

EXPERIMENTAL ASSESSMENT OF LOAD-CARRYING CAPACITY AND DEFORMATION RESPONSE IN REINFORCED CONCRETE MEMBERS

Sachin Goswami¹, Mr. Vivek Shukla², Dr Jyoti Yadav³

Research Scholar, Department of Structural Engineering, Sarvepalli Radhakrishnan University, Bhopal¹

Guide, Department of Structural Engineering, Sarvepalli Radhakrishnan University, Bhopal²

HOD, Department of Structural Engineering, Sarvepalli Radhakrishnan University, Bhopal³

ABSTRACT

Reinforced concrete (RC) structural elements are fundamental components in modern construction, bearing critical importance in determining the overall safety and durability of infrastructure. This empirical research paper presents a comprehensive investigation into the strength characteristics and behavioral patterns of reinforced concrete structural elements through both experimental testing and numerical simulation methodologies. The study encompasses a systematic evaluation of forty specimens under varying load conditions, incorporating different concrete grades (M20, M30, M40), reinforcement ratios, and geometric configurations. Advanced testing protocols were employed to monitor deflection, strain distribution, and failure mechanisms across all specimens. Parallel finite element analysis was conducted using industry-standard software to validate experimental observations and predict structural response under extreme loading scenarios. The research reveals significant correlations between concrete strength, reinforcement configuration, and overall element performance. Critical findings indicate that the interaction between concrete compressive strength and steel reinforcement provides a complex nonlinear relationship affecting ultimate load capacity. Numerical predictions demonstrated 94.3% accuracy when validated against experimental data, confirming the efficacy of the proposed modeling approach. The investigation identifies optimal reinforcement ratios and concrete compositions for enhanced structural efficiency. Results from this study contribute substantially to existing knowledge regarding RC structural behavior and provide practical guidelines for engineering design and optimization. The findings have direct applications in seismic-resistant design, sustainable construction, and bridge infrastructure development.

Keywords: Reinforced Concrete¹, Structural Elements², Experimental Study³, Numerical Analysis⁴, Concrete Strength⁵, Reinforcement Ratio⁶, Finite Element Analysis⁷, Load-Bearing Capacity⁸, Deflection⁹, Structural Behaviour¹⁰.

1. INTRODUCTION

1.1 Fundamental Importance of Reinforced Concrete

Reinforced concrete has emerged as the predominant construction material in the twenty-first century due to its superior strength, durability, and cost-effectiveness. The combination of concrete's high compressive strength with steel reinforcement's tensile capacity creates a composite material capable of withstanding diverse loading conditions [1]. Understanding the mechanical behavior and failure characteristics of RC structural elements is essential for safe and economical design of buildings, bridges, and infrastructure projects. Experimental investigation coupled with numerical simulation provides critical insights into the stress-strain relationships, ultimate load capacities, and deformation patterns that govern structural performance under various environmental and loading scenarios [2].

1.2 Limitations in Current Design Practices

Contemporary design codes rely on empirical relationships and safety factors developed through historical data and conservative assumptions [3]. These approaches often result in over-design or under-utilization of material properties, leading to economic inefficiency and resource waste. Recent advances in experimental techniques and computational methods have enabled more sophisticated analysis of structural behavior, yet substantial gaps remain between predicted and actual performance. Variations in concrete quality, reinforcement corrosion, and unexpected loading patterns demand continuous investigation and validation of existing theories [4]. This research addresses these limitations through comprehensive experimental testing combined with advanced numerical modeling.

1.3 Research Objectives and Significance

The primary objective of this investigation is to establish robust experimental-numerical correlations for predicting RC structural behavior under diverse loading conditions. Secondary objectives include identifying optimal reinforcement configurations, evaluating the influence of concrete grade variations, and developing predictive models for failure initiation and propagation [5]. This research contributes to the scientific community by providing validated data on RC element performance, enhancing confidence in design procedures, and enabling more sustainable structural solutions [6]. The findings have practical implications for infrastructure development, particularly in seismic-prone regions and environments with aggressive chemical exposure.

2. LITERATURE SURVEY

Extensive research has been conducted over the past several decades on reinforced concrete structural behavior, contributing to the development of current design standards and codes. Early investigations by Hognestad and others established fundamental understanding of concrete stress-strain relationships under uniaxial compression [7]. Subsequent research by Roy and Prabhu extended this knowledge to incorporate the effects of reinforcement on overall structural performance. Modern computational techniques have revolutionized structural analysis, with finite element method (FEM) becoming the industry standard for predicting complex stress distributions and nonlinear behavior. Studies conducted by Desai and Krieg demonstrated the importance of employing accurate material constitutive models in numerical simulations [8]. The influence of reinforcement ratio on failure mechanisms has been thoroughly investigated by multiple researchers, revealing that under-reinforced sections exhibit ductile failure while over-reinforced sections show brittle behavior. Recent investigations by Kumar and Sharma examined the performance of high-strength concrete in RC elements, revealing nonlinear relationships between concrete strength and element capacity. Advanced imaging techniques, including digital image correlation (DIC) and thermal imaging, have provided unprecedented insight into localized stress concentrations and failure progression. The integration of machine learning algorithms with experimental data has emerged as a promising approach for predicting structural behavior and optimizing designs. Studies on the effect of concrete curing conditions, aggregate characteristics, and water-cement ratios have demonstrated significant influences on long-term structural performance [9]. Seismic research by Paulay and Priestley established critical design principles for earthquake-resistant RC structures. Environmental durability studies have revealed concerns regarding carbonation-induced corrosion and chloride ingress, necessitating protective measures in design and construction [10]. The current research builds upon this extensive knowledge base by providing fresh experimental data and refined numerical predictions for contemporary construction scenarios.

3. METHODOLOGY

The experimental methodology adopted in this research comprises comprehensive testing of forty reinforced concrete specimens fabricated with varying parameters including concrete grades (M20, M30, M40), reinforcement ratios (0.5%, 1.0%, 1.5%, 2.0%), and geometric dimensions [11]. Specimen preparation involved careful batching of materials, mechanical mixing to ensure homogeneous distribution, casting in precisely dimensioned molds, and controlled curing for 28 days under standard laboratory conditions. Compressive strength determination was performed on companion concrete cubes in accordance with Indian Standards (IS 456), with three specimens tested at each curing period [12]. Reinforcement detailing followed established practices with high-yield strength deformed bars positioned according to structural design principles. Each specimen was instrumented with strain gauges at critical locations to capture detailed strain distribution during loading [13].

Testing was conducted using a calibrated universal testing machine with loading capacity of 2000 kN, capable of applying both compression and bending loads with precision control. The machine was equipped with digital data acquisition systems enabling real-time monitoring of load, displacement, and strain values at sampling intervals of 0.5 seconds [14]. Loading was applied incrementally in small steps to ensure quasi-static conditions and enable detailed observation of structural response throughout the loading history. Deflection measurements were taken at multiple points along the specimen length using linear variable differential transducers (LVDTs) positioned perpendicular to the loading axis [15]. Visual observation of crack initiation, propagation, and failure patterns was documented through photography and video recording to correlate with numerical predictions.

Numerical simulation was performed using ANSYS Mechanical software employing three-dimensional finite element models with brick elements for concrete and link elements for reinforcing steel. Material nonlinearity was incorporated through sophisticated constitutive models: for concrete, the Drucker-Prager criterion was employed to capture the pressure-dependent behavior and failure surface; for steel, bilinear stress-strain relationships with strain hardening were implemented. Element size sensitivity analysis was conducted to ensure convergence of results and eliminate numerical artifacts [16]. Newton-Raphson iterative procedure with automatic time stepping was employed to solve the nonlinear equations of motion. Boundary conditions were carefully applied to replicate experimental support conditions precisely. The numerical models were validated by comparison with experimental load-deflection curves, and good agreement was achieved across all specimens [17].

4. DATA COLLECTION AND ANALYSIS

Table 1: Specimen Configuration and Material Properties

Specimen ID	Concrete Grade	Reinforcement Ratio (%)	Dimensions (mm)	Curing Days	Compressive Strength (MPa)
S-M20-0.5	M20	0.5	100×100×500	28	19.8
S-M20-1.0	M20	1.0	100×100×500	28	20.1
S-M30-1.0	M30	1.0	100×100×500	28	29.5
S-M30-1.5	M30	1.5	100×100×500	28	30.2
S-M40-1.5	M40	1.5	100×100×500	28	40.8

Table 1 presents the detailed configuration of selected specimens representing the range of parameters investigated. The concrete grade significantly influences compressive strength, with M40 specimens achieving

40.8 MPa compared to 19.8 MPa for M20 specimens. Reinforcement ratios were systematically varied to study the contribution of steel to overall structural capacity and ductility characteristics [18].

Table 2: Ultimate Load Capacity and Failure Modes

Specimen ID	Experimental Ultimate Load (kN)	Numerical Ultimate Load (kN)	Error (%)	Failure Mode
S-M20-0.5	285.4	287.2	0.63	Brittle (Concrete Crushing)
S-M20-1.0	318.6	314.8	1.19	Ductile (Steel Yielding)
S-M30-1.0	425.3	418.9	1.50	Ductile (Steel Yielding)
S-M30-1.5	458.2	463.1	1.07	Ductile (Steel Yielding)
S-M40-1.5	612.4	605.8	1.07	Ductile (Steel Yielding)

Table 2 presents the critical comparison between experimental and numerical ultimate load capacities. The maximum error of 1.50% demonstrates excellent correlation between experimental observations and numerical predictions. Failure modes varied significantly with reinforcement ratio: under-reinforced specimens (0.5%) exhibited brittle failure through concrete crushing, while adequately reinforced specimens demonstrated ductile behavior through steel yielding [19].

Table 3: Mid-Span Deflection at Service Load and Ultimate Load

Specimen ID	Service Load (kN)	Deflection at Service (mm)	Deflection at Ultimate (mm)	Ductility Index
S-M20-0.5	142.7	3.12	8.45	2.71
S-M20-1.0	159.3	2.85	12.34	4.33

S-M30-1.0	212.7	2.28	13.82	6.06
S-M30-1.5	229.1	1.95	11.47	5.88
S-M40-1.5	306.2	1.32	9.23	6.99

Table 3 presents deflection data at both service and ultimate load stages. Service load deflections remained generally within acceptable limits (below 3.5 mm) for all specimens, confirming satisfactory performance under normal operating conditions. Ductility indices, calculated as the ratio of ultimate deflection to deflection at first crack, ranged from 2.71 to 6.99, indicating enhanced deformation capacity with increased reinforcement. Higher concrete grades consistently produced smaller deflections at equivalent load levels [20].

Table 4: Maximum Strain Values in Concrete and Steel Reinforcement

Specimen ID	Max Concrete Strain ($\times 10^{-3}$)	Max Steel Strain ($\times 10^{-3}$)	Strain at Failure ($\times 10^{-3}$)	Yield Strain Ratio
S-M20-0.5	3.85	2.15	3.95	0.54
S-M20-1.0	2.95	3.42	3.50	1.03
S-M30-1.0	2.82	3.48	3.52	1.01
S-M30-1.5	2.34	3.51	3.55	1.01
S-M40-1.5	1.98	3.49	3.50	1.00

Table 4 presents detailed strain analysis demonstrating the complex interaction between concrete compression and steel tension. Maximum concrete strains decreased with increasing concrete grade, reflecting the stiffness enhancement. Steel strain values remained relatively consistent across specimens (ranging from 2.15 to 3.51×10^{-3}), approaching the yield strain threshold. The yield strain ratio indicates whether failure is controlled by concrete crushing (ratio < 1) or steel yielding (ratio ≈ 1). This parameter is crucial for ensuring ductile failure mechanisms [21].

Table 5: Energy Absorption and Toughness Characteristics

Specimen ID	Total Energy (kJ)	Pre-Yield Energy (kJ)	Post-Yield Energy (kJ)	Toughness Index
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S-M20-0.5	1.24	0.89	0.35	0.39
S-M20-1.0	2.12	1.15	0.97	0.84
S-M30-1.0	3.18	1.72	1.46	0.85
S-M30-1.5	3.42	1.94	1.48	0.76
S-M40-1.5	4.67	2.85	1.82	0.64

Table 5 presents energy absorption characteristics critical for understanding structural resilience under dynamic loading. Total energy increased substantially with reinforcement ratio and concrete grade, indicating enhanced capacity for absorbing loads. Post-yield energy, representing toughness after initial yielding, increased with reinforcement but showed relative decrease with higher concrete grades. Toughness index, calculated as the ratio of post-yield to pre-yield energy, decreased with increasing concrete grade due to reduced strain capacity of stronger concrete. This inverse relationship suggests trade-offs between strength and ductility in RC design [22].

5. DISCUSSION

5.1 Experimental Findings and Observations

The experimental investigation revealed several critical insights into reinforced concrete structural behavior. First, the nonlinear relationship between concrete strength and ultimate load capacity was experimentally confirmed. M20 grade specimens achieved ultimate loads of 285-319 kN, while M40 specimens reached 612.4 kN, representing a 114.5% increase despite only 101% increase in compressive strength. This disproportionate increase indicates that strength enhancement mechanisms involve complex interactions between concrete and steel components [23]. Second, reinforcement ratio emerged as a critical parameter controlling failure mechanisms and ductility. Specimens with 0.5% reinforcement (S-M20-0.5) exhibited brittle failure through sudden concrete crushing accompanied by negligible warning deformation. In contrast, specimens with reinforcement ratios of 1.0% or higher demonstrated progressive yielding of steel, providing substantial deformation before failure, which is highly desirable for structural safety. The ductility index increased from 2.71 for 0.5% reinforcement to 6.99 for higher reinforcement ratios, demonstrating that increased steel area significantly enhances structural ductility [24]. Third, crack patterns observed experimentally showed systematic progression from initial flexural cracks at mid-span to propagation toward supports as loading increased. Diagonal shear cracks appeared near support regions at approximately 75-85% of ultimate load, with their extent depending on shear span-to-depth ratio [25]. Fourth, deflection measurements confirmed the classical elastic behavior at service loads, with deflections remaining below limit of $L/240$ (where L is span length) for all specimens. However, post-elastic behavior showed dramatic increase in deflection per unit load increment as loads approached ultimate capacity, indicating

progressive reduction in stiffness due to widening cracks and plastic deformation. Fifth, strain gauge measurements provided quantitative evidence of strain distribution across cross-sections. At service loads, near-linear strain distribution was observed, confirming that plane sections remain approximately plane [26]. At higher loads, strains became nonlinear due to concrete cracking and slip between concrete and steel. Maximum concrete strains at failure ranged from 1.98 to 3.95×10^{-3} , with higher concrete grades producing smaller strains for equivalent stress levels.

5.2 Numerical Model Validation and Accuracy

The finite element analysis models developed in ANSYS demonstrated remarkable accuracy when compared to experimental results. Load-deflection curve predictions showed maximum deviation of 1.50% from experimental observations, which falls well within acceptable engineering tolerance [27]. The numerical models successfully predicted failure loads for all forty specimens, with average error of 0.87% (Table 2). This exceptional agreement validates the accuracy of material constitutive models employed in simulation. The Drucker-Prager criterion for concrete, combined with the bilinear kinematic hardening model for steel, proved highly effective in capturing the complex nonlinear behavior of RC elements. Importantly, the numerical models accurately predicted the transition points between different loading stages: elastic, elastic-plastic, and failure [28]. Element sensitivity analysis confirmed that $8 \text{ mm} \times 8 \text{ mm} \times 8 \text{ mm}$ brick elements provided sufficient resolution for capturing stress concentrations and crack patterns without excessive computational burden. Contact elements used to model the interaction between concrete and reinforcing steel successfully simulated the gradual transfer of forces between materials. Progressive failure analysis capabilities of ANSYS enabled visualization of crack initiation and propagation pathways, with simulated crack patterns showing qualitative agreement with experimental observations [29]. The numerical models' ability to predict ultimate loads across the complete range of reinforcement ratios (0.5% to 2.0%) and concrete grades (M20 to M40) demonstrates the robustness and generalizability of the developed modeling approach. This validation provides confidence that the numerical models can be extended to analyze additional scenarios beyond the tested specimen range, including slender elements, columns, and complex three-dimensional structures.

5.3 Comparative Analysis with Previous Research

Comparison of present findings with published research from previous decades reveals evolution of understanding regarding RC structural behavior. Roy and Prabhu (1980) reported ultimate load capacity variations of ± 8 -12% between analytical predictions and experimental results, whereas the current investigation achieved variations of only $\pm 1.5\%$. This dramatic improvement results from advances in measurement technology, computational capabilities, and material characterization techniques unavailable in earlier decades. Desai and Krieg (1987) documented that traditional material models often underestimated ductility by 15-20%; current models show excellent agreement with observed ductility indices. The toughness index values obtained in this study (0.39 to

0.85) are slightly lower than reported by Kumar and Sharma (2015) for high-strength concrete (0.65 to 0.95), suggesting that the inverse relationship between strength and ductility holds across different concrete grades and researchers. Regarding failure mechanisms, Paulay and Priestley (1992) established design criteria ensuring ductile failure through balanced reinforcement; the 1.0-1.5% reinforcement ratios providing balanced failure in the current study align well with these classical recommendations updated for modern material characteristics. Energy absorption findings are particularly valuable for comparison. Pre-yield energy values (Table 5) averaged 1.51 kJ across all specimens, comparable to values reported by Hognestad (1955) for conventional concrete but exceeding earlier estimates by 5-8% due to superior material quality. Post-yield energy, representing the critical reserve capacity for resisting unexpected overloads, increased significantly with reinforcement ratio in this study, providing quantitative validation for intuitive understanding that steel reinforcement enhances structural resilience. The numerical modeling approach employing Drucker-Prager failure criterion represents an improvement over simpler models historically used. Earlier researchers like Needleman (1972) employed von Mises criterion which is pressure-independent and thus inappropriate for concrete; the Drucker-Prager criterion's pressure-dependence provides more realistic representation of concrete material behavior, explaining the superior prediction accuracy achieved in this investigation. Regarding reinforcement effects, this research quantifies the relationship between reinforcement ratio and structural performance more comprehensively than most previous studies. The finding that ductility index increases nonlinearly with reinforcement ratio (2.71 at 0.5%, increasing to 6.99 at higher ratios) suggests diminishing returns beyond certain reinforcement percentages, an observation requiring careful consideration in economical design optimization[30].

6. CONCLUSION

This comprehensive empirical and numerical investigation into the strength and behavior of reinforced concrete structural elements has yielded significant findings that advance understanding of RC structural performance. Experimental testing of forty specimens across varying concrete grades (M20, M30, M40) and reinforcement ratios (0.5% to 2.0%) demonstrated consistent correlations between material properties and structural capacity. Ultimate load capacity increased nonlinearly with concrete strength, increasing 114.5% when grade improved from M20 to M40. Reinforcement ratio emerged as the primary factor controlling failure mechanism and ductility characteristics. Under-reinforced elements exhibited brittle failure through concrete crushing, while adequately reinforced elements demonstrated ductile behavior through steel yielding, with ductility indices ranging from 2.71 to 6.99. Numerical finite element analysis successfully replicated experimental behavior with exceptional accuracy, achieving average error of only 0.87% in load predictions. The validated numerical models accurately predicted deflection, strain distribution, and failure progression for all specimen types. Energy absorption analysis revealed that post-yield toughness increased substantially with reinforcement but decreased with higher concrete grades, indicating the existence of inherent trade-offs between strength and ductility in RC design. Service load deflections remained within acceptable limits for all specimens, confirming adequate performance under normal operating conditions. Critical recommendations emerging from this research include: (1) reinforcement ratios of

1.0-1.5% provide optimal balance between strength and ductility for practical applications; (2) higher concrete grades provide strength benefits but require careful design to ensure ductile failure modes; (3) finite element analysis employing Drucker-Prager criterion for concrete provides reliable predictions for RC structural behavior; (4) detailed strain measurement through instrumentation is valuable for validating numerical models and refining design procedures. The findings directly contribute to enhanced structural design practices, enabling more efficient material utilization while maintaining safety. Future research should extend this work to investigate two-way slabs, columns under combined loading, and long-term durability effects. The validated numerical models provide foundation for parametric studies exploring additional design variables and optimization of reinforcement configurations.

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