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Column structure strengthening with FRP (Fiber Reinforced Polymer) due to story addition

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ABSTRACT

This study focuses on strengthening scheme of an existing structure with added story. The addition of a new story increases gravitational loading, which affects the seismic and wind responses of the structure and, as a consequence, the loading combination. To ensure the structure's capacity requirement, the strengthening scheme uses CFRP (Carbon Fiber Reinforced Polymer). In order to adequately define the structure's performance, a series of structural analyses were performed. The structure's state before and after story addition, subsequently the state after CFRP strengthening, were evaluated. It is demonstrated that the additional story to the structure causes an exceedance in internal forces; however, the strengthening with CFRP is sufficient to withstand these forces, proving that the strengthening scheme is effective and beneficial.

Keywords: added story; design capacity; strengthening; structure performance; CFRP

1 Introduction

Adding new story levels to existing structures has the potential to be an innovative way to increase a building's usable space and value in a world where most major cities lack vacant space and available space can be prohibitively expensive. This could mean adding a unique and modern space on top of an existing structure, or it could involve maintaining the structure's continuity and repeating the existing story on the additional levels [1], [2]. The addition of the story increases the gravitational loading, which has an impact on the structure's seismic and wind responses. As a result, existing building structures must be assessed through various analysis [3]–[7] to determine their ability to withstand the addition of a story, with strengthening required if the capacity of the structure is insufficient.

A composite strengthening system, along with external restraints, are commonly used to restore or improve the performance of concrete structures. Composite strengthening has traditionally been achieved by adding new structural members [8]–[11], section enlargement [12], external posttensioning [13], and externally bonded steel elements [14], All of which should be oriented to serve the structure's intended use for the structure's designed service life without compromising its functionality.

One of the advanced methods is to use fiber-reinforced polymer (FRP) composites [15]. Based on their building materials, FRPs are classified into three types: CFRP (Carbon Fiber Reinforced Polymer), GFRP (Glass Fiber Reinforced Polymer), and AFRP (Aramid Fiber Reinforced Polymer) [16]. CFRP has a higher tensile strength limit than other types of FRPs [17], [18] that have recently been used. CFRP's advantages include corrosion-resistant materials, superior ductility, and light weight, making it easy to transport to the construction site, as well as the fact that its use does not disrupt existing activities in the structure's area. With full or partial application, retrofitting beams with CFRP can improve bending and shear strength, while retrofitting columns with CFRP can improve axial strength and column ductility [19]–[21].

In this study, the existing building is a real structure located in an active seismic area on Bali Island, which requires an additional story due to an increase in service demand in school management. The consideration lead to the investigation of the structure's capacity. Hypothetically, the demand force will exceed the building's existing capacity. As a result, the structure is first evaluated to identify the member that has exceeded its capacity due to the additional load. A series of structural analyses were carried out in order to adequately define the structure's performance. The structure's state before and after story addition, as well as the state after CFRP strengthening, were assessed.

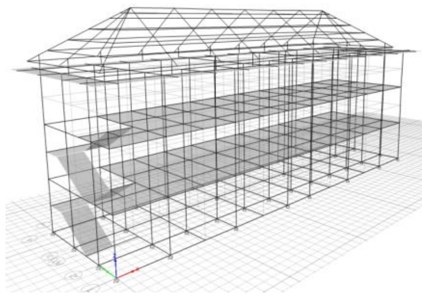
The additional story causes internal forces to exceed the capacity of several columns, while the beam capacity remains adequate to withstand the additional load. It is demonstrated that the strengthening with CFRP is sufficient to withstand the increase in load combinations, proving that the strengthening scheme is effective and beneficial.

2 Strengthening Upgraded Structure

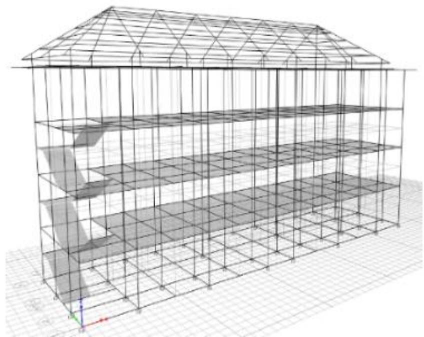
The internal forces and strength capability of structural members were first modeled in the state before and after story addition to evaluate the internal forces and strength capability of structural members under various factored loads. A series of structural analyses were carried out in order to identify the member that has exceeded its capacity due to the increased load caused by the addition of stories, and which will be strengthened with Carbon Fiber Reinforced Polymer (CFRP). The effectiveness of the strengthening scheme was determined by comparing the performance of the upgraded structures before and after strengthening.

2.1 Structure Details

The existing structure is a three-story reinforced concrete school building on Bali Island, Indonesia. This building will be extended to meet service space demand by adding a story with an additional story equal to the story below, as shown in Figure 1.



(a)



(b)

Figure 1. Structure model; (a) existing; (b) after additional story.

The first two stories have a story high of 4.08 meters, while the third and additional stories have a story high of 3.95 meters. The strength of the reinforced concrete material, which includes concrete, transversal bar, and longitudinal bar, is 20.75 MPa, 240 MPa, and 400 MPa, respectively. Figure 2 shows a typical floor plan for the existing structure, including the additional floor.

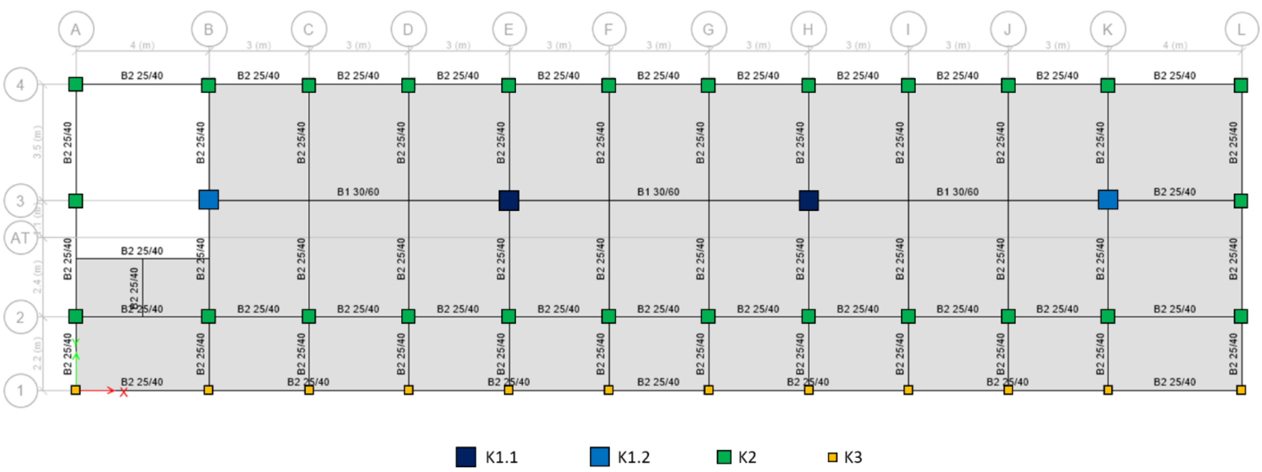


Figure 2. Typical floor plan of the structure.

Table 1. Cross-sectional dimensions of beams and columns

Code	Section (mm)		Longitudinal bar	Transversal bar
Column K1.1	450x450	end	24D19	Ø10-100
		mid	24D19	Ø10-150
Column K1.2	450x450	end	18D19	Ø10-100
		mid	18D19	Ø10-150
Column K2	400x400	end	12D19	Ø10-100
		mid	12D19	Ø10-150
Column K3	300x300	end	12D19	Ø10-100
		mid	12D19	Ø10-150
Beam B1	300x600	end	12D16	Ø10-100
		mid	12D16	Ø10-150
Beam B2	250x400	end	8D16	Ø10-100
		mid	8D16	Ø10-150
Beam B3	200x400	end	5D16	Ø10-100
		mid	5D16	Ø10-140
Tie Beam TB1	250x400	end	4D16	Ø10-100
		mid	4D16	Ø10-140

Table 1 shows the cross-sectional dimensions of beams and columns. Structure analysis program, ETABS[22], was used to create a three-dimensional model of the existing building, as well as an upgraded building without and with a strengthening scheme, using the above-mentioned input dimensions and materials. For this specific building, primary external loads such as dead load, live load, rain load, and wind load were used for simulation. Because the investigated structure is located in a seismically active area, the effect of this load was also taken into account. The structure was built on stiff soil (class D) and designed in accordance with the third risk category (school). According to the Indonesian National Earthquake Research Center database and SNI 1726:2019 code [23], the spectral acceleration for the maximum considered earthquake (MCER) is 0.963g for short period (S_S) and 0.395g for long period (S_1). These values are 0.71g and 0.5g for design basis earthquake (DBE), respectively.

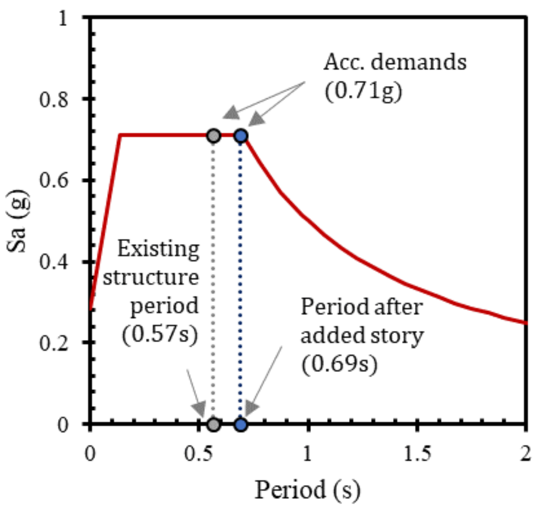


Figure 3. Design response spectrum (DBE).

Figure 3 depicts the structure period as it corresponds to the design response spectrum of the building site. All of the factored loads were applied to the structure models in various combinations in accordance with SNI 1727:2020 [24], to obtain the corresponding internal forces (M_u, V_u and P_u).

Analysis was performed on the elements of the structure of columns and beams for each modeled structure to obtain the nominal capacity of each cross-section. According to SNI 2847:2019 [25], the nominal strength provided must be greater than the ultimate load calculated using structural analysis for factoring loads, $\phi P_n \geq P_u$; $\phi M_n \geq M_u$, $\phi V_n \geq V_u$. The internal force analysis results as a consequence of the floor are controlled with a nominal capacity of current cross-section. If the strength of such member is insufficient to withstand the load imposed by the addition of the floor, it will be strengthened to increase its capacity.

2.2 Strengthening Method

CFRP (Carbon Fiber Reinforced Polymer) provides a quick and easy construction solution while preserving the architecture design of existing buildings, providing the desired benefits for this strengthening. In this study, 12K UD carbon fiber fabrics with the thickness (t_f) of 0.45mm and tensile strength (f_u) of at least 3400MPa was adopted for structural members strengthening.

Due to the affectively of environmental conditions, the ultimate tensile strength of FRP (f_{fu}) that will be used for design and analysis is the product of FRP tensile strength (f_u) multiplied by the reduction factor (C_E) of 0.95 for carbon/epoxy fiber FRP-confined concrete. Furthermore, the installation of FRP on structure member also play an important role in FRP performance. Thus, the reduction factor based on wrap position and shear resistance was put in consideration. Such factor can be assigned as 0.95 for the component that wrapped on four sides (all sides) and 0.85 for three-sided U-wrap or plate shape.

According to ACI 440.2R-02, using restrained concrete strength equation [26], the compressive strength of FRP-confined concrete ($f'cc$) can be evaluated using the following expression:

$$f'cc = f'c\left(2{,}25\sqrt{1+7{,}9\frac{f_l}{f'c}} - 2\frac{f_l}{f'c} - 1{,}25\right) \quad (1)$$

In which, f_l is FRP-confined compressive strength. The relationship between FRP-confined compressive strength, f_l, column efficiency factor, k_a, FRP strengthening ratio, ρ_f, FRP young modulus, E_f, FRP ultimate strain, ε_{fu} can be described as the following expression:

$$f_l = \frac{k_a.\rho_f.E_f.\varepsilon_{fu}}{2} \quad (2)$$

Where,

$$k_a = \frac{1-(b-2r^2)+(h-2r^2)}{3.b.h.(1-\rho_g)} \quad (3)$$

And,

$$\rho_f = \frac{2.n.t_f.(b+h)}{b.h} \quad (4)$$

Subsequently, the column gross ratio can be calculated as follow:

$$\rho_g = \frac{As+A's}{Ag} \quad (5)$$

In which, As, A’s, and Ag is tension steel rebar, compression steel rebar, and gross area of the column, respectively.

Furthermore, since structural columns are subjected to a combination of axial loads and bending moments, the compressive strength capacity of concrete columns was described using a moment-axial load interaction diagram. Axial forces with varying eccentricities about the section centroid will result in a variety of stress distributions. As a result, the nominal strength of FRP-confined concrete columns at major points of the P-M interaction diagram can be calculated as follows:

(1) Nominal compressive strength of column with pure axial load:

$$P_n = \emptyset P_0 \quad (6)$$

Or,

$$\emptyset P_0 = 0.85\,(\psi_f.f''_{cc}.(A_g - A_{st}) + (f_y.A_{st}). \quad (7)$$

Where nominal moment $M_n = 0$

(2) Column analysis in balanced conditions ($c = c_b$), compression control conditions ($c > c_b$), tension control conditions ($c < c_b$) are using the same equation. Where, c_b, can be calculated as follow:

$$C_b = \frac{600.d}{600+f_y} \quad (8)$$

The strengths in each conditions can be evaluate by following expression:

$$P_n = 0{,}85\,.f'_{CC}.b.a_{fb} + A'_S\,.f'_S - A_S\,.f_y - A_f.f_{fet} \quad (9)$$

Nominal moment capacity:

$$M_n = 0{,}85\,.f'_{CC}.b.a_{fb}\left(\frac{h-a}{2}\right) + A'_S\,.f'_S\left(\frac{h}{2}-d'\right) + A_S\,.f_y\left(\frac{h}{2}-d'\right) + A_f.f_{fet}\left(\frac{h}{2}\right) \quad (10)$$

(3) Column analysis in pure bending conditions. Nominal moment of pure bending conditions:

$$Mn = As.fy\left(d-\frac{a}{2}\right) + A'_s f'_s(d-d') + \psi_f.Af.f_{fe}\left(h-\frac{a}{2}\right) \quad (11)$$

Where, the nominal axial capacity, $Pn = 0$

The column capacity meets the design criterion if the combination of internal force (M_u, P_u) from the interaction curve is within this nominal design strengths of M_n, and P_n interaction diagram.

3 Structures Performance Evaluation Results

Analysis was performed on structures before and after story addition to evaluate the structure performance, subsequently solution then be applied to efficiently strengthen critical member. Under seismic loading, the structural natural period is of considerable importance factor as it has significant influence in structure performance. It was taken from the results that the structure period increases from 0.57 seconds in existing building to 0.69 seconds as one story was added.

The performance of structure with addition story can be further evaluated by its deformation, as shown in Table 2. The comparisons in two directions show that the structure meets the SNI 1726-2019 standard code criterion in term of deformation and the maximum inter-story drift is 21.62mm. In this study, the results of the internal force analysis due to the addition of the story was investigated through strength capacity of the cross-sections.

Table 2. Maximum inter-story drift in two directions

Story	Maximum inter-story drift (mm)	Allowable inter-story drift (mm)
1	18.74	31.38
2	21.62	31.38
3	15.48	30.38
4	10.48	30.38

3.1 Beams Performance

Figure 4 shows the condition of each component of the beams before and after the addition of the story, at the middle (mid) and end sections, respectively. The demand shown represents the maximum internal forces in the structure's members.

Figure 4(a) depicted the moment demand and capacity of the beam, whereas Figure 4(b) depict the shear demand and capacity of the beam. The figure show that, the addition of the story incur significant increment in beams' internal forces. The increase of maximum moment is, 159%, 85%, 23% and 4%, for B1, B2, B3, and TB1, respectively. While the shear forces increase, 15%, 23%, 1%, and 15%, for B1, B2, B3, and TB1, respectively. However, despite those increment, all beam capacity still can withstand the forces, therefore no further strengthening are required.

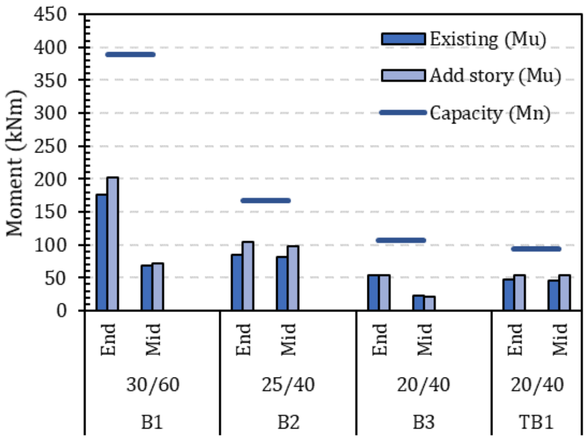


Figure 4(a). Beams moment condition before and after story addition.

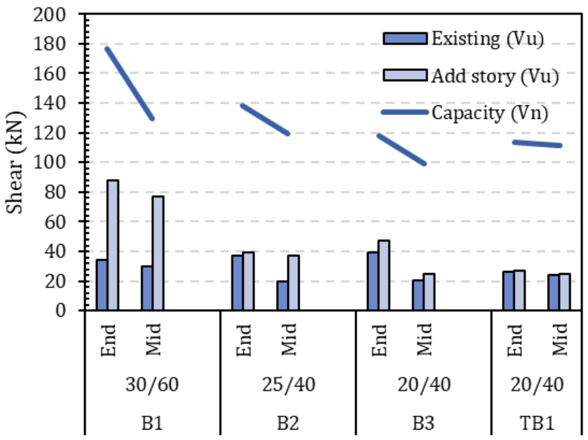


Figure 4(b). Beams shear condition before and after story addition.

3.2 Columns Performance

The internal forces demand correspond to its capacity were assessed separately between the shear and the axial-moment interaction in the column performance shown in Figure 5 and 6. Figure 5 depicts the shear demand and capacity on each column component before and after the story was added. The figure shows that the shear demand increased by 21%, 20%, 34%, and 44% after the story was added for K1.1, K1.2, K.2, and K.3, respectively. However, none of considered columns shear force exceed the capacity which justified the ability of existing columns against the increasing load.

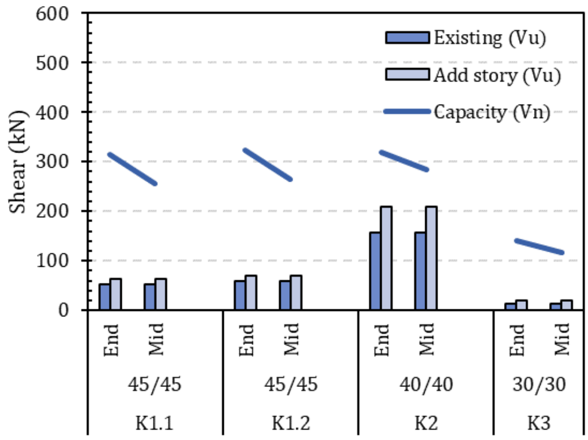


Figure 5. Columns shear condition before and after story addition.

Figure 6 depicts the compressive and bending strength analyses of the columns which represented in the P-M interaction diagrams. It was discovered that after the story was added, the maximum internal forces of the columns increased. For K1.1, K1.2, K.2, and K.3, the axial forces increase by 43%, 59%, 65%, and 37%, respectively. While the bending moments of K1.1, K1.2, K.2, and K.3 were 52%, 83%, 96%, and 45%, respectively. This force combination resulted in a column capacity exceedance, as shown in Figure 6(c), implying that the K2 column is unable to withstand the axial-moment load combination, despite having sufficient shear capacity. According to the findings of the analysis, the number of K2 columns that need to be strengthened is one member on the first floor, as located in Figure 7.

3.3 Performance of FRP-Strengthened Structure

The strengthening of K2 member employing one layer of the FRP wrapping four side and covering thorough the column height, as shown in Figure 8. Through Equation 1, the application of FRP results in an increase in compressive strength of the K2 column of up to 72.63MPa. This is 3.5 times the current capacity of 20.75 MPa.

The strength improvement of the K2 column can also be seen in the P-M interaction diagram, as shown in Figure 9. Accordingly, the internal axial-moment force combination can be covered by the strength capacity of column K2 after strengthened with FRP.

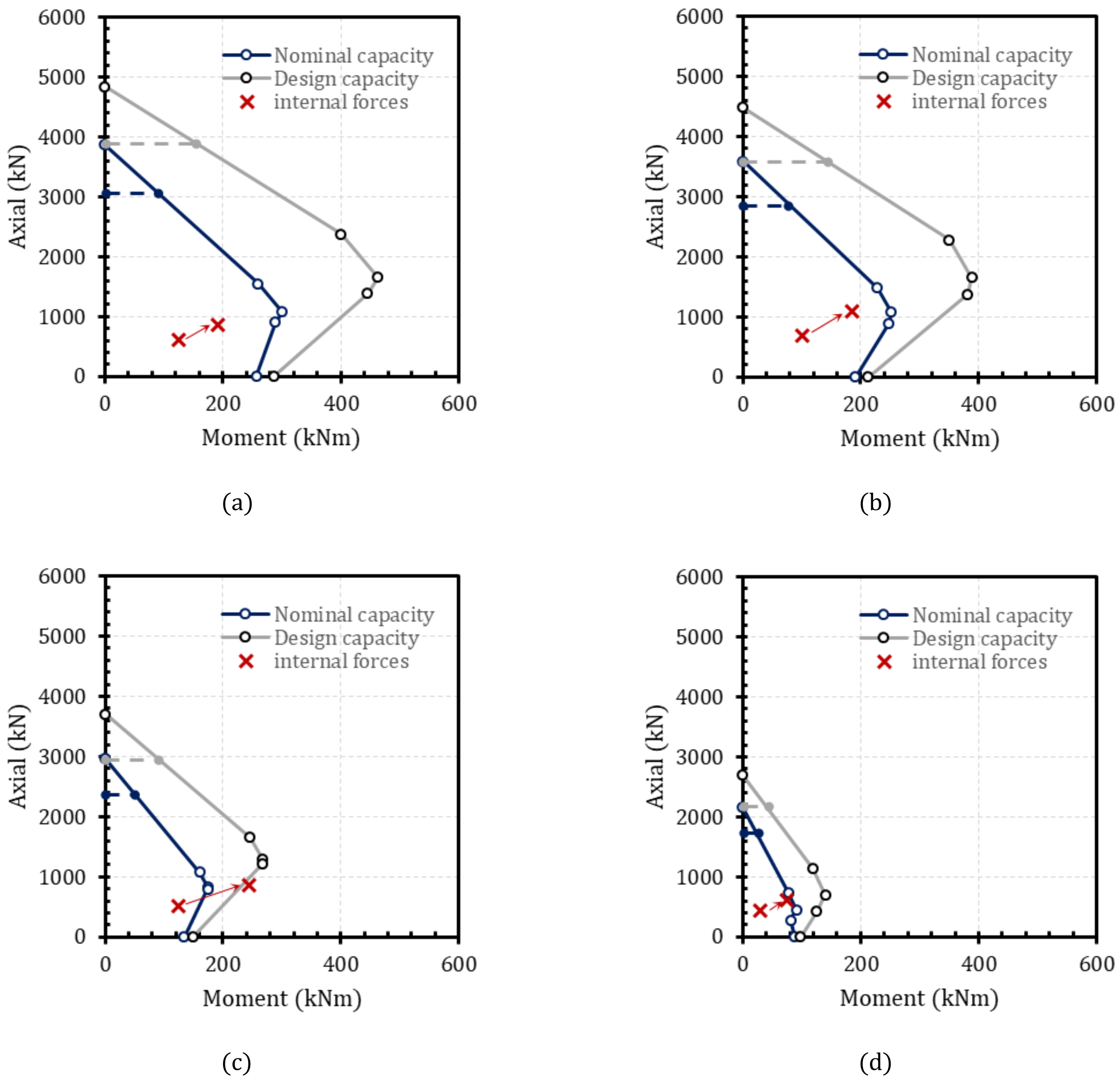


Figure 6. Columns performance comparison: (a) K1.1; (b) K1.2; (c) K.2: (d) K.3.

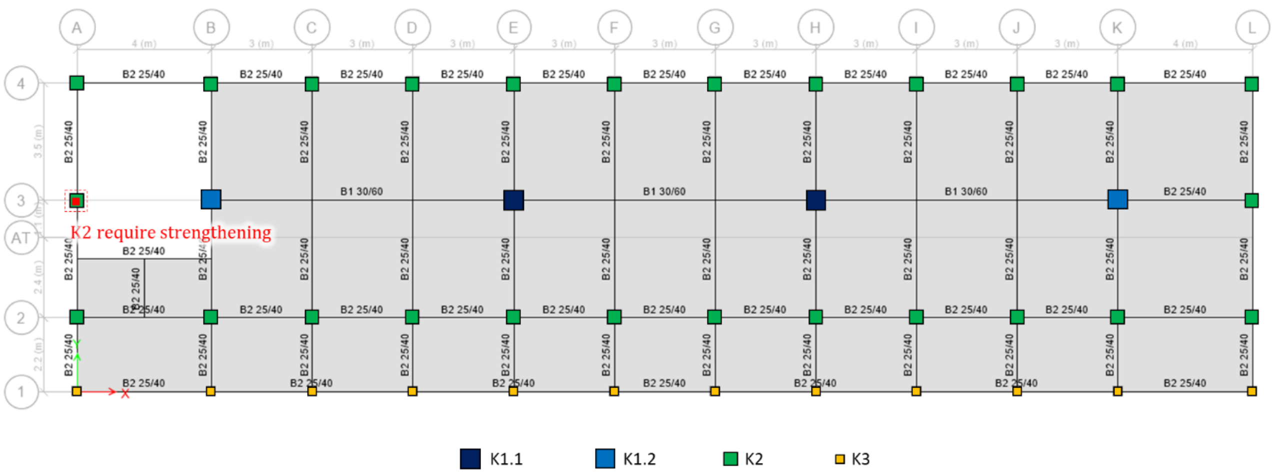


Figure 7. Position of the K2 column frame that requires FRP strengthening.

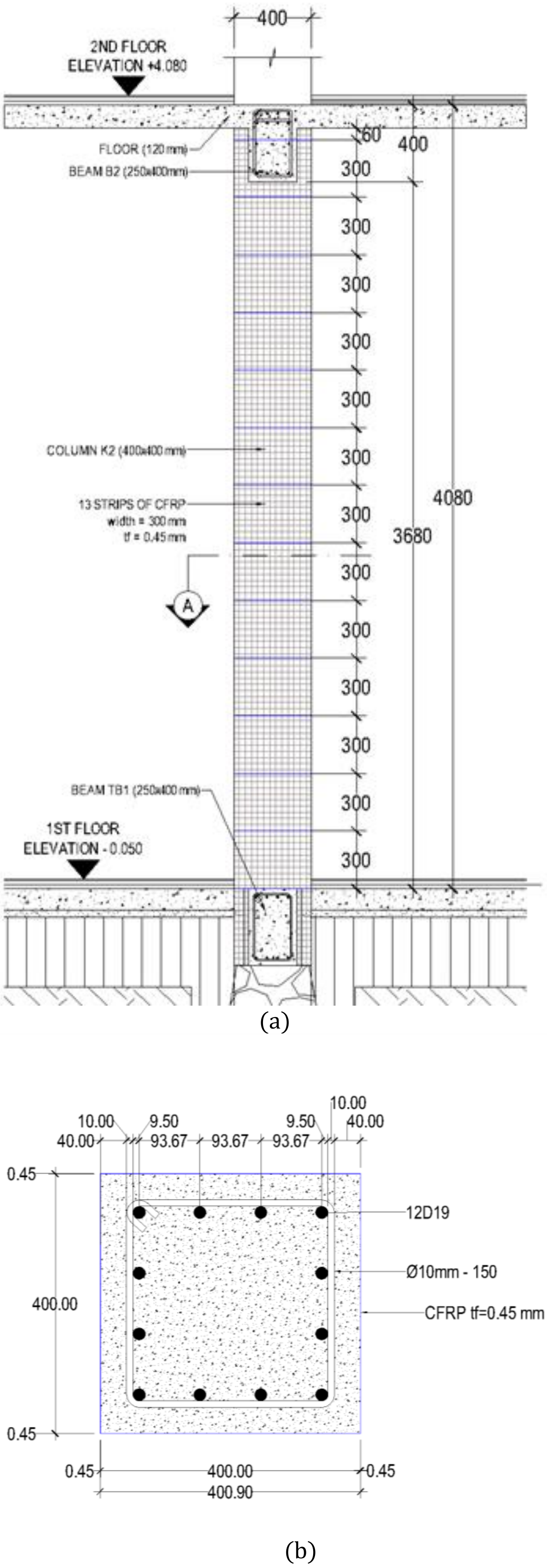


Figure 8. The application of FRP-strengthening on K2 column: (a) global view; (b) cross-section.

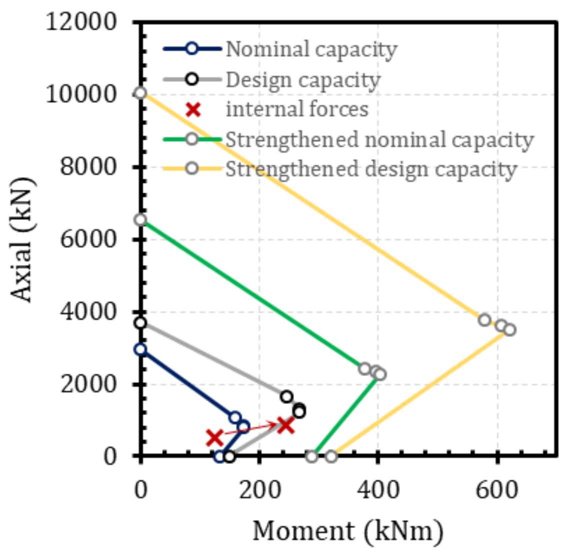


Figure 9. Performance comparison of K2 column P-M interaction diagram before and after strengthening.

4 Conclusions

Various analyses were carried out for the FRP-strengthening process of the three-story school building with an additional story. The additional story level causes an increase in internal forces in the beam element of up to 159% and 23%, respectively, in addition to existing moment and shear forces. In column element, the shear, axial, and moment forces increment can be up to 44%, 65%, and 96%, respectively. These loading conditions resulted in a FRP-strengthening scheme for a first-story column using a single layer of 0.45mm carbon type fiber. The strengthening results in a 2.5-fold increase in column compressive strength over its existing state, subsequently increase the column capacity to resist bending moments. This strengthening scheme allow the column to withstand the load combination due to the addition of the story level. The substantial results validate the effectiveness and applicability of the strengthening method.

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