Formosa Journal of Science and Technology (FJST)
Vol. 4, No. 12, 2025: 4089-4102

Analysis of Beam Strengthening Using Carbon Fiber Reinforced Polymer (CFRP) in Multi-Storey Buildings

Aviska Triayaska[1*], Hanie Teki Tjendani[2], Buntara Sthenly Gan[3]
Master of Civil Engineering, Faculty of Engineering, Universitas 17 Agustus 1945 Surabaya, Indonesia[1,2]
Department of Architecture, College of Engineering, Nihon University, Koriyama, Japan[3]
Corresponding Author: Aviska Triayaska, aviskatriayaska@gmail.com

A R T I C L E I N F O

Keywords: Seismic Performance, CFRP Strengthening, Beam Elements, ACI 440.2R-17, Pushover Analysis

Received : 27, October
Revised : 29, November
Accepted: 31, December

A B S T R A C T

Indonesia is located in a region with high seismic activity due to tectonic plate interactions and its position along the Pacific Ring of Fire. The update of the seismic design code from SNI 1726:2012 to SNI 1726:2019 has increased seismic demand, raising concerns regarding the safety of existing multi-storey buildings. This study aims to evaluate the seismic performance of a multi-storey building in Surabaya using a performance-based approach in accorandce with ASCE 41-17. Nonlinear static (pushover) analysis was conducted to identify beam elements exceeding the Collapse Prevention performance limit under BSE-2E earthquake demand. Subsequently, structural strengthening using Carbon Fiber Reinforced Polymer (CFRP) was implemented based on ACI 440.2R-17 provisions. The results indicate that CFRP strengthening effectively enhances beam capacity and overall structural performance, enabling the building to achieve the Life Safety performance level under the maximum design earthquake.

ISSN-E: 2964-6804
DOI: https://doi.org/10.55927/fjst.v4i12.354
https://traformosapublisher.org/index.php/fjst

INTRODUCTION

Earthquakes are natural phenomena that generate significant dynamic forces on building structures due to the sudden release of energy within the Earth's crust. Seismic excitations induce structural deformations that depend on ground acceleration and structural characteristics such as stiffness, mass, and building height (Tantyoko et al., 2023). Excessive deformation may lead to structural failure, therefore buildings located in seismic-prone areas must be designed and evaluated using stringent seismic standards to ensure adequate strength and ductility (Santoso & Astawa, 2022).

Indonesia is classified as a high seismic risk country because it lies at the convergence of four major tectonic plates and along the Pacific Ring of Fire (Novena, 2022). Numerous destructive earthquakes, both globally and nationally, such as the 1960 Great Chilean Earthquake and the 2004 Aceh Earthquake, have demonstrated the severe impact of seismic events on buildings and infrastructure, resulting in massive casualties and economic losses. These events highlight the urgent need to enhance the seismic resilience of building structures (Fata, 2022).

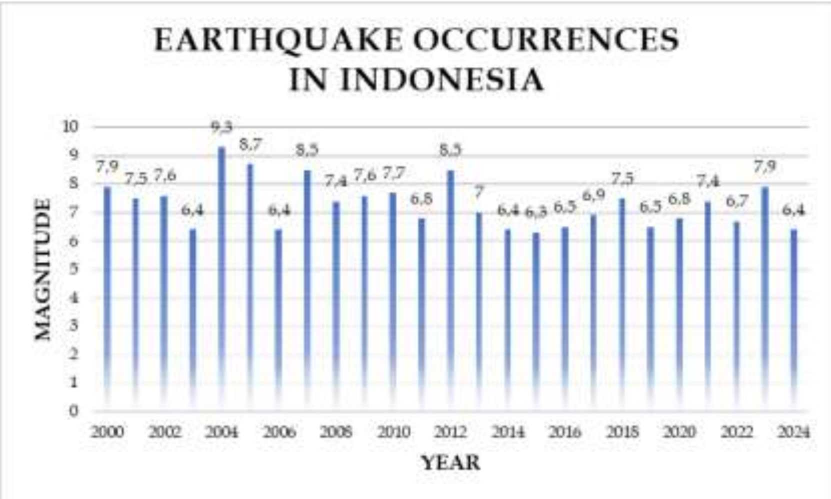

Figure 1. Damaging Earthquakes in Indonesia from 2000 to 2022

The update of the Indonesian seismic design code from SNI 1726:2012 to SNI 1726:2019 has led to a significant increase in design seismic loads in several regions, including Surabaya. The increase in base shear demand raises concerns regarding the safety of existing buildings designed using earlier standards (Wicaksana & Rosyidah, 2021). Consequently, seismic performance evaluation becomes essential to assess whether beam elements are capable of resisting the increased seismic demands imposed by the updated code (Trimurtiningrum et al., 2020).

Seismic evaluation of existing buildings is commonly conducted using a performance-based approach in accorandce with ASCE 41-17, which provides comprehensive procedures for assessing structural performance levels and demand-to-capacity ratios (DCR). This standard enables the identification of deficient beam elements and determines acceptable performance objectives such as Life Safety or Immediate Occupancy, forming a rational basis for seismic rehabilitation planning (Hilmi et al., 2021).

When beam elements are found to be inadequate, seismic strengthening using Carbon Fiber Reinforced Polymer (CFRP) is considered an effective rehabilitation method (Hirwo & Rozak, 2022). CFRP offers a high strength-to-weight ratio and is capable of significantly enhancing the flexural capacity, shear resistance, and ductility of reinforced concrete beams without substantially increasing structural mass (Sari et al., 2022). The application of CFRP, particularly for multi-storey buildings, represents an efficient and reliable solution to improve seismic performance (Febrianto et al., 2024).

THEORETICAL REVIEW

Performance-Based Seismic Engineering (PBSE)

Performance-Based Seismic Engineering (PBSE) is a seismic design and evaluation approach that focuses on predicting how a structure will perform under different levels of earthquake intensity (Nasution, 2023). Rather than relying solely on strength-based criteria, PBSE evaluates structural response in terms of performance levels such as Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP). This approach allows engineers to identify structural deficiencies and potential failure mechanisms, particularly through nonlinear analysis methods such as pushover analysis (ASCE 41-17). In this study, PBSE is implemented following ASCE 41-17 to assess the seismic performance of an existing multi-storey building and to identify beam elements that exceed the Collapse Prevention limit under BSE-2E earthquake demand.
Previous studies have demonstrated that performance-based evaluation provides a more realistic assessment of existing structures designed under older seismic codes and effectively identifies elements requiring strengthening.

H1: Existing beam elements designed according to SNI 1726:2012 do not fully satisfy the seismic performance requirements of SNI 1726:2019 at the BSE-2E hazard level.

Nonlinear Static (Pushover) Analysis

Pushover analysis is a nonlinear static analysis method used to evaluate the inelastic behavior of structures under gradually increasing lateral loads. This method enables the identification of plastic hinge formation, structural capacity, and performance points based on capacity–demand relationships (Hutama, 2021). The distribution and progression of plastic hinges indicate whether structural elements exceed acceptable performance limits. In accordance with FEMA 440 and ASCE 41-17, pushover analysis is employed in this study to determine the seismic performance level of the structure before and after strengthening. Previous research confirms that pushover analysis is effective in identifying critical beam elements and evaluating improvements in structural performance due to retrofitting measures.

H2: Pushover analysis can effectively identify beam elements that exceed the Collapse Prevention performance limit under seismic loading.

Carbon Fiber Reinforced Polymer (CFRP) Strengthening Theory

Carbon Fiber Reinforced Polymer (CFRP) is a composite material widely used for structural strengthening due to its high strength-to-weight ratio, corrosion resistance, and ease of installation (Purnama & Nugroho, 2023). When applied to reinforced concrete beams, CFRP enhances flexural capacity, shear resistance, and ductility without significantly increasing structural mass. Design and application of CFRP follow provisions outlined in ACI 440.2R-17, considering failure modes such as debonding, rupture, and concrete crushing (Hakiki, 2025). In this research, CFRP laminates are applied to critical beam sections to increase moment capacity and control plastic hinge behavior. Numerous studies have shown that CFRP strengthening significantly improves seismic performance of deficient beam elements in existing structures.

H3: Strengthening beam elements using CFRP increases flexural capacity and prevents plastic hinge development beyond the Collapse Prevention limit.

Seismic Retrofitting and Structural Performance Improvement

Seismic retrofitting aims to restore or enhance the strength, stiffness, and ductility of existing structures to meet updated seismic demands. Effective retrofitting should result in improved global structural performance, reflected in increased base shear capacity and acceptable displacement at the performance point (Utomo et al., 2024). CFRP-based retrofitting is particularly suitable for existing buildings due to minimal architectural disruption and high structural efficiency (Suprapto et al., 2022). In this study, the effectiveness of CFRP retrofitting is evaluated by comparing seismic performance before and after strengthening. Previous findings indicate that CFRP retrofitting leads to significant improvements in overall structural performance under maximum considered earthquake conditions.

H4: CFRP retrofitting improves overall structural performance, enabling the building to achieve the Life Safety performance level under BSE-2E earthquake demand.

METHODOLOGY

This study employs a quantitative method with a performance-based analysis approach to evaluate and enhance the seismic performance of an existing multi-storey building. The research object is a multi-storey building located in Surabaya, which was originally designed in accorandce with the seismic design code SNI 1726:2012.

The initial stage of the study involves data collection, including structural drawings, element dimensions, concrete and reinforcing steel material properties, and building load data. Subsequently, the structural model is developed using SAP2000 V.26.3.0 by applying seismic loads in accorandce with the provisions of SNI 1726:2019.

Seismic performance evaluation is conducted using nonlinear static (pushover) analysis based on ASCE 41-17 to identify beam elements with insufficient capacity that exceed the Collapse Prevention performance limit under the BSE-2E earthquake level.

Critical beam elements identified from the evaluation are then strengthened using Carbon Fiber Reinforced Polymer (CFRP), designed in accorandce with ACI 440.2R-17. After strengthening, a re-evaluation using pushover analysis is performed to assess the improvement in beam capacity and overall structural performance. The seismic performance before and after strengthening is compared to evaluate the effectiveness of the CFRP strengthening.

RESEARCH RESULTS

Location of Plastic Hinge Failure

The structural element requiring strengthening due to exceeding the Collapse Prevention (CP) performance limit is beam B6-1 (150 mm × 400 mm) located on the 4th floor. The location of plastic hinge failure for this beam is illustrated as follows.

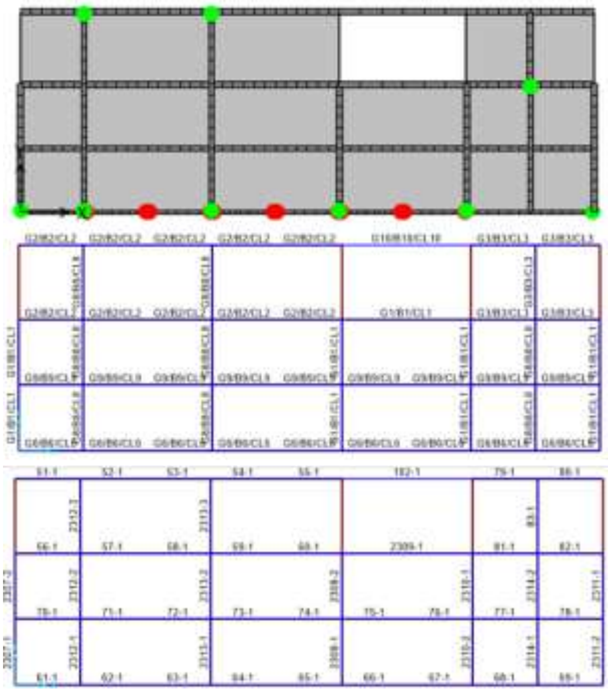

Figure 2 Location of Plastic Hinge Failure on the 4th Floor

A summary of the comparison of support and midspan moment capacity values of the beams requiring strengthening on each floor is obtained as follows.

Table 1. Comparison of Support and Midspan Moments at Critical Plastic Hinge Locations

Floor	Beam Location	Hinge Status	M_u Support (N)	M_u Midspan (N)
4th Floor	AS 2-D *joint* 62-1 and 63-1	>CP	22205956,27	6300686046
	AS 2-E *joint*	>CP	127431654,3	5931412103

	64-1 and 65-1 AS 2-F *joint* 66-1 and 67-1	>CP	2039567729	5683352858

Table 1. Comparison of Support and Midspan Moments at Critical Plastic Hinge Locations (Continued)

Floor	**Beam Location**	**Hinge Status**	**M_u Support (N)**	**M_u Midspan (N)**
5th Floor	AS 2-D joint 136-1 and 137-1	>CP	40236532,96	5835544842
	AS 2-E joint 138-1 and 139-1	>CP	117656431,7	5459721744
	AS 2-F joint 140-1 and 141-1	>CP	76837536,09	5175578703
6th Floor	AS 2-D joint 2357-1 and 2358-1	>CP	40697585,13	5088719975
	AS 2-E joint 2359-1 and 2360-1	>CP	78849595,06	4766044623
	AS 2-F joint 2361-1 and 2362-1	>CP	83360336,95	4638888731
7th Floor	AS 2-D joint 2408-1 and 2409-1	>CP	42998909,59	4487261494
	AS 2-E joint 2410-1 and 2411-1	>CP	103747398,5	4094990889
	AS 2-F joint 2412-1 and 2413-1	>CP	86814125,67	3865758084
8th Floor	AS 2-D joint 2459-1 and 2460-1	>CP	46539504,98	3634667407
	AS 2-E joint 2461-1 and 2462-1	>CP	75793120,94	3280554858
	AS 2-F joint 2463-1 and 2464-1	>CP	80197496,06	3144077785
9th Floor	AS 2-D joint 2510-1 and 2511-1	>CP	46448327,66	2802225521
	AS 2-E joint 2512-1 and 2513-1	>CP	91021632,01	2425459583
	AS 2-F joint 2514-1 and 2515-1	>CP	73712602,13	2212047114
10th Floor	AS 2-D joint 2561-1 and 2562-1	>CP	254410606,5	1880776221
	AS 2-E joint 2563-1 and 2564-1	>CP	161367022	1574041730
	AS 2-F joint 2565-1 and 2566-1	>CP	51552131,01	1443733322

Strengthening Material Data

The following CFRP material properties are used for strengthening the existing building:

Material Name = SIKA Carbodur S1012	
Type	= CFRP Laminate Tape
Width	= 100 mm
Thickness (t_f)	= 1,2 mm
FRP Area (A_f)	= 120 mm²
Ultimate Tensile Strength (f_{fu})	= 2800 MPa
Ultimate Strain (e_{fu})	= > 1,69%
Elastic Modulus (E_f)	= 165.000 MPa
Environmental Reduction Factor (CE)	= 0,95 (Table 9.4, ACI 440.2R-17)
Strength Reduction Factor (ψ)	= 0,85 (Section 10.2.10, ACI 440.2R-17)

The existing beam B6-1 (150 mm × 400 mm) on the 4th floor has the following properties:

Beam Depth (d_f)	= 400 mm
Beam Width (b)	= 150 mm
Effective Depth (d)	= 347 mm
Concrete Compressive Strength (f'_c)	= 24,9 MPa
Steel Yield Strength (f_y)	= 400 MPa
Concrete Elastic Modulus (E_c)	= 23452,95 MPa
Concrete Ultimate Strain (ε_{cu})	= 0,003
Steel Elastic Modulus (E_s)	= 200000 MPa
Stress Block Parameter	= 0,8 (Section 10.2.10, ACI 440.2R-17)

The moment data are summarized as follows:

Moment (DL + SIDL)	= 91021632,02 Nmm
Support Ultimate Moment (M_u)	= 11010600000 Nm
Existing Nominal Moment at Support (M_n)	= 10892147960,34 Nmm
Nominal Moment without FRP	= 35084086,25 Nmm
Reduced FRP Moment Capacity (M_{nf})	= 9802933164,30 Nmm
Midspan Ultimate Moment (M_u)	= 11010600000 Nm
Existing Nominal Moment at Midspan (M_n)	= 10892147960,34 Nmm
Nominal Moment without FRP	= 35084086,25 Nmm
Reduced FRP Moment Capacity (M_{nf})	= 9802933164,30 Nmm

Environmental Reduction Factor

To determine the reduction due to environmental effects, the calculation is multiplied by the environmental reduction factor in accordance with Table 9.4 of ACI 440.2R-17, as shown in the following calculation.

$$f_{fu} = CE \times f_{fu} = 0{,}95 \times 2800\ MPa = 2660\ MPa$$

Maximum FRP Strain after Reduction

The maximum FRP strain after applying the reduction factor is calculated by dividing the reduced tensile strength by the elastic modulus of the FRP, as shown in the following calculation.

$$\varepsilon_{fu} = \frac{f_{fu}}{E_f} = \frac{2660\ MPa}{165000\ MPa} = 0{,}01697$$

Initial Concrete Strain due to Dead Load

The initial concrete strain resulting from dead load is determined using the following calculation.

$$\varepsilon_{bi} = \frac{M_{DL} - y}{E_C I_y} = \frac{91021632{,}02\ Nmm - \left(\frac{400\ mm}{2}\right)}{23452{,}95\ MPa \times \frac{(150\ mm \times (400\ mm)^3)}{12}} = 0{,}00097$$

Maximum Debonding Strain

The maximum debonding strain is determined to ensure that the FRP strain does not exceed the debonding limit, thereby preventing premature debonding when the structural element is subjected to ultimate loading. The calculation is performed as follows.

$$\varepsilon_{fd} = 0{,}41\sqrt{\frac{f'_c}{nE_f t_f}} \le 0{,}9\varepsilon_{fu}$$

$$\varepsilon_{fd} = 0{,}41\sqrt{\frac{24{,}9\ MPa}{0{,}5 \times 165000\ MPa \times 1{,}2\ mm}} \le 0{,}9 \times 0{,}01697$$

$$\varepsilon_{fd} = 0{,}0065 \le 0{,}0153\ (meet\ the\ requirements)$$

Effective FRP Strain

To determine the effective FRP strain, the value of c is first evaluated. In this calculation, the effective FRP strain (εfe) is assumed to be equal to the debonding strain (εfd), and the calculation procedure is carried out as follows.

$$\begin{aligned} \frac{(\varepsilon_{fe} - \varepsilon_{bi})}{\varepsilon_{cu}} &= \frac{(d_f - c)}{c} \\ \frac{(0{,}0065 - 0{,}00097)}{0{,}003} &= \frac{(400\ mm - c)}{c} \\ 2{,}490847 &= 400 - c \\ c &= 114{,}58536\ mm \end{aligned}$$

Effective FRP Stress

The effective FRP stress is determined using the following calculation.

$$f_{fe} = E_f \varepsilon_{fe} = 165000\ MPa \times 0{,}0065 = 1072{,}8769\ MPa$$

CFRP Requirement

The required amount of CFRP for strengthening the beam element is determined using the following calculation.

<u>Support Calculation</u>

$$A_{f\ Tumpuan} = \frac{\Delta M}{f_{fe} \times z} = \frac{(11010600000\ Nmm - 10892147960{,}34\ \text{Nmm})}{1072{,}8769\ MPa - (0{,}9 \times 347\ mm)}$$

$$A_{f\ Tumpuan} = 353{,}52545\ mm^2$$

$$n_{ply} = \frac{A_{f\ Tumpuan}}{t_f \times b} = \frac{353{,}52544\ mm^2}{1{,}2\ mm \times 150\ mm} = 1{,}96403 \approx 2\ layer$$

<u>Midspan Calculation</u>

$$A_{f\ Lapangan} = \frac{\Delta M}{f_{fe} \times z} = \frac{(10925000000\ Nmm - 10892147960\ \text{Nmm})}{1072{,}8769\ MPa - (0{,}9 \times 347\ mm)}$$

$$A_{f\ Lapangan} = 98{,}04839\ mm^2$$

$$n_{ply} = \frac{A_{f\ Lapangan}}{t_f \times b} = \frac{98{,}04839\ mm^2}{1{,}2\ mm \times 150\ mm} = 0{,}54471 \approx 1\ layer$$

Nominal Moment Capacity

The nominal moment capacity is determined using the following calculation.

<u>Support Calculation</u>

$$M_{n\ Tumpuan} = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right)$$

$$M_{n\ Tumpuan} = 265{,}57 \times 17{,}785 \left(347\ mm - \frac{0{,}85 \times 114{,}58536\ mm}{2}\right) +$$
$$0{,}85 \times 353{,}52544\ mm^2 \times\ 1072{,}8769\ MPa \left(400\ mm - \frac{0{,}85 \times 114{,}58536\ mm}{2}\right)$$

$$M_{n\ Tumpuan} = 114666994{,}8\ Nmm$$

<u>Midspan Calculation</u>

$$M_{n\ Lapangan} = A_s f_s \left(d - \frac{\beta_1 c}{2}\right) + \psi_f A_f f_{fe} \left(d_f - \frac{\beta_1 c}{2}\right)$$

$$M_{n\ Lapangan} = 265{,}57 \times 17{,}785 \left(347\ mm - \frac{0{,}85 \times 114{,}58536\ mm}{2}\right) +$$
$$0{,}85 \times 98{,}04839\ mm^2 \times\ 1072{,}8769\ MPa \left(400\ mm - \frac{0{,}85 \times 114{,}58536\ mm}{2}\right)$$

$$M_{n\ Lapangan} = 32820447{,}25\ Nmm$$

Since the beam width is 150 mm and the FRP width is 100 mm 1,5 CFRP strips are applied for each layer. Based on this configuration, the following values are obtained:

Installed FRP Area per Layer	= 400 mm²
ψM_{nf} at Support	= 114666994,8 Nmm
M_n at Support	= 11005406027 Nmm
Increase in Beam Moment Capacity	= 1,010398139
ψM_{nf} at Midspan	= 32820447,25 Nmm
M_n at Midspan	= 10859327513 Nmm
Increase in Beam Moment Capacity	= 0,996986779

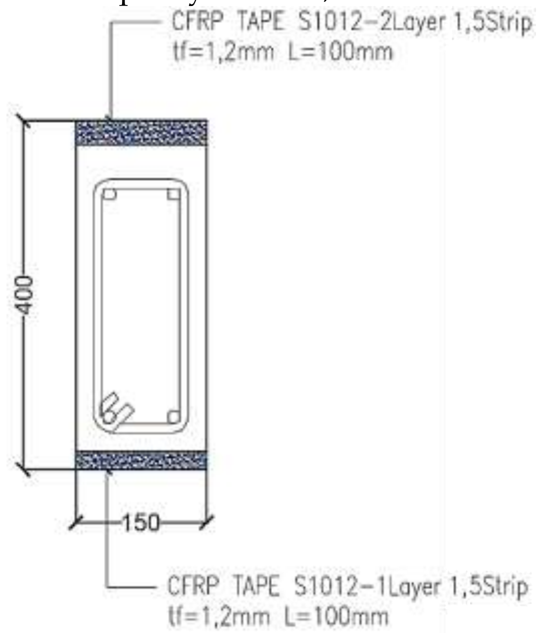

Figure 3. Detail of CFRP Installation for Beam B6-1 (150 mm × 400 mm)

Post-CFRP Installation Structural Performance Evaluation

Since pushover analysis does not generate cyclic loading, the Carbon Fiber Reinforced Polymer (CFRP) is installed continuously along grid line AS 2 and grid line AS C–F. Subsequently, the post-strengthening pushover evaluation is conducted by increasing the yield moment capacity to account for the additional moment capacity provided by the CFRP strengthening, while maintaining the same plastic hinge parameters as those used for Beam B6-1 (150 mm × 400 mm).

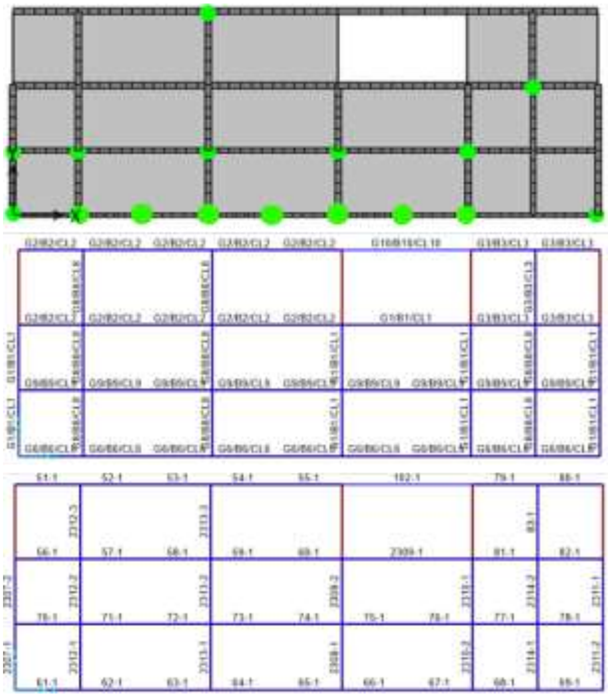

Figure 4 Post-Retrofit Plastic Hinge Locations on the 4th Floor

The post-retrofitting analysis results indicate that the overall structure satisfies the Life Safety (LS) performance criteria in accordance with the design requirements at the BSE-2E earthquake level. After strengthening, all structural elements, including Beam B6-1 on the 4th floor that was previously classified as critical, no longer exceed the Collapse Prevention (CP) performance limit. This confirms that the implemented strengthening strategy is effective in improving the seismic performance of the structure.

The distribution of plastic hinges shown in the figure also indicates that several structural elements have reached the Life Safety (LS)–Collapse Prevention (CP) performance level, as reflected by the predominance of green-colored components.

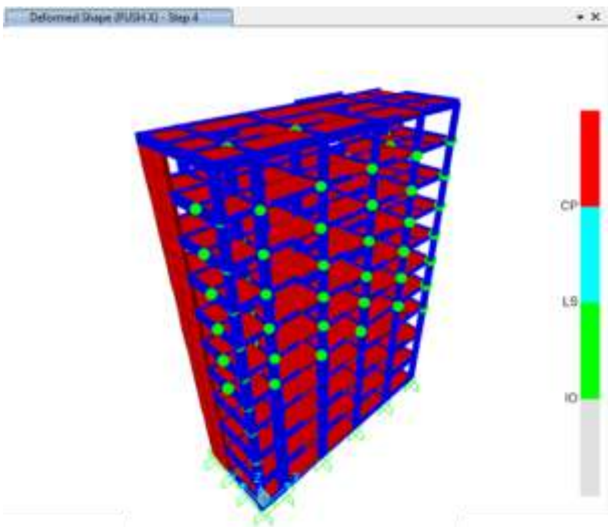

Figure 5 Post Retrofit Structural Element Condition at Step 4

Accordingly, the strengthening analysis results demonstrate that the post-retrofitted structure has successfully achieved and satisfied the Life Safety (LS)–Collapse Prevention (CP) performance criteria under the highest design earthquake level, namely BSE-2E (or the maximum considered earthquake). Consequently, an increase in base shear and displacement values at the performance point is obtained, as presented in the following table.

Table 2. Comparison of Performance Points Before and After Retrofitting

Position	**Performance Point Before CFRP**		**Performance Point After CFRP**	
	Base Shear (N)	**Displacement (mm)**	**Base Shear (N)**	**Displacement (mm)**
X Direction	3317814	182,498	3501787	172,663
Y Direction	3406188	185,217	3587411	180,954

Thus, it can be concluded that CFRP strengthening can be used as an effective alternative for retrofitting buildings to meet higher seismic force demands than those considered in the existing design strength.

CONCLUSIONS AND RECOMMENDATIONS

The results of the performance level analysis of the building based on the BSE-2E seismic level after the implementation of seismic rehabilitation using CFRP Laminate Tape SIKA Carbodur S1012 applied with 3 strips in the support regions and 1,5 strips in the span regions indicate that the post-retrofitted structure has successfully achieved and satisfied the Life Safety (LS)–Collapse Prevention (CP) performance criteria. The performance point prior to CFRP strengthening shows base shear and displacement values of 3317814 N and 182,498 mm in the X direction, and 3406188 N and 185,217 mm in the Y direction. After CFRP strengthening, the performance point increases to 3501787 N and 172,498 mm in the X direction, and 3587411 N and 180,954 mm in the Y direction. Furthermore, the post-retrofit nominal moment capacity at the supports reaches 11005406027 Nmm, corresponding to an increase in beam moment capacity of 1,0104%, while the nominal moment capacity at mid-span reaches 32820447,25 Nmm, with a moment capacity increase of 0,9969%.

FURTHER STUDY

The output results of this study only present the required CFRP strengthening schemes; therefore, future research is recommended to include detailed drawings and reinforcement detailing.

The software used in this study was SAP2000 V.26.3.0; hence, future studies are encouraged to utilize software capable of explicitly modeling CFRP material properties, including the nonlinear interaction between concrete, steel reinforcement, and CFRP laminates.

The analysis method employed in this study was linear static pushover analysis; therefore, future research is recommended to evaluate the structural response using nonlinear time history analysis in order to obtain a more detailed representation of the dynamic behavior.

REFERENCES

ACI 440.2R-17. (2017). *Guide for The Design and Construction of Externally Bonded FRP Systems for Strengthening Concrete Structures*.

ASCE 41-17. *Seismic Evaluation And Retrofit Of Existing Buildings ASCE 41-17.*

Fata, R. (2022). *18 Tahun Bencana Tsunami Aceh, Duka Indonesia dan Dunia*. Kementerian Keuangan Direktorat Jenderal Kekayaan Negara.

Febrianto, A., Erizal, & Putra, H. (2024). Analisis Seismik Struktur Bangunan Mengunakan ASCE 41-17 dan SNI 1726:2019. *Jurnal Teknik Sipil Dan Lingkungan*, *9*(2), 211–220. https://doi.org/10.29244/jsil.9.2.211-220

Hakiki, R. (2025). EVALUASI KINERJA ENERGI SERAP BALOK JEMBATAN KOMPOSIT KAYU LAMINASI-BETON BERLAPIS CFRP PADA BEBAN STATIS. *Jurnal Jalan Jembatan*, *42*(1). https://doi.org/10.58499/jatan.v42i1.1380

Hilmi, M., Erizal, & Febrita, J. (2021). Analisis Kinerja Struktur pada Bangunan Bertingkat dengan Metode Analisis Respon Spektrum Berdasarkan SNI 1726:2019. *Jurnal Teknik Sipil Dan Lingkungan*, *6*(3), 143–158. https://doi.org/10.29244/jsil.6.3.143-158

Hirwo, N., & Rozak, A. (2022). Evaluasi Perkuatan Struktur Menggunakan Carbon Fiber Reinforced Polymer (Cfrp) Pada Struktur Beton Bertulang Proyek Transformasi Gedung Sarinah Thamrin, Jakarta Pusat. *Jurnal Ismetek*, *14*(2), 75–80.

Hutama, B. P. (2021). Evaluasi Kinerja Bangunan Rumah Sakit Santa Maria Pemalang dengan Non-linier Static Pushover Analysis Metode ATC-40 dan FEMA 440. *INERSIA Lnformasi Dan Ekspose Hasil Riset Teknik Sipil Dan Arsitektur*, *17*(2), 118–129. https://doi.org/10.21831/inersia.v17i2.25511

Nasution, A. F. H. (2023). *ANALISA RESPON SPEKTRUM STRUKTUR GEDUNG BERTINGKAT*.

Novena, M. (2022). *Gempa Super Pernah Melanda Chile 3.800 Tahun Lalu, Berkekuatan M 9,5*. Kompas.

Purnama, A., & Nugroho, M. B. (2023). *PENGUATAN BALOK KAYU SENGON DENGAN MENGGUNAKAN CFRP DALAM MENAHAN BEBAN LENTUR*. http://journal.unita.ac.id/index.php/daktilitas/

Santoso, A. N., & Astawa, M. D. (2022). Performance Evaluation of 34 Floors Building Structure in Surabaya Based on Sni 1726:2012 and Sni 1726:2019. *Jurnal Teknik Sipil*, *18*(2), 185–201. https://doi.org/10.28932/jts.v18i2.3807

Sari, D., Natalia, M., Atmaja, J., Negeri Padang, P., & Limau Manis, K. (2022). *Carbon Fiber Reinforced Polymer Sebagai Bahan Retrofit Struktur Rumah Tinggal* (Vol. 4, Issue 2). https://ejournal2.pnp.ac.id/index.php/jppm

Suprapto, E., Andryan, M., Purnama, C., & Santoso, T. B. (2022). *Evaluasi Kinerja Perkuatan Gedung Menggunakan Carbon Fiber Reinforced Polymer (CRFP) Perfomance Evaluation of Building Reinforcement Fiber Reinforced Polymer (CRFP)*. *7*, 50–57. https://doi.org/doi.org/10.32528/hgn.v7i2

Tantyoko, H., Sari, D. K., & Wijaya, A. R. (2023). Prediksi Potensial Gempa Bumi Indonesia Menggunakan Metode Random Forest Dan Feature

Selection. *IDEALIS : InDonEsiA JournaL Information System*, *6*(2), 83–89. https://doi.org/10.36080/idealis.v6i2.3036

Trimurtiningrum, R., Saves, F., Fatmawati, L. E., & Setiawan, Y. A. (2020). Kinerja Struktur Gedung Beton Bertulang Dengan Bentang Kantilever 4 M Menggunakan Metode Analisis Pushover. *Extrapolasi*, *17*(2), 16–25. https://doi.org/10.30996/exp.v17i2.4429

Utomo, J., Lisantono, A., & Hermawan, H. (2024). SEISMIK RETROFIT BANGUNAN BETON BERTULANG EKSISTING DENGAN PERKUATAN DINDING GESER. *KoNTekS Ke-18 Kupang*, *2*(1). https://doi.org/10.62603/konteks.v2i1.239

Wicaksana, A., & Rosyidah, A. (2021). Pembandingan Perancangan Bangunan Tahan Gempa Menggunakan SNI 1726:2012 Dan SNI 1726:2019. *Jurnal Ilmiah Rekayasa Sipil*, *18*(1), 88–99. https://doi.org/10.30630/jirs.v18i1.416