Experimental Study on the Influence of Length-to-Depth Ratio on the Axial Load Capacity of Reinforced Concrete Square Columns at Varying Concrete Grades

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Abstract
This experimental study investigates the influence of length-to-depth (L/D) ratio on the axial load capacity and failure behavior of reinforced concrete (RC) square columns constructed with varying concrete grades (M15, M20, and M25). A total of 54 column specimens were tested under axial compression, each with a constant cross-section of 100 mm × 100 mm, a fixed reinforcement ratio of 2.8%, and varying L/D ratios ranging from 1 to 10. The results revealed a strong inverse relationship between L/D ratio and axial load capacity across all concrete grades. Columns with lower L/D ratios exhibited significantly higher axial load capacities due to their reduced susceptibility to buckling, with specimens at L/D = 1 demonstrating up to a 293% increase in axial load capacity compared to those at L/D = 10. Additionally, the concrete grade had a pronounced effect on axial performance: at an L/D ratio of 1, M25-grade columns (RC-A1-25) achieved axial loads 10.2% and 26.4% higher than M20 (RC-A2-20) and M15 (RC-A3-15) grades, respectively. At the slenderest ratio (L/D = 10), M25 columns maintained capacities 11.1% and 22.8% greater than M20 and M15 columns. Failure modes were strongly influenced by slenderness; slender columns (L/D ≥ 9) predominantly failed by buckling, while shorter columns (L/D ≤ 7) exhibited crushing failure. These findings highlight the critical importance of both L/D ratio and concrete strength in optimizing the structural design and axial load capacity of reinforced concrete columns.

Keywords: *Concrete Grade, Columns, Length-to-Depth Ratio, Failure Modes, Axial load*

1.0 INTRODUCTION

Reinforced concrete (RC) columns are critical structural elements designed to carry compressive loads from superstructures down to the foundations (Acun & Sucuoglu, 2010; Isleem et al., 2021). Their performance under axial loading is vital to the overall safety and integrity of buildings and infrastructure. The axial load-bearing capacity of these columns is influenced by various interrelated factors, including the geometry of the column, material strength, the configuration of reinforcement, boundary conditions, and more importantly, the slenderness ratio, often represented as the length-to-depth (L/D) ratio (MacGregor & Wight, 2012).

The L/D ratio is a key parameter in column design, as it determines whether a column behaves as a "short" or "slender" member. Short columns (with lower L/D values) predominantly fail due to crushing when the compressive strength of the concrete is exceeded, often with minimal lateral deformation. In contrast, slender columns (with higher L/D values) are susceptible to lateral instability and buckling, and therefore their failure is often initiated by bending moments induced by axial load eccentricities or imperfections, as predicted by Euler's buckling theory (Nilson, Darwin, & Dolan, 2010).

The behavior of columns across various slenderness ratios is crucial, especially in multi-storey buildings and infrastructure projects where column length can vary significantly due to architectural and functional requirements. A column's susceptibility to buckling can compromise its effective load-carrying capacity, necessitating accurate prediction models and validation through experimental testing. While design codes such as IS 456:2000 and ACI 318 provide guidelines for calculating axial strength and classifying columns as short or slender, actual performance may deviate from theoretical values due to complex real-world conditions, including microstructural imperfections in concrete, construction variability, and steel-concrete interaction under load (ACI Committee 318, 2014).

Concrete grade also plays a pivotal role in determining axial strength. Higher concrete strength generally leads to improved performance under compressive loads. However, when used in slender columns, the benefits may be offset by instability issues if geometric parameters are not properly accounted for. Studies by Mendis et al. (2007) and Khan & Amin (2008) have highlighted that while increasing concrete grade enhances load capacity, the impact of slenderness becomes more pronounced in high-strength concrete columns, often leading to premature buckling if not properly braced or detailed.

Given the above context, this paper presents an experimental investigation into the axial load behavior of RC square columns with varying L/D ratios and concrete grades (M15, M20, and M25). The primary objective is to assess how these parameters interact to influence load capacity and failure modes. The findings aim to bridge the gap between theoretical design assumptions and practical behavior, providing structural engineers and designers with empirical data to support safer and more efficient design practices, particularly in regions prone to overloading, design underestimation, or economic material use.

This study is especially relevant in developing regions, where cost optimization often leads to the selection of lower-grade concrete and simplified construction practices. In such cases, understanding the limits and behavior of slender and short columns becomes even more critical for ensuring structural safety.

2. MATERIALS AND METHODS

2.1 Concrete Mix Design

Concrete grades M15, M20, and M25 were selected for the study based on common structural applications. Mix proportions were designed in accordance with IS 10262:2019 to ensure uniform workability and target compressive strengths as shown in Figure 1. The constituent materials included Ordinary Portland cement (OPC), fine and coarse aggregates, and potable water. Mix designs were carefully controlled to ensure consistency across batches.

Following casting, the specimens were left in their molds for 24 hours before being demolded and transferred to a water-curing tank. All columns experienced a standard 28-day curing period to facilitate full hydration and strength gain.

Figure 1: Experimental Form Works and the Mixing of Concrete

2.2 Reinforcement Details

Each column specimen was reinforced with four high-yield strength deformed bars of 8 mm diameter (4Y8) with a characteristic yield strength of 400 MPa. To ensure effective confinement and prevent buckling, lateral ties made of 6 mm mild steel bars were placed at 100 mm center-to-center spacing. All reinforcement was arranged symmetrically to maintain uniform stress distribution and minimize eccentricity.

2.3 Column Geometry

The cross-sectional dimensions of all column specimens were fixed at 100 mm × 100 mm. Column lengths were varied to achieve six different length-to-depth ratios: 1, 3, 5, 7, 9, and 10. This range enabled a detailed analysis of both short and slender columns. Each specimen was labeled to reflect its reinforcement ratio and concrete grade for easy identification during testing.

2.4 Compression Strength Test

After curing, the columns were tested under axial compression using a 150- ton capacity reactant frame at the Civil Engineering Laboratory of the Faculty of Engineering, Niger Delta University Bayelsa state, to facilitate the execution of the experimental work program as shown in Figure 2. The load was applied concentrically at a controlled rate until failure occurred. Load and deformation data were captured using calibrated load cells and dial gauge to monitor axial shortening and observe failure patterns.

Figure 2: Compression Test of Samples

3. RESULTS AND DISCUSSION

The experimental results of Column **Group A** are presented in Tables 1 to 3 the data set were studied to examine the compression behavior of reinforced concrete columns with square cross-sectional area. The column group contains RC-**A_1-25, RC-A_2-20, and RC-A_3-15** each representing samples of square reinforced concrete columns with varying lengths and concrete mix grade with a reinforcement ratio ***ρ (%)*** of 2.8%.

Table 1: Compression Test Results of Reinforced Concrete Columns for Square Sections with M25 (1: 1.68: 2.37) at 28 Days

Sample I D	Length /Depth ratio	Cross section (mm)	fcu (Mpa)	Average Load (kN)	Average Stress (N/mm^2)	Failure mode
RC-A_1-25	10	100 x 100	32.37	116.12	11.61	Buckling
RC-A_1-25	9	100 x 100	32.37	126.44	12.64	Buckling
RC-A_1-25	7	100 x 100	32.37	156.6	15.66	Crushing
RC-A_1-25	5	100 x 100	32.37	212.09	21.21	Crushing
RC-A_1-25	3	100 x 100	32.37	308.0	30.80	Crushing
RC-A_1-25	1	100 x 100	32.37	456.6	45.66	Crushing

Table 2: Compression Test Results of Reinforced Concrete Columns for Square Sections with M20 (1: 1.5: 3) at 28 Days

Sample I D	Length /Depth ratio	Cross section (mm)	fcu (Mpa)	Average Load (kN)	Average Stress (N/mm^2)	Failure mode
RC-A_2-20	10	100 x 100	28.96	103.22	10.32	Buckling
RC-A_2-20	9	100 x 100	28.96	114.88	11.49	Buckling
RC-A_2-20	7	100 x 100	28.96	141.4	14.14	Crushing
RC-A_2-20	5	100 x 100	28.96	182.55	18.26	Crushing
RC-A_2-20	3	100 x 100	28.96	276.36	27.64	Crushing
RC-A_2-20	1	100 x 100	28.96	410.11	41.01	Crushing

Table 3: Compression Test Results of Reinforced Concrete Columns for Square Sections with M15 (1:2:4) at 28 Days

Sample I D	Length /Depth ratio	Cross section (mm)	fcu (Mpa)	Average Load (kN)	Average Stress (N/mm^2)	Failure mode
RC-A_3-15	10	100 x 100	20.59	89.67	8.97	Buckling
RC-A_3-15	9	100 x 100	20.59	99.91	9.99	Buckling
RC-A_3-15	7	100 x 100	20.59	127.68	12.77	Crushing
RC-A_3-15	5	100 x 100	20.59	153.75	15.38	Crushing
RC-A_3-15	3	100 x 100	20.59	220.3	22.03	Crushing
RC-A_3-15	1	100 x 100	20.59	336.1	33.61	Crushing

3.1 Influence of Length-to-Depth Ratio

The length-to-depth (L/D) ratio significantly influenced the axial load capacity and stress distribution in reinforced concrete columns. Figure 1 illustrates the relationship between L/D ratios and the axial load capacity of columns constructed with varying concrete grades M25, M20, and M15 after 28 days of curing. A pronounced inverse correlation was observed: as the L/D ratio decreased, the axial load capacity of the columns increased substantially. Columns with an L/D ratio of 1 exhibited the highest axial load capacity, whereas those with an L/D ratio of 10 showed a marked decline in strength due to heightened vulnerability to buckling a well-documented phenomenon in slender structural members (MacGregor & Wight, 2012; Nilson et al., 2010).

For instance, the axial load capacity of specimen RC-A1-25 rose from 116.12 kN at an L/D ratio of 10 to 456.60 kN at an L/D ratio of 1, reflecting a substantial increase of approximately 293%. Similar enhancements were recorded for RC-A2-20 and RC-A3-15, which exhibited increases of 297% and 275%, respectively. These trends were consistently observed across all concrete grades and reinforcement configurations, underscoring the critical role of the L/D ratio in structural design (ACI Committee 318, 2019; BS EN 1992-1-1:2004).

The reduction in slenderness associated with lower L/D ratios enhances the stability of the columns by minimizing the risk of buckling and improving their capacity to withstand axial compression. This finding aligns with existing literature emphasizing the enhanced load-bearing performance of stocky columns under axial loads (Park & Paulay, 1975; Wang et al., 2018). Hence, careful consideration of the L/D ratio is imperative in the design and optimization of reinforced concrete elements to ensure structural efficiency and safety.

3.2 Impact of Concrete Grade

The concrete grade considerably influences the axial load capacity of reinforced concrete columns. A comparative analysis of the axial load capacities across the three concrete grades demonstrates a direct correlation between concrete strength and axial performance. In Figure 3, RC-A1-25, which has the highest concrete strength (Grade M25), consistently exhibits superior axial load capacity compared to RC-A2-20 (Grade M20) and RC-A3-15 (Grade M15). At an L/D ratio of 1, RC-A1-25 achieves an axial load capacity of 456.6 kN, while RC-A2-20 and RC-A3-15 reach 410.11 kN and 336.1 kN respectively, indicating reductions of approximately 10.2% and 26.4% relative to RC-A1-25. Similarly, at an L/D ratio of 10, RC-A1-25 maintains a capacity of 116.12 kN, while RC-A2-20 and RC-A3-15 drop to 103.22 kN and 89.67 kN, reflecting reductions of 11.1% and 22.8%, respectively.

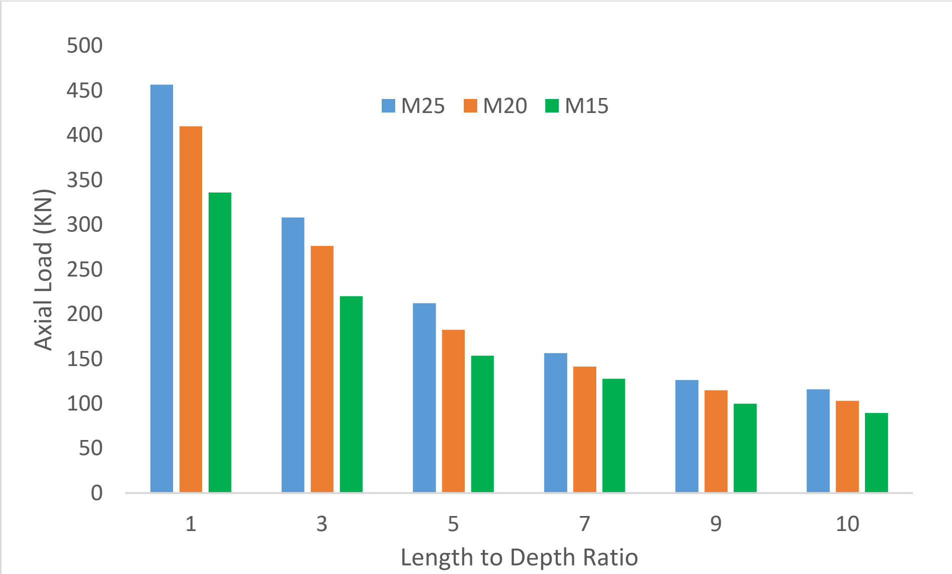

Figure 3: Effect of Concrete Grade on the Axial Load Capacity at Varying Length to Depth Ratio

These results, as presented in Figure 3, clearly indicate that the axial load capacity improves with increasing concrete grade. This relationship aligns with the findings of Neville (2011), who emphasized that compressive strength is a critical determinant of a concrete element's load-bearing performance. Moreover, Mehta and Monteiro (2014) assert that higher-grade concretes, due to their denser microstructure and superior aggregate bonding, demonstrate enhanced mechanical strength and reduced deformability under axial loads.

The variation in compressive strength among the tested grades can be attributed to differences in mix design parameters such as water-cement ratio, aggregate quality, and curing conditions (Shetty, 2005). RC-A1-25's superior performance makes it ideal for structural applications requiring high strength and durability, such as high-rise buildings, bridge piers, and load-bearing columns (ACI Committee 318, 2019). In contrast, RC-A3-15 may be more suitable for non-load-bearing elements or low-rise structures where reduced strength demands can be tolerated economically.

3.3 Failure Modes

Figure 4, presented a detailed illustration of the failure modes across different concrete grade. The experimental results reveal a significant correlation between the length-to-depth (L/D) ratio and the failure modes of specimens under axial load. Specimens with higher L/D ratios (10 and 9) predominantly failed due to buckling, characterized by lateral deflection and premature failure. This is because slender specimens are more prone to buckling under axial loads, where the specimen tends to bow or deform laterally, leading to failure. In contrast, specimens with lower L/D ratios (7, 5, 3, and 1) tended to fail in crushing, indicating a more ductile failure mode. The crushing failure mode is characterized by the specimen failing due to the compressive stress exceeding the concrete's compressive strength.

Figure 4: Failure Mode of Column Samples

Notably, the majority of the tested specimens behaved like short columns, with failure modes attributed to the restrictive influence of the testing machine platen at the supports. This caused localized stress concentrations at the top and bottom ends of the columns, initiating cracks that propagated progressively into the column structure. The failure modes observed in the experiment highlight the importance of considering the L/D ratio in the design of structural elements. As the L/D ratio increases, the failure mode transitions from crushing to buckling, emphasizing the need to account for slenderness in design.

The distinction between the failure modes of short and slender columns is also noteworthy. Short columns typically failed through concrete crushing, exhibiting a more ductile failure pattern. In contrast, slender columns showed signs of lateral deflection and premature buckling, leading to a more brittle failure pattern.

4. CONCLUSION

The experimental findings clearly demonstrate that both the length-to-depth (L/D) ratio and concrete grade significantly affect the axial load capacity and failure behavior of reinforced concrete square columns. A decrease in the L/D ratio notably enhances the axial load-carrying capacity, primarily by reducing the risk of buckling and promoting more stable, ductile crushing failures. Furthermore, higher-grade concretes (such as M25) consistently deliver superior load performance due to their increased compressive strength and structural integrity. The transition in failure modes from buckling in slender columns to crushing in shorter ones reinforces the importance of considering slenderness in structural design. Overall, this study highlights the necessity of optimizing both geometric proportions and material properties in the design of RC columns to ensure enhanced performance, safety, and reliability in structural applications.

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