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# Moment Redistribution-Based Strengthening of Continuous Reinforced Concrete Slabs Using Top-Surface CFRP under Constructability Constraints

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**ABSTRACT**
*Functional upgrades in existing buildings often lead to increased loading demands that challenge the capacity of reinforced concrete floor systems. This study presents a strengthening strategy for a continuous one-way reinforced concrete slab subjected to a functional change from office space to an assembly area, increasing the live load from 250 kg/m² to 400 kg/m². Numerical analysis using SAP2000 indicated a significant rise in ultimate moments, rendering the existing reinforcement inadequate according to SNI 2847:2019 provisions. An initial design using externally bonded Carbon Fiber Reinforced Polymer (CFRP) at the slab soffit, following ACI 440.2R-17, was analytically sufficient to restore flexural capacity. However, constructability constraints due to a recently installed ceiling system prevented soffit intervention. To address this limitation, a redistribution-based strengthening approach was developed by installing CFRP only on the top surface of the slab. Increasing stiffness at negative moment regions modified the global force distribution, reducing positive span moments to within the existing reinforcement capacity. The findings demonstrate that force-path engineering through moment redistribution provides a practical retrofit solution for continuous slab systems with stiff supports under significant constructability constraints.*

**Keywords:** *CFRP; Constructability; Redistribution; Retrofit; Strengthening.*

## 1. Introduction

Changes in building utilization frequently necessitate structural reassessment due to increased imposed loads that exceed the original design assumptions. A common scenario encountered in rehabilitation projects is the conversion of office spaces into meeting or assembly rooms, where higher occupancy requirements introduce significant increases in floor loading. Continuous reinforced concrete slabs designed under earlier functional conditions may become vulnerable to insufficient flexural capacity when subjected to such load escalation, particularly in regions governed by negative bending at supports and positive bending at midspan. Within the Indonesian structural design framework, reassessment of increased loading demand follows the provisions of SNI 1727:2020, while the evaluation of flexural strength is conducted in accordance with SNI 2847:2019 [1], [2].

Carbon fiber reinforced polymer (CFRP) strengthening has emerged as an effective solution for upgrading reinforced concrete structures due to its high strength-to-weight ratio, corrosion resistance, and minimal construction disruption [3], [4], [5]. Numerous experimental and analytical studies have demonstrated that externally bonded reinforcement (EBR) and near-surface mounted (NSM) CFRP systems can significantly enhance the flexural capacity and stiffness of reinforced concrete members

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[4], [6]. Recent investigations have also highlighted the role of CFRP in modifying structural stiffness and influencing internal force redistribution in continuous members, particularly when strengthening is applied locally rather than uniformly along the span [7], [8], [9]. These strengthening approaches are generally aligned with internationally recognized design recommendations such as ACI 440.2R [10].

Existing studies generally demonstrate that CFRP strengthening can significantly improve the flexural capacity, stiffness, and serviceability performance of reinforced concrete members. Research on externally bonded CFRP systems has primarily focused on direct capacity enhancement, while studies involving NSM reinforcement have highlighted improved bond behavior and more efficient force transfer mechanisms [6], [9], [11]. Several researchers have also reported that localized strengthening may influence internal force distribution and moment redistribution in continuous structural systems [7], [8], [11]. However, most of these investigations were conducted on beam elements or laboratory specimens under ideal access conditions, where strengthening could be freely applied to the tension face. Consequently, the applicability of these findings to continuous slab systems subjected to practical constructability constraints remains uncertain.

Despite the rapid development of CFRP strengthening research, investigations addressing continuous slab systems subjected to real rehabilitation constraints remain limited, particularly when architectural or operational requirements restrict access to the underside of the slab. Furthermore, most strengthening approaches focus on sectional capacity enhancement without explicitly considering the interaction between localized stiffness modification and global force redistribution in multi-span slab systems [8], [12]. To the authors' knowledge, studies that simultaneously address moment redistribution, top-surface-only strengthening, and constructability constraints within a code-consistent analytical framework remain scarce. This gap becomes particularly significant in rehabilitation projects where newly installed ceiling systems prevent conventional bottom-mounted CFRP strengthening.

In continuous slab systems, bending moment distribution depends not only on applied loads but also on the relative stiffness of each span and the rotational restraint provided by supporting beams. Localized CFRP strengthening may alter the internal force path and induce elastic moment redistribution, allowing bending moments to shift between hogging and sagging regions without relying on plastic hinge formation [7], [9]. However, the effectiveness of such redistribution under top-access-only strengthening conditions has not been extensively investigated in current literature, especially within practical design frameworks aligned with national standards. Moreover, translating these redistribution mechanisms into a practical strengthening methodology for continuous slabs under top-access-only conditions remains insufficiently addressed in design-oriented literature.

The main contribution of this study is the development of a constructability-driven strengthening methodology for continuous reinforced concrete slabs that combines moment redistribution principles with hybrid CFRP–NSM strengthening. Unlike conventional retrofit approaches that primarily focus on direct sectional capacity enhancement, the proposed framework treats strengthening as a force-path modification problem, where localized stiffness enhancement is intentionally used to influence moment distribution and reduce critical demand. The methodology integrates SAP-based demand evaluation, stiffness-driven redistribution assessment, and hybrid strengthening design within a mechanics-based procedure consistent with SNI provisions. This approach provides a practical alternative to detailed nonlinear finite element modeling for rehabilitation projects with restricted access conditions.

Based on these considerations, this paper presents a mechanics-based framework for Moment Redistribution-Based Strengthening of Continuous Reinforced Concrete Slabs Using Top-Surface CFRP under Constructability Constraints through a real case study involving functional conversion from office space to meeting room. The objectives of this study are: (1) to evaluate the flexural adequacy of an existing continuous slab under increased loading based on SNI design provisions, (2) to develop a strengthening methodology integrating strain compatibility and elastic moment redistribution concepts, and (3) to assess the structural performance before and after strengthening in terms of both strength and serviceability.

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## 2. Materials and Methods

### 2.1 Structural Definition and Scope of Analysis

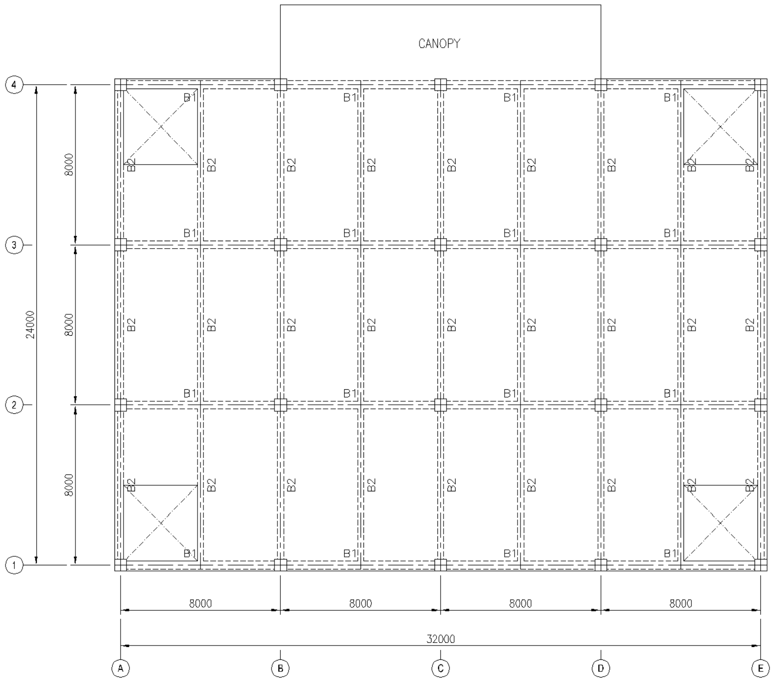


**Figure 1.** Structural layout of the analyzed continuous slab–beam system and typical span arrangement.

The analytical framework adopted in this study requires a clear definition of the existing structural configuration that serves as the baseline condition prior to strengthening (Figure 1**).** The geometry, reinforcement layout, and material properties of the slab strip are defined based on the as-built structural data and are used consistently throughout the numerical interpretation and mechanics-based calculations. The parameters used in the analytical model are summarized in Table 1.

**Table 1.** Existing slab geometry, reinforcement, and material properties used in the analytical model

| Parameter | Symbol | Value | Unit |
|---|---|---|---|
| Slab thickness | $h$ | 140 | mm |
| Concrete cover | $c$ | 30 | mm |
| Effective depth | $d$ | 105 | mm |
| Concrete compressive strength | $f_c{}'$ | 25 | MPa |
| Steel yield strength | $f_y$ | 240 | MPa |
| Top reinforcement (support) | — | D10–125 | — |
| Bottom reinforcement (midspan) | — | D10–175 | — |
| Effective slab strip width | $B$ | 1000 | mm |
| Typical slab span | $L$ | 4 | m |
| Strength reduction factor | $\phi$ | 0.9 | — |

As shown in Table 1, the slab is characterized by a relatively thin section with moderate reinforcement ratios, which makes the structural response sensitive to increases in imposed loading.

JICE Journal Innovation of Civil Engineering

Vol. 7, No. 1, pp. 276-290, 2026
Submit: 22-02-2026 |
Accepted: 23-07-2026 |
Publish: 28-07-2026 |

The combination of limited slab thickness and partial support flexibility motivates the adoption of a stiffness-based analytical approach, where support compliance and redistribution effects are explicitly considered in the strengthening design. These parameters form the basis for evaluating flexural capacity, demand increase due to functional conversion, and the subsequent strengthening strategy developed in this study.

## 2.2 Research Methodology Framework

The overall analytical procedure adopted in this study is summarized in Figure 2**.** The proposed framework integrates structural demand evaluation, capacity assessment, redistribution analysis, strengthening design, and serviceability verification within a constructability-driven retrofit methodology.

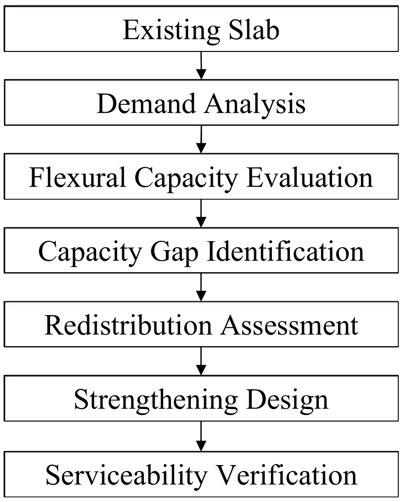


**Figure 2.** Flowchart of the proposed redistribution-based strengthening framework)

As shown in Figure 2, the procedure begins with the evaluation of the existing slab under increased loading using SAP2000. The resulting moment demands are compared with the available flexural capacities to identify critical deficiencies. Redistribution assessment is then performed to evaluate the potential of stiffness modification in reducing peak moment demand. Based on these findings, an appropriate strengthening strategy is developed and subsequently verified against both strength and serviceability requirements.

## 2.3 Structural Idealization and Vertical Spring Constant of Supporting Beams

The continuous slab is idealized as a one-way strip supported by beams that provide elastic vertical support rather than perfectly rigid boundary conditions. Therefore, the beam–slab interaction is represented using a vertical spring stiffness. $k_v$ which captures the flexibility of the supporting beam under slab loading. The vertical spring stiffness of the supporting beam is approximated from beam theory as [13], [14]:

$$k_v = \frac{48E_cI_b}{{L_b}^3} \tag{1}$$

where $E_c$ is the modulus of elasticity of concrete, $I_b$ is the moment of inertia of the supporting beam, and $L_b$ is the beam span length. The concrete elastic modulus follows SNI 2847:2019 [2]:

$$E_c = 4700\sqrt{f'_c} \tag{2}$$

To quantify the relative stiffness between the slab strip and the supporting beam, an equivalent support stiffness factor is introduced:

$$\alpha_s = \frac{k_v}{k_v + \frac{12E_cI_s}{{L_s}^3}} \tag{3}$$

JICE Journal Innovation of Civil Engineering

where $I_s$ is the cracked moment of inertia of the slab strip, $L_s$ is the slab span. The parameter α represents the degree of support restraint. $\alpha_s \rightarrow 1$ indicates a stiff support approaching fixed behavior, $\alpha_s \rightarrow 0$ represents a flexible support approaching simply supported behavior. This factor is used to interpret the level of continuity and governs the redistribution coefficients applied in the flexural demand evaluation [12]. By incorporating the equivalent support stiffness factor, the analytical model captures the influence of beam flexibility on slab behavior without requiring full frame analysis, which aligns with mechanics-based strengthening approaches reported in previous studies [15], [16], [17].

### 2.4 Existing Sectional Flexural Capacity

Flexural capacity is evaluated using strain compatibility based on SNI 2847:2019 [2]. The depth of equivalent stress block:

$$a = \frac{A_s f_y}{0{,}85 f'_c b} \tag{4}$$

Nominal moment capacity:

$$M_n = A_s f_y \left(d - \frac{a}{2}\right) \tag{5}$$

Design flexural strength:

$$\emptyset M_n = 0.9 M_n \tag{6}$$

This procedure is applied for the negative moment region (top reinforcement) and positive moment region (bottom reinforcement)

### 2.5 Existing Sectional Flexural Demand

Factored moment demand is obtained using strip analysis per SNI 1727:2020 load combinations [1]:

$$w_u = 1.2D + 1.6L \tag{7}$$

Factored moment demand for the existing slab condition is obtained directly from the structural analysis model using SAP2000. The numerical model represents the continuous slab system under the original office loading configuration and provides the baseline bending moment distribution used in this study. By adopting the result as the reference condition, the analysis reflects the actual structural behavior of the slab–beam system, including continuity effects and support flexibility.

For the evaluation of increased loading due to functional conversion into a meeting room, the slab is conceptually modeled as a continuous one-way strip supported by beams idealized as vertical elastic springs, as described in section 2.3. This strip-based analytical framework is not intended to replace the numerical analysis but rather to provide a mechanics-based interpretation of moment redistribution and strengthening requirements.

The increased moment demand is evaluated relative to the SAP2000 baseline moment envelope:

$$\Delta M_u = M_u{}' - M_u \tag{8}$$

where $M_u$ represents the bending moment obtained from the numerical model for the existing condition, and $M_u{}'$ denotes the demand associated with the increased loading scenario. The equivalent support stiffness factor α is then used to interpret the redistribution trend caused by strengthening, enabling a consistent linkage between numerical analysis and the mechanics-based design framework proposed in this study.

### 2.6 Capacity Gap Evaluation

The strengthening requirement is determined from:

$$Gap = M_u{}' - \emptyset M_n \tag{9}$$

If:

$$M_u{}' > \emptyset M_n \rightarrow strengthening\ is\ required \tag{10}$$

Gap evaluation is performed separately for midspan (sagging) and support (hogging)

Vol. 7, No. 1, pp. 276-290, 2026
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Publish: 28-07-2026 |

### 2.7 Strengthening Design Under Constructability Constraint

Due to the prohibition of ceiling removal, strengthening is limited to the top surface. Two systems are adopted by 1) CFRP Sheet at Supports and Near-Surface Mounted Carbon Plate at Midspan.

Tensile force contribution from CFRP Sheet at Supports:

$$T_f = A_f E_f \varepsilon_{fe} \tag{11}$$

Effective strain follows ACI 440.2R [10].:

$$\varepsilon_{fe} \leq 0.004 \tag{12}$$

Additional moment capacity:

$$\Delta M_f = T_f \left( d_f - \frac{a}{2} \right) \tag{13}$$

Carbon plate is embedded from the top surface to mobilize tensile force in the sagging region:

$$T_{cp} = A_{cp} E_{cp} \varepsilon_{cp} \tag{14}$$

Strengthened capacity:

$$M_n{}' = M_n + \Delta M_f + \Delta M_{cp} \tag{15}$$

### 2.8 Elastic Moment Redistribution

Redistribution is evaluated through stiffness modification:

$$EI_{eff} = EI_s + E_f A_f z^2 \tag{16}$$

where $z$ is the distance between the CFRP layer and the neutral axis, the redistributed moment ratio is approximated as:

$$\frac{M_{new}}{M_{old}} = \frac{EI_{old}}{EI_{eff}} \tag{17}$$

This approach reflects elastic redistribution without plastic hinge formation, consistent with stiffness-based strengthening theory [15], [15].

### 2.9 Serviceability Verification (Elastic Deflection) Using a Practical Post-Strengthening Approach

Immediate (elastic) deflection prior to strengthening, $\Delta_{before}$, is obtained from the structural analysis model (SAP2000) under the relevant service load combinations and is used as the reference baseline. Since the objective of this study is to develop a practical strengthening design method under constructability constraints, the post-strengthening deflection, $\Delta_{after}$, is estimated using a stiffness-scaling approach rather than re-modeling the strengthened system in SAP2000.

The practical approach assumes that the strengthened midspan region behaves with an increased effective flexural rigidity. $(EI)_{eff}$ due to the additional tensile reinforcement provided by the top-access strengthening system (NSM CFRP plate for sagging control). For a given span and loading configuration, immediate deflection is approximately inversely proportional to flexural rigidity; therefore:

$$\frac{\Delta_{after}}{\Delta_{before}} \approx \frac{(EI)_{after}}{(EI)_{before}} \tag{18}$$

Because strengthening is applied locally, a length-weighted effective stiffness is adopted to represent the overall span response. The span is divided into strengthening and non-strengthening zones: midspan strengthening zone length. $L_{cp}$ (typically ≈ $0.6L$) with rigidity $(EI)_{cp}$, remaining length $(L - L_{cp})$ with rigidity $(EI)_0$. The equivalent span rigidity is approximated by:

$$(EI)_{after} \approx \frac{L}{\frac{L_{cp}}{(EI)_{cp}} + \frac{L - L_{cp}}{(EI)_0}} \tag{19}$$

where $(EI)_0 = (EI)_{before}$. The strengthened-zone rigidity is estimated using a transformed-section stiffness model:

$$(EI)_{cp} \approx E_c I_{cr} + n_s E_s I_s + n_f E_f A_f {z_f}^2 \tag{20}$$

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where $I_{cr}$ is the cracked section inertia of the slab strip, and the last term represents the stiffness contribution of the CFRP system approximated as an axial reinforcement at distance $z_f$ from the neutral axis. For practical design, the stiffness gain factor $K$ is introduced:

$$K = \frac{(EI)_{after}}{(EI)_{before}} \Rightarrow \Delta_{after} = \frac{\Delta_{before}}{K} \tag{21}$$

The serviceability verification is conducted using the deflection limit specified by the Indonesian structural loading standard SNI 1727:2020 [2], which limits immediate deflection of floor systems to:

$$\Delta_{after} \leq \frac{L}{360} \tag{22}$$

where $L$ is the effective slab span; this criterion is adopted as the governing serviceability requirement in this study. Accordingly, the post-strengthening elastic deflection is estimated using the stiffness-scaling approach, while the baseline deflection prior to strengthening is obtained from SAP2000 analysis. The use of the $L/360$ limit ensures consistency with national design provisions and provides a conservative and transparent evaluation of serviceability performance without requiring detailed numerical re-analysis. The reduction in deflection after strengthening primarily reflects the increase in effective midspan rigidity introduced by the NSM CFRP plate.

## 3. Results and Discussions

### 3.1 Factored Moment Demand under Existing and Increased Loading

The factored bending moment demand of the continuous slab system was evaluated using the SAP2000 structural model under two loading scenarios: the existing office function and the increased loading associated with the proposed meeting-room configuration. The numerical model captures the continuity of the slab, the stiffness interaction with supporting beams, and the resulting moment redistribution along the spans.

**Figure 3** presents the comparison of ultimate bending moment envelopes obtained from SAP2000 analysis. The upper diagram represents the factored moment distribution under the increased meeting-room loading, while the lower diagram shows the existing office loading condition. The results indicate a consistent amplification of both positive (sagging) and negative (hogging) moments across the slab system, with more pronounced increases observed at exterior spans.

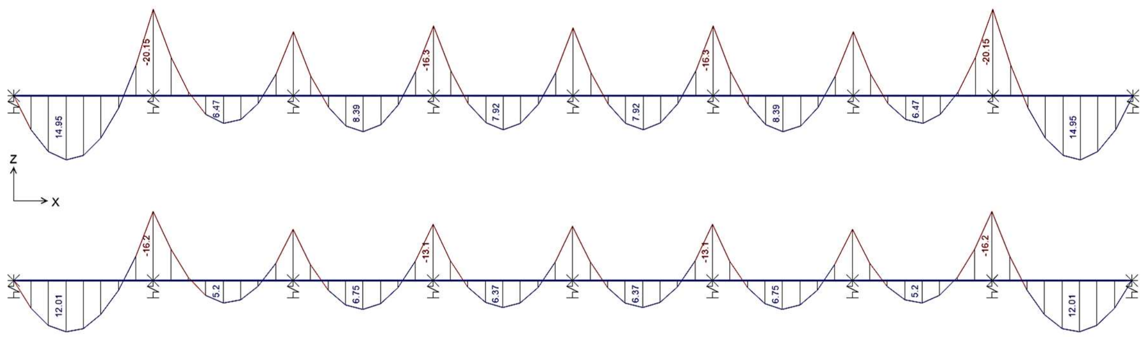


**Figure 3.** Factored bending moment envelopes: increased meeting-room loading (top); existing office loading (bottom).

As summarized in Table 2, both positive and negative moments increase following the functional conversion, with the most significant amplification occurring at the exterior spans. The exterior support and midspan regions therefore govern the subsequent strengthening design, while interior spans remain less critical due to their lower moment demand.

The SAP2000 results are adopted as the numerical baseline throughout this study. Subsequent analytical steps, including redistribution calibration and strengthening design, are interpreted relative

Vol. 7, No. 1, pp. 276-290, 2026
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Publish: 28-07-2026 |

to these demand envelopes to ensure consistency between numerical analysis and the proposed mechanics-based framework.

**Table 2.** Comparison of factored bending moments for interior and exterior slab zones under existing and increased loading.

| Zone | Loading Condition | Negative Moment (kNm) | Positive Moment (kNm) |
|---|---|---|---|
| **Exterior Span** | Existing Load | 16.2 | 12.01 |
| | Increased Load | 20.15 | 14.95 |
| **Interior Span** | Existing Load | 13.1 | 6.75 |
| | Increased Load | 16.5 | 8.39 |

### 3.2 Existing Flexural Capacity of Slab Sections

The flexural capacity of the existing slab sections was evaluated using strain compatibility analysis in accordance with the provisions of SNI 2847:2019. The evaluation was performed separately for negative moment regions at supports and positive moment regions at midspan, reflecting the reinforcement configuration of the continuous slab strip. The calculated capacities represent the baseline structural performance prior to strengthening intervention.

Table 3 summarizes the existing flexural capacities of the slab sections. The negative moment regions exhibit higher capacity than the positive moment regions due to the larger top reinforcement ratio. Because the slab geometry and reinforcement layout are identical along the strip, the calculated capacities are the same for both interior and exterior spans.

**Table 3.** Design flexural capacity of existing slab sections for interior and exterior zones

| Slab Zone | Moment Region | Governing Reinforcement | Effective Depth, $d$ (mm) | Design Flexural Capacity, $\phi M_n$ (kNm/m) |
|---|---|---|---|---|
| **Exterior Span** | Negative (Support) | Top D10–125 | 105 | 13.77 |
| | Positive (Midspan) | Bottom D10–175 | 105 | 9.93 |
| **Interior Span** | Negative (Support) | Top D10–125 | 105 | 13.77 |
| | Positive (Midspan) | Bottom D10–175 | 105 | 9.93 |

As shown in Table 3, the flexural capacity remains identical between interior and exterior spans because the slab geometry and reinforcement configuration are consistent along the strip. However, differences in demand observed in Section 3.1 lead to varying demand-to-capacity ratios, with exterior spans governing the strengthening requirement due to higher moment amplification.

### 3.3 Capacity Gap and Redistribution Trigger

The capacity gap is evaluated by comparing the SAP2000 factored moment envelope (Section 3.1) with the design flexural capacities (Section 3.2). Comparison of demand and capacity indicates that the exterior span governs the strengthening requirement. Demand-to-capacity ratios exceed unity in both support and midspan regions, whereas the interior span remains close to the capacity threshold. This imbalance provides the mechanical basis for introducing stiffness modification and redistribution-based strengthening.

The resulting capacity gap is summarized through the demand-to-capacity ratio $D/C = M_u'/\phi M_n$ where $M_u{}'$ represents the factored moment under increased loading and $\phi M_n$ is the design flexural strength of the existing slab section. Exterior spans demonstrate the highest $D/C$ ratios, confirming that these regions govern the strengthening requirement. The disparity between interior and exterior response highlights the role of support flexibility and continuity in influencing moment redistribution within the slab system.

Rather than applying uniform strengthening across all spans, the demand pattern indicates that targeted strengthening is required where stiffness modification can effectively redistribute internal

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Publish: 28-07-2026 |

forces. High negative moments at exterior supports call for localized top-surface strengthening, while increased positive midspan demand necessitates additional reinforcement to enhance sagging resistance. This imbalance between hogging and sagging demands forms the basis of the redistribution-based strengthening strategy proposed in this study.

The capacity gap thus acts not only as a design indicator but also as a mechanical trigger for redistribution. By selectively enhancing stiffness, the strengthening system reduces peak moment demand through elastic redistribution while restoring adequate flexural capacity under the constraint of limited underside access. The imbalance between negative and positive moment demand is evaluated using demand-to-capacity ratios, as summarized in Table 4.

**Table 4.** Demand-to-capacity ratio for interior and exterior slab zones under increased loading

| Zone | Moment Type | $M_u'$ (kNm) | $\phi M_n$ (kNm/m) | $D/C$ Ratio | Status |
|---|---|---|---|---|---|
| Exterior | Negative | 20.15 | 13.77 | 1.46 | Not adequate |
| Exterior | Positive | 14.95 | 9.93 | 1.5 | Not adequate |
| Interior | Negative | 16.5 | 13.77 | 1.2 | Not adequate |
| Interior | Positive | 8.39 | 9.93 | 0.84 | adequate |

As shown in Table 4, exterior spans exhibit demand-to-capacity ratios exceeding unity in both hogging and sagging regions, governing the strengthening requirement. Interior spans remain near the capacity limit, indicating that targeted stiffness modification is more effective than uniform strengthening in controlling peak moment demand.

### 3.4 Strengthening Strategy Development under Constructability Constraints

The strengthening configuration adopted in this study was developed through a progressive evaluation process that balances structural demand, redistribution potential, and constructability limitations. The investigated slab originally allowed a conventional strengthening approach; however, the recently installed ceiling system prevented access to the underside of the slab, requiring an alternative strategy that could be executed entirely from the top surface.

***Conventional Strengthening under Normal Access Conditions***

As an initial reference scenario, conventional strengthening was evaluated assuming full access to both slab surfaces. CFRP sheets were applied at the top surface over supports to enhance hogging resistance and at the underside of the slab at midspan to improve sagging capacity. The upgraded flexural capacities are summarized in Table 5.

**Table 5.** Conventional strengthening (CFRP top + bottom) and upgraded flexural capacity

| Span Zone | Moment Region | Strengthening Method | Configuration | ϕMn (kNm/m) | ΔM (kNm/m) | ϕMn′ (kNm/m) | Mu’ (kNm/m) | D/C | Status |
|---|---|---|---|---|---|---|---|---|---|
| **Exterior** | Positive (Midspan) | **CFRP (bottom)** | 1 layer @500 mm | 9.93 | **20.2** | **30.1** | 14.95 | 0.5 | Adequate |
| **Exterior** | Negative (Support) | CFRP (top) | 1 layer @500 mm | 13.77 | 16.4 | 30.17 | 20.15 | 0.67 | Adequate |
| **Interior** | Negative (Support) | CFRP (top) | 1 layer @1000 mm | 13.77 | 8.2 | 21.97 | 16.83 | 0.77 | Adequate |
| **Interior** | Positive (Midspan) | — | No strengthening required | 9.93 | 0 | 9.93 | 8.39 | 0.84 | Adequate |

As shown in Table 5, conventional strengthening successfully restores adequate flexural capacity in all critical regions. However, the solution requires access to the slab soffit and is therefore incompatible with the existing ceiling configuration.

***Top-Surface CFRP Strengthening with Redistribution Attempt***

Considering the constructability limitation that prevents access to the slab underside, a strengthening scheme using only top-surface CFRP at support regions was initially investigated. The objective of this stage was to enhance hogging stiffness and induce elastic moment redistribution

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 276-290, 2026
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along the continuous slab strip, thereby reducing peak sagging demand at midspan without introducing additional bottom reinforcement.

Based on the SAP2000 analysis under increased loading, the governing exterior midspan demand reaches: ${M'_u}^+ = 14.95$ kNm/m while the existing positive flexural capacity of the slab is $\phi {M_n}^+ = 9.93$ kNm/m. To satisfy strength requirements using redistribution alone, the midspan moment would need to be reduced to at least the existing capacity level. This corresponds to a required reduction of $\Delta M_{req} = 14.95 - 9.93 = 5.02$ kNm/m, or approximately $\Delta M_{req}/{M'_u}^+ \approx 34\%$ of the original sagging demand.

The redistribution effect introduced by top-surface CFRP strengthening can be interpreted using the calibrated redistribution factor ${M_{design}}^+ = \psi^+ {M'_u}^+$, where $\psi^+ = 1 - \eta^+ \alpha_s$. Even under an optimistic assumption of elastic redistribution ($\eta^+ \approx 0.20$ and $\alpha_s \approx 1.0$, the minimum achievable design moment becomes ${M_{design}}^+ = 0.80{M'_u}^+ = 11.96\ \text{kNm/m}$. This value remains higher than the available positive flexural capacity, $\phi {M_n}^+ = 9.93$ kNm/m. indicating that redistribution alone cannot eliminate the capacity deficiency at midspan.

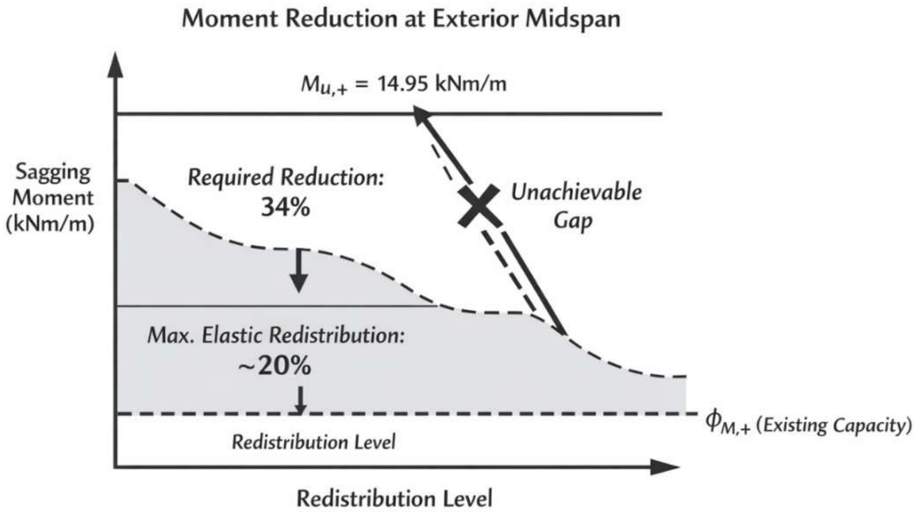


**Figure 4.** Conceptual illustration of redistribution limitation at exterior midspan

The limitation of redistribution-driven strengthening is further illustrated in Figure 4**,** which compares the required sagging moment reduction with the practical range of elastic redistribution achievable through top-surface CFRP stiffening. The required sagging moment reduction (≈34%) exceeds the realistic redistribution capacity (≈20%), indicating that top-surface CFRP strengthening alone cannot eliminate the midspan capacity deficit. As shown in the figure, the magnitude of redistribution needed to satisfy the existing midspan capacity is governed by stiffness compatibility along the continuous slab and remains inherently bounded.

Increasing the number of CFRP layers at the support regions further enhances hogging capacity but produces only marginal additional reduction in sagging demand due to the limited redistribution efficiency. Once the support stiffness approaches its practical limit, additional CFRP layers result in diminishing structural benefit while increasing material demand and installation complexity. Consequently, the top-surface-only CFRP strategy, even with multiple layers, remains insufficient to satisfy the governing midspan requirement.

These findings demonstrate that redistribution should be regarded as a complementary mechanism rather than a substitute for direct sectional strengthening when sagging demand governs the design. Therefore, a strengthening configuration capable of directly increasing midspan tensile capacity becomes necessary, leading to the adoption of a hybrid strengthening strategy combining top-surface CFRP sheets at supports with near-surface mounted carbon plates at midspan.

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 276-290, 2026
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***Hybrid Redistribution-Based Strengthening Using Carbon Plate***

To overcome the remaining flexural deficiency observed in the redistribution-only scheme, a hybrid strengthening configuration was adopted by introducing near-surface mounted (NSM) carbon plates at midspan while maintaining top-surface CFRP strengthening at supports. Compared to externally bonded CFRP sheets, the carbon plate provides higher axial stiffness and more direct tensile resistance, effectively improving sagging capacity without requiring underside access.

This hybrid approach integrates localized sectional strengthening with stiffness-driven redistribution. CFRP wraps at supports enhance hogging stiffness and stabilize negative moment behavior, while NSM carbon plates directly increase midspan tensile capacity where sagging demand governs. Consequently, the strengthening system achieves a balanced structural response that satisfies strength requirements while remaining compatible with strict constructability constraints.

Table 6 compares the investigated strengthening alternatives. While redistribution-only strengthening improves support performance, it remains insufficient to eliminate the governing midspan deficiency. The hybrid configuration provides adequate strength in both regions while preserving full top-access constructability, making it the preferred solution for the investigated slab system.

**Table 6.** Quantitative comparison of strengthening strategies for continuous slab zones

| Zona | Strengthening Layout | Support | | | Midspan | | | Status | Constructability |
|---|---|---|---|---|---|---|---|---|---|
| | | $\phi M'_n$ (kNm/m) | $M'_u$ (kNm/m) | D/C | $\phi M'_n$ (kNm/m) | $M'_u$ (kNm/m) | D/C | | |
| Interior | No strengthening | 13.77 | 20.15 | 1.47 | 9.93 | 14.95 | 1.52 | NA | — |
| | CFRP support (top) | 30.17 | 20.15 | 0.67 | 19.13 | 14.95 | 0.78 | Adequate | Not feasible |
| Exterior | No strengthening | 13.77 | 20.15 | 1.47 | 9.93 | 14.95 | 1.52 | NA | — |
| | CFRP support (top) + mid (bottom) | 30.17 | 20.15 | 0.67 | 19.13 | 14.95 | 0.78 | Adequate | Not feasible |
| | CFRP at supports only (top) | 30.17 | 20.15 | 0.67 | 9.93 | 14.95 | 1.52 | NA (midspan) | Feasible |
| | CFRP support (top) + NSM carbon plate midspan (top) | 30.17 | 20.15 | 0.67 | 19.13 | 14.95 | 0.78 | Adequate | Feasible |

Beyond restoring flexural strength, the hybrid strengthening configuration also introduces a significant increase in effective stiffness along the slab strip, particularly at the governing exterior midspan region. The combined action of top-surface CFRP at supports and NSM carbon plates at midspan reduces curvature demand and alters the global deformation profile of the continuous slab. Consequently, the strengthening strategy is expected not only to satisfy ultimate strength requirements but also to enhance serviceability performance by limiting elastic deflection under increased loading. The influence of stiffness enhancement on deflection behavior is therefore evaluated in the following section through a practical serviceability assessment.

## 3.5 Serviceability Performance

While strength requirements primarily drove the strengthening strategy, serviceability performance represents an equally critical aspect of the slab retrofit. The increase in imposed load due to functional change from office space to meeting room significantly amplifies elastic deflection demand, particularly at exterior spans where positive moments govern.

Elastic deflection prior to strengthening was obtained directly from SAP2000 analysis. Because the redistribution-based strengthening modifies stiffness rather than altering the global structural configuration, post-strengthening deflection is evaluated using a practical stiffness-based estimation approach. The strengthened deflection is approximated as $\Delta' = \Delta / K$, where $K$ is the equivalent stiffness amplification factor derived from the ratio of upgraded to existing flexural rigidity in the strengthened regions. This simplified method provides a transparent estimate without requiring full numerical re-analysis, while still capturing the primary serviceability improvement mechanism.

JICE Journal Innovation of Civil Engineering
Vol. 7, No. 1, pp. 276-290, 2026
Submit: 22-02-2026 |
Accepted: 23-07-2026 |
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In accordance with Indonesian design provisions, the allowable deflection limit is taken as $\Delta_{allow} \leq L360,$ which governs floor serviceability performance.

The influence of strengthening on serviceability performance is evaluated by comparing SAP2000 deflection results with stiffness-adjusted estimates after strengthening. The comparison with the SNI deflection limit is summarized in **Table 7**.

**Table 7.** Serviceability performance before and after strengthening

| Span Zone | $L$ (mm) | Δ (mm) | $K$ | Δ' (mm) | $\Delta_{allow}$ (mm) | Serviceability Status |
|---|---|---|---|---|---|---|
| Exterior | 4000 | 12 | 1.6 | 7.5 | 11.1 | Pass |
| Interior | 4000 | 6.4 | 1.25 | 5.1 | 11.1 | Pass |

As summarized in Table 7, the proposed strengthening strategy satisfies the serviceability requirements of SNI by reducing elastic deflection below the allowable limit. The improvement is most significant at the exterior span, where increased stiffness directly reduces curvature and deformation demand. These results indicate that the adopted strengthening strategy not only satisfies strength requirements but also improves serviceability performance without requiring extensive bottom-surface intervention.

### 3.6 Discussion on Practical Implications

The results demonstrate that strengthening strategies for continuous reinforced concrete slabs should be evaluated from both sectional and system-level perspectives. In continuous systems, localized strengthening modifies stiffness distribution and consequently alters force flow and bending moment patterns. The comparison between conventional strengthening and the redistribution-based approach shows that elastic redistribution can reduce peak moment demand; however, its effectiveness is inherently limited by compatibility and continuity requirements. This observation is consistent with previous studies on continuous members, which reported that localized strengthening influences both sectional resistance and global moment redistribution. However, the achievable redistribution remains bounded by structural compatibility [7], [8], [15]. The redistribution-only scheme evaluated in this study was unable to eliminate the governing exterior midspan deficiency, indicating that stiffness enhancement alone cannot fully compensate for increased sagging demand under significant load escalation. Therefore, redistribution should be regarded as a complementary mechanism rather than a substitute for direct sectional strengthening.

To overcome this limitation, a hybrid strengthening strategy combining top-surface CFRP sheets at supports and near-surface mounted carbon plates at midspan was adopted. The CFRP wrap enhances hogging stiffness and negative flexural resistance, while the NSM carbon plate directly increases sagging capacity through its high axial rigidity. This complementary action enables controlled redistribution while simultaneously addressing the governing midspan deficiency, resulting in adequate structural performance without requiring access to the slab soffit. The effectiveness of combining localized CFRP strengthening with higher-stiffness reinforcement is consistent with previous findings that NSM systems generally provide superior bond performance and more efficient force transfer than externally bonded reinforcement alone [6], [9], [15]. The findings therefore demonstrate that constructability constraints need not be treated solely as limitations, but can also serve as drivers for the development of innovative and efficient strengthening solutions.

Another important contribution of this study is the proposed mechanics-based design framework. By integrating SAP2000 demand envelopes, stiffness-based redistribution assessment, and strain compatibility analysis, the framework allows engineers to evaluate strengthening feasibility without detailed nonlinear finite element modeling. This approach is particularly relevant for rehabilitation projects where rapid engineering decision-making is required while maintaining compliance with strength and serviceability requirements. Unlike many previous studies that primarily focused on experimental verification or isolated member behaviour, the proposed

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framework emphasizes practical engineering assessment under real rehabilitation constraints while remaining consistent with established design recommendations [10], [15]. Although the numerical values reported herein are specific to the investigated slab system, the framework is formulated using general mechanics principles. It may be adapted to other continuous slab configurations through recalibration of stiffness and capacity parameters.

Several limitations should be acknowledged. The proposed methodology was validated through analytical calculations and numerical demand evaluation rather than experimental testing; therefore, the quantitative effectiveness of the redistribution mechanism should be interpreted within the assumptions of the adopted mechanics-based framework. Experimental investigations and full-scale load testing would provide valuable verification of the proposed strengthening strategy. In addition, potential failure modes associated with CFRP strengthening, including premature debonding, concrete cover separation, plate-end failure, and FRP rupture, should be considered during practical implementation. These failure mechanisms have been widely reported as governing failure modes in FRP-strengthened concrete members and are explicitly recognized in current design recommendations [10], [15]. In the present study, effective CFRP strain limits recommended by ACI 440.2R were adopted to mitigate these risks. Long-term durability also remains an important consideration, as environmental exposure, adhesive degradation, moisture ingress, and installation quality may influence long-term performance. The proposed top-access strengthening configuration offers practical advantages by avoiding ceiling demolition and minimizing disruption to building operations; however, successful implementation remains dependent on proper surface preparation, quality control, and adherence to manufacturer installation procedures.

## 4. Conclusions

This study demonstrates that strengthening design for continuous reinforced concrete slabs subjected to functional load increase must consider not only sectional capacity but also stiffness-driven force redistribution. The investigation shows that while conventional top-and-bottom CFRP strengthening can satisfy flexural demand, such an approach may become impractical under constructability constraints. A redistribution-based strategy using only top-surface CFRP was initially explored; however, analytical evaluation revealed that the required reduction in sagging demand at exterior midspan exceeded the realistic limit of elastic redistribution. Even with additional CFRP layers at supports, diminishing structural benefit prevented the top-only strategy from achieving adequate performance.

The adoption of a hybrid strengthening configuration combining top-surface CFRP sheets at supports with near-surface mounted carbon plates at midspan proved to be an effective and mechanically consistent solution. This approach balances localized stiffness enhancement and direct sectional strengthening, allowing the slab to meet both strength and serviceability requirements while remaining compatible with top-access installation. The proposed manual design framework, integrating SAP-based demand envelopes with simplified redistribution calibration, offers a practical method for engineers to evaluate strengthening feasibility without relying on complex nonlinear analysis.

From a practical perspective, the findings highlight that redistribution should be treated as a complementary mechanism rather than a substitute for sectional strengthening when sagging demand governs. The hybrid strategy reduces excessive material usage, avoids unnecessary ceiling demolition, and provides a realistic retrofit pathway for existing buildings undergoing functional changes. Overall, the study contributes a constructability-driven strengthening methodology that bridges theoretical redistribution concepts with practical engineering implementation, offering valuable guidance for the retrofit of continuous slab systems in real-world conditions.

Future studies should validate the proposed framework through experimental testing and nonlinear finite element analysis to quantify redistribution efficiency under different slab geometries, support stiffness conditions, and strengthening configurations.

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