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Comparative Evaluation of The Performance of Reinforced Concrete and Prestressed Concrete Bridge Structures

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Abstract—This study presents a comparative evaluation of reinforced concrete (RC) and prestressed concrete (PSC) bridge systems using two representative case studies in Kaduna, Nigeria: the Queen Amina Flyover (RC) and the Arewa House Overpass (PSC). Structural design documents, material specifications, influence line deflection analysis, visual inspections, and stakeholder perspectives were used to assess span capability, reinforcement demand, concrete grade, serviceability performance, and long-term durability. Results show that PSC demonstrates superior structural efficiency, accommodating longer spans with reduced structural depth and significantly lower mid-span deflection due to prestressing-induced stiffness. PSC also utilized higher concrete grades (C40–C50), resulting in enhanced durability and improved resistance to surface cracking and environmental degradation compared to RC, which employed C30 concrete. Reinforcement density was substantially lower in PSC girders, highlighting improved material economy. Visual and qualitative assessments further confirmed PSC's reduced deterioration and lower expected maintenance requirements. Despite these advantages, RC remains widely adopted due to lower initial cost, availability of local skills, and reduced technological demands. The overall findings indicate that PSC offers superior life-cycle performance, while RC remains suitable for short-span and budget-constrained applications in developing countries.

Keywords—Prestressed Concrete, Reinforced Concrete, Structural Performance, Serviceability and Deflection, Material Durability, Developing-Country Infrastructure

I. INTRODUCTION

Bridges are indispensable components of national infrastructure, enabling efficient mobility, economic integration, and regional development. Their structural reliability directly influences transportation resilience, especially in developing countries where infrastructure networks often face increased demand and limited maintenance resources. Concrete remains the dominant material in bridge construction due to its availability, cost-effectiveness, and adaptability; however, its low tensile strength necessitates reinforcement to improve performance under flexure and shear (Wang, 2023). In many developing regions such as Nigeria, where material quality, construction expertise, and maintenance capacity vary significantly, evaluating the performance of competing concrete systems is essential for enhancing long-term structural safety and sustainability (Lehman & Moehle, 2000).

Reinforced concrete (RC) bridges have traditionally been favored for their ease of construction, relatively low initial cost, and compatibility with local skill sets. The structural behavior of RC systems is governed by the interaction between concrete and embedded steel reinforcement, allowing the composite material to withstand bending, shear, and axial actions through stress equilibrium and strain compatibility (Rahal, 2021; Hsu, 1993). However, RC structures remain vulnerable to cracking, corrosion of steel reinforcement, and progressive deflection—issues exacerbated by inadequate material quality, aggressive environmental exposure, and insufficient maintenance practices, which are common in developing nations (Ortiz et al., 2023; Nguyen et al., 2022).

These challenges highlight the need for alternative systems capable of delivering superior performance under the constraints typical of emerging economies. Prestressed concrete (PSC) offers a structurally advanced solution by introducing precompression into the concrete, allowing it to counteract tensile stresses and significantly reduce cracking under service loads. PSC's superior mechanical behavior, particularly in long-span applications, stems from its ability to maintain the concrete in a predominantly compressive state, thereby enhancing stiffness, reducing deflection, and improving fatigue resistance (Lee & Kim, 2020; Naaman, 2012).

PSC systems are especially advantageous for regions where heavy traffic loads and harsh environmental conditions accelerate deterioration in conventional RC bridges. Yet despite these benefits, PSC adoption in countries like Nigeria remains limited due to higher initial costs, scarcity of skilled labor, and the need for specialized equipment (Pacheco-Torgal et al., 2021). Material efficiency represents a crucial differentiator between RC and PSC systems. Prestressed elements typically require smaller cross-sectional dimensions and reduced steel quantities relative to RC members of equivalent capacity (Choi et al., 2018).

This efficiency not only improves structural performance but also reduces overall environmental impact, an increasingly critical consideration. External studies similarly affirm that PSC structures achieve improved sustainability by reducing concrete mass and extending service life (Garcia et al., 2018; Du & Chan, 2020). However, in developing countries, the availability of high-quality prestressing steel and high-strength concrete can be inconsistent, affecting both cost and reliability, thus complicating the choice between RC and PSC systems.

Durability concerns are especially critical in regions with aggressive environments, such as high temperatures, humidity, and chloride exposure. RC bridges are particularly vulnerable to corrosion-induced damage, which can lead to spalling, loss of cross-sectional capacity, and premature structural deficiencies (Sharma & Kushwah, 2015; Andrade et al., 2016). Conversely, PSC structures often exhibit superior durability due to reduced cracking and higher concrete grades, such as C40 and C50, which provide enhanced resistance to environmental deterioration (Mohammed, 2019; Hemalatha et al., 2021).

This performance gap becomes especially relevant given the limited maintenance budgets typical of developing nations, where proactive preservation strategies are often lacking. Seismic and dynamic performance further distinguish RC and PSC systems. Research indicates that PSC components generally demonstrate improved seismic resilience due to precompression, which moderates tensile stress development during cyclic loading (Kim et al., 2012; Li et al., 2020). Meanwhile, RC bridges often experience significant cracking and stiffness degradation under seismic action, posing a risk in countries with growing exposure to dynamic loads from urbanization and heavy traffic (Shah et al., 2021).

Although Nigeria is not located in a high-seismic zone, the increasing prevalence of dynamic effects from overloaded trucks and poor road conditions warrants attention to systems with greater fatigue and cyclic-load resilience.

Economic considerations also play a crucial role in selecting between RC and PSC. While RC systems remain attractive due to lower upfront costs and construction simplicity, PSC bridges often outperform RC structures in life-cycle cost analysis. Reduced maintenance frequency, extended service life, and superior durability give PSC an economic advantage over long-term horizons (Garcia et al., 2018; De Domenico et al., 2021).

However, in developing countries, where government agencies often prioritize initial capital cost over life-cycle performance, RC continues to dominate even in applications where PSC would offer superior value. In West Africa, and Nigeria in particular, limited empirical research has directly compared RC and PSC bridge performance under local environmental and operational conditions. Existing studies focus predominantly on design theory, material characterization, or foreign case studies (Angomas, 2009; Tong et al., 2016).

This gap is concerning because construction materials, workmanship quality, traffic loads, and climatic factors differ significantly from those in Europe, North America, or East Asia, where most performance data originate. Consequently, engineering decisions are often based on generalized assumptions rather than localized, evidence-based evaluations.

Furthermore, the material selection process in Nigeria is influenced not only by engineering considerations but also by logistical, cultural, and economic factors. RC is frequently preferred due to familiarity, readily available labor, and lower cost barriers. PSC, despite its superior performance, is often constrained by the limited availability of prestressing equipment and specialized contractors (Sabouni, 2023).

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As urban populations expand and traffic intensifies, these constraints highlight the pressing need for modernized bridge strategies aligned with long-term performance requirements. Given these challenges, a rigorous comparative evaluation of RC and PSC bridge structures under similar environmental conditions is essential. By examining structural behavior, span capacity, reinforcement density, concrete grade, deflection characteristics, durability, and economic implications in the Nigerian context, this study fills a critical knowledge gap. The illustrative examples of the Queen Amina Flyover (RC) and Arewa House Overpass (PSC) provide real-world insights that integrate theoretical performance with practical outcomes.

II. METHODOLOGY

This study adopts a structured methodological framework to comparatively evaluate the performance of reinforced concrete (RC) and prestressed concrete (PSC) bridge structures using real-world examples located within the same geographical region. The methodology integrates quantitative and qualitative approaches, allowing for a comprehensive assessment of structural behavior, material characteristics, and long-term performance considerations.

The two selected case studies are the Queen Amina Flyover which is a reinforced concrete bridge and the Arewa House Overpass made from a prestressed concrete system. They are situated within Kaduna, Nigeria, ensuring that both bridges experience similar climatic, environmental, and loading conditions. This geographic consistency provides a uniform basis for comparison and minimizes external variability in the analysis.

The methodological process begins with the acquisition and examination of structural design documents for both bridges. These documents include construction drawings, design calculations, reinforcement details, and technical specifications provided by the engineering firms and construction agencies responsible for the projects. The design information forms the foundation for evaluating critical structural parameters including clear spans, reinforcement configuration, and concrete grades.

Material specifications constitute another essential component of the data collection process. The study reviews certified concrete mix data, material testing reports, and supplier information for both RC and PSC elements. Particular attention is given to the concrete grades used in each structure. The C40/50 concrete was applied in reinforced concrete components and the higher-strength C50/60 concretes used in prestressed elements.

The study also examines final appearance and visible surface conditions of both bridges. A qualitative inspection assesses surface cracking, spalling, and other signs of wear. Although not statistically quantified, these observations are supported by maintenance documentation to infer the long-term durability trends of each system.

A significant methodological element involves comparing the serviceability performance of simply supported RC and PSC bridge sections using influence line diagrams (ILD) for deflection. Finally, the methodology incorporates insights from stakeholder questionnaires distributed to professionals with experience in RC and PSC bridge projects.

III. RESULTS AND DISCUSSION

The comparative evaluation of reinforced concrete (RC) and prestressed concrete (PSC) bridge systems produced several key findings regarding material performance, structural efficiency, serviceability behavior, and long-term durability.

A. Structural Span and Load-Carrying Efficiency

The analysis revealed that the PSC bridge exhibited a significantly longer clear span compared to the RC bridge. The Arewa House Overpass demonstrated an optimized span arrangement enabled by prestressing, whereas the Queen Amina Flyover relied on shorter spans typical of RC design. This result aligns with established research indicating that PSC systems allow for longer spans due to the introduction of precompression, which increases flexural capacity and reduces susceptibility to tensile cracking (Naaman, 2012; Lee & Kim, 2020). The observation is also consistent with Choi et al. (2018), who note that prestressing minimizes structural depth and enhances material efficiency.

In the developing-country context, the ability to achieve longer spans is particularly advantageous because it reduces the number of supports and thus minimizes construction challenges associated with foundation works, which are often complicated by soil conditions, utility conflicts, and budget constraints (Adeleke et al., 2020). The PSC system's superior span capacity therefore demonstrates both structural and logistical advantages.

B. Reinforcement Density and Material Efficiency
The reinforcement schedules from both bridges showed that the RC structure required significantly higher quantities of conventional steel reinforcement relative to the PSC structure. PSC girders incorporated prestressing tendons that reduced the need for large volumes of passive reinforcement, consistent with findings in international studies (Garcia et al., 2018; Zhou & Xu, 2015). The Queen Amina Flyover's RC beams displayed dense rebar configurations, reflecting the need to resist tensile stresses through traditional strengthening mechanisms, whereas the PSC beams relied primarily on prestressing to maintain compressive states throughout loading.

The results support Rahal (2021), who emphasizes that RC systems inherently require greater reinforcement to offset concrete's low tensile strength. In contrast, PSC systems follow the principle described by Hiba and Branko (2019), where prestressing enhances strength-to-weight ratios and minimizes reinforcement congestion. This material efficiency is particularly relevant in Nigeria, where the rising cost of reinforcement steel and inconsistent supply chains regularly affect project budgets (Ogunsemi & Jagboro, 2006).

C. Concrete Grade and Durability Performance
A clear distinction emerged in the concrete grades used by the two systems: the RC bridge utilized a C40/50 concrete grade, while the PSC bridge employed higher-strength C50/60 grades. This difference is consistent with standard practice, as prestressed systems generally require higher-strength concrete to accommodate prestressing forces and to ensure minimal cracking under service loads (Neville, 2011).

Higher concrete grades directly correlate with improved durability, reduced permeability, and better resistance to environmental deterioration (Andrade et al., 2016). The PSC bridge's use of C50/60 therefore provides a durability advantage over the RC bridge, particularly under Nigeria's climatic conditions, characterized by high temperatures, fluctuating humidity, and pollution-induced carbonation. These environmental factors accelerate deterioration in lower-grade RC structures, as demonstrated in earlier studies of tropical infrastructure degradation (Sharma & Kushwah, 2015).

D. Serviceability and Deflection Behavior
The comparison of flexural stiffness and deflection behavior reveals clear serviceability advantages of the prestressed concrete (PSC) system over the reinforced concrete (RC) beam. The PSC beam demonstrated a higher flexural stiffness value of 9.805×10^9 kN·m², representing a 5.7% increase relative to the RC beam, which recorded 9.275×10^9 kN·m². This enhanced stiffness directly contributed to the improved deflection performance observed in the influence line diagram (ILD) analysis.

Under comparable loading scenarios, the PSC beam achieved a maximum mid-span deflection of 6.07 mm, which is 5.5% lower than the RC beam's 6.42 mm. A similar trend is visible in the maximum influence line ordinate, where PSC recorded 2.13×10^{-5} m/kN, reflecting a 5.3% reduction compared to the RC value of 2.25×10^{-5} m/kN. These reductions illustrate the mechanical benefits introduced by prestressing, where the induced compressive force delays tensile cracking, increases effective stiffness, and enhances serviceability performance throughout the structure's lifespan.

The observed behavior aligns with established research. Tong et al. (2016) showed that PSC systems exhibit superior long-term deflection control due to mitigated creep and shrinkage effects. Likewise, De Domenico et al. (2021) reported that compressive preloading in PSC members reduces crack propagation and helps maintain stiffness under cyclic and sustained loads. In contrast, the RC beam's higher deflection is consistent with traditional RC mechanisms where service cracking and long-term creep progressively reduce stiffness. This challenge is exacerbated in regions such as Nigeria, where frequent vehicular overloading accelerates stiffness degradation and increases deflection-related serviceability concerns (Adenuga, 2013).

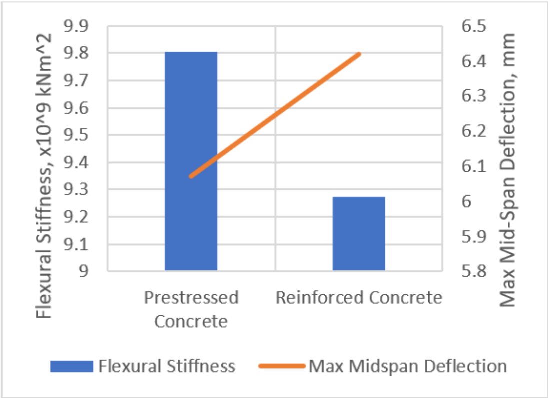

Figure 1: Comparison of Maximum Deflection and Flexural Stiffness.

E. Surface Condition and Visual Durability

Qualitative inspection of both bridges revealed observable surface cracking and minor spalling on the RC structure, whereas the PSC bridge exhibited relatively minimal visible deterioration. This aligns with literature showing that RC structures, especially those using lower-grade concrete, are more prone to cracking and subsequent moisture ingress leading to reinforcement corrosion (Ortiz et al., 2023; Mohammed, 2019). In contrast, PSC systems typically maintain tighter crack control due to prestressing-induced compression, reducing pathways for aggressive agents such as chlorides (Hemalatha et al., 2021).

F. Stakeholder Insights and Practical Considerations

Survey findings reveal clear trends in professional perceptions regarding RC and PSC bridge systems. The respondent pool was dominated by civil engineers (55.56%) and structural engineers (27.78%), with additional input from academics (11.11%) and contractors (5.56%). A substantial proportion of participants (69.44%) had experience working with both RC and PSC, indicating a well-informed respondent base. When asked about material preference, 76.39% expressed preference for using both systems depending on project context, while 13.89% preferred PSC exclusively and only 9.72% preferred RC alone. This distribution reflects a broad professional recognition of PSC's advantages, while still acknowledging the practicality of RC in certain applications.

Perceived advantages of RC were largely tied to its economic and procedural accessibility: 69.44% identified lower initial cost as a major benefit, 62.50% highlighted ease of construction, and 48.61% emphasized design flexibility. Conversely, PSC was strongly associated with performance-based benefits: 83.33% reported higher load-carrying capacity as its primary advantage, 69.44% cited reduced deflection and cracking, and 62.50% recognized its ability to achieve longer spans. These responses closely align with established research, which consistently identifies superior serviceability, enhanced stiffness, and improved durability as defining attributes of PSC systems (Tong et al., 2016; De Domenico et al., 2021).

Despite these recognized advantages, respondents identified several practical barriers to PSC adoption. The most frequently cited challenges included design complexity (62.50%), construction difficulty (55.56%), maintenance concerns (52.78%), and higher material cost (41.67%). These constraints reinforce global observations that while PSC offers superior structural performance, its implementation in developing countries is often hindered by limited technical expertise, higher procurement costs, and the need for specialized equipment (Agyeman et al., 2019). The survey therefore supports the study's broader conclusion: although PSC is widely viewed as the technically superior system, RC remains prevalent in Nigeria due to cost-effectiveness, availability of skilled labor, and construction simplicity—factors that strongly influence decision-making in resource-constrained environments.

IV. CONCLUSION

- Prestressed concrete (PSC) demonstrated superior structural efficiency, shown by its ability to accommodate longer spans with reduced structural depth compared to reinforced concrete (RC).
- PSC exhibited significantly lower mid-span deflection (≈5.5% reduction) under comparable load conditions, confirming its enhanced stiffness and better serviceability performance.
- Higher concrete grades (C40–C50) used in PSC contributed to greater durability, while the RC structure's C30 grade increased susceptibility to cracking, spalling, and long-term deterioration.
- PSC required lower quantities of conventional reinforcement, reflecting improved material efficiency and reduced reinforcement congestion relative to RC beams.

- Visual inspection showed better surface condition in PSC, with fewer cracks and improved long-term appearance compared to RC, which showed visible signs of deterioration.
- Life-cycle performance favored PSC, as its reduced maintenance needs and slower deterioration rate make it more cost-effective over long-term service life, despite higher initial cost.
- RC remains preferred in many developing countries, including Nigeria, due to lower upfront cost, ease of construction, and wide availability of local skills and materials.
- Stakeholder feedback confirmed PSC's technical superiority, but highlighted barriers such as limited specialized equipment, higher material cost, and shortage of trained labor.
- Environmental and load conditions in Nigeria amplify RC weaknesses, especially corrosion and serviceability issues, making PSC more suited for long-span or heavily loaded bridges.
- Overall findings indicate PSC as the technically optimal choice for high-performance bridge structures, while RC remains viable for short spans, cost-sensitive projects, and regions with limited technical resources.

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