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ANALISIS EKSPERIMENTAL PERILAKU LENTUR BALOK BETON BERTULANG SISTEM RANGKA DENGAN VARIASI TULANGAN TEKAN

EXPERIMENTAL ANALYSIS OF THE FLEXURAL BEHAVIOR OF REINFORCED CONCRETE FRAME BEAMS WITH VARIATIONS IN COMPRESSION REINFORCEMENT

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Abstrak— Beton bertulang adalah struktur komposit yang memadukan beton untuk menahan gaya tekan dengan baja tulangan untuk menahan gaya tarik. Dalam sistem balok beton bertulang, efisiensi penggunaan tulangan merupakan aspek krusial dalam perancangan struktur. Penelitian ini bertujuan untuk menganalisis pengaruh konfigurasi penulangan terhadap kapasitas lentur balok, dengan membandingkan penggunaan tulangan tekan tunggal dan ganda. Metode yang digunakan adalah eksperimen laboratorium terhadap empat variasi balok berukuran 124 cm × 15 cm × 20 cm, dengan campuran beton yang mengacu pada SNI 03-2834-2000. Variasi spesimen meliputi STR T25, STR T50, STR G25, dan STR G50, yang dibedakan berdasarkan jenis tulangan (tunggal atau ganda) dan jarak sengkang. Hasil pengujian menunjukkan bahwa kapasitas lentur tertinggi dicapai oleh spesimen STR G25, diikuti oleh STR T50, STR G50, dan STR T25. Balok dengan tulangan ganda dan jarak sengkang yang lebih rapat menunjukkan kinerja lentur yang lebih unggul. Studi ini menyimpulkan bahwa konfigurasi tulangan yang optimal dapat meningkatkan kapasitas lentur balok secara signifikan sekaligus mengefisienkan penggunaan material.

Kata kunci: balok tulangan sistem rangka, kapasitas kuat lentur, tulangan tekan ganda, tulangan tekan tunggal

Abstract— Reinforced concrete is a composite material that combines concrete, which resists compressive forces, with steel reinforcement, which resists tensile forces. In the design of reinforced concrete beams, the efficiency of the reinforcement system is a critical aspect of structural design. This study aims to analyze the influence of the reinforcement frame configuration on the flexural capacity of beams, specifically by comparing the performance of singly and doubly reinforced sections. An experimental method was employed using four beam specimens, each measuring 124 cm × 15 cm × 20 cm. The concrete mix was designed according to the Indonesian National Standard (SNI) 03-2834-2000. The variations, labeled STR T25, STR T50, STR G25, and STR G50, were categorized based on the reinforcement type (singly or doubly reinforced) and the spacing of the stirrups. The test results indicated that the highest flexural capacity was achieved by the STR G25 specimen, followed by STR T50, STR G50, and STR T25. Beams with double reinforcement and closer stirrup spacing exhibited superior flexural performance. This study concludes that an optimized reinforcement configuration significantly enhances the flexural capacity of concrete beams and improves material efficiency.

Keywords: beam reinforcement frame system, single press reinforcement, double press reinforcement, bending strong capacity

I. INTRODUCTION

Concrete is a widely recognized structural material valued for its high compressive strength and versatility. Continuous advancements in its mix design and construction techniques have solidified its crucial role in the modern construction industry. A key development in this evolution is the combination of concrete with steel reinforcement to create a composite system known as reinforced concrete.

Reinforced concrete components, such as beams and columns, must be equipped with both longitudinal (flexural) reinforcement and transverse (shear) reinforcement. Flexural reinforcement is designed to resist the bending moments that occur in these elements, while shear reinforcement—typically consisting of vertical stirrups, spiral ties, or inclined stirrups—is designed to resist shear forces.

Previous research has explored the use of frame-type reinforcement, which involves arranging conventional vertical stirrups into inclined configurations. This modification in reinforced concrete beams has been demonstrated to improve both flexural and shear strength compared to traditional reinforcement systems [1].

The strength of a reinforced concrete beam is significantly influenced by its reinforcement configuration. As essential structural components, stirrups must be designed in compliance with technical standards to ensure both strength and functionality. Stirrups serve several critical roles: they secure the main longitudinal reinforcement within the concrete core, provide lateral restraint for compression reinforcement, confine the core concrete, and enhance the bond between reinforcing bars.

In a reinforced concrete beam, compressive forces are primarily resisted by the concrete, while tensile forces are carried by the embedded steel reinforcement. Given this fundamental behavior, research aimed at enhancing the efficiency of reinforcement is essential. Therefore, this study was conducted to assess the influence of different frame-type reinforcement systems on structural performance by comparing singly and doubly reinforced configurations. The research focuses on optimizing material use without compromising structural integrity, utilizing reinforced concrete beam specimens for the analysis.

This study employs an experimental approach with variations in the frame-type reinforcement, specifically comparing singly and doubly reinforced configurations. While the general impact of reinforcement on the flexural capacity of concrete beams is well-documented, the novelty of this research lies in its direct comparative analysis of these frame-type configurations within the context of Indonesian design practices. The investigation focuses specifically on the performance of doubly reinforced systems with varying stirrup spacing, evaluating their deflection behavior and crack patterns.

Additionally, this study utilizes locally sourced materials—fine aggregate from the Tapparan River (Toraja) and coarse aggregate from Sidrap (Tanduk Tedong)—and adheres to structural design guidelines based on Indonesian National Standards (SNI). These factors ensure that the findings contribute practical insights for regionally relevant structural design. Consequently, the results of this study are expected to serve as technical guidance for designing more efficient and context-appropriate reinforced concrete beams, particularly for mid-scale construction projects in Indonesia.

II. LITERATURE REVIEW

A. Characteristic of Concrete

Concrete is a composite material composed of cement, fine and coarse aggregates, and water, to which admixtures may be added to modify its properties [2]. It is widely used in construction due to its high compressive strength, durability under various weather conditions, and ease of being molded into different shapes [3]. However, concrete possesses very low tensile strength and thus requires reinforcement with materials such as steel.

According to SNI 03-2847-2002, concrete is a construction material consisting of cement, fine aggregate, coarse aggregate, and water, with or without additional admixtures. The strength and durability of concrete are greatly influenced by the quality and proportions of its constituent materials. Cement serves as the primary hydraulic binder through the hydration reaction [4], while water facilitates this chemical reaction and affects the workability of the mix. Aggregates, which can constitute up to 75% of the concrete volume, act as a filler and provide dimensional stability to the structural matrix [5].

B. Concrete Components

1. Cement

Cement serves as the primary hydraulic binder in concrete. According to ASTM C150, cement types range from Type I to Type V, each possessing distinct characteristics for specific technical requirements, such as sulfate resistance and heat of hydration [6]. The reaction between cement and water, known as hydration, produces a cement paste that is crucial for developing the strength and durability of concrete. In accordance with SNI 03-2834-2000 and SNI 03-2847-2002, the quality of the cement paste determines key performance metrics, including compressive strength, splitting tensile strength, flexural strength, workability, and porosity. Therefore, the selection of cement type is critical to the final performance of concrete in various structural applications.

2. Water

Water used in concrete mixtures must be clean and free of chemicals or impurities that could damage the concrete or corrode the reinforcing steel. Water quality significantly affects both the compressive strength and the porosity of the resulting concrete [7]. An excessive amount of water can lead to segregation and bleeding, which weakens the bond between the cement paste and aggregates.

3. Aggregates

Aggregates are categorized as fine (e.g., sand) and coarse (e.g., gravel or crushed stone). The proportions and physical characteristics of the aggregates strongly influence the workability, strength, and durability of the concrete. Aggregates must be clean, hard, and free from reactive substances or other deleterious materials [8].

C. Steel and Reinforced Concrete

1. Reinforcing Steel

Steel's excellent mechanical properties, particularly its high tensile strength and ductility, make it an ideal reinforcement material. There are several types of steel based on chemical composition, including carbon steel, high-strength low-alloy (HSLA) steel, and alloy steel [9]. In reinforced concrete, steel's primary function is to resist the tensile forces that concrete alone cannot withstand.

2. Mechanism of Reinforced Concrete

The combination of concrete and steel creates a composite material with complementary properties, effectively resisting both compressive and tensile stresses. This interaction is possible due to their similar coefficients of thermal expansion and the strong mechanical bond that forms between the two materials. Reinforcing bars may be plain (e.g., BJTP-24) or deformed (e.g., BJTD-30), with surface rib patterns that conform to relevant standards to improve bonding [10].

D. Reinforced Concrete Beams

Reinforced Concrete Beams are structural elements designed primarily to resist bending moments and shear forces. Because concrete is weak in tension, longitudinal reinforcement is placed in the tension zone of the beam (typically the bottom for a simply supported beam). Shear forces are resisted by transverse reinforcement, usually in the form of stirrups. The reinforcement design must be based on the moment and force distributions determined from structural analysis [11]. To overcome the limitations of conventional designs, advanced materials and alternative reinforcement strategies are increasingly being investigated [12].

E. Mechanical Behavior of Concrete

1. Compressive Strength

Compressive strength is a primary indicator of concrete quality, representing its ability to resist axial loads. It is typically measured at 28 days and expressed in megapascals (MPa). Concrete continues to gain strength over time as the hydration process progresses [13].

2. Splitting Tensile Strength

This parameter provides an indirect measurement of concrete's ability to withstand tensile forces. Concrete is brittle in tension, and this test quantifies the stress at which it will crack under tensile loading [14].

3. Flexural Strength

Flexural strength, or modulus of rupture, measures a concrete beam's capacity to resist failure in bending. Bending stresses are induced by loads that cause structural deformation, with tensile cracks typically initiating on the face of the member subjected to the highest tensile stress [15].

F. Cracks in Concrete Beams

Cracks in concrete beams are generally classified into three types [16]:

1. **Flexural cracks**, which are caused by bending moments and typically appear in the region of maximum moment (e.g., mid-span).
2. **Shear cracks**, which are caused by transverse forces and typically form near supports.
3. **Flexural-shear cracks**, which result from the combined action of bending and shear.

Crack control is achieved through the proper detailing and distribution of reinforcement throughout the member.

G. Strut-and-Tie Model

The strut-and-tie model is an analysis method used for designing reinforced concrete members in regions where stress is highly non-linear ("D-regions"), such as near supports or concentrated loads. This model idealizes the complex internal forces into a system of compressive struts, tensile ties, and connecting nodal zones [17]. In the context of this study, the reinforcement configuration—whether singly or doubly reinforced—influences the efficiency of this force transfer mechanism. A singly reinforced beam primarily uses steel to form the tension tie, whereas a doubly reinforced beam adds steel in the compression zone to enhance compressive capacity and ductility. The reliability of the strut-and-tie model depends on maintaining force equilibrium and ensuring that the materials have adequate strength and ductility to form the assumed truss mechanism.

H. Trusses and Welded Connections

Truss structures are composed of linear elements connected at joints and arranged into stable triangular configurations to efficiently transfer loads. In steel construction, welding is a common method for joining these elements. Common joint types include fillet welds, lap welds, and butt welds. The quality and integrity of these welded connections are critical to the overall strength and performance of the steel structure.

III. METHODS

This study employed an experimental laboratory approach based on relevant ASTM standards. Two types of test specimens were prepared: (1) eight concrete cylinders (15 cm x 30 cm) for material property testing, and (2) four reinforced concrete beams (124 cm x 15 cm x 20 cm) for flexural testing. The primary structural variation was the reinforcement configuration, comparing singly and doubly reinforced sections. This variation was applied to the upper longitudinal reinforcement, while the dimensions of all other reinforcement elements were kept constant.

A. Materials and Equipment

The primary materials consisted of Portland cement (Tonasa, 50 kg bag), fine aggregate from the Tapparan River (Toraja), coarse aggregate from Sidrap (Tanduk Tedong), and clean, potable water. The reinforcement details for each system were as follows:

- Singly reinforced sections: Ø8 mm stirrups, 3Ø13 bottom longitudinal bars, and 1Ø12 top longitudinal bar.
- Doubly reinforced sections: Ø8 mm stirrups, 3Ø13 bottom longitudinal bars, and 2Ø6 top longitudinal bars.

The equipment used included cylinder and beam molds, a slump cone, a universal testing machine for compression and tensile strength tests, a flexural testing apparatus equipped with a hydraulic jack and dial gauge, an oven, a pycnometer, and a set of sieves for gradation analysis.

B. Material Characterization

Characterization of the aggregates included the following assessments:

- Particle size distribution, determined by sieve analysis according to ASTM standards.
- Moisture content and silt content, to assess contamination levels.
- Specific gravity and water absorption, measured under oven-dry and saturated surface-dry (SSD) conditions.

Bulk density in both loose and compacted states, to aid in concrete mix design calculations.

C. Concrete Mix Design

The concrete mix design was developed based on the material characterization results. It was designed to meet a targeted compressive strength while considering workability, durability, and cost-efficiency. The final mix composition was validated for each batch through slump testing to ensure consistency.

D. Specimens Casting and Curing

Prior to casting, each mold was coated with a release agent (oil) to prevent adhesion and facilitate demolding. The concrete was cast in three layers, with each layer compacted by 25 strokes of a tamping rod. After casting, the concrete cylinders were cured by immersion in clean water for 3, 7, 14, and 28 days. The reinforced concrete beams were moist-cured by water spraying twice daily for a period of 7 days.

E. Mechanical Testing

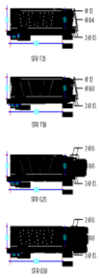
The compressive strength of the concrete was tested in accordance with ASTM C39, with axial loading applied to cylindrical specimens until failure.

- The splitting tensile strength test was conducted following ASTM C496, which involves applying a diametral compressive load along the length of a cylindrical specimen.
- The flexural test for the beams was performed based on ASTM C78, using a single-point concentrated load applied at mid-span. The load was applied incrementally, and the resulting crack patterns were recorded using a digital camera and strain measurement software (HPM15).

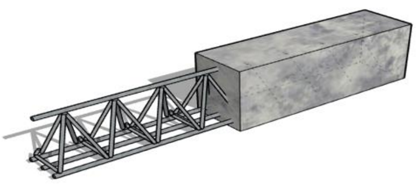
A consistent concrete mix was used for all specimens to ensure the validity of comparative results. In this study, each beam variation (STR T25, STR T50, STR G25, and STR G50) was represented by a single test sample, with an approximate concrete volume of 0.0372 m³ per beam. Although only one specimen was tested for each beam variation, the results from eight cylindrical specimens (for compressive and splitting tensile strength) served as a quality control measure and provided a basis for the overall evaluation of the concrete's performance.

F. Reinforcement Configuration and Modeling

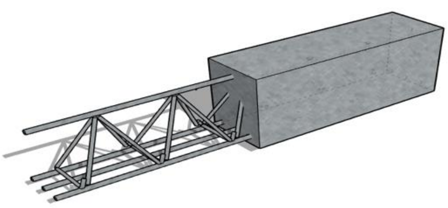
The reinforcement configurations were categorized into four types: STR T25 and STR T50 (single compression system), as well as STR G25 and STR G50 (double compression system). Each design was modeled in 3D to ensure geometric accuracy and alignment with actual field conditions.



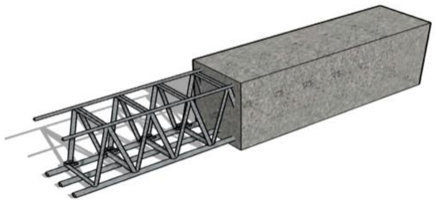
Figure–1. Design of frame-reinforced specimens with single compression reinforcement and frame-reinforced specimens with double compression reinforcement



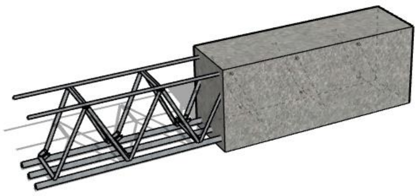
Figure–2. Design of Reinforced Concrete Beam Specimen with Frame System and Single Compression Reinforcement (STR T25)



Figure–3. Design of Reinforced Concrete Beam Specimen with Frame System and Single Compression Reinforcement (STR T50)



Figure–4. Design of Reinforced Concrete Beam Specimen with Frame System and Double Compression Reinforcement (STR G25)



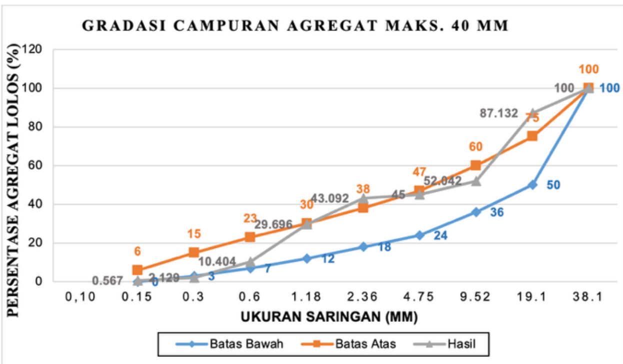
Figure–5. Design of Reinforced Concrete Beam Specimen with Frame System and Double Compression Reinforcement (STR G50)

IV. RESULTS AND DISCUSSION

A. Aggregate Characteristics

The test results for the fine aggregate indicate that most of its physical properties comply with ASTM specifications. The one exception was the moisture content, which was measured at 7.45%, exceeding the typical permissible limit of 0.5% to 5.0%. Conversely, all evaluated parameters of the coarse aggregate—including moisture content, silt content, bulk density, specific gravity, and water absorption—were within the acceptable limits defined by ASTM standards. These results confirm that the coarse aggregate meets the quality standards required for use in structural concrete.

B. Gradation and Fineness Modulus of Aggregates



The gradation curve for the fine aggregate plots within the acceptable range specified by standard grading charts (Zone I to Zone IV). The fineness modulus (FM) was 5.089 for the fine aggregate and 9.872 for the coarse aggregate, indicating a particle size distribution suitable for structural concrete applications. The combined gradation of the fine and coarse aggregates produced a well-graded blend, which was deemed appropriate for the concrete mix design.

C. Concrete Mix Design

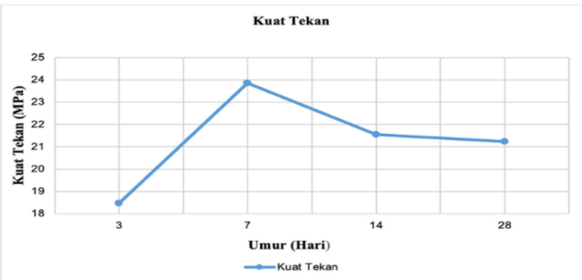
Table–1. *Mix design*

Specimen	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)
Cylinder	2,45	1,18	5,05	6,17
Beam	17,21	8,26	35,45	43,32

The concrete mix was developed using the volumetric method, targeting a 28-day compressive strength of 22.5 MPa. A water-cement ratio (w/c) of 0.48 was selected to achieve an optimal balance between strength and workability. The final mix proportions per cubic meter of concrete consisted of 385.42 kg of cement, 185 kg of water, 794.06 kg of fine aggregate, and 970.48 kg of coarse aggregate.

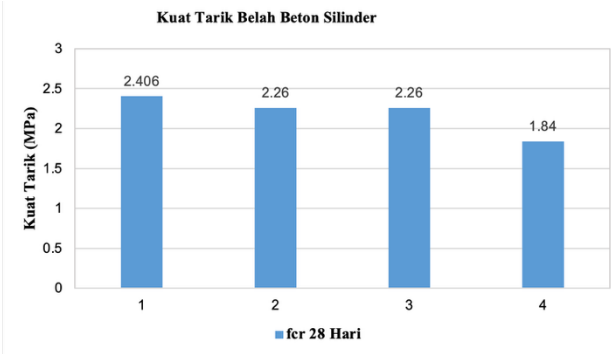
For laboratory testing, these proportions were scaled down according to the volume of each specimen. A single concrete cylinder (volume ≈ 0.0053 m³) required 2.45 kg of cement, 1.18 kg of water, 5.05 kg of fine aggregate, and 6.17 kg of coarse aggregate. A single reinforced concrete beam (volume ≈ 0.0372 m³) required 17.21 kg of cement, 8.26 kg of water, 35.45 kg of fine aggregate, and 43.32 kg of coarse aggregate. These adjustments ensured that all specimens were produced with proportions consistent with the parent mix design.

D. Compressive Strength Results of Concrete Cylinders



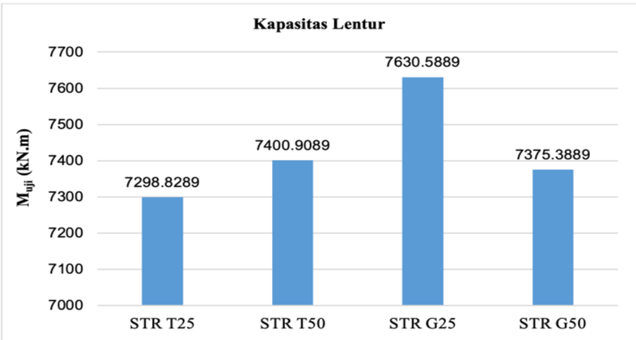
The average compressive strength of the concrete at 3 days was 18.463 MPa. The strength increased to 23.86 MPa at 7 days; however, a decline was observed at 14 and 28 days, with average compressive strengths of 21.553 MPa and 21.231 MPa, respectively. This unexpected decrease after 7 days is presumed to be influenced by inconsistencies during the mixing, compaction, or curing processes, which may have led to heterogeneity in the concrete matrix.

E. Splitting Tensile Strength Results of Concrete Cylinders



Four concrete specimens were tested for splitting tensile strength at 28 days. The results ranged from 1.840 MPa to 2.406 MPa, with an average value of 2.192 MPa. These values are consistent with the expected range for concrete of this compressive strength class and indicate adequate cohesion and bonding within the material.

F. Flexural Capacity of Reinforced Concrete Beams

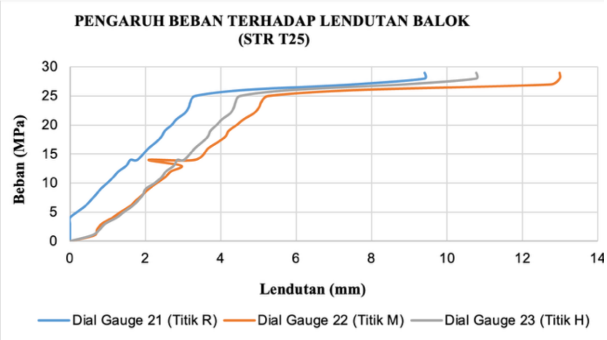


Flexural tests on the four reinforced concrete beam types yielded the following ultimate moment capacities:

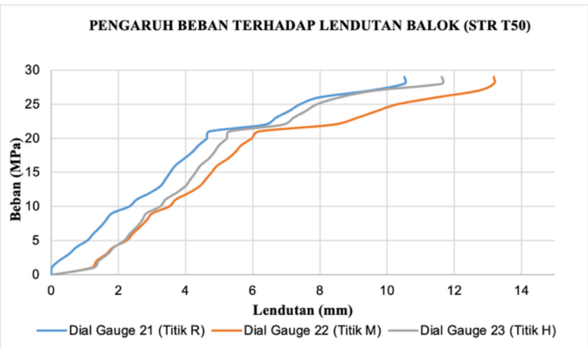
- STR T25: 7298.83 kN·m
- STR T50: 7400.91 kN·m
- STR G25: 7630.59 kN·m
- STR G50: 7375.39 kN·m

The STR G25 specimen, which featured double compression reinforcement, exhibited the highest flexural capacity. This result suggests that the doubly reinforced configuration, combined with its specific reinforcement spacing, improved stress distribution and enhanced the beam's resistance to bending moments.

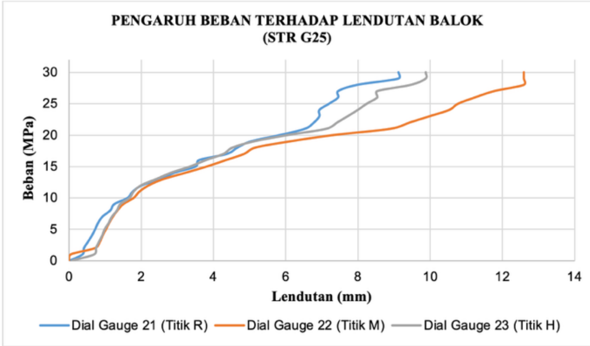
G. Deflection and Crack Pattern Analysis



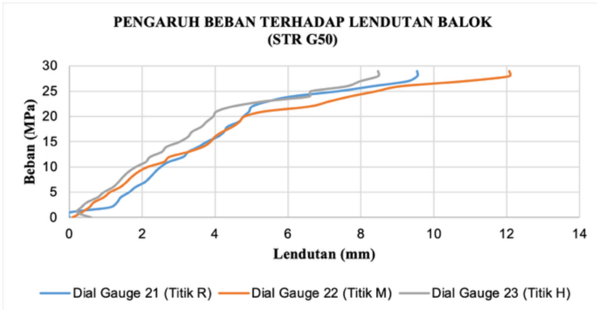
Figure–6. Cracks Observed in the STR T25 Reinforced Concrete Beam

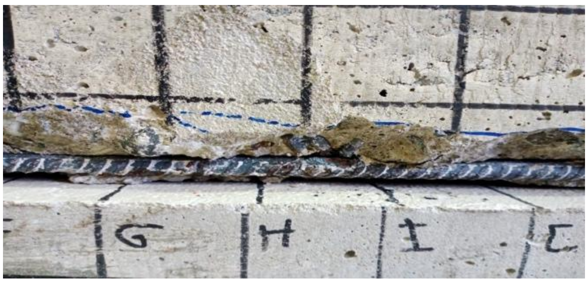


Figure–7. Cracks Observed in the STR T50 Reinforced Concrete Beam



Figure–8. Cracks Observed in the STR G25 Reinforced Concrete Beam





Figure–9. Cracks Observed in the STR G50 Reinforced Concrete Beam

Load-deflection analysis indicated that the doubly reinforced beams (STR G25 and STR G50) generally sustained higher loads before failure. For the STR T25 beam, initial cracking occurred at a load of 22.2 kN with a corresponding deflection of 4.61 mm; the maximum deflection reached 12.98 mm at a failure load of 28.6 kN. For the STR G25 beam, initial cracking was observed at a higher load of 27.2 kN with a deflection of 11.25 mm, and the maximum deflection was 12.6 mm at a failure load of 29.9 kN. The load-deflection curves for all specimens exhibited a linear-elastic behavior followed by a nonlinear phase with rapidly increasing deflection as the beams approached failure.

Based on the overall flexural capacity and deflection behavior, the STR G25 beam demonstrated the best performance, exhibiting the highest moment capacity and stable deformation characteristics. Therefore, it is concluded that the doubly reinforced system with closer spacing (STR G25) was the most effective configuration for enhancing flexural strength while controlling deflection.

V. CONCLUSION

Based on the experimental results, this study concludes that the reinforcement configuration, including the use of singly or doubly reinforced sections and stirrup spacing, has a significant influence on the flexural capacity of reinforced concrete beams. The results demonstrate that closer reinforcement spacing generally leads to higher load-bearing capacity. The highest flexural capacity was achieved by the STR G25 specimen, which utilized a doubly reinforced system, reaching an ultimate moment of **7630.59 kN·m**. The performance ranking of the other specimens, in descending order, was STR T50, STR G50, and STR T25.

A comparison of the systems revealed that the doubly reinforced configuration, particularly STR G25, provided the highest overall structural performance. It not only exhibited the greatest flexural strength but also maintained stable deformation behavior up to failure. While both systems showed significant load-carrying capabilities, the addition of compression reinforcement in a doubly reinforced scheme proved more effective for maximizing the flexural capacity and controlling deflection in the tested beams.

For future work, a comparative study is recommended between beams using these frame-type reinforcement systems and conventionally reinforced beams. Such research would help quantify the specific efficiency and performance benefits of the proposed frame configurations. Furthermore, it is recommended to extend this investigation to structural columns, particularly by implementing inclined stirrup systems, to evaluate their contribution to both the axial capacity and the overall ductility of vertical structural elements.

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