

The Effect of Bar Ductility Reinforcement on the Flexural Behavior of Reinforced Concrete Beams

Baiq Asiani

Department of Civil Engineering, Hasanuddin University, Makassar, Indonesia
asianib23d@student.unhas.ac.id

Rudy Djamaluddin

Department of Civil Engineering, Hasanuddin University, Makassar, Indonesia
rudy0011@gmail.com

Fakhruddin

Department of Civil Engineering, Hasanuddin University, Makassar, Indonesia
fakhruddin@unhas.ac.id (corresponding author)

Received: 11 December 2025 | Revised: 21 January 2026 | Accepted: 31 January 2026

Licensed under a CC-BY 4.0 license | Copyright (c) by the authors | DOI: <https://doi.org/10.48084/etasr.16889>

ABSTRACT

This study investigates the influence of reinforcing steel ductility, directly associated with carbon content, on the flexural behavior of reinforced concrete beams. Three beam specimens with identical dimensions (150 mm × 200 mm × 3300 mm) were tested under static loading, each reinforced with steel bars classified as Low-Carbon Steel (LCS), Medium-Carbon Steel (MCS), or High-Carbon Steel (HCS). The experimental program evaluated the load deflection response, load-strain behavior, and crack pattern of each beam. The results show that variations in carbon content significantly affect the ductility and stiffness of reinforced concrete beams. The beam reinforced with LCS exhibited the highest flexural ductility ($\mu = 4.64$), indicating superior plastic deformation capacity and greater energy absorption before failure. MCS and HCS reinforcements produced lower ductility values of 2.84 and 2.19, respectively, corresponding to higher stiffness and more limited deformation beyond yielding. Crack pattern observations confirmed that all beams initially developed flexural cracks, which transitioned into flexure shear cracks at higher load levels. Overall, reinforcing LCS substantially improves strain compatibility, flexural performance, and energy dissipation capacity of reinforced concrete beams. These findings highlight the importance of selecting highly ductile reinforcement to enhance structural safety and seismic resistance.

Keywords-reinforced concrete beam; ductility; reinforcing steel; carbon content; flexural behavior; crack pattern

I. INTRODUCTION

The rapid development of infrastructure in Indonesia has increased the demand for construction materials and structural systems that provide not only adequate strength but also sufficient ductility, particularly in earthquake-prone regions. Ductile structural behavior is crucial to ensure that reinforced concrete members can sustain large inelastic deformations and effectively dissipate seismic energy without sudden brittle failure. This requirement was clearly demonstrated during the 2018 Palu earthquake (Mw 7.4), which caused extensive structural damage associated with strong ground motion, liquefaction, and the limited deformation capacity of many reinforced concrete components, especially beams and columns. The mechanical properties and chemical composition

of reinforcing steel significantly influence the strength, stiffness, and ductility of reinforced concrete structures.

Research into reinforcing bars commonly used in Indonesia has shown that variations in carbon content, arising from differences in raw materials and manufacturing processes, result in significant differences in yield strength, tensile strength, and elongation capacity among products from different local producers [1, 2]. These findings indicate that compliance with nominal standards alone is insufficient when reinforcing steel is intended for seismic-resistant structures. While higher-strength reinforcement may increase flexural capacity, it can simultaneously reduce ductility, delay stable plastic hinge formation, and limit energy dissipation under severe seismic loading [3]. Conversely, reinforcement with lower or moderate carbon content generally exhibits greater

plastic deformation capacity, which contributes to preventing brittle flexural failure and improving post-yield structural performance. Insufficient ductility of reinforced concrete members has been directly associated with severe structural damage during past seismic events. The decrease in rebar ductility is shown in Figure 1.



Fig. 1. Collapsed buildings observed after structural failure.

Despite these findings, either the mechanical properties of reinforcing steel or the flexural behavior of reinforced concrete beams have been examined independently. Experimental investigations that directly correlate the ductility of reinforcing steel, particularly associated with different carbon contents, with the complete flexural response of reinforced concrete beams, including post-peak behavior, displacement ductility, energy dissipation, and failure mechanisms, remain limited [4]. This limitation is especially evident when reinforcing steels produced and widely used in Indonesia. Moreover, most previous research has focused on strength enhancement, while the influence of steel ductility on post-peak performance and seismic safety has received less attention. To address this gap, the current study experimentally investigates the influence of reinforcing steel ductility, associated with different carbon contents, on the flexural behavior of reinforced concrete beams. Three types of reinforcing steel, LCS, MCS, and HCS, are systematically evaluated under identical test conditions. The flexural response is assessed in terms of load–displacement behavior, moment capacity, displacement ductility, energy dissipation, and failure modes. The novelty of this study lies in establishing a direct and systematic experimental relationship between the ductility of reinforcing steel and the overall flexural behavior of reinforced concrete beams. Particular attention is given to post-peak behavior and deformation capacity, rather than strength alone. The findings provide new empirical evidence clarifying how variations in steel ductility influence structural safety and seismic performance. These results offer practical insights regarding the implementation of performance-based seismic design of reinforced concrete structures in Indonesia and other regions with similar seismic conditions.

II. RESEARCH METHODOLOGY

A. Concrete Material

The concrete used in this study was ready-mix concrete with an average compressive strength of 23.74 MPa at 28 days

of curing. This value falls within the typical range for normal-strength concrete and satisfies the minimum compressive strength requirements specified in [5].

TABLE I. COMPRESSIVE STRENGTH AT 28 DAYS

Age of concrete (days)	Section area (mm ²)	Load (kN)	Compressive strength (MPa)
28	7850	187.770	23.92
28	7850	185.000	23.57
28	7850	186.385	23.75

B. Steel Material

The reinforcing steel specimens for the tensile test were machined and prepared in accordance with the requirements specified in [6]. The elongation percentage was calculated using (1), and the results were evaluated against the minimum elongation requirements defined in [7]:

$$\text{Elongation (\%)} = \frac{L_u - L_0}{L_0} \times 100\% \quad (1)$$

where L_0 is the original gauge length (mm), and L_u is the final gauge length after fracture (mm). This behavior is characterized by minimal necking and a smoother fracture surface, indicating rapid failure with low ductility. The complete tensile test results for the three types of steel are presented in Table II.

TABLE II. RESULTS OF THE TENSILE TEST OF REINFORCING STEEL

Specimens	Strain ($\mu\epsilon$)		Carbon percentage (%)	Ductility (μ)
	Yield	Ultimate		
LCS	2226	117593	0.302	52.83
MCS	1990	63101	0.318	31.7
HCS	2415	113943	0.411	26.06

The test results indicate that LCS steel exhibits the highest ductility ($\mu = 52.83$) and the lowest carbon content (0.302%), providing the greatest capacity for deformation and energy absorption. MCS steel shows an intermediate ductility level ($\mu = 31.7$; $C = 0.318\%$), whereas HCS steel records the lowest ductility ($\mu = 26.06$) and demonstrates the most brittle mechanical response due to its higher carbon content (0.411%). Accordingly, LCS steel is identified as the most ductile and mechanically efficient among the three materials. An increase in carbon content generally leads to higher strength and hardness but reduces ductility, as the material becomes more brittle and shows lower plastic deformation capacity [8].

C. Test Specimens

This study investigated three reinforced concrete beam specimens, each measuring 150 mm × 200 mm × 3300 mm. The beams differed only in the type of tensile reinforcement, which was classified based on the tensile test results of the reinforcing steel as LCS, MCS, and HCS. All specimens were reinforced with D16 bars as tensile reinforcement, D10 bars as compression reinforcement, and Ø8 stirrups as shear reinforcement.

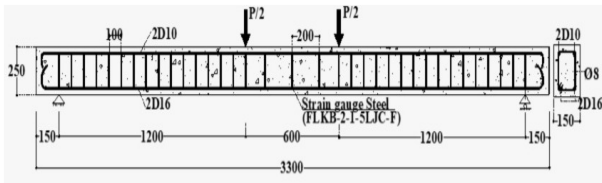


Fig. 2. Design of the reinforced concrete beam specimen.

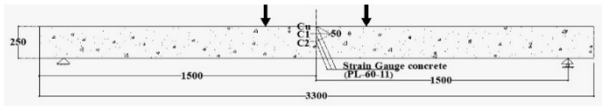


Fig. 3. Layout of strain gauge placement on the test specimen.

The flexural test was performed at 28 days of curing using a 1500 kN static loading machine. The load was applied incrementally at a displacement rate of 0.2 mm/s at the mid-span. A 200 kN load cell measured the applied load, while three LVDTs were installed at the mid-span and below the two loading points to monitor deflection. Strain, maximum stress, and deformation data were automatically recorded through the strain-gauge data acquisition system, as displayed in Figure 4.



Fig. 4. Loading test.

D. Ductility

In this study, the displacement ductility ratio ($\mu\Delta$) was used to evaluate the ductility of reinforced concrete beams. The displacement ductility ratio is defined as the ratio of the ultimate displacement (Δ_u) to the yield displacement (Δ_y). The yield displacement (Δ_y) was defined as the displacement corresponding to the yielding of the longitudinal reinforcement, which was identified when the measured steel strain reached the yield strain obtained from tensile testing of the reinforcing bars. The ultimate displacement (Δ_u) was defined as the displacement corresponding to the point at which the applied load decreased to 85% of the maximum load on the descending branch of the load–displacement curve. These definitions and determination methods were applied to all test specimens. This definition of yield and ultimate displacement is consistent with the general concept of structural ductility proposed in [10], which emphasizes the ability of structural members to undergo significant inelastic deformation beyond first yield while maintaining a substantial portion of their load-carrying capacity. The displacement ductility ratio was calculated using

(2) following procedures adopted in experimental research on the cyclic behavior of reinforced concrete members [11]:

$$\mu\Delta = \frac{\Delta_u}{\Delta_y} \quad (2)$$

where $\mu\Delta$ is the displacement ductility ratio, Δ_u is the ultimate displacement (mm), and Δ_y is the yield displacement (mm).

In seismic structural design, ductility is evaluated using the displacement ductility ratio (μ), defined as the ratio of ultimate displacement (Δ_u) to yield displacement (Δ_y). This parameter represents the inelastic deformation capacity of a structural member and is widely employed in experimental seismic studies and code-based performance evaluations [9, 10]. The ductility capacity (μ) is related to the seismic response modification factor (R), which represents the ability of a structural system to undergo inelastic deformation, dissipate energy, and maintain load-carrying capacity during strong ground motions [12]. Structural systems with higher ductility generally permit larger R values, allowing the design seismic forces to be reduced relative to the elastic demand levels. In Indonesia, the assignment of the seismic response modification factor follows the provisions in [13], which specifies R values only for recognized seismic-force-resisting systems. For systems outside these categories, additional analysis, experimental evidence, or special detailing requirements may be needed to justify the assumed ductility level and the corresponding R value.

III. RESULTS AND DISCUSSION

A. Load–Deflection Relationship of Reinforced Concrete Beams

Figure 5 illustrates the load–deflection behavior of all tested beams. The first flexural cracks were observed at loading levels of 7.9 kN LCS, 7.6 kN MCS, and 6.9 kN HCS. Yielding occurred at loads of 41.98 kN, 51.11 kN, and 55.31 kN for the LCS, MCS, and HCS beams, respectively, with corresponding yield deflections of 15.39 mm, 20.18 mm, and 19.06 mm. After yielding, all beams continued to sustain additional load until reaching their ultimate capacities of 48.45 kN LCS, 56.18 kN MCS, and 61.24 kN HCS, accompanied by maximum deflections of 71.41 mm, 74.69 mm, and 41.73 mm, respectively. Based on the ductility criteria for earthquake-resistant structural components specified in [13], the beam reinforced with LCS exhibited the highest ductility performance, achieving a displacement ductility ratio of 4.64 and a stiffness value of 3.32. This result classifies the beam as a highly ductile member capable of sustaining significant plastic deformation before failure. In contrast, the MCS- and HCS-reinforced beams demonstrated moderate ductility, with displacement ductility ratios of 2.84 and 2.19, respectively, placing them within the semi-ductile classification.

It has been reported that higher steel strength does not necessarily enhance the seismic performance of reinforced concrete members. Instead, lower-strength steel with greater ductility is often preferable, as it promotes more uniform plastic hinge development and improves the energy dissipation capacity of the structural system [14, 15]. Moreover, the mechanical characteristics of reinforcing steel, particularly its

strength grade, rib geometry, and plastic deformation capacity, significantly influence the bond interaction with concrete and may govern failure mechanisms such as pull-out or splitting. Authors in [16] reported that variations in rib pattern and steel mechanical properties substantially affect bond strength, thereby influencing the global deformation capacity of reinforced concrete members. These findings are consistent with the results of the present study, in which the beam reinforced with LCS exhibited superior ductility performance and a more uniform pattern of plastic deformation compared to the MCS and HCS beams.

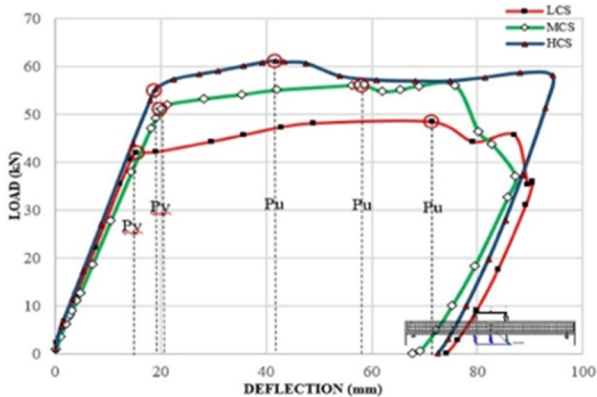


Fig. 5. Load-deflection relationship of tested beams.

B. Load-Strain Relationship of Steel

Figure 6 illustrates the load-strain response of the tensile reinforcing steel for all specimens. At the early stage of loading, the steel bars exhibited linear-elastic behavior, followed by yielding and subsequent strain hardening until fracture. The LCS steel reached a yield strain of 2136 $\mu\epsilon$ and an ultimate strain of 6580 $\mu\epsilon$. The MCS steel exhibited a higher yield strain of 2466 $\mu\epsilon$ and an ultimate strain of 13721 $\mu\epsilon$, while the HCS steel recorded a yield strain of 2532 $\mu\epsilon$ and an ultimate strain of 6957 $\mu\epsilon$. These results indicate that the tensile strain capacity of the reinforcing steel varies with carbon content and manufacturing characteristics. The tensile strain response obtained from the steel tensile test represents material ductility, which is evaluated in this study using the ductility ratio ($\mu = \epsilon_u/\epsilon_y$), as reported in Table II, and therefore differs from the absolute ultimate strain shown in Figure 6. Consequently, reinforcing steel with a higher ultimate strain does not necessarily exhibit a higher material ductility ratio if its yield strain is also relatively high. Although the MCS steel exhibited the highest ultimate strain in the tensile test, the beam reinforced with LCS steel demonstrated the highest displacement ductility in the load-deflection response. This behavior is attributed to better strain compatibility between the LCS reinforcement and the surrounding concrete, more stable yielding behavior, and more effective plastic hinge development. Structural ductility is therefore governed not only by the mechanical properties of reinforcing steel, but also by bond behavior, stress redistribution, and section detailing. Consequently, the ductility of a reinforced concrete member must be evaluated at the structural level rather than inferred solely from steel tensile properties [17].

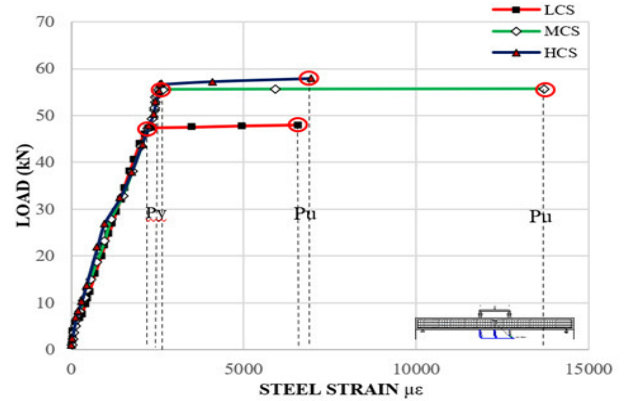


Fig. 6. Load-strain relationship of reinforcing steel.

C. Load-Strain Relationship of Concrete

Figure 7 presents the load-strain response of concrete for all tested beams. The strain increased progressively up to the peak load, followed by a rapid rise as cracking and crushing developed in the compression zone. The LCS beam reached a yield strain of 968 $\mu\epsilon$ and an ultimate strain of 3354 $\mu\epsilon$. Meanwhile, the MCS beam recorded a yield strain of 1317 $\mu\epsilon$ and an ultimate strain of 2771 $\mu\epsilon$, and the HCS beam exhibited a yield strain of 1293 $\mu\epsilon$ with an ultimate strain of 2628 $\mu\epsilon$. These results indicate that the LCS beam possessed the highest strain capacity, reflecting superior strain compatibility between the concrete and the reinforcing steel. Such compatibility enables larger compressive deformation before concrete crushing, contributing to improved flexural ductility and enhanced energy dissipation capacity. This observation aligns with [18, 19], where it was reported that the interaction between concrete and steel reinforcement, particularly strain compatibility, plays a critical role in determining the ductility and deformation capacity of reinforced concrete elements.

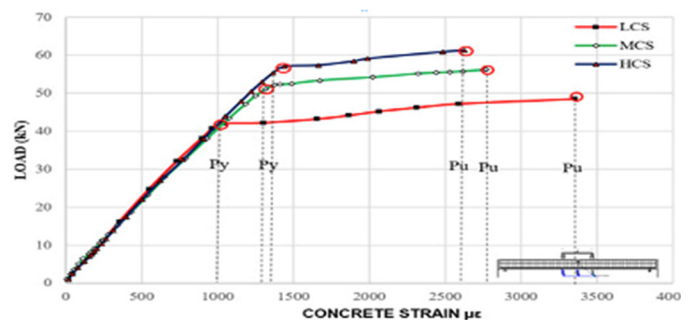


Fig. 7. Load-strain relationship of concrete.

D. Comparison of the Ductility of Reinforced Concrete Beams

Figure 8 presents the comparison of ductility values for all tested beams with different carbon contents in the reinforcing steel. The LCS beam achieved the highest ductility value of 4.64. This was followed by the MCS beam with a ductility value of 2.84, while the HCS beam exhibited the lowest ductility value of 2.19. These findings show that beams reinforced with LCS possess a superior ability to undergo plastic deformation before failure. Conversely, beams reinforced with medium- and HCS demonstrated reduced

ductility due to their higher strength but lower plastic deformation capacity. This confirms an inverse relationship between the carbon content of reinforcing steel and the ductility of reinforced concrete members. An increase in carbon content typically results in decreased ductile behavior under flexural loading, as higher-carbon steels tend to exhibit greater brittleness and limited elongation capacity [20, 21].

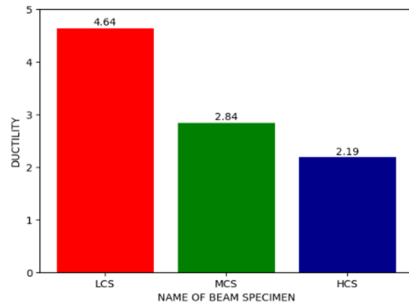


Fig. 8. Ductility comparison of tested beams.

E. Crack Pattern

1) LCS-Beam

During testing of the LCS beam, the first flexural crack appeared at mid-span under a load of 7.53 kN. With increasing load, the crack propagated vertically and subsequently developed into inclined flexure-shear cracks at approximately 30°–45°, accompanied by compression zone spalling near ultimate load. This crack evolution is characteristic of reinforced concrete beams, where flexural cracks at the maximum moment region progressively develop into combined flexure-shear cracks as loading increases [22]. Similar crack propagation and concrete crushing behavior reported in previous studies confirm that the LCS beam exhibited a ductile failure mechanism with gradual crack development and significant deformation before failure [23].

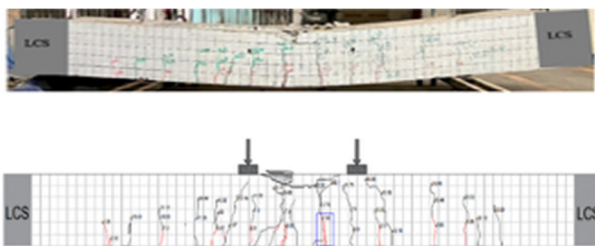


Fig. 9. Crack pattern of the LCS beam.

2) MCS-Beam

Figure 10 illustrates the crack pattern observed in the MCS beam. The first crack appeared vertically at the tension zone when the applied tensile stress exceeded the tensile strength of the concrete. As the applied load increased, these cracks extended upward, and additional cracks developed near the loading point. The overall crack pattern was characterized as flexural shear cracking, with the failure mode dominated by flexural damage in the compression zone. The damage progression from initial flexural cracking, subsequent crack

propagation, to crushing of the concrete in the compression zone resulted in a reduction of stiffness and a significant change in the deformation behavior of the beam. This sequence of cracking and crushing is consistent with the nonlinear structural response commonly reported in reinforced concrete beams under flexural loading [24, 25].

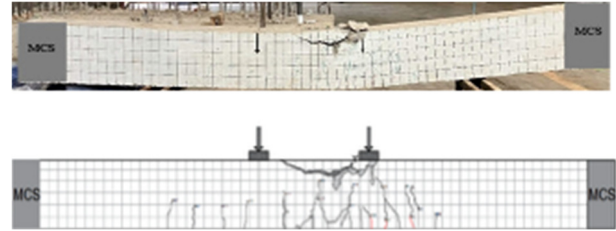


Fig. 10. Crack pattern of the MCS beam.

3) HCS-Beam

Figure 11 illustrates the crack development of the HCS beam. Initial vertical cracks formed in the tensile region near mid-span, where the bending moment was the highest. As the load increased, these cracks propagated upward and widened progressively. At the final loading stage, significant damage developed in the compression zone, characterized by concrete spalling and localized crushing above the tensile reinforcement. The presence of vertical flexural cracks at mid-span, combined with inclined flexure-shear cracks near the loading points, indicates that the failure mechanism was predominantly flexural. The localized crushing of the compression zone suggests that the concrete at the top fibers exceeded its compressive capacity, while the tensile reinforcement approached or reached its yield strain.

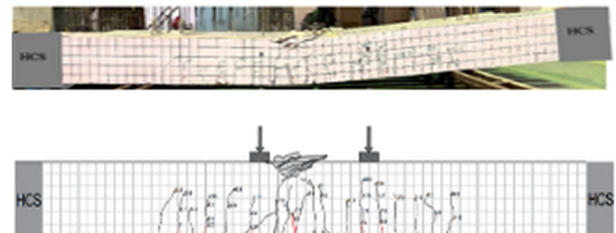


Fig. 11. Crack pattern of HCS beam.

IV. CONCLUSIONS

The Medium-Carbon Steel (MCS) and High-Carbon Steel (HCS) beams showed lower displacement ductility and more localized damage compared to the Low-Carbon Steel (LCS) beam. This behavior indicates that the failure modes are likely influenced by the reduced ductility of the reinforcing steel, which may restrict strain compatibility, plastic hinge formation, and post-yield deformation capacity. However, the overall failure behavior of reinforced concrete beams results from the interaction between steel properties, concrete response, and bond behavior.

REFERENCES

- [1] W. O. A. R. Malim, R. Djamaluddin, R. Irmawaty, and Fakhruddin, "The Effect of the Carbon Content on the Ductile Behavior of Reinforcing Steel," *Engineering, Technology & Applied Science*

- Research, vol. 15, no. 5, pp. 26808–26813, Oct. 2025, <https://doi.org/10.48084/etasr.12148>.
- [2] R. Aryanti, "Pengaruh Variasi Mutu Baja Tulangan Pada Penampang Balok Beton Bertulang," *Jurnal Bangunan, Konstruksi & Desain*, vol. 2, no. 4, pp. 254–261, Dec. 2024, <https://doi.org/10.25077/jbkd.2.4.254-261.2024>.
- [3] D. Luo and B. Li, "Moment redistribution capacity of continuous RC beams with High-Strength steel reinforcement," *Structures*, vol. 51, pp. 13–24, May 2023, <https://doi.org/10.1016/j.istruc.2023.03.005>.
- [4] V. L. de la Concepción, H. N. Lorusso, and H. G. Svoboda, "Effect of Carbon Content on Microstructure and Mechanical Properties of Dual Phase Steels," *Procedia Materials Science*, vol. 8, pp. 1047–1056, Jan. 2015, <https://doi.org/10.1016/j.mspro.2015.04.167>.
- [5] SNI 2847:2019 Persyaratan Beton Struktural untuk Bangunan Gedung. Indonesia: Badan Standardisasi Nasional, 2019.
- [6] A. S. for T. and Materials, ASTM E8/E8M-21: Standard Test Methods for Tension Testing of Metallic Materials. USA: ASTM, 2021.
- [7] SNI 2052:2017 Baja tulangan beton. Indonesia: Standar Nasional Indonesia, 2017.
- [8] J. L. Dossett and G. E. Totten, Heat Treating Irons and Steels. USA: ASM International, 2014.
- [9] ACI 374.2R-13: Guide for Testing Reinforced Concrete Structural Elements under Slowly Applied Simulated Seismic Loads. USA: American Concrete Institute, 2013.
- [10] R. Park and T. Paulay, Reinforced Concrete Structures. UK: John Wiley & Sons, 1975.
- [11] K. Palaniappan, P. S. Joanna, M. Rajasekaran, A. Prabhavathy, D. Cruze, and S. James, "Flexural behaviour of pre-damaged RC beams retrofitted using CFRP laminates," *Advances in Civil and Architectural Engineering*, vol. 16, no. 30, pp. 55–66, Feb. 2025, <https://doi.org/10.13167/2025.30.4>.
- [12] C. Xu, L. Li, S. Miramini, and L. Zhang, "Experimental investigation of the mechanical performance of novel rigid connections in prestressed circular composite precast concrete columns under cyclic lateral loading," *Journal of Building Engineering*, vol. 89, July 2024, Art. no. 109150, <https://doi.org/10.1016/j.jobe.2024.109150>.
- [13] SNI 1726:2019 Tata Cara Perencanaan Ketahanan Gempa untuk Struktur Bangunan Gedung dan Non-Gedung. Indonesia: Standar Nasional Indonesia, 2019.
- [14] D. Gautam, G. Fabbrocino, and F. Santucci de Magistris, "Derive empirical fragility functions for Nepali residential buildings," *Engineering Structures*, vol. 171, pp. 617–628, Sept. 2018, <https://doi.org/10.1016/j.engstruct.2018.06.018>.
- [15] T. Paulay and M. J. N. Priestley, Seismic Design of Reinforced Concrete and Masonry Buildings. UK: John Wiley & Sons, 1992.
- [16] S. Krishnaveni and S. Rajendran, "Experimental studies on bond behaviour of steel rebar with different rib patterns in concrete," *Journal of Building Engineering*, vol. 95, Oct. 2024, Art. no. 110157, <https://doi.org/10.1016/j.jobe.2024.110157>.
- [17] G. Fisher and C. L. Victor, "Influence of Matrix Ductility on Tension-Stiffening Behavior of Steel Reinforced Engineered Cementitious Composites (ECC)," *ACI Structural Journal*, vol. 99, no. 1, 2002, <https://doi.org/10.14359/11041>.
- [18] F. J. Vecchio and M. P. Collins, "The Modified Compression Field Theory For Reinforced Concrete Elements Subject To Shear," USA: American Concrete Institute, 1986, pp. 219–231.
- [19] H. A. Kottb, "Behavior of high strength concrete columns under eccentric loads," 2014, <https://doi.org/10.1016/J.HBRCJ.2014.02.006>.
- [20] A. Çalık, "Effect of Carbon Content on the Mechanical Properties of Medium Carbon Steels," *Zeitschrift für Naturforschung*, May 2010, <https://doi.org/10.1515/ZNA-2010-0512>.
- [21] A. Grimaldi and Z. Rinaldi, "Influence of the Steel Properties on the Ductility of R.C. Structures," in *Novel Approaches in Civil Engineering*, M. Frémond and F. Maceri, Eds. Berlin, Heidelberg: Springer, 2004, pp. 297–309.
- [22] A. Carpinteri, J. R. Carmona, and G. Ventura, "Propagation of flexural and shear cracks through reinforced concrete beams by the bridged crack model," *Magazine of Concrete Research*, vol. 59, no. 10, pp. 743–756, Dec. 2007, <https://doi.org/10.1680/macr.2007.59.10.743>.
- [23] Y. Yang, H. Yang, Z. Fan, and Z. Mu, "Crack Propagation Law of Reinforced Concrete Beams," *Applied Sciences*, vol. 14, no. 1, Jan. 2024, <https://doi.org/10.3390/app14010409>.
- [24] A. Belarbi and T. T. C. Hsu, "Constitutive Laws of Concrete in Tension and Reinforcing Bars Stiffened By Concrete," *Structural Journal*, vol. 91, no. 4, July 1994, <https://doi.org/10.14359/4154>.
- [25] H. R. Sobuz and E. Ahmed, "Flexural Performance of RC Beams Strengthened with Different Reinforcement Ratios of CFRP Laminates," *Key Engineering Materials*, vol. 471–472, pp. 79–84, 2011, <https://doi.org/10.4028/www.scientific.net/KEM.471-472.79>.