimizing resources and minimizing disruptions to ongoing operations.

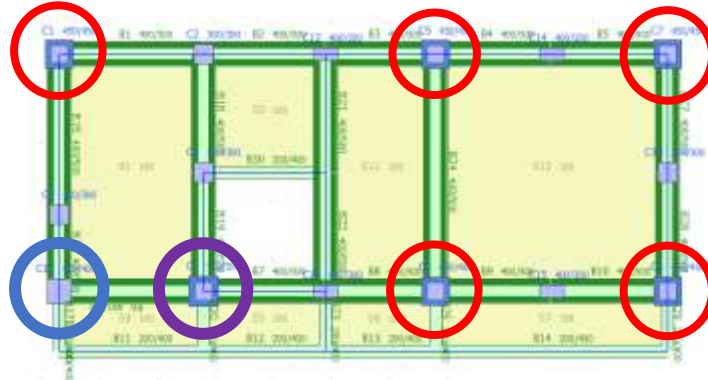


Figure 3: Second Floor Plan highlighting the columns subject to retrofit

The columns subject to retrofit, spanning from the footing to the second-floor level, are indicated with red circles in Figure 3. Each column, to be encased with new concrete measuring 450 mm x 450 mm, as shown in Figure 4, is reinforced with 8 pieces of 16 mm diameter bars, with lateral ties spaced at 100 mm on centers. Additionally, 12 pieces of 10 mm diameter dowels will be incorporated, spaced at 100 mm on center.

Meanwhile, the column marked with violet circles in Figure 4 will undergo concrete encasement, measuring 500 mm by 500 mm, as illustrated in Figure 5. The column will be reinforced with 8 pieces of 16 mm diameter bars, with lateral ties spaced 100 mm apart on center. Additionally, 12 pieces of 16 mm diameter dowels will be incorporated, spaced at 100 mm on center.

On the other hand, a column marked with a blue circle in Figure 4 will be added to the building at a joint where no column currently exists. This addition is intended to enhance the stability of the structure. It's important to note that the existing column in front, not included in the approved plans, does not significantly contribute to the structure's load-bearing capacity. The concrete column has dimensions of 400 mm x 400 mm and is reinforced with 12 pcs - 16mm diameter bars. Also, lateral ties are spaced at 100 mm on centers.

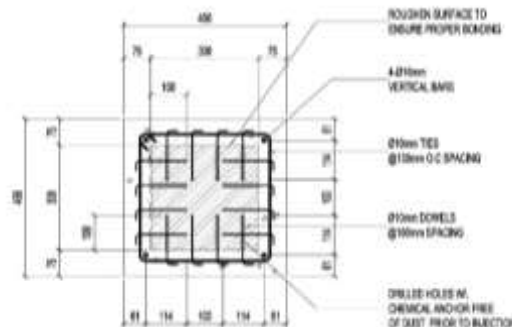


Figure 4: Column Cross Section detailing 450 mm encasement

3.5.1.1 Continuation of the jacket until the existing footing

Due to the considerable rise in stiffness of the new member compared to the existing one, and to prevent stiffness inconsistencies, the jackets must encompass the entire length of the member. Consequently, at ground level, column jackets should not terminate at the ground floor level; instead, they should be prolonged until reaching the upper surface of the footing, as shown in Figure 6. In numerous instances, this

may necessitate extensive excavations, particularly in buildings where multiple weak columns are closely situated at ground level.

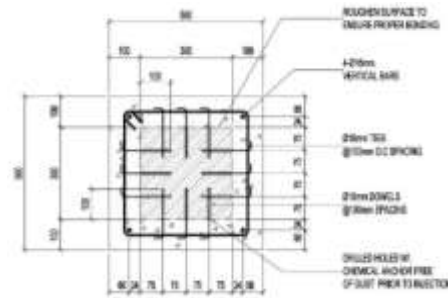


Figure 5: Column Cross Section detailing 500mm encasement

The columns subject to retrofit, spanning from the second floor to the roof deck, are circled in red and extend from the ground floor, except for C6, as presented in Figure 7. These columns will be encased in 450 mm x 450 mm concrete and reinforced with 8 pieces of 16 mm diameter bars, with lateral ties at 100 mm spacing. The blue-circled column represents a new column extending from the ground floor. Columns from the roof deck to the roof beam, not yet constructed, are included in the analysis to integrate their loads into the design. These columns will measure 300 mm x 300 mm with the same reinforcement and tie spacing.

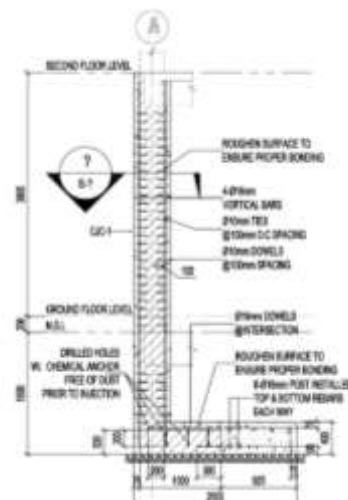


Figure 6: Column - Footing Connection

3.5.1.2 Beam – Column Connections

Beam-column joints require special attention, often strengthened with jackets. To splice longitudinal rebars between floors, small holes are made in the concrete slab using a demolition hammer or electric drill. Adjacent beams also need vertical holes, carefully drilled to avoid damage. Precise placement of 4-5 stirrups at beam level is essential, requiring multiple holes to fit each stirrup. This process ensures proper reinforcement while minimizing impact on the structure.

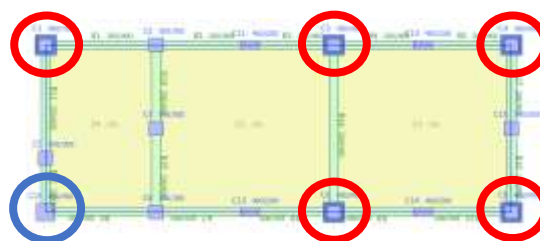


Figure 7: Roof Deck Floor Plan Highlighting Columns subject to retrofit

3.5.2 Beam Concrete Jacketing

The transverse reinforcement is crucial for shear strength in reinforced concrete members. Several beams, particularly on the second floor and roof deck level, exhibited failures based on the assessment, as presented on Figure 8. Remedial measures like adding stirrups or concrete jacketing are recommended. This involves removing deteriorated concrete and adding reinforcements. On the roof deck, corrosion levels will determine whether stirrups need to be added or existing reinforcements replaced. After applying the concrete jacket method, no beams failed in terms of shear stress, demonstrating satisfactory performance under applied loads.

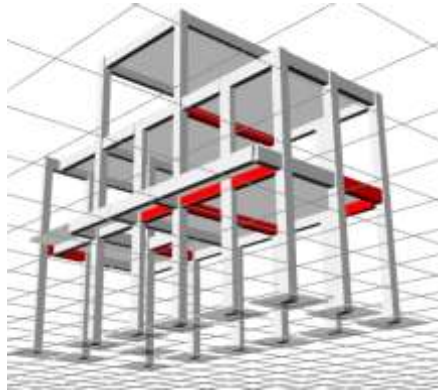


Figure 8: Failed Beam Member caused by Shear Capacity (Force Controlled)

Additional beams (200 x 400 mm) are needed on the second floor to support overhanging beams and slabs, reinforced with 6 pieces of 16 mm diameter bars, placed top and bottom. On the other hand, several beams, need concrete jacketing due to insufficient transverse reinforcement. Concrete jacketing, a structural reinforcement technique, enhances load-bearing capacity and durability by encasing the original beam in a new concrete layer. The beams will be reinforced with a three-sided jacket, as shown in Figure 9, including 4 longitudinal 16 mm diameter bars and U-shaped 10 mm stirrups spaced at 100 mm intervals. The jacketing includes 15 dowels (10 mm diameter) spaced 100 mm apart.

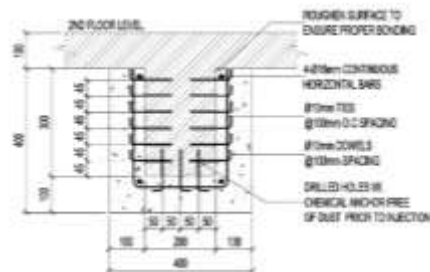


Figure 9: Beam Cross Section detailing three - sided encasement

The roof deck beams have failed due to shear stress and are exposed to environmental elements, leading to potential corrosion. Remedial measures include adding stirrups or replacing reinforcements. If corrosion is minimal, stirrups spaced at 100 mm may suffice.

If corrosion is extensive, reinforcement replacement is necessary. The roof beams, not yet constructed, are included in the analysis to account for the loads they will bear. These beams are planned to measure 200 mm x 400 mm, with stirrups spaced at 150 mm centers, ensuring proper integration into the overall design for structural integrity.

4.5.3 Concrete Slab Applying a concrete overlay to the entire slab surface is an efficient way to ensure uniform thickness and strengthen the structure. The retrofitting will adjust the slab thickness to a consistent 150 mm, enhancing overall performance and durability.

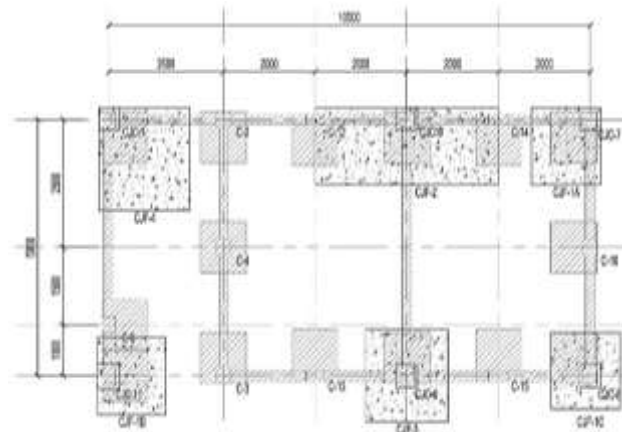


Figure 10: Foundation Plan highlighting Footings subject to retrofit

3.5.4 Foundation Design

The analysis indicates that the maximum soil pressure on the existing footing reaches 700 kPa, surpassing the allowable limit, as illustrated in Figure 11-a. After retrofitting, the footing's soil pressure distribution meets the design bearing capacity of 150 kPa, with a maximum soil pressure of 135 kPa, as shown in Figure 11-b. This represents an 80.71% improvement in the retrofitted footing's soil pressure distribution. The foundation plan is presented in Figure 10

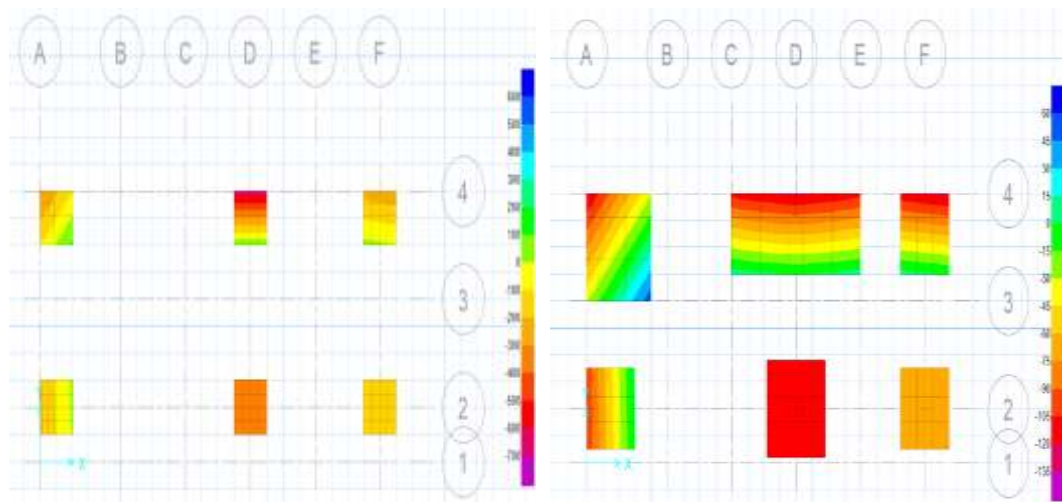
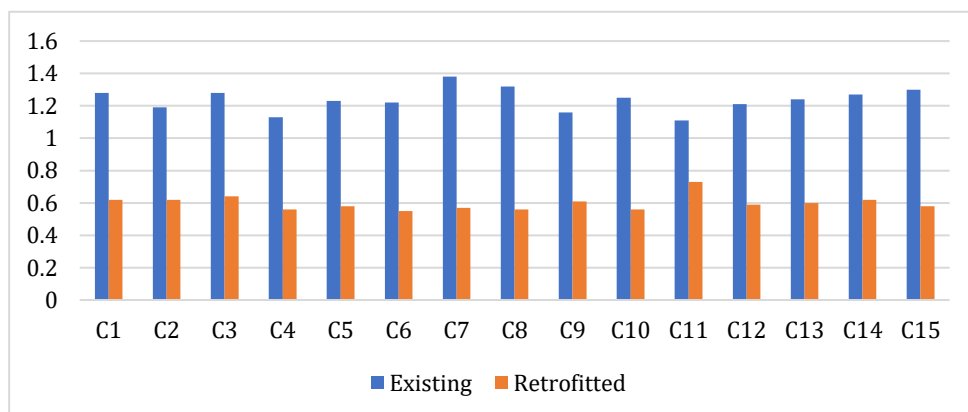


Figure 11: Soil Pressure Distribution of (a) Existing footings; (b) Retrofitted Footings

3.6 Performance Ratio of Compression Members caused by Chord Rotation (Deformation Controlled)



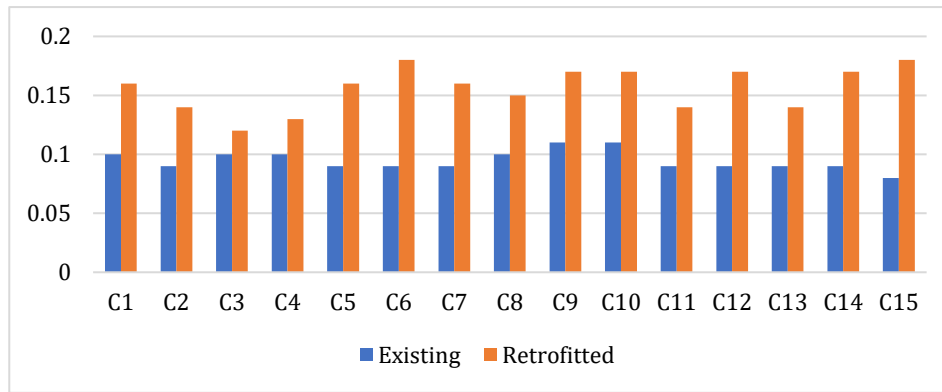
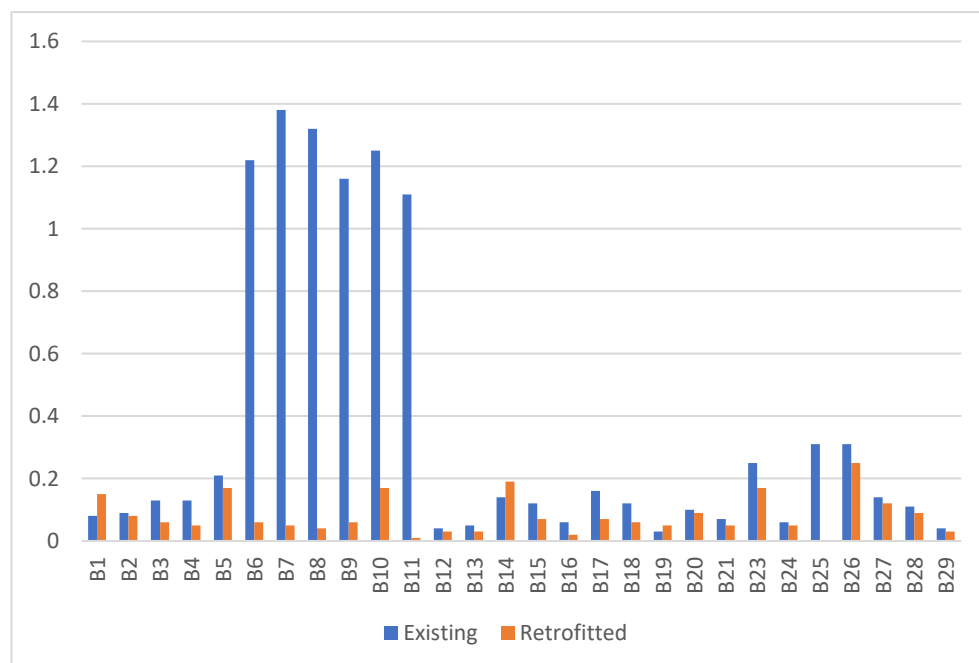


Figure 12: Average Critical Performance Ratio on Chord Rotation (Deformation Controlled of RC Columns at the (a) Ground Floor Level; (b) Second Floor

The analysis of the Ground Floor columns' performance capacity ratio in terms of Chord Rotation, as presented in Figure 12 – a, shows a value of 1.2387, exceeding the allowable limit of 1.0, indicating non-compliance. A Paired Samples Correlation between the Existing and Retrofitted Building shows a significant difference, with a p-value of less than 0.001. After retrofitting, the capacity ratio decreases to 0.5987, reflecting a 51.67% improvement. The concrete jacket method significantly enhanced the building's structural capacity. For the Second-Floor columns, as presented in Figure 12 – b, the performance capacity ratio is 0.0954, well within the allowable limit. Retrofitting has maintained this compliance, with significant improvements noted between existing and retrofitted conditions, also with a p-value less than 0.001.

3.7 Performance Ratio of Flexural Members caused by Chord Rotation (Deformation Controlled)

The performance capacity ratio analysis for the existing beams at the Second Floor and Roof Deck, as presented in Figure 13, shows they are within the allowable limit of 1.0, with values of 0.3564 and 0.0896, respectively, indicating adequacy. After retrofitting, the ratios improved to 0.083 and 0.1091, still within acceptable limits. Paired Samples Correlation revealed a significant difference in performance capacity at the Ground Floor but showed no significant difference at the Second Floor. Longitudinal reinforcements remain sufficient, but inspections and approved plans highlighted insufficient shear reinforcements, requiring additional measures to ensure the beams' structural integrity. Shear capacity is addressed in the next section.



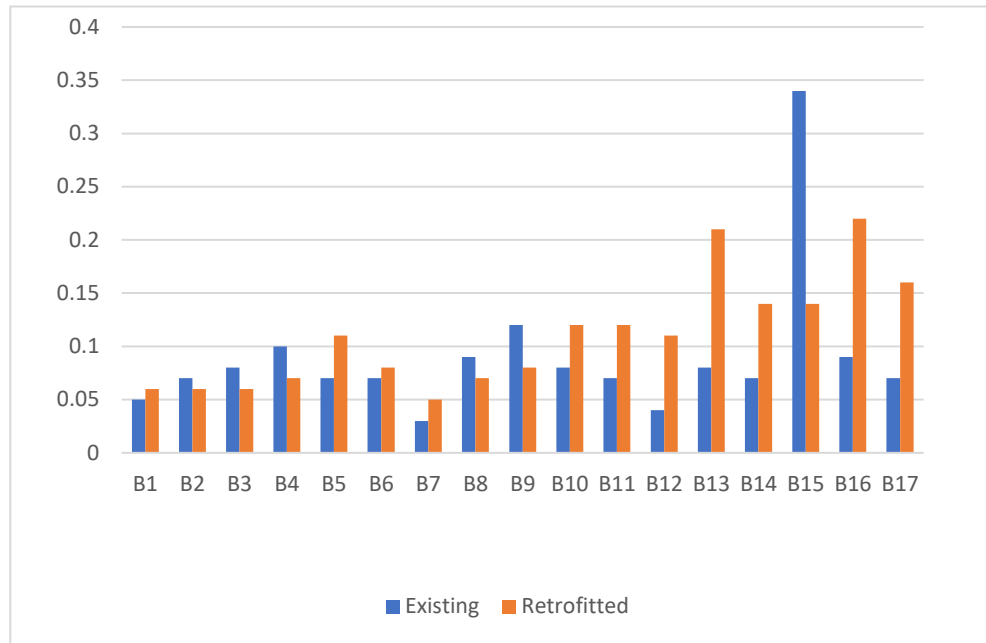
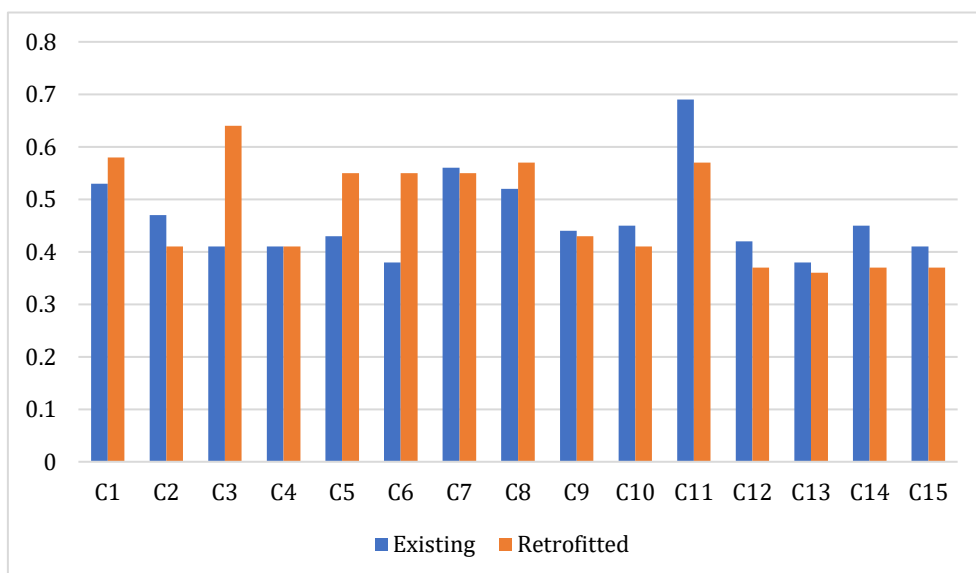


Figure 13: Average Critical Performance Ratio on Chord Rotation (Deformation Controlled) of RC Beams at the (a) Second Floor Level; (b) Roof Deck Level

4.8 Performance Ratio of Compression Members caused by Shear Capacity (Force Controlled)

The performance capacity ratio analysis for both the ground and second-floor columns, as shown in Figures 14-a and 14-b, demonstrates adequacy in shear capacity. The ground floor columns have a shear capacity ratio of 0.4628, while the second-floor columns exhibit a ratio of 0.4163, both within the allowable limit of 1.0. After retrofitting, both columns remain compliant. However, paired samples correlation for the ground floor columns shows no significant improvement in performance, with a p-value of 0.344, whereas the second-floor columns reveal a significant performance enhancement, with a p-value of less than 0.001.



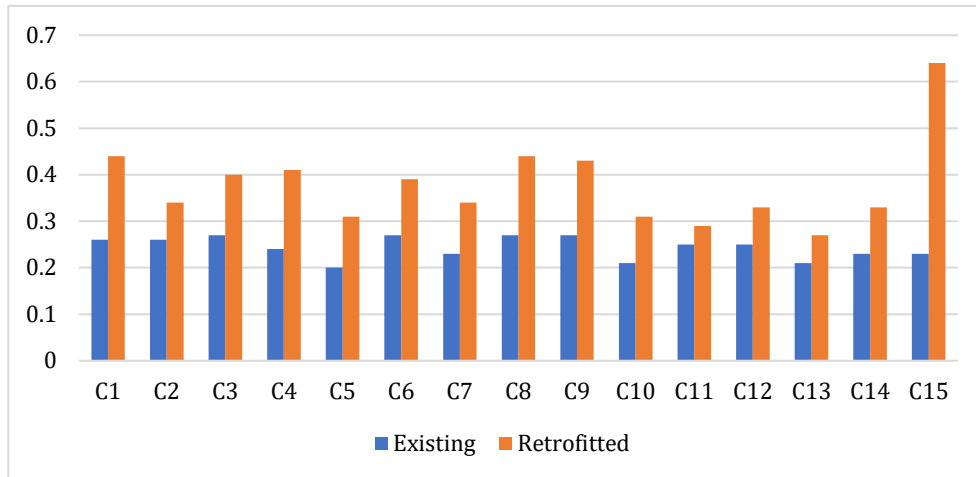
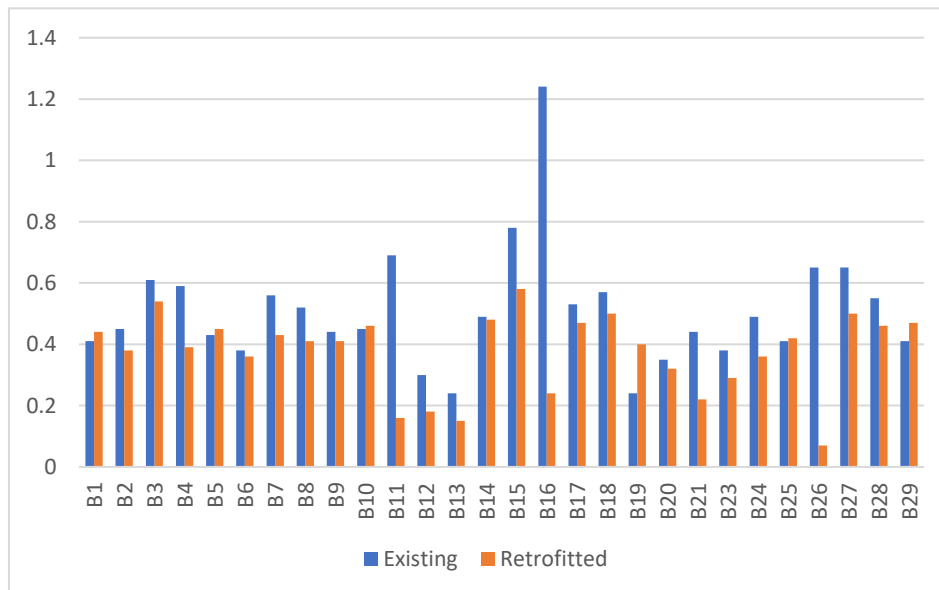


Figure 14: Average Critical Performance Ratio on Shear Capacity (Force Controlled) of RC Columns at the (a) Ground Floor Level; (b) Second Floor Level

3.9 Performance Ratio of Flexural Members caused by Shear Capacity (Force Controlled)

The performance capacity ratio analysis for the existing second-floor and roof deck beams, as shown in Figures 15-a and 15-b, indicates adequacy in shear capacity. The second-floor beams have a shear capacity ratio of 0.4965, while the roof deck beams exhibit a ratio of 0.1094, both well within the allowable limit of 1.0. After retrofitting, both elements remain compliant. Paired samples correlation reveals a significant improvement in performance for both beams and columns, with a p-value of less than 0.001.



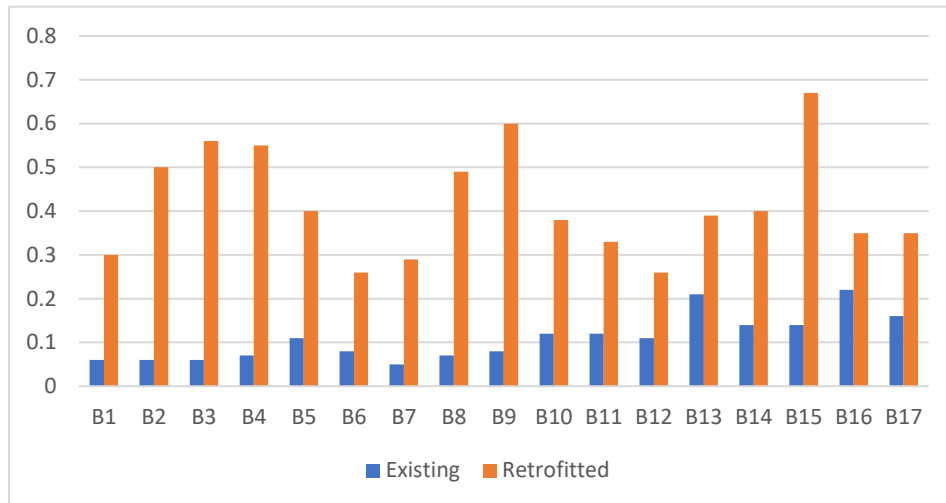


Figure 15: Average Critical Performance Ratio on Shear Capacity (Force Controlled) of RC Beams at the (a) Second Floor Level; (b) Roof Deck Level

4. Cost Estimates

The retrofitting works encompass the footing, columns, beams, and the second-floor suspended slab, with costs amounting to PhP 379,929.38 for the footing, PhP 302,938.13 for the columns, PhP 319,836.56 for the beams, and PhP 112,607.50 for the second-floor suspended slab. The total cost, including general requirements, amounts to PhP 1,122,607.50.

On the other hand, the costs for the Architectural Works, Sanitary and Plumbing Works, Waterproofing Works, Electrical Works, Ceiling Works, and Painting Works amount to PhP627,564.01, PhP153,954.94, PhP13,440.00, PhP131,449.50, PhP99,250.59, and PhP96,107.81, respectively. This brings the total to PhP1,121,766.84.

5] Conclusion

1. The compressive strength of concrete, predicted by the equation derived through SPSS, indicates a strong correlation between core compressive strength and rebound hammer readings, making it a valid tool for estimating concrete strength.
2. The concrete jacketing applied to columns, beams, and footings effectively increases their strength and capacity, enhancing the overall structural performance.
3. Retrofitting the footings resulted in an 80.71% improvement in soil pressure distribution. The analysis focused on six (6) footings, recommending that these footings bear the majority of the building's loads, while other footings were excluded from consideration due to their insufficiency.
4. After retrofitting, the columns, spanning from the footing to the second floor, experienced a significant strength improvement, with the capacity ratio decreasing to 0.5987, representing a 51.67% enhancement.
5. There is a notable improvement in the chord capacity of retrofitted columns and beams at both the ground and second-floor levels, indicating a substantial increase in structural performance.
6. Retrofitted columns and beams spanning from the second floor to the roof deck showed a significant increase in shear capacity, further improving the building's resistance to loads.
7. The reinforcement in beams remains insufficient, particularly with inadequate stirrup spacing. The application of concrete jackets and additional stirrups has been used to address this issue.
8. The performance of new structural members, such as columns and beams from the roof deck to the roof beam, could not be analyzed for improvement as these members were not present in the existing structure.
9. Overall, the retrofitting measures, including concrete jacketing and the introduction of new members, have led to significant structural enhancements, improving both the strength and compliance of the building with the existing codes and standards.
10. The total cost for the Retrofitting works, amounting to PhP 1,122,607.50, covers the General Works, Footing Works, Beam Works, Column Works, and Second Floor Suspended Slab.

8] Data Availability: No new data were created or analyzed in this study. Data sharing is not applicable to this article.

9] **Conflict of interest:** The author declares that there is **no conflict of interest"**

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