

Experimental Study on the Effects of Stirrup Spacing, Diameter, and Inclination Angle on the Flexural Strength of Reinforced Concrete Beams

Sudarno P Tampubolon^{1*}, Medyawanti Pane²
Universitas Kristen Indonesia

Corresponding Author: Sudarno P Tampubolon, sudarno.tampubolon@uki.ac.id

ARTICLE INFO

Keywords: Experimental, Reinforced Concrete Beams, Crack, Flexural Strength.

Received : 17, July

Revised : 19, August

Accepted: 25, September

©2026 Tampubolon, Pane: This is an open-access article distributed under the terms of the [Creative Commons Atribusi 4.0 Internasional](https://creativecommons.org/licenses/by/4.0/).



ABSTRACT

Reinforced concrete beams are essential structural elements that resist and transfer loads; therefore, their flexural performance and deformation capacity are important considerations in structural design. One of the factors affecting beam behavior is the configuration of shear reinforcement, particularly the diameter, spacing, and inclination angle of the stirrups. This study aims to investigate the effects of variations in stirrup diameter and configuration on the flexural strength and deflection of reinforced concrete beams. An experimental investigation was conducted through laboratory testing of four reinforced concrete beam specimens (B1–B4) with different stirrup diameters and configurations. The specimens were subjected to flexural loading until failure, with load, flexural strength, and deflection recorded as the primary parameters. The results showed that the flexural strength of beams B1, B2, and B3 was 71.01 MPa, whereas beam B4 achieved 52.07 MPa. Beam B1, reinforced with D8 stirrups spaced at 100 mm and an inclination angle of 45°, exhibited a deflection of 56.4 mm at a load of 75 kN. In comparison, beam B3, reinforced with D6 stirrups at an inclination angle of 90°, exhibited a deflection of 75.5 mm under the same load. The maximum deflection of 75.5 mm was observed in beam B3. These findings indicate that variations in stirrup diameter and configuration affect the deformation response of reinforced concrete beams, with D8 stirrups inclined at 45° resulting in lower deflection than D6 stirrups at 90° under the same stirrup spacing

INTRODUCTION

Indonesia is located in a region characterized by high seismic activity, making the country highly vulnerable to earthquake hazards. Earthquakes can cause varying degrees of damage to buildings, ranging from low-rise to high-rise structures. Structural damage or failure may occur when the seismic loads and forces acting on structural elements exceed their strength and capacity to withstand the induced stresses. Such conditions can compromise the overall stability and integrity of the structure, (Sudarno P Tampubolon, 2021). The use of reinforced concrete structures has become increasingly widespread in the construction of multi-story buildings and various infrastructure projects due to their ability to withstand applied loads and provide high structural capacity. The performance of reinforced concrete systems is strongly influenced by the quality and strength of the concrete used. Therefore, concrete with moderate to high strength is required to ensure that structural elements can effectively carry and transfer applied loads. To further enhance the load-carrying capacity and structural performance of concrete members, steel reinforcement is incorporated into the concrete matrix, (Ginting & Iman Gulo, 2019).

Reinforcement in reinforced concrete beams is provided to ensure adequate resistance to tensile and shear forces. In reinforced concrete members, shear reinforcement can be arranged in several forms, including vertical stirrups, spiral reinforcement, and inclined stirrups. For rectangular beam cross-sections, vertical stirrups are generally configured to follow the geometry of the beam cross-section, forming a rectangular enclosure around the longitudinal reinforcement. According to SNI 2847:2019, the ends of stirrups may be provided with 135° hooks, while 90° hooks are also commonly encountered in construction practice. Differences in hook configuration represent an important aspect to consider when evaluating the performance and shear-resisting capacity of stirrup reinforcement in reinforced concrete beams, (Rachman et al., 2013a). Failure in beam elements generally occurs when the designed structural capacity is insufficient to resist the applied loads and shear forces. Such conditions can lead to a reduction in structural performance and, ultimately, damage to the structural member. Under seismic loading, beams are among the structural components that may experience significant damage due to the large internal forces generated during cyclic loading.

In addition, failure in reinforced concrete beams may result from inadequate consideration and detailing of the reinforcement system, including both the longitudinal reinforcement and shear reinforcement (stirrups). Proper selection, arrangement, and detailing of reinforcement are therefore essential to ensure that reinforced concrete beams can adequately resist the applied loads and maintain their structural performance, (Sharma et al., 2011). The installation and detailing of beam reinforcement, including longitudinal reinforcement and stirrups, are still not always implemented in accordance with established design standards. Therefore, the design of reinforced concrete beams and their reinforcement detailing should be carried out carefully in accordance with applicable structural design codes and construction requirements. Proper reinforcement detailing is essential to ensure that the designed beam can

adequately resist the applied loads and minimize the risk of excessive damage and structural failure, (Guner & Vecchio, 2010). The capacity and failure modes of beams should be evaluated through analytical approaches, numerical simulations, and experimental investigations. In principle, the design of reinforced concrete structures aims to ensure structural safety and adequate performance throughout their service life. Shear and flexural failures exhibit fundamentally different mechanisms. Shear failure is generally characterized by relatively brittle behavior and may occur suddenly without significant prior deformation or deflection.

Consequently, shear failure represents a critical failure mode that must be adequately considered in the design of reinforced concrete beams. In addition to the contribution of concrete, shear resistance is also influenced by the configuration, spacing, anchorage, and detailing of transverse reinforcement or stirrups. Inadequate placement or detailing of stirrups in beam and column elements can adversely affect their shear resistance and overall structural performance, as illustrated in Figure 1.



Figure 1. Improper Installation of Shear Reinforcement in Reinforced Concrete Beam-Column Members

Therefore, the function and importance of shear reinforcement should be carefully considered and properly understood by structural engineers. In the design and construction of reinforced concrete beams, shear reinforcement should be installed and detailed in accordance with the applicable structural design standards, including SNI 2847:2019. Proper implementation of shear reinforcement detailing in the field is essential to enhance the shear resistance of beam elements and reduce the risk of structural damage or failure, (Stevie Andrian, M. D. J. Sumajow, 2015). To investigate the structural behavior, strength, and failure mechanisms of designed reinforced concrete beams, both numerical simulations and laboratory experiments are required. In general, the shear forces acting on reinforced concrete beams can induce diagonal cracking, particularly in regions where shear stresses are significant.

Previous studies have investigated the role and effectiveness of shear reinforcement in improving the structural performance of reinforced concrete beams. For example, Agus Sugianto investigated the effect of stirrup diameter on the shear strength of reinforced concrete beams using stirrup diameters of 6, 8, and 10 mm. Meanwhile, Fanto Pardomuan Pane examined the flexural tensile strength of concrete under variations in concrete compressive strength. These

studies provide a basis for further investigation into the influence of shear reinforcement configuration on the strength and deformation behavior of reinforced concrete beams, (Sugianto & Indriani, 2016), Analysis and Experimental Investigation of Reinforced Concrete Beam Behavior Using VecTor2 Simulation, (S. Tampubolon, 2020; S. P. Tampubolon, 2022, 2023), Experimental Study of Reinforced Concrete Beam Behavior with and without Stirrups and under Different Inclined Stirrup Configurations, (Dimas Arief Wicaksono et al., 2019)(Rachman et al., 2013b).

This study investigates the effects of variations in stirrup spacing, diameter, and inclination angle on the flexural strength of reinforced concrete beams. The shear mechanism and flexural capacity of structural members are important aspects that require careful consideration, particularly in reinforced concrete beams that are subjected to significant shear forces. In practical structural systems, shear forces rarely act independently and commonly occur in combination with flexure, torsion, and axial forces. Therefore, the influence of stirrup configuration, spacing, diameter, and inclination angle should be properly understood to support the appropriate design and detailing of reinforced concrete beams in accordance with applicable structural standards. Proper reinforcement detailing is essential for improving the structural capacity and reducing the potential for damage and failure in reinforced concrete beam elements.

The use of plain and deformed reinforcing bars also warrants consideration, particularly when evaluating existing structures constructed under earlier design practices. Current Indonesian structural provisions place greater emphasis on the use of deformed reinforcement for structural applications, while some existing buildings constructed before the implementation of these provisions may still contain plain reinforcing bars. This condition highlights the importance of evaluating the structural behavior of beams with different reinforcement configurations through experimental investigation. Accordingly, laboratory testing is required to evaluate the strength, deformation response, and failure behavior of reinforced concrete beams with variations in stirrup diameter, spacing, and inclination angle. Based on the reviewed literature and the identified research needs, this study is entitled “Experimental Study on the Effects of Stirrup Spacing, Diameter, and Inclination Angle on the Flexural Strength of Reinforced Concrete Beams”.

THEORETICAL REVIEW

Hammer Test

The rebound hammer test is a non-destructive testing (NDT) method commonly used to estimate the compressive strength of concrete without causing significant damage to the tested element. The method is relatively simple, economical, and capable of providing test results within a short period. The test principle involves applying impact energy to the concrete surface using a spring-driven mass released against a properly selected and prepared test area. The rebound of the mass following impact is expressed as the *rebound number*, which serves as an indicator of the surface hardness of the concrete. The resulting measurements can subsequently be used to assess the uniformity and consistency

of concrete quality within a structural element or throughout a structure, (Lubis, 2003). In general, the rebound hammer test is a non-destructive testing method used to assess the uniformity of concrete quality and to provide an initial estimate of compressive strength before conducting direct strength tests on concrete specimens, (Sumajouw et al., 2018). The testing was conducted after the specimens had reached an age of 28 days and completed the curing process by water immersion. The specimens were subsequently removed from the curing tank and allowed to dry for a certain period before testing. The preparation and testing procedures using the rebound hammer method were performed in accordance with SNI 03-4430-1997. The instrument readings were recorded as rebound numbers (R) at predetermined testing points. The measured rebound values were then averaged to obtain a representative value for each specimen. The average rebound number was subsequently used to estimate the concrete compressive strength based on the rebound hammer correlation curve. The resulting correlation curve is presented in Figure 2.

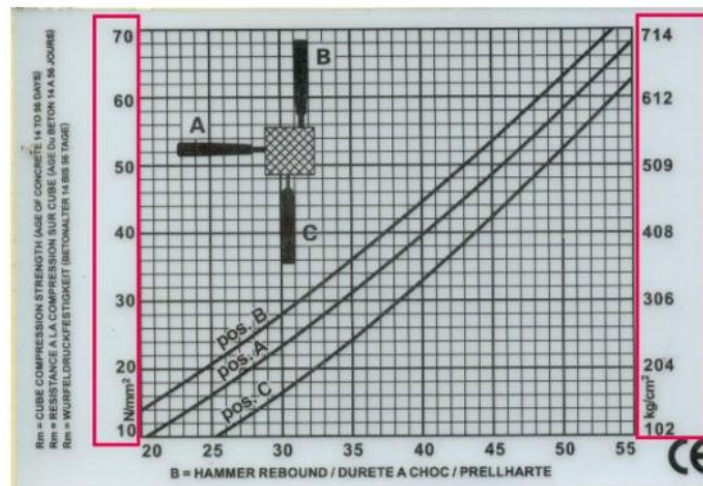


Figure 2. Rebound Hammer Test Curve for Estimating Concrete Compressive Strength

Flexural Strength of Reinforced Concrete Beams

Flexural strength testing was conducted using a one-point loading (OPL) configuration, also referred to as a three-point bending test. In this method, a concentrated load is applied at the midpoint of the specimen span and gradually increased until failure occurs. The loading procedure was performed in accordance with the relevant testing standards. The flexural strength of the concrete was subsequently determined using the following equation:

$$f_r = \frac{3PL}{b \times d^2} \quad (1)$$

The modulus of rupture of concrete generally ranges from approximately 11% to 23% of its compressive strength. The relationship between the modulus of rupture and compressive strength can be expressed as follows:

$$f_r = 0,62 \lambda \sqrt{f'_c} \quad (2)$$

Where λ is the modification factor for lightweight concrete.

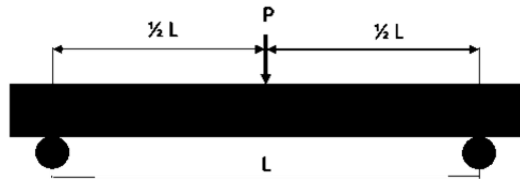


Figure 3. One-Point Loading (OPL) Test Configuration

Shear Stirrups

The nominal shear strength provided by the shear reinforcement (stirrups) is calculated using the following equation, (Sudarno et al., 2022):

$$V_r = \phi \cdot V_n; \text{ dan } \phi \cdot V_n \geq V_u \quad (3)$$

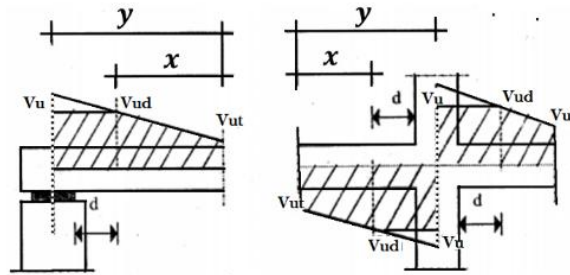


Figure 4. Analysis of Shear Reinforcement Design Calculations

The shear force resisted by the concrete (V_c) can be calculated using the following equation, (Igbal et al., 2013):

$$V_c = \frac{1}{6} \cdot \sqrt{f'_c} \cdot b \cdot d \quad (4)$$

Inclined Stirrups

Reinforced concrete beams subjected to shear force (V) may develop inclined cracks. Shear cracks generally form at an angle of $\theta = 30^\circ - 45^\circ$ relative to the longitudinal axis of the beam. To resist these inclined cracks, transverse reinforcement in the form of stirrups is provided. Inclined stirrups, typically arranged at an angle of 45° , can provide an effective contribution to shear resistance. For inclined stirrups with $\alpha < 90^\circ$, the shear capacity provided by the stirrups is determined from the vertical component of the tensile force. When $\alpha = 45^\circ$, the shear capacity contributed by the inclined stirrups can be calculated using the following equation:

$$V_s = \frac{A_v \cdot f_y \cdot d}{s} \times \sin \alpha \quad (5)$$

where $\sin 45^\circ = 0.707$, indicating that 45° inclined stirrups provide approximately 70.7% of their tensile force as a vertical component. The remaining

component acts in the horizontal direction, which may contribute to resisting longitudinal shear effects in the longitudinal reinforcement and influence the development and distribution of shear cracks, potentially resulting in a more stable crack pattern.

Vertical Stirrups

Vertical stirrups are shearing reinforcement members installed perpendicular to the longitudinal axis of a reinforced concrete beam. Their primary functions are to resist shear forces and confine the longitudinal tensile reinforcement, maintaining its position within the beam cross-section. Properly detailed vertical stirrups help prevent shear failure and improve the ductility of the beam. When a beam is subjected to transverse loading, such as concentrated or uniformly distributed loads, shear force (V) and bending moment (M) are generated. The applied shear force may induce inclined shear cracks, commonly referred to as diagonal tension cracks, at an angle of approximately 30°–45° relative to the longitudinal axis of the beam. Because concrete has limited capacity to resist diagonal tensile stresses, shear reinforcement is required to enhance the beam's resistance to these cracks. Once an inclined crack develops, the vertical stirrups crossing the crack are subjected to tensile forces and contribute to the overall shear resistance of the beam. Therefore, the total shear capacity of the reinforced concrete beam can be expressed as:

$$V_n = V_c + V_s \quad (6)$$

where:

V_c = shear contribution provided by the concrete (kN);

V_s = shear contribution provided by the vertical stirrups (kN).

Contribution of Vertical Stirrups:

$$V_s = \frac{A_v \cdot f_y \cdot d}{s} \quad (7)$$

where:

A_v = total cross-sectional area of the stirrups crossing the inclined crack;

f_y = yield strength of the stirrups; d = effective depth of the beam;

s = stirrup spacing.

METHODOLOGY

Crack Patterns and Deflection

Crack patterns in reinforced concrete beams can generally be classified into several types, including vertical flexural cracks and inclined shear cracks. Vertical cracks develop when the beam is unable to adequately resist the tensile stresses induced by flexure. These cracks typically occur in the central span of the beam, where the bending moment is relatively high. In contrast, inclined shear cracks develop when the beam has insufficient shear resistance. Such cracks commonly occur near the supports, where the shear force is relatively high. The development and distribution of these crack patterns provide important

information for evaluating the flexural and shear behavior of reinforced concrete beams, (Sudarno et al., 2022).

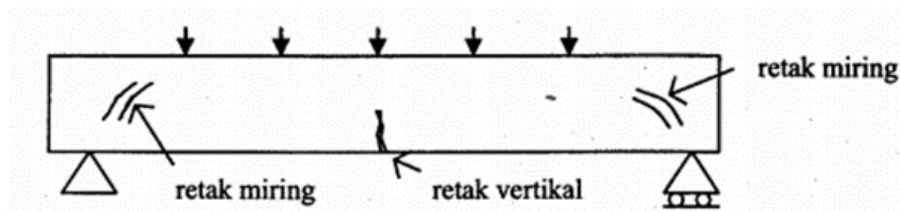


Figure 5. Crack Patterns and Failure Modes in Reinforced Concrete Beams

Deflection in reinforced concrete structures generally increases with the duration of sustained loading. Excessive deflection may contribute to deviations from the intended structural geometry and serviceability performance. This phenomenon is commonly associated with long-term deflection, which is influenced by several factors, including temperature, humidity, curing age, concrete storage conditions, reinforcement ratio, and sustained load magnitude. The typical deflection behavior observed in reinforced concrete beams is presented below, (Sangadji et al., 2020).

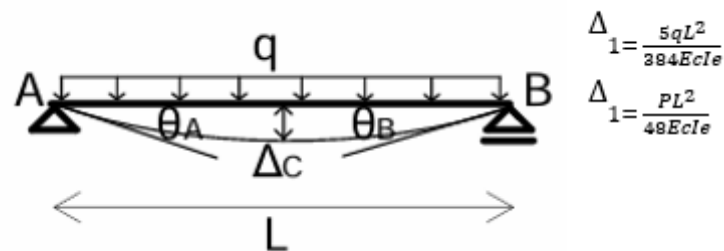


Figure 6. Deflection of Reinforced Concrete Beams

RESEARCH RESULT AND DISCUSSION

Reinforcement Detailing

In this study, two reinforced concrete beam specimens, each measuring (150 × 150 × 800) mm, were investigated. The specimens differed in stirrup spacing, with 100 mm and 150 mm spacing, respectively. Both beams were reinforced with 13 mm diameter longitudinal reinforcement (D13) and 8 mm diameter stirrups (D8) arranged at an angle of 45°.

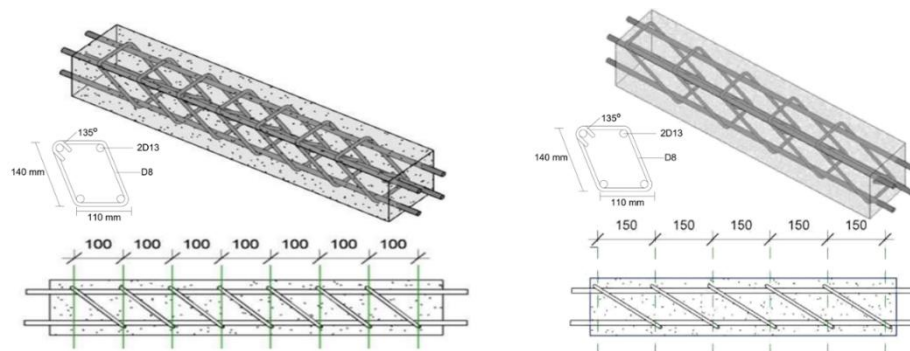


Figure 7. Reinforcement detailing of the reinforced concrete beam specimens B1 and B2

The other beam specimens had dimensions of $800 \times 150 \times 150$ mm, with stirrup spacing varied at 100 mm and 150 mm. The stirrups were provided with 135° hooks. In all specimens, the longitudinal reinforcement consisted of 13 mm diameter bars (D13), while the stirrups had a diameter of 6 mm (D6) and were arranged at an angle of 90° .

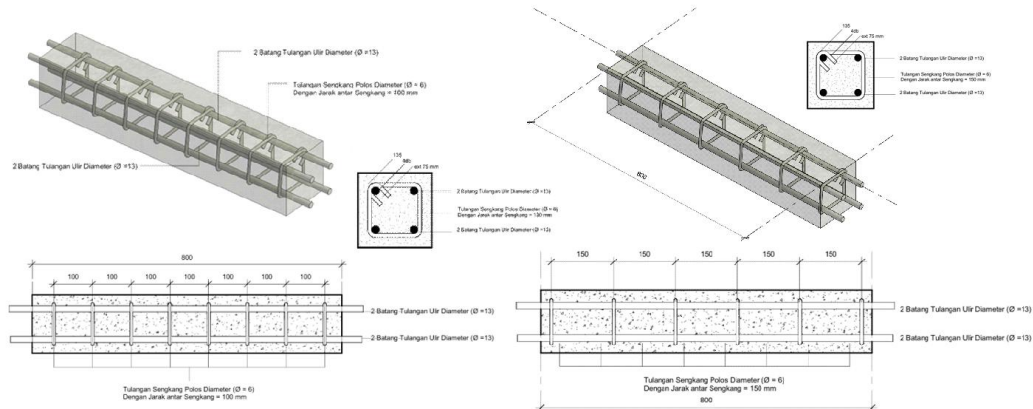


Figure 8. Reinforcement detailing of the reinforced concrete beam specimens B3 and B4

Concrete Compressive Strength and Reinforcement Tensile Strength Test Results

Based on the tensile tests conducted in the laboratory, the yield strength f_y and ultimate tensile strength f_u of the reinforcement bars were obtained, as presented in Table 1.

Table 1. Results of the Concrete Compressive Strength and Reinforcement Tensile Strength Tests

N o	Beam Specim en	Concrete Compres sive Strength (f'_c) MPa	Main Reinforce ment	f_y (MP a)	f_u (MP a)	Stirrup Diameter	f_y (MPa)	f_u (MPa)	Stirru p Spaci ng (mm)
1	Beam B1	28	D-13	354	510	D-8	369	515	@ 100
2	Beam B2	29	D-13	354	510	D-8	369	515	@150
3	Beam B3	28	D-13	354	510	D-6	415	510	@100
4	Beam B4	26	D-13	354	510	D-6	415	510	@150

Based on the flexural strength tests conducted in the laboratory, the compressive strength and deflection values of beam specimens B1, B2, B3, and B4 were obtained, as presented in Table 2. The corresponding test results are illustrated in Figures 9 and 10.

Table 2. Compressive Strength and Deflection Test Results

Beam B1 @100 mm			Beam B2 @150 mm		Beam B3 @100 mm		Beam B4 @150 mm	
N o.	Compre ssion Test (kN)	Deflec tion (mm)	Compre ssion Test (kN)	Deflec tion (mm)	Compre ssion Test (kN)	Deflec tion (mm)	Compre ssion Test (kN)	Deflec tion (mm)
1.	0	0	0	0	0	0	0	0
2.	25	14	25	11	25	25,5	25	25,5
3.	50	26	50	28,8	50	41	50	31
4.	75	46,4	75	47	75	65.5	55	60
5.	75	56,4	75	57	75	75.5	55	73

Figure 9 shows that Beam B1, with stirrups inclined at an angle of 45°, exhibited greater stiffness, with a measured deflection of 56.4 mm. In comparison, Beam B3, with stirrups arranged at 90°, experienced a higher deflection of 75.5 mm.

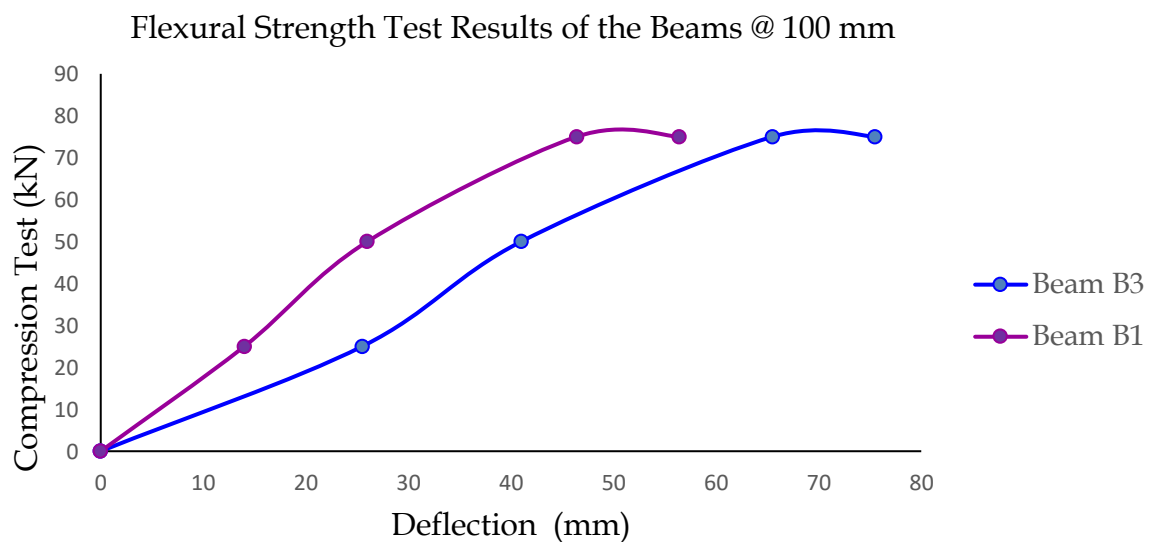


Figure 9. Compressive Strength and Deflection Test Results for Beams B1 and B3

Figure 10 shows that Beam B2, with stirrups inclined at 45°, exhibited greater stiffness, with a measured deflection of 57 mm. In comparison, Beam B4, with stirrups arranged at 90°, experienced a higher deflection of 73 mm.

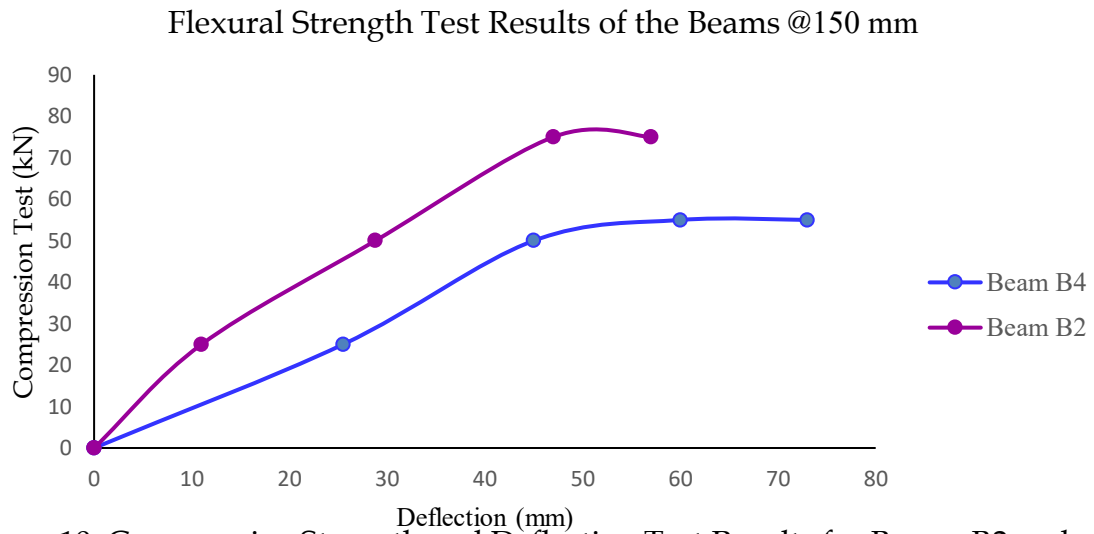


Figure 10. Compressive Strength and Deflection Test Results for Beams B2 and B4

The test results indicate that variations in stirrup diameter and spacing affected the deflection behavior of the reinforced concrete beams, while all specimens were provided with the same longitudinal reinforcement, D13. At a stirrup spacing of 100 mm, Beam B1, reinforced with D8 stirrups, exhibited a deflection of 56.4 mm under a load of 75 kN, which was lower than the 75.5 mm deflection recorded for Beam B3 with D6 stirrups. This result indicates that the larger stirrup diameter provided greater control over beam deformation under the same spacing condition. In addition to stirrup diameter, increasing the stirrup spacing from 100 mm to 150 mm also affected the deflection response of the beams during loading.

Flexural Strength Analysis of Reinforced Concrete Beams

1. Flexural Strength of Beam B1 @ 100 mm

$$f_r = \frac{3p \times l}{b \times d^2}$$

$$f_r = \frac{3 \times 75000 \text{ N} \times 800 \text{ mm}}{150 \text{ mm} \times (130)^2 \text{ mm}} = 71.01 \text{ MPa}$$

Relationship between the Modulus of Rupture and Concrete Compressive Strength

$$f_r = 0,62 \lambda \sqrt{f'c} = 0,62 \cdot 1 \sqrt{28} = 3,28 \text{ MPa}$$

2. Flexural Strength of Beam B2 @ 150 mm

$$f_r = \frac{3p \times l}{b \times d^2}$$

$$f_r = \frac{3 \times 75000 \text{ N} \times 800 \text{ mm}}{150 \text{ mm} \times (130)^2 \text{ mm}} = 71.01 \text{ MPa}$$

Relationship between the Modulus of Rupture and Concrete Compressive Strength

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \cdot \sqrt{29} = 3,34 \text{ MPa}$$

3. Flexural Strength of Beam B3 @ 100 mm

$$f_r = \frac{3p \times l}{b \times d^2}$$

$$f_r = \frac{3 \times 75000 \text{ N} \times 800 \text{ mm}}{150 \text{ mm} \times 130^2 \text{ mm}} = 71.01 \text{ Mpa}$$

Relationship between the Modulus of Rupture and Concrete Compressive Strength

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \cdot \sqrt{26,26} = 3,17 \text{ Mpa}$$

4. Flexural Strength of Beam B4 @ 150 mm

$$f_r = \frac{3p \times l}{b \times d^2}$$

$$f_r = \frac{3 \times 55000 \text{ N} \times 800 \text{ mm}}{150 \text{ mm} \times 130^2 \text{ mm}} = 52.07 \text{ Mpa}$$

Relationship between the Modulus of Rupture and Concrete Compressive Strength

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \cdot \sqrt{26,26} = 3,17 \text{ Mpa}$$

Based on the calculations, the flexural strength of Beams B1, B2, and B3, with a stirrup spacing of 100 mm, was 71.01 MPa, with corresponding modulus of rupture values of 3.28 MPa, 3.34 MPa, and 3.17 MPa, respectively. In comparison, Beam B4, with a stirrup spacing of 150 mm, exhibited a flexural strength of 52.07 MPa and a modulus of rupture of 3.17 MPa.

Crack Pattern Analysis Results

Following the one-point loading test, the crack patterns and failure modes observed in reinforced concrete Beams B1 and B2 are presented in Figure 11. Beam B1, with a stirrup spacing of 100 mm, exhibited a maximum crack width of 0.5 cm and a minimum crack width of 0.05 cm. Meanwhile, Beam B2, with a stirrup spacing of 150 mm, showed a maximum crack width of 0.6 cm and a minimum crack width of 0.06 cm. The observed failure pattern was characterized by diagonal cracking with an approximately 45° inclination, indicating a shear-related failure mechanism, (Tampubolon, 2022).



Figure 11. Front and Rear Views of Crack Patterns in Beams B1 and B2

The crack pattern observed in Beams B3 and B4 is presented in Figure 12. For Beam B3, with a stirrup spacing of 100 mm, the first crack appeared at a load of 25 kN, corresponding to a deflection of 25.5 mm. As the applied load increased, the beam ultimately failed at a load of 75 kN, with a deflection of 65.5 mm. The maximum and minimum crack widths recorded in Beam B3 with a stirrup spacing of 100 mm were 0.5 cm and 0.05 cm, respectively.



Figure 11. Front and Rear Views of Crack Patterns in Beams B3 and B4

For Beam B4, with a stirrup spacing of 150 mm, the first crack occurred at a load of 25 kN, corresponding to a deflection of 25.5 mm. The beam ultimately failed at a load of 55 kN, with a recorded deflection of 60 mm. The maximum crack width measured in Beam B4 was 2.0 cm, while the minimum crack width was 0.05 cm.

Analysis of the Cracking Moment of Reinforced Concrete Beams

1. Analysis of the Cracking Moment of Beams B1 and B3

$$b = 150 \text{ mm}; h = 150 \text{ mm}$$

Thus:

- Modulus of Rupture of Concrete

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \sqrt{28} = 5,3 \text{ MPa}$$

- Gross Moment of Inertia of the Cross-Section:

$$I_g = \frac{bh^3}{12} = \frac{150 \times 150^3}{12} = 42.187.500 \text{ mm}^4$$

- Cracking Moment

$$M_{cr} = f_r \frac{I_g}{c}$$

$$f_r = 5,3 \text{ MPa} ; I_g = 42.187.500 \text{ mm}^4 ; c = \frac{h}{2} = \frac{150}{2} = 75 \text{ mm}$$

Thus:

$$M_{cr} = f_r \frac{I_g}{c} = 5.3 \text{ MPa} \times \frac{42.187.500}{75} = 2981250 \text{ N.mm} = 304 \text{ kg. m}$$

2. Analysis of the Cracking Moment of Beam B2

$$b = 150 \text{ mm}; h = 150 \text{ mm}$$

Thus:

- Modulus of Rupture of Concrete

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \sqrt{29} = 5,4 \text{ MPa}$$

- Gross Moment of Inertia of the Cross-Section:

$$I_g = \frac{bh^3}{12} = \frac{150 \times 150^3}{12} = 42.187.500 \text{ mm}^4$$

- Cracking Moment

$$M_{cr} = f_r \frac{I_g}{c}$$

$$f_r = 5,4 \text{ MPa} ; I_g = 42.187.500 \text{ mm}^4 ; c = \frac{h}{2} = \frac{150}{2} = 75 \text{ mm}$$

Thus :

$$M_{cr} = f_r \frac{I_g}{c} = 5.4 \text{ MPa} \times \frac{42.187.500}{75} = 3037500 \text{ N.mm} = 309.7 \text{ kg. m}$$

3. Analysis of the Cracking Moment of Beam B4

$$b = 150 \text{ mm}; h = 150 \text{ mm}$$

Thus:

- Modulus of Rupture of Concrete

$$f_r = 0,62 \lambda \sqrt{f'_c} = 0,62 \cdot 1 \sqrt{26} = 3,2 \text{ MPa}$$

➤ Gross Moment of Inertia of the Cross-Section:

$$I_g = \frac{bh^3}{12} = \frac{150 \times 150^3}{12} = 42.187.500 \text{ mm}^4$$

➤ Cracking Moment

$$M_{cr} = f_r \frac{I_g}{c}$$

$$f_r = 3,2 \text{ MPa} ; I_g = 42.187.500 \text{ mm}^4 ; c = \frac{h}{2} = \frac{150}{2} = 75 \text{ mm}$$

Thus:

$$M_{cr} = f_r \frac{I_g}{c} = 3,2 \text{ MPa} \times \frac{42.187.500}{75} = 1800000 \text{ N.mm} = 183.6 \text{ kg.m}$$

CONCLUSIONS AND RECOMMENDATIONS

Based on the laboratory investigation, the following conclusions were obtained:

1. The flexural strength of Beams B1, B2, and B3 was 71.01 MPa, whereas Beam B4 exhibited a flexural strength of 52.07 MPa.
2. Beam B1, reinforced with D8 stirrups spaced at 100 mm and inclined at 45°, exhibited a deflection of 56.4 mm under a load of 75 kN, which was lower than the 75.5 mm deflection recorded for Beam B3, reinforced with D6 stirrups arranged at 90°. These results indicate that the larger stirrup diameter and inclined stirrup configuration provided better deformation control than D6 stirrups under the same spacing condition.
3. The maximum deflection of 75.5 mm was observed in Beam B3 under a load of 75 kN, with the stirrups arranged at an angle of 90°.

FURTHER STUDY

Future research should include a larger number of beam specimens to improve the reliability and statistical significance of the experimental results. The experimental results should be complemented by numerical simulations, such as finite element analysis, to further evaluate the stress distribution, crack propagation, deflection, and failure mechanisms of reinforced concrete beams. Should investigate the relationship between stirrup configuration, cracking behavior, flexural capacity, and deformation control to establish more effective reinforcement configurations for reinforced concrete beams.

REFERENCES

- Dimas Arief Wicaksono, Reni Suryanita, & Zulfikar Djauhari. (2019). STUDI EKSPERIMENTAL BALOK BETON BERTULANG DENGAN DAN TANPA SENGKANG. Sainstek (e-Journal), 7(1).
<https://doi.org/10.35583/js.v7i1.14>

- Ginting, R., & Iman Gulo, R. (2019). Pengaruh Kuat Lekat Besi Tulangan D13 Terhadap Beton Normal. Februari, VIII.
- Guner, S., & Vecchio, F. J. (2010). Pushover analysis of shear-critical frames: Formulation. *ACI Structural Journal*. <https://doi.org/10.14359/51663389>
- Igbal, M., Sumajouw, M. D. J., Windah, R. S., & Imbar, S. E. J. (2013). Pengujian Geser Balok Beton Bertulang Dengan Menggunakan Sengkang Konvensional. *Jurnal Sipil Statik*, 1(2).
- Lubis, M. (2003). Pengujian Struktur Beton dengan Metode Hammer Test dan Metode Uji Pembebanan (Load Test). USU Digital Library.
- Rachman, A., Aulia, R., Sri Tudjono, B., & Lie, H. A. (2013a). Studi Eksperimental Perbandingan Variasi Sengkang Miring Terhadap Kuat Geser Balok Beton Bertulang. *Jurnal Karya Teknik Sipil*.
- Rachman, A., Aulia, R., Sri Tudjono, B., & Lie, H. A. (2013b). Studi Eksperimental Perbandingan Variasi Sengkang Miring Terhadap Kuat Geser Balok Beton Bertulang. *Jurnal Karya Teknik Sipil*.
- Sangadji, P., Sultan, M. A., & Ahadian, E. R. (2020). PENGARUH VARIASI TULANGAN TERHADAP LENDUTAN PADA BALOK BETON BERTULANG. *CLAPEYRON: JURNAL ILMIAH TEKNIK SIPIL*. <https://doi.org/10.33387/clapeyron.v2i1.3501>
- Sharma, A., Eligehausen, R., & Reddy, G. R. (2011). A new model to simulate joint shear behavior of poorly detailed beam-column connections in RC structures under seismic loads, Part I: Exterior joints. *Engineering Structures*. <https://doi.org/10.1016/j.engstruct.2010.12.026>
- Stevie Andrian, M. D. J. Sumajow, R. S. W. (2015). Pengujian Kuat Lentur Balok Beton Bertulang Dengan Variasi Ratio Tulangan Tarik. *Jurnal Sipil Statik* Maret, 3(3).
- Sudarno, Tampubolon, P., & Sc, M. (2022). STRUKTUR BETON I CIVIL ENGINEERING (Vol. 10).
- Sugianto, A., & Indriani, A. M. (2016). Pengaruh Diameter Sengkang Terhadap Kuat Geser Balok Dengan Variasi Diameter Tulangan Sengkang 6mm, 8 Mm Dan 10 Mm. *JTT (Jurnal Teknologi Terpadu)*, 4(1). <https://doi.org/10.32487/jtt.v4i1.126>
- Sumajouw, A. J., Pandaleke, R., & Wallah, S. E. (2018). Perbandingan Kuat Tekan Menggunakan Hammer Test Pada Benda Uji Portal Beton Bertulang Dan Menggunakan Mesin Uji Kuat Tekan Pada Benda Uji Kubus. *Jurnal Sipil Statik*, 6(11).
- Tampubolon, S. (2020). Analisa Perilaku Balok Beton Bertulang dengan Menggunakan Simulasi VecTor2. *Jurnal Rekayasa Konstruksi Mekanika Sipil (JRKMS)*. <https://doi.org/10.54367/jrkms.v3i2.898>
- Tampubolon, S. P. (2022). Analisa Perilaku Pushover pada Pengujian Balok Beton Bertulang. *Bentang : Jurnal Teoritis Dan Terapan Bidang Rekayasa Sipil*, 10(1). <https://doi.org/10.33558/bentang.v10i1.3078>
- Tampubolon, S. P. (2023). Bond Stress-Slip Effect for Simulation and Experiment Test of Reinforced Concrete Beam on the Pushover Behavior. *AIP Conference Proceedings*, 2689(1). <https://doi.org/10.1063/5.0120808>