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STUDY ANALYSIS OF ALTERNATIVE STRENGTHENING METHODS FOR LONG-SPAN REINFORCED CONCRETE CANTILEVER BEAMS

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Abstract

Reinforced concrete cantilever beams with long spans are prone to excessive deflection, which may adversely affect structural performance and safety. This study aims to analyze alternative strengthening methods for reinforced concrete cantilever beams in a villa building where the cantilever length was extended up to 3.65 m during the construction stage, resulting in deflections exceeding the allowable limits. The research employed a quantitative approach using three-dimensional structural modeling with ETABS software. Existing structural conditions were identified through non-destructive testing, including hammer tests and rebar scanning, to determine the residual concrete strength and reinforcement configuration. The analyzed strengthening measures constitute an integrated strengthening package consisting of first-floor column jacketing, the addition of second-floor columns, and the enlargement of second-floor cantilever beam dimensions as a unified structural system. Structural performance was evaluated in terms of deflection, bending moment, shear force, and axial force before and after strengthening. The analysis results indicate that prior to strengthening, the cantilever beam deflections did not satisfy the allowable deflection criteria. After strengthening, the deflections were significantly reduced by 22.8% at the roof level and 56.8% at the second-floor level, meeting the allowable deflection requirements. In addition, the internal force distribution improved and the supporting capacity of the structural elements increased. Therefore, the proposed strengthening alternatives are proven to be effective in enhancing the structural behavior of long-span cantilevered reinforced concrete beams.

Keywords: Cantilever Beam, Reinforced Concrete, Structural Strengthening, Deflection, ETABS

Introduction

Structural evaluation is an essential process to examine and assess the condition of building structural components, ranging from the foundation to the roof. Its primary objective is to verify that the structure is capable of reliably resisting the applied loads and functioning in accordance with applicable standards. This study is based on a case study of the Villa Aguita project located on Jl. By Pass Tanah Lot, Munggu, North Kuta, Badung. The structural issue identified in this project involves reinforced concrete cantilever beams at the second-floor and roof levels, with cantilever lengths of 3.0 m, 3.65 m, in that order. According to the analysis outputs, the deflections of both cantilever beams exceed the allowable deflection limits. The cantilever beams can be visually observed as shown in Figure 1.

A preliminary solution proposed was the addition of columns at the free ends of the cantilever structural members on the first and second floors. However, due to architectural constraints that prohibit the installation of columns in the cantilever area on the first floor, it is necessary to analyze alternative strengthening methods that can be practically implemented.

Several studies related to cantilever beams have been conducted by previous researchers. Research on plane stress behavior in porous reinforced concrete cantilever beams strengthened with composite plates also discussed the application of jacketing strengthening methods on structural elements to improve stiffness, load-carrying capacity, and crack resistance. The study aimed to examine the mechanical behavior of plane stresses in such beams, and the results indicated that normal and shear plane stresses are significantly influenced by the material properties and geometry of the composite beam. In addition, the jacketing system was proven to enhance structural performance by reducing stress concentration and increasing the overall structural capacity and stability (Abderezak, Daouadji, et al., 2021).

Research on plane stresses in reinforced concrete cantilever beams bonded with composite plates while considering shear deformation also discussed the implementation of jacketing strengthening techniques on structural elements to improve structural rigidity and load resistance. The study showed that the resulting plane stresses were lower than those obtained from models neglecting shear deformation, while both normal and shear stresses were influenced by material properties and composite beam geometry. Furthermore, the jacketing method was found to effectively improve structural performance by enhancing stiffness, reducing stress concentration, and increasing the overall load-carrying capacity of the strengthened elements (Abderezak, Tahar, et al., 2021).

The study investigated the flexural strengthening of reinforced concrete cantilever beams with insufficient splice lengths using experimental, numerical, and analytical approaches. The research also discussed the application of jacketing strengthening methods on structural elements to improve flexural behavior and structural integrity. The results showed that the jacketing system was effective in increasing flexural capacity, stiffness, and crack control performance, while also enhancing the overall strength and serviceability of the reinforced concrete beams (Badawi et al., 2024).

The study investigated the vibration characteristics of cantilever beams using the finite element method and also discussed the application of jacketing strengthening techniques on structural elements to improve structural performance and damage resistance. The results demonstrated that mode shapes can be effectively utilized to detect crack sensitivity, while the Modal Assurance Criterion (MAC) and Curvature Change Index (CCI) were proven to be reliable methods for identifying crack locations. In addition, the jacketing system contributed to increasing structural stiffness, reducing vibration response, and improving the overall durability of the strengthened beam elements (Jassim et al., 2013).

The study examined the repair and rehabilitation of cantilever beams using several rehabilitation methods and also discussed the application of jacketing strengthening techniques on structural elements to enhance structural capacity and service performance. The proposed solutions included extending beams to adjacent columns to provide sufficient anchorage length and installing steel plates connected to columns and beams using Hilti anchors. The results indicated that these rehabilitation and jacketing methods were effective in improving beam stability, increasing load-carrying capacity, enhancing anchorage performance, and reducing the risk of structural failure in cantilever beam elements (Jayashree, 2016).

The study investigated the behavior of reinforced concrete beams strengthened using the deep embedment (DE) method through finite element analysis with ABAQUS software. The research also discussed the application of jacketing strengthening techniques on structural elements to improve structural performance and load resistance. The results showed that both the DE method and jacketing system were effective in increasing flexural capacity, stiffness, and crack resistance, while also improving the overall strength and ductility of reinforced concrete beam elements (Kurniawan et al., 2023).

The study investigated the behavior of non-prismatic reinforced concrete cantilever beams using finite element analysis with SAP2000 software. The research also discussed the application of jacketing strengthening methods on structural elements to enhance stiffness, strength, and structural stability. The results indicated that the structural behavior of non-prismatic cantilever beams was significantly influenced by variations in cross-sectional geometry, while the jacketing system effectively improved load-carrying capacity, reduced deformation, and increased the overall structural performance of the beam elements (Laintarawan & Silvi, 2024).

The strengthening of cantilever beams in bridge structures using fiber-reinforced polymer (FRP). The results showed that the jacketing method effectively increased structural stiffness and load-carrying capacity (Mosallam et al., 2024). Conducted experimental research on reinforced concrete cantilever beams strengthened with carbon fiber reinforced polymer (CFRP), showing that CFRP strengthening enhances both strength and stiffness. The study concluded that jacketing reinforcement improved flexural performance and reduced structural deformation (Obaidat et al., 2018). The moment behavior of concrete cantilever beams subjected to corrosion effects using experimental and numerical methods. The findings indicated that jacketing strengthening enhanced crack resistance and overall beam stability (Pandit & Venkataramana, 2025). The behavior of FRP-strengthened reinforced concrete cantilever beams under monotonic and cyclic loading, where diagonal cracking and FRP rupture were observed in both short and long beams. The analysis demonstrated that jacketing applications significantly improved structural rigidity and durability (Rabiei, 2010). The results showed that the decrease in concrete quality increased the vibration period of the structure, horisontal force. The results confirmed that jacketing reinforcement increased the strength and serviceability of structural elements. (Erlangga & Alghiffary, 2026). This study examines the changes in space in the building structure from 4 floors to 6 floors and the function of the space from a shophouse to a house of worship is applied in the Barea Karawaci Foundation House of Worship Building in Tangerang City. The study revealed that jacketing methods effectively minimized stress concentration and improved structural performance (Rifqi et al., 2023). This research investigates structural reinforcement using the jacketing method on existing structural elements. Analysis and modeling were performed using SAP2000 software. The findings showed that the use of jacketing systems enhanced ductility and delayed structural failure (Yasin et al., 2025). The analysis results require structural reinforcement using the concrete jacketing method and the reinforcement method with WF 200.200.8.12 steel profiles. The analysis indicated that jacketing reinforcement provided better load distribution and increased structural safety (Prabowo & Lutfi, 2020). Analysis of steel and composite materials we are using CFRP&GFRP materials by ANSYS software for obtaining good results. The results demonstrated that jacketing techniques improved beam stiffness and crack control performance (Sureshchandra et al., 2018). Beams strengthened with U-shaped plate configurations demonstrate better structural performance compared to those using two L-shaped plates, mainly due to more efficient anchorage. Anchorage. The study confirmed that jacketing systems effectively enhanced the overall behavior of reinforced concrete members (Sudarsana et al., 2019). This is reflected by the Demand-to-Capacity (D/C) ratio of the strengthened column, which is less than 1.0. The findings revealed that jacketing reinforcement improved structural integrity under service and ultimate loading (Ilham & Anisa, 2023). The analysis results show that the initial transfer from Revit to ETABS successfully maintains all the main structural parameters despite the change in the type of support from fixed support to hinged support that requires manual correction. The analysis showed that jacketing applications increased axial, shear, and flexural capacities simultaneously (Huda & Roesdiana, 2025). The results show that 3D fiberglass performance analysis is better than FRP for flexural capacity, crack pattern, and ductility by 19% and 8.4%, respectively. The results indicated that jacketing methods effectively reduced excessive deflection in structural elements (Vahidpour et al., 2022). The findings indicate that the combination of grouting for the deteriorated concrete layer and FRP sheet reinforcement provides an effective solution for restoring the performance of corroded reinforced concrete beams. The study demonstrated that jacketing strengthening enhanced the stability and reliability of reinforced concrete systems (Djamaluddin et al., 2024). Carbon sheets increase the maximum load on structural components. The findings confirmed that jacketing reinforcement improved structural resistance against external loading effects (Bdair & Alwash, 2025). A total of fourteen beam–column joint specimens, each with cantilever lengths of 750 mm (150 mm), were subjected to load testing after the application of CFRP sheets in the negative moment region of the cantilever. The results showed that the jacketing method effectively increased structural stiffness and load-carrying capacity (Obaidat et al., 2018). MATLAB models can be used for the analysis of concrete columns with casing. The study concluded that jacketing reinforcement improved flexural performance and reduced structural deformation (Imron et al., 2022). The results of the analysis with the addition of levels are carried out with existing columns reinforced using concrete jacketing with a thickness of 10 cm, concrete quality f'c 20.75 MPa. The existing beams are reinforced using steel bolted plates with a plate thickness of 6 mm and steel plate quality BJ37. The findings indicated that jacketing strengthening enhanced crack resistance and overall beam stability (Wibawa & Wiryadi, 2024). Performance of EBF vertical connectors is comparable to EBF with conventional connectors for low-rise and high-rise buildings. The analysis demonstrated that jacketing applications significantly improved structural rigidity and durability (Rommel et al., 2023). Structural irregularity buildings (SNI 1726: 2019) result horizontal irregularity model (torque ratio > 1.4). The results confirmed that jacketing reinforcement increased the strength and serviceability of structural elements (Simbolon et al., 2023). Reinforced concrete cantilever retaining wall that is experiencing a slope is analyzed using Geo5 software with 200 mm thick, width of 1500 mm with a depth of 2000 mm from the upper limit result level of stability parameters overturning, sliding and bearing capacity is very safe. The study revealed that jacketing methods effectively minimized stress concentration and improved structural performance (Silvi, 2024). Reinforcing columns with concrete layers increases the axial, shear and flexural capacity of reinforced concrete columns, making it an effective and efficient solution. The findings showed that the use of jacketing systems enhanced ductility and delayed structural failure (Balqis et al., 2024). Polymer rods with CFRP reinforcement in cantilevered concrete beams provide very satisfactory results. The analysis indicated that jacketing reinforcement provided better load distribution and increased structural safety (Al-mahmoud et al., 2010). In G+5 buildings, the seismic zone provides soft story behavior in the middle of the building height. The results demonstrated that jacketing techniques improved beam stiffness and crack control performance (Jun & Kim, 2024). FRP strengthening on bridges reduces corrosion and increases service loads due to earthquake loads (Chauhan et al., 2021). The study confirmed that jacketing systems effectively enhanced the overall behavior of reinforced concrete members. Strengthening with carbon fiber reinforced polymer (CFRP) strips and laminates can increase the strength and stiffness of beams by 37% to 67%, respectively. The findings revealed that jacketing reinforcement improved structural integrity under service and ultimate loading (Ahmed & Abdulrahman, 2025). Test results on post-fire buildings showed a very significant reduction in concrete quality. The analysis showed that jacketing applications increased axial, shear, and flexural capacities simultaneously (Susanto et al., 2025). The behavior of shear wall buildings due to earthquake loads using the equivalent static analysis method provides better resistance compared to buildings without shear walls. The results indicated that jacketing methods effectively reduced excessive deflection in structural elements (Jadhao et al., 2025). Structural irregularities have a significant impact on the seismic performance of buildings, especially in high-risk earthquake zones. The study demonstrated that jacketing strengthening enhanced the stability and reliability of reinforced concrete systems (Bayanaka et al., 2026). The dilation system is very effective in preventing horizontal translation between levels in multi-storey buildings in areas prone to high earthquakes. The findings confirmed that jacketing reinforcement improved structural resistance against external loading effects (Amami et al., 2023). The pushover results place the structure in the Damage Control category, but some ground-floor columns in older buildings exceed CP limits. The results showed that the jacketing method effectively increased structural stiffness and load-carrying capacity (Potalangi et al., 2026). For structures located in earthquake-prone areas, energy absorption capacity is a critical parameter with one possible reinforcement method is jacketing. The study concluded that jacketing reinforcement improved flexural performance and reduced structural deformation (Wuaten, 2022).

Figure 1. Existing Structure of the Cantilever Beam without Strengthening

Research Methods

The analytical approach employed in this study is a quantitative method supported by ETABS software. Prior to conducting the structural analysis, non-destructive testing was performed, consisting of hammer tests and rebar scanning, to determine the residual concrete strength as well as the diameter and quantity of reinforcement in the structural components. The rebar scanning results for the existing 300 × 300 mm column indicate that the main reinforcement consists of 8D13 bars, with transverse reinforcement of Ø8 at 100 mm spacing in the end span region and Ø8 at 150 mm spacing in the middle span region. The results of these tests were used as the basis for the structural analysis to identify appropriate strengthening alternatives. The material properties of the existing reinforced concrete structural components based on the hammer test results are as follows: concrete compressive strength (f'c) of 23.33 MPa for columns, 29.95 MPa for beams, and 35.54 MPa for slabs. Young's modulus of concrete was computed using the expression $\boxed{E_c = 4700\sqrt{f'c}}$ MPa, with a lateral strain ratio of 0.2 (BSN, 2019).

The reinforcing steel used in the structure complies with the Indonesian National Standards *SNI 2015:2017 and SNI 2847:2019,* (BSN, 2017) and (BSN, 2019). Longitudinal reinforcement steel has a minimum yield strength of 420 MPa (BjTS 420), a minimum tensile strength of 525 MPa, and an elongation of 9%. Transverse reinforcement steel has a minimum yield strength of 280 MPa (BjTP 280), a minimum tensile strength of 380 MPa, and an elongation of 11%. The initial stage of the analysis involved three-dimensional structural modeling using ETABS, incorporating the geometry and loading conditions of the structure. The analysis takes into account several types of loads, including gravity loads, wind loads and seismic loads. Load Combination is U1 = 1.4D, U2 = 1.2D+1.6L, U3 = 1.2D+L±E, U4 = 1.2D+1.6L ± W. The gravity load primarily represents the self-weight of the structural elements, which is automatically computed by the analysis software. Additional dead loads include finishes, floor tiles, ceilings, and mechanical–electrical–plumbing (MEP) systems of 150 kg/m², finishes, ceilings, and MEP systems of 100 kg/m², masonry wall loads of 250 kg/m², and roof loads of 600 kg/m. Live loads were taken as 200 kg/m² and 100 kg/m² for floors and roofs. Wind loads were applied using the ASCE 7-16 (ASCE, 2017) autolateral load provisions with a wind speed of 70 km/h (40 mph) in accordance with (BSN, 2020). Seismic loads were applied using the response spectrum method according to the seismic parameters for Badung Regency with medium soil conditions.

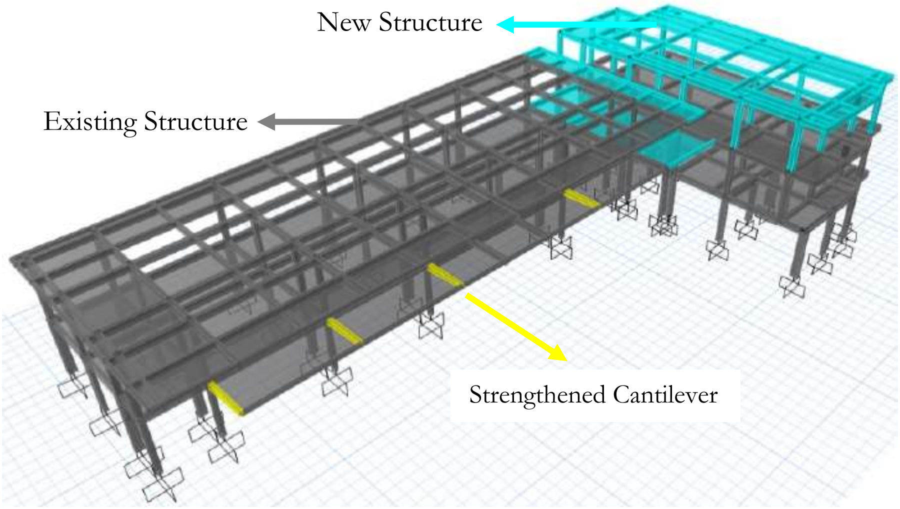

Figure 2. Existing Structure Model

Figure 2 illustrates the existing structural model together with the additional structural elements and the cantilever beam to be strengthened. The structural component dimensions consist of a cantilever column with a diameter of 300 mm, while the second-floor cantilever beam is a non-prismatic beam with cross-sectional dimensions of 200 × 400 mm at the fixed support and 200 × 200 mm at the unsupported end. Figure 3 shows the strengthened zones or regions of the structure.

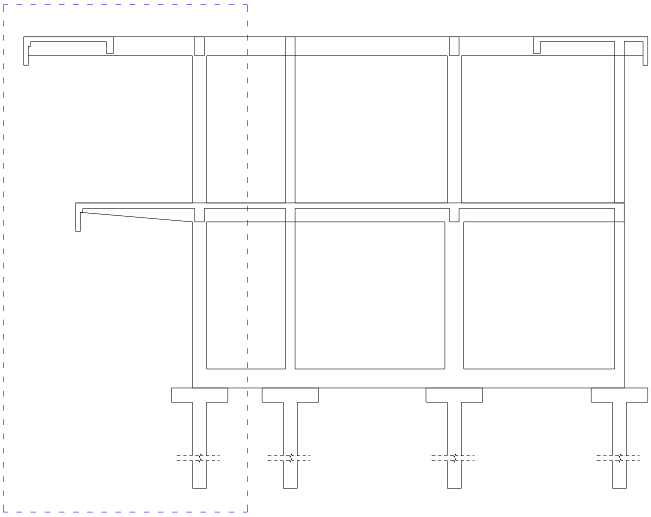

Figure 3. Strengthened Structural Zone

Research Results and Discussion

The analysis results examined in this study include structural deformations and internal forces before and after strengthening. One of the strengthening measures implemented involved column jacketing and the addition of columns at the second-floor to support roof cantilever, as well as increasing the dimensions of the second-floor cantilever beam.

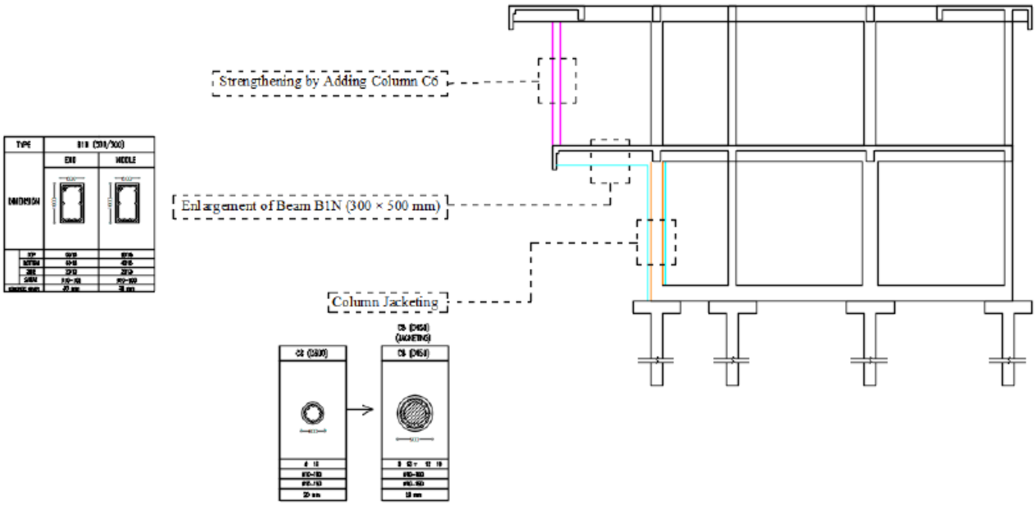

Figure 4. Beam and Column Strengthening

Figure 4 presents the beam and column strengthening for the first and second floors. Column strengthening at the first-floor level was carried out using the jacketing method by increasing the column diameter to 450 mm, with 12D16 mm longitudinal reinforcement and transverse reinforcement of Ø8–100 mm in the support region and Ø8–150 mm in the span region, using concrete f'c = 21 MPa. Column strengthening at the second-floor level was performed by adding new columns with cross-sectional dimensions of 200 × 300 mm, reinforced with 10D13 mm longitudinal bars and transverse reinforcement of Ø8–100 mm in the support region and Ø8–150 mm in the span region, using concrete f'c = 21 MPa.

Strengthening of the second-floor cantilever beam was carried out by enlarging the beam dimensions to 300 × 500 mm, flexure steel consisting of 6D16 mm negative reinforcement and 4D16 mm positive reinforcement, and transverse reinforcement of Ø8–100 mm in the support region and Ø8–150 mm in the span region, using concrete f'c = 21 MPa.

Figure 5 shows cantilever beam deflection under factored loads before and after strengthening. The cantilever beam length at the roof level is 3725 mm, while the cantilever beam length at the second-floor level is 2625 mm. The analysis results indicate that, prior to strengthening, the cantilever beam deflections did not satisfy the allowable deflection requirement (L/180) (Pasal 24.2.2 SNI 2848:2019), where L represents the cantilever beam length. After strengthening, the cantilever beam deflections meet the allowable deflection criteria.

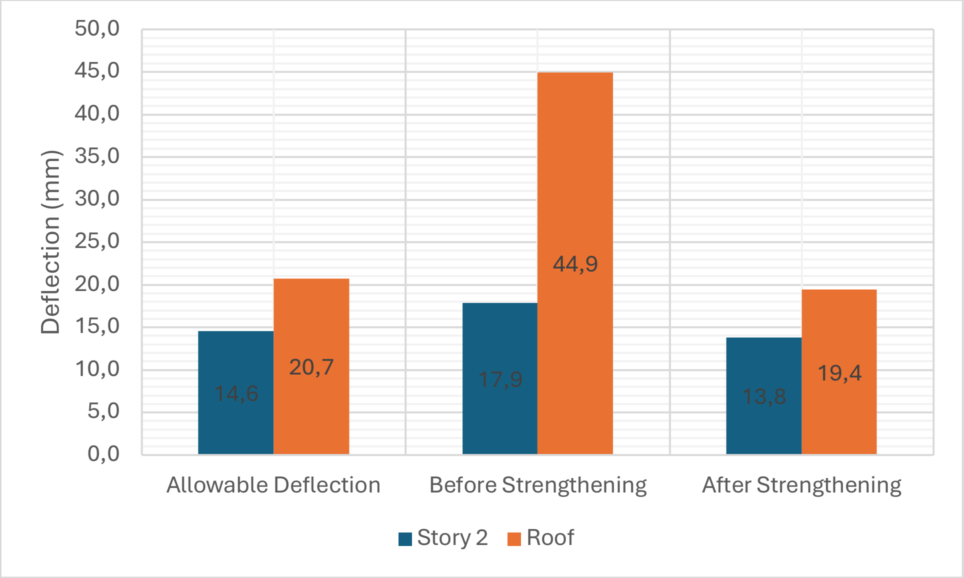

Figure 5. Cantilever Beam Deflection

The initial deflection measured in the field was consistent with the ETABS modeling results prior to strengthening. The deflections under factored loads after strengthening were reduced by 22.8% at the roof level and 56.8% at the second-floor level, respectively. Thus, the strengthening method applied is effective in improving the serviceability behavior concrete cantilever beams.

Table 1. Maximum Bending Moment of the Cantilever Beam

		Moment (kNm)					
Story	**L (mm)**	**Demand Before Strengthening**	**Capacity Before Strengthening**	**D/C Ratio**	**Demand After Strengthening**	**Capacity After Strengthening**	**D/C Ratio**
Roof	3725	212.1	285	0.74	101.8	140	0.73
Story 2	2625	123.1	165	0.75	225.8	305	0.74

(Source: Analysis Result, 2026)

Table 1 presents the maximum bending moments of the cantilever beams. At the roof level, the maximum bending moment before strengthening is 52% greater than that after strengthening. In contrast, at the second-story, the maximum flexure moment before strengthening is 45.5% lower than that after strengthening. Table 1 and 2 shows this behavior is attributed to the roof-level cantilever being supported by an additional column, which altered the structural load path and stiffness distribution of the system. Following the strengthening, part of the loads and internal forces previously resisted by the cantilever beam were redistributed through the additional column and transferred to the supporting beams and lower structural elements. This redistribution mechanism generated larger reaction forces and increased frame interaction near the beam-column connection region. Consequently, the supporting beam experienced increases in bending moment and shear force due to the higher restraint effect, concentrated vertical reactions, and additional force transfer generated by the modified structural system. These results indicate that the strengthening design should not only focus on reducing cantilever response, but also consider the increased force demand in the supporting beam, particularly regarding flexural reinforcement capacity, stirrup detailing, anchorage development, and beam-column joint performance to ensure adequate structural safety and ductility after force redistribution.

Table 2. Maximum Shear Force of the Cantilever Beam

Story	**L (mm)**	**Shear Force (kN)**					
		Demand Before Strengthening	**Capacity Before Strengthening**	**D/C Ratio**	**Demand After Strengthening**	**Capacity After Strengthening**	**D/C Ratio**
Roof	3725	100.2	135	0.74	63.3	90	0.7
Story 2	2625	102.1	140	0.73	153.2	205	0.75

(Source: Analysis Result, 2026)

Table 2 shows the maximum shear forces of the cantilever beams. At the roof story, the maximum transverse force before strengthening is 36.8% greater than that after strengthening. Conversely, at the second-story, the maximum transverse force before strengthening is 33.4% lower than that after strengthening. This behavior is attributed to the roof-level cantilever being supported by an additional column.

Table 3. Maximum Bending Moment of the Column

Story	**L (mm)**	**Moment (kNm)**					
		Demand Before Strengthening	**Capacity Before Strengthening**	**D/C Ratio**	**Demand After Strengthening**	**Capacity After Strengthening**	**D/C Ratio**
Story 2	3500	6.4	9	0.71	3.3	5	0.66
Story 1	3500	10.6	15	0.71	26.9	36	0.75

(Source: Analysis Result, 2026)

Table 3 shows the maximum bending moments of the columns. At the second story, the maximum flexure moment before strengthening is 48.4% greater than that after strengthening. In contrast, at the first story, the maximum flexure moment before strengthening is 60.6% lower than that after strengthening. Table 3,4, 5 shows This behavior is attributed to the roof-level cantilever being supported by an additional column, which significantly altered the structural load path and stiffness distribution of the system. Following the strengthening, part of the loads and internal forces that were previously resisted mainly by the cantilever beam were redistributed through the additional column and transferred to the lower structural elements. This redistribution mechanism generated larger reaction forces and increased frame interaction at the beam-column connection region. Consequently, the supporting column experienced increases in bending moment, shear force, and axial force due to the combined effects of higher moment transfer, concentrated vertical reactions, and additional axial load participation within the modified load-resisting system. These results indicate that the strengthening design should not only focus on reducing cantilever response, but also consider the increased force demand in the supporting column, particularly regarding longitudinal reinforcement capacity, transverse confinement reinforcement, shear detailing, anchorage development, and beam-column joint performance to ensure adequate structural safety and ductility after force redistribution.

Table 4. Maximum Shear Force of the Column

Story	**L (mm)**	**Shear Force (kN)**					
		Demand Before Strengthening	**Capacity Before Strengthening**	**D/C Ratio**	**Demand After Strengthening**	**Capacity After Strengthening**	**D/C Ratio**
Story 2	3500	3.5	5	0.7	1.8	3	0.6
Story 1	3500	17.1	24	0.71	25.1	34	0.74

(Source: Analysis Result, 2026)

Table 4 presents the maximum shear forces of the columns. At the second-floor level, the maximum shear force before strengthening is 48.6% greater than that after strengthening. Conversely, at the 1-st floor, the shear force before strengthening is 31.9% lower than that after strengthening. This behavior is attributed to the addition of a column at the second-floor level.

Table 5. Maximum Axial Force of the Column

Story	**L (mm)**	**Axial Force (kN)**					
		Demand Before Strengthening	**Capacity Before Strengthening**	**D/C Ratio**	**Demand After Strengthening**	**Capacity After Strengthening**	**D/C Ratio**
Story 2	3500	277.5	370	0.75	169.1	230	0.74
Story 1	3500	647.1	865	0.75	977.6	1305	0.75

(Source: Analysis Result, 2026)

Table 5 presents the peak axial forces of the columns. At the second story, the peak axial force before strengthening is 39.1% greater than that after strengthening. In contrast, at the first story, the peak axial force before strengthening is 31.9% less than that after strengthening. This response is due to the addition of a column at the second-floor level.

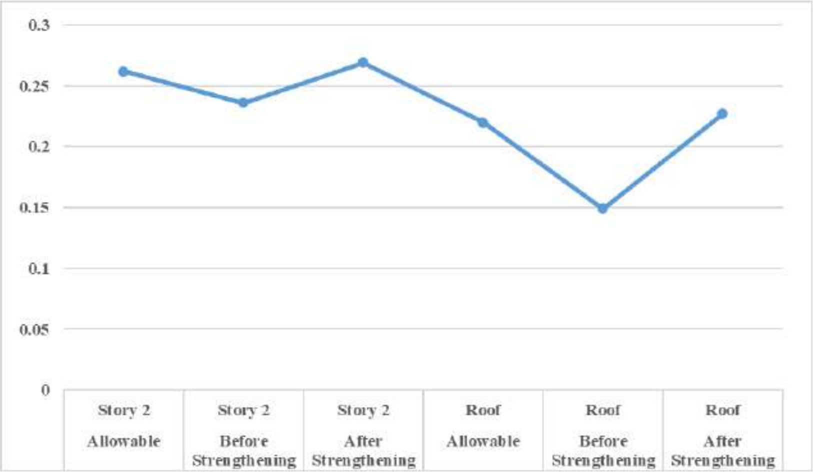

Figure 6. Frequency Index

Figure 6 illustrates the comparison between the allowable ratio and the structural response ratios before and after strengthening at both Story 2 and Roof levels. At Story 2, the allowable ratio was approximately 0.26, while the ratio before strengthening decreased slightly to about 0.24. After strengthening, the ratio increased to approximately 0.27, indicating an increase of about 12.5% compared to the condition before strengthening. This increase suggests that the strengthening system caused force redistribution toward the lower supporting structural members, resulting in higher internal force demand at Story 2. At the Roof level, the allowable ratio was approximately 0.22. Before strengthening, the ratio was significantly lower at around 0.15, indicating relatively small structural demand. However, after strengthening, the ratio increased to approximately 0.23, representing an increase of about 53% compared to the original condition. This behavior indicates that the additional supporting column altered the stiffness distribution and load transfer mechanism, producing greater interaction forces in certain structural elements. Despite the increases observed after strengthening, all response ratios remained below the allowable limit of 0.30, indicating that the strengthened structural system still satisfied the required safety and serviceability criteria. Overall, the results demonstrate that the strengthening system effectively modified the structural behavior and redistributed internal forces without exceeding the permissible structural performance limits.

Conclusion

According to the results of the analysis and discussion, it can be inferred that the existing long-span reinforced concrete cantilever beam structure was unable to satisfy the allowable deflection requirements due to an increase in the cantilever length during the construction stage. The proposed strengthening alternatives, including column jacketing at the first story, the addition of columns at the second story, and the enlargement of the second-floor cantilever beam dimensions, significantly enhanced the rigidity of the structure and its ability to sustain applied loads. After strengthening, the cantilever beam deflections were substantially reduced and met the allowable deflection limits at both the roof and second story. The strengthening measures also resulted in a redistribution of internal forces, in which the bending moments and shear forces in the roof-level cantilever beam decreased due to the addition of supporting elements, while the forces in the column elements increased but remained within safe limits. Therefore, the analyzed strengthening alternatives can be considered effective and practical solutions for addressing long-span reinforced concrete cantilever beam problems without adversely affecting the architectural aspects of the building. However, this study is limited to analytical and numerical evaluations using ETABS modeling and does not include experimental validation or long-term structural monitoring under actual service conditions. In addition, the effects of material deterioration, construction imperfections, and dynamic loading behavior were not comprehensively investigated. Therefore, further studies are recommended to include experimental testing, nonlinear analysis, long-term monitoring, and seismic performance evaluation to better understand the structural behavior after strengthening. From a constructability perspective, the proposed strengthening methods should also consider field implementation aspects such as construction accessibility, temporary support requirements, connection detailing, and compatibility between existing and new structural elements to ensure effective and safe execution during retrofitting works.

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