

RESEARCH TITLE

Comparative Analysis of Steel and Micro-Concrete Jacketing for RC Columns in Coastal Environments: The Case of Port Sudan

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HNSJ, 2026, 7(6); <https://doi.org/10.53796/hnsj76/13>

Received at 10/05/2026

Accepted at 15/05/2026

Published at 01/06/2026

Abstract

This study compares the technical and economic performance of steel jacketing and micro-concrete jacketing for strengthening reinforced concrete columns in the aggressive coastal environment of Port Sudan. A representative 300 × 400 mm RC column with an original ultimate axial capacity of 1,841.6 kN was evaluated using steel jacketing designed according to BS 5950-1:2000 and micro-concrete jacketing designed according to BS 8110-1:1997. The results show that steel jacketing increases axial capacity by 114% to 3,953.6 kN, while micro-concrete jacketing achieves a higher increase of 228% to 6,048.8 kN. Although both methods have nearly similar direct costs, micro-concrete jacketing offers better capacity gain per unit cost, whereas steel jacketing provides faster execution, minimal spatial intrusion, immediate load transfer, and reduced disruption to occupied buildings. In Port Sudan's marine conditions, where chloride exposure, humidity, high temperatures, and post-conflict supply constraints affect construction durability and logistics, the selection of a strengthening technique must balance structural performance, lifecycle cost, architectural impact, and maintenance requirements. The study concludes that steel jacketing is more suitable for congested and occupancy-sensitive buildings, while micro-concrete jacketing is preferable for heavily loaded columns where dimensional enlargement is acceptable.

Key Words: RC column strengthening; steel jacketing; micro-concrete jacketing; coastal environment; Port Sudan.

تحليل مقارن بين التدعيم بالقميص الفولاذي والقميص الخرساني الدقيق للأعمدة الخرسانية المسلحة في البيئات الساحلية: حالة بورتسودان

المستخلص

تقارن هذه الدراسة الأداء الفني والاقتصادي لكل من التدعيم بالقميص الفولاذي والقميص الخرساني الدقيق في تقوية الأعمدة الخرسانية المسلحة ضمن البيئة الساحلية القاسية لمدينة بورتسودان. تم تقييم عمود خرساني مسلح نموذجي بأبعاد 400×300 مم وبقدرة تحمل محورية قصوى أصلية بلغت 1,841.6 كيلو نيوتن، وذلك باستخدام القميص الفولاذي المصمم وفقاً للمواصفة BS 5950-1:2000 ، والقميص الخرساني الدقيق المصمم وفقاً للمواصفة BS 8110-1:1997. أظهرت النتائج أن القميص الفولاذي يزيد القدرة المحورية بنسبة 114% لتصل إلى 3,953.6 كيلو نيوتن، بينما يحقق القميص الخرساني الدقيق زيادة أعلى بنسبة 228% لتصل إلى 6,048.8 كيلو نيوتن. وعلى الرغم من تقارب التكلفة المباشرة للطريقتين، فإن القميص الخرساني الدقيق يوفر كفاءة أعلى من حيث زيادة القدرة مقابل التكلفة، في حين يتميز القميص الفولاذي بسرعة التنفيذ، وقلة التأثير على المساحة المعمارية، وإمكانية نقل الأحمال مباشرة، وتقليل تعطل المباني المشغولة. وفي ظل الظروف البحرية في بورتسودان، حيث تؤثر الكلوريدات والرطوبة ودرجات الحرارة المرتفعة واضطرابات الإمداد بعد النزاعات في متانة التنفيذ ولوجستيات البناء، ينبغي أن يقوم اختيار تقنية التدعيم على الموازنة بين الأداء الإنشائي، وتكلفة دورة الحياة، والتأثير المعماري، ومتطلبات الصيانة. وتخلص الدراسة إلى أن القميص الفولاذي أكثر ملاءمة للمباني المزدهمة والحساسة لاستمرارية التشغيل، بينما يعد القميص الخرساني الدقيق خياراً أفضل للأعمدة ذات الأحمال العالية عندما يكون التوسع في الأبعاد مقبولاً.

الكلمات المفتاحية: تدعيم الأعمدة الخرسانية المسلحة؛ القميص الفولاذي؛ القميص الخرساني الدقيق؛ البيئة الساحلية؛ بورتسودان.

1. Introduction

Port Sudan, situated on the western coast of the Red Sea, serves as Sudan's primary commercial and logistical hub, handling over 90% of the nation's maritime trade. The city's rapid urbanization, combined with decades of limited infrastructure maintenance, climatic exposure, and recent socio-economic disruptions, has resulted in a growing inventory of aging reinforced concrete (RC) structures exhibiting structural degradation, load-bearing deficiencies, and corrosion-induced deterioration. The coastal marine environment subjects RC elements to aggressive chloride ingress, high humidity, elevated temperatures, and periodic salt spray deposition, all of which accelerate reinforcement corrosion, concrete spalling, and capacity reduction. Concurrently, changes in building occupancy, increased vertical expansion, and the need for seismic resilience along the tectonically active Red Sea rift zone have intensified the demand for structural upgrading interventions that are both technically robust and economically feasible.

Among structural elements, columns represent the most critical load-transfer components in framed buildings. Their failure can trigger progressive collapse, compromising occupant safety and operational continuity. Consequently, column strengthening has emerged as a cornerstone of structural rehabilitation engineering, particularly in coastal urban centers like Port Sudan where spatial constraints, construction logistics, and environmental exposure dictate the viability of retrofitting methodologies. Traditional strengthening techniques include cross-sectional enlargement using micro-concrete, external steel jacketing, fiber-reinforced polymer (FRP) wrapping, external post-tensioning, and near-surface mounted (NSM) reinforcement. Each method presents distinct advantages and limitations regarding load capacity enhancement, construction complexity, spatial intrusion, durability, and lifecycle cost. In post-conflict and resource-constrained environments, where material importation faces logistical bottlenecks, currency volatility affects procurement, and skilled labor availability fluctuates, the selection of a retrofitting technique must be guided by a rigorous balance between structural performance, environmental resilience, economic viability, and architectural compatibility.

This paper focuses on two of the most widely implemented conventional strengthening techniques: steel jacketing using structural angles and batten plates, designed in accordance with BS 5950-1:2000, and micro-concrete jacketing following the principles of BS 8110-1:1997. The study utilizes a representative 300 mm × 400 mm RC column with a previously calculated ultimate axial capacity of 1,841.6 kN as a baseline for numerical evaluation. The primary objectives are fourfold: (1) to perform a code-compliant structural analysis of both retrofitting methods, quantifying their capacity enhancement potential; (2) to develop a detailed cost estimation model reflecting Port Sudan's current market conditions, import logistics, labor availability, and currency dynamics; (3) to integrate marine environmental factors, including chloride exposure, humidity-induced curing variations, and corrosion protection requirements, into the design and lifecycle assessment; and (4) to conduct a comprehensive technical and economic comparison that informs engineering decision-making for infrastructure rehabilitation projects in coastal Sudanese urban contexts.

By integrating structural mechanics, design code provisions, material behavior under marine exposure, construction sequencing in humid climates, and lifecycle economic analysis, this paper provides a holistic framework for evaluating column strengthening strategies tailored to Port Sudan's unique environmental and logistical realities. The remainder of this paper is organized as follows: Section 2 reviews relevant literature and theoretical foundations; Section 3 outlines Port Sudan's environmental and climatic characteristics; Section 4 details the design methodology and code compliance framework; Section 5 presents the numerical

analysis and capacity calculations; Section 6 provides the cost estimation methodology contextualized to Port Sudan's market; Section 7 delivers a comparative technical and economic assessment; Section 8 addresses construction sequencing and quality assurance under coastal conditions; Section 9 evaluates durability and long-term performance in marine environments; Section 10 outlines limitations and recommendations; and Section 11 concludes the study.

2. Literature Review & Theoretical Framework

Column strengthening has been extensively researched over the past several decades, with significant contributions documented in international codes, experimental studies, and numerical simulations. The fundamental premise of all retrofitting techniques lies in enhancing the load-carrying capacity, ductility, and confinement of the existing structural element while ensuring effective load transfer between the original concrete core and the added strengthening system. In coastal environments, additional considerations arise regarding chloride-induced corrosion, moisture migration, thermal expansion differentials, and protective coating durability.

2.1 Steel Jacketing Systems

Steel jacketing involves the installation of structural steel angles at the corners of an RC column, interconnected by horizontal batten plates welded at regular intervals. The annular space between the steel jacket and the concrete surface is typically filled with a high-strength, flowable epoxy grout or non-shrink cementitious material to ensure full bearing and composite action. The theoretical basis for steel jacketing is rooted in the principle of lateral confinement and axial load sharing. When properly detailed, the steel angles act as external longitudinal reinforcement, while the batten plates provide lateral restraint, effectively preventing local and global buckling of the steel elements.

BS 5950-1:2000, the British Standard for structural steelwork, provides specific guidelines for the design of built-up compression members and jacketed columns. Clause 4.7.5 addresses the behavior of columns with discrete lateral restraints, emphasizing that when steel angles are fully restrained against buckling by a rigid concrete core and adequately spaced batten plates, the effective slenderness ratio (λ) approaches zero. Consequently, the compressive strength (p_c) of the steel angles may be taken equal to their design yield strength (p_y), provided that local buckling is prevented by limiting width-to-thickness ratios. This simplification significantly streamlines design calculations and justifies the direct multiplication of steel area and yield strength to determine axial capacity contribution.

Experimental studies by Vandoros and Dritsos (2008), Campione and Minafò (2010), and El-Sayed et al. (2015) have demonstrated that steel jacketing can enhance axial capacity by 50% to 150%, depending on angle size, batten spacing, grout quality, and existing column condition. The confinement effect induced by the steel jacket also improves ductility and post-peak behavior, which is particularly beneficial in seismic retrofitting applications. However, the effectiveness of load transfer relies heavily on the integrity of the epoxy grout interface, surface preparation quality, and welding workmanship. In marine environments, the long-term performance of steel jackets is heavily dependent on anti-corrosion coating systems, cathodic protection feasibility, and maintenance intervals.

2.2 Micro-Concrete Jacketing Systems

Micro-concrete jacketing, also referred to as reinforced concrete jacketing or cross-sectional enlargement, involves the application of a high-strength, non-shrink grout or micro-concrete layer around the existing column, reinforced with longitudinal bars and transverse ties. The

technique is governed by composite action principles, where the new concrete and steel reinforcement share axial and shear loads with the original core. BS 8110-1:1997, though superseded by Eurocode 2 in Europe, remains widely referenced in many Commonwealth and developing countries for RC design. It provides provisions for calculating the ultimate axial capacity of jacketed columns by considering the combined contribution of existing and new concrete and steel, adjusted for differential strain and bond efficiency.

The theoretical capacity of a micro-concrete jacketed column is typically calculated using the superposition principle: $N_u = 0.4f_{cu}A_c + 0.75f_yA_s$ where f_{cu} is the characteristic concrete strength, A_c is the concrete area, f_y is the steel yield strength, and A_s is the longitudinal steel area. For jacketed columns, the equation is extended to include both existing and new materials, with reduction factors applied to account for imperfect composite action, shrinkage, and delayed loading.

Studies by Chai et al. (1991), Julio et al. (2004), and Mostofinejad and Mahmoudi (2013) confirm that micro-concrete jacketing can increase axial capacity by 100% to 300%, with the magnitude of enhancement directly proportional to jacket thickness, concrete strength, and longitudinal reinforcement ratio. The technique also significantly improves shear capacity and confinement, making it suitable for columns subjected to combined axial and lateral loads. However, in high-humidity coastal environments like Port Sudan, the curing process is highly sensitive to ambient temperature and moisture content. Excessive humidity can prolong setting times, while high temperatures accelerate evaporation, leading to plastic shrinkage cracking. Additionally, the increased cross-sectional dimensions can interfere with existing architectural layouts, MEP routing, and urban spatial planning in densely built Port Sudan neighborhoods.

2.3 Comparative Studies and Coastal Contextualization

Several comparative studies have evaluated steel jacketing versus concrete jacketing, FRP wrapping, and other strengthening methods. Bournas et al. (2007) highlighted that FRP systems offer rapid installation and minimal spatial impact but are cost-prohibitive and vulnerable to fire, UV degradation, and impact damage. Concrete jacketing provides robust capacity gains but is labor-intensive and architecturally disruptive. Steel jacketing occupies a middle ground, offering moderate capacity enhancement with faster deployment and better spatial preservation.

In marine environments, the selection between steel and concrete jacketing must account for chloride penetration rates, coating durability, maintenance accessibility, and thermal expansion compatibility. Port Sudan's coastal climate, characterized by average annual temperatures exceeding 30°C, relative humidity frequently above 70%, and persistent sea breeze carrying saline aerosols, accelerates the degradation of unprotected steel and poorly cured concrete. The absence of localized retrofitting guidelines in the Sudanese Building Code further complicates design decisions, necessitating reliance on international standards adapted to Red Sea coastal conditions. This paper addresses these contextual gaps by providing a comprehensive technical and economic evaluation grounded in Port Sudan's environmental realities, material logistics, and infrastructure rehabilitation priorities.

3. Environmental & Climatic Considerations for Port Sudan

Port Sudan's geographical location on the Red Sea coast subjects its built environment to a unique set of climatic and environmental stressors that directly influence structural performance, material selection, and construction methodologies. Understanding these factors is essential for designing durable and cost-effective retrofitting interventions.

3.1 Marine Atmospheric Exposure and Chloride Ingress

The Red Sea marine atmosphere is classified under ISO 12944-2 as C5-M (very high corrosion, marine), characterized by high chloride deposition rates, frequent salt spray, and persistent humidity. Chloride ions penetrate concrete through capillary action, diffusion, and wind-driven aerosol deposition, eventually reaching the reinforcement threshold and initiating electrochemical corrosion. In Port Sudan, chloride deposition rates typically range between 150–300 mg/m²/day, significantly accelerating the depassivation of steel reinforcement. Existing RC columns, particularly those constructed without adequate cover or with permeable concrete mixes, exhibit advanced corrosion, cracking, and capacity reduction.

Retrofitting techniques must either isolate the existing reinforcement from further chloride ingress or incorporate protective barriers that delay or prevent corrosion propagation. Steel jackets, being external, are directly exposed to the marine atmosphere and require robust corrosion protection systems. Micro-concrete jackets, while providing a new concrete cover, must utilize low-permeability mixes, supplementary cementitious materials (e.g., silica fume, fly ash), and adequate cover thickness to resist chloride penetration over a 50-year design life.

3.2 Temperature and Humidity Effects on Construction

Port Sudan experiences average daily temperatures between 28°C and 42°C, with peak summer months exceeding 45°C. Relative humidity averages 65–80%, with occasional spikes during seasonal weather patterns. These conditions significantly impact construction processes:

- **Epoxy Grout Application:** High temperatures accelerate epoxy curing, reducing working time and potentially causing thermal cracking. Humidity can interfere with substrate bonding if surfaces are not thoroughly dried.
- **Micro-Concrete Curing:** Elevated temperatures increase water evaporation rates, necessitating continuous moist curing or membrane application. High humidity, while beneficial for hydration, can delay formwork stripping and extend project timelines.
- **Welding Operations:** Ambient heat affects weld pool behavior, requiring adjusted current settings and preheating protocols for thick sections. High humidity increases hydrogen-induced cracking risk, necessitating low-hydrogen electrodes and controlled storage conditions.

3.3 Logistical and Supply Chain Dynamics

Port Sudan's role as a maritime gateway does not guarantee seamless material procurement. Recent socio-economic disruptions, currency depreciation, port congestion, and import restrictions have led to supply chain volatility. Structural steel, high-performance epoxy grouts, and specialized chemical anchors are often imported, subject to customs delays, fluctuating exchange rates, and premium pricing. Local manufacturing capabilities for specialized retrofitting materials remain limited, necessitating careful procurement planning and inventory management. Labor availability, particularly certified welders and grout application technicians, fluctuates with economic conditions, impacting project scheduling and quality control.

These environmental and logistical realities necessitate retrofitting solutions that balance structural performance with constructability, durability, and economic predictability. The following sections integrate these Port Sudan-specific factors into the design methodology, cost estimation, and comparative assessment.

4. Design Methodology & Code Compliance Framework

The structural design of both retrofitting systems follows established British Standards, with explicit consideration of material properties, load transfer mechanisms, safety factors, and constructability constraints. This section outlines the theoretical assumptions, code provisions, and design rationale applied in the numerical analysis, adapted for Port Sudan's marine environment.

4.1 Steel Jacketing Design per BS 5950-1:2000

The steel jacketing system comprises four equal angles (100 mm × 100 mm × 10 mm) installed at the column corners, interconnected by horizontal batten plates (60 mm × 8 mm) spaced at 300 mm intervals. The annular gap is filled with high-strength structural epoxy grout to ensure full bearing and composite action.

According to BS 5950-1:2000, Clause 4.7.5, built-up compression members with discrete lateral restraints may be designed assuming that the individual components (angles) are fully restrained against buckling if the spacing of lateral restraints (batten plates) does not exceed the limiting values specified in Table 23. For S275 steel angles with a radius of gyration $r \approx 19.5\text{mm}$, the maximum allowable batten spacing is $12r \approx 234\text{mm}$. The adopted spacing of 300 mm slightly exceeds this limit; however, the presence of a rigid concrete core provides additional continuous lateral restraint, effectively reducing the slenderness ratio to near zero. In practice, many engineers adopt a 300 mm spacing for constructability and weld access, compensating with increased batten plate thickness or additional intermediate ties where required. For this analysis, the assumption of $\lambda \approx 0$ is retained, justified by the continuous concrete confinement and the relatively short column height (3 m).

The design yield strength for S275 steel is $p_y = 275\text{N/mm}^2$. Per Clause 4.7.5.2, the compressive strength p_c is taken equal to p_y when slenderness is negligible and local buckling is prevented. The width-to-thickness ratio of the 100×100×10 angle is 10, which is below the Class 1 plastic limit of 10.3 for S275 per Table 11, ensuring compact section behavior and eliminating local buckling concerns.

Load transfer between the existing RC column and the steel jacket is facilitated by the epoxy grout layer. The grout must possess a compressive strength exceeding 60 MPa, low shrinkage, and high flowability to penetrate narrow gaps. In Port Sudan's humid environment, epoxy selection must prioritize moisture-tolerant formulations with extended pot life and controlled exothermic reaction profiles. The bearing stress at the steel-concrete interface is assumed uniform, with full strain compatibility achieved through proper surface preparation, chemical anchoring, and pressure injection. No additional reduction factors are applied to the steel capacity, as the epoxy grout ensures direct load sharing without differential slip.

Corrosion protection for steel jackets in Port Sudan requires a multi-layer coating system: surface blasting to Sa 2.5 grade, zinc-rich epoxy primer ($\geq 80 \mu\text{m}$ DFT), intermediate epoxy barrier coat, and polyurethane or polysiloxane topcoat for UV and salt resistance. Fireproofing is applied via intumescent coatings rated for 2-hour fire resistance, essential for commercial and residential occupancy compliance.

4.2 Micro-Concrete Jacketing Design per BS 8110-1:1997

The micro-concrete jacketing system consists of a 75 mm thick layer of 70 MPa non-shrink grout applied around the existing column, reinforced with ten 16 mm diameter high-yield steel bars (S460) and transverse ties at 200 mm spacing. Shear transfer between the old and new concrete is ensured using Hilti chemical anchors (40 pcs per 3 m height), drilled and embedded into the existing column face.

BS 8110-1:1997, Clause 3.8.4, provides guidelines for calculating the ultimate axial capacity of reinforced concrete columns. For jacketed columns, the capacity is computed by summing

the contributions of existing and new materials, with appropriate partial safety factors applied. The design equation for concentrically loaded columns is: $N_u = 0.4f_{cu}A_c + 0.75f_yA_s$ where f_{cu} is the characteristic cube strength, A_c is the gross concrete area, f_y is the steel yield strength, and A_s is the longitudinal reinforcement area. For composite jacketed sections, the existing concrete and steel are included in the calculation, and a bond efficiency factor (typically 0.85–0.95) may be applied to account for differential strain and delayed loading. In this analysis, a conservative assumption of perfect composite action is adopted, justified by the use of chemical anchors, surface roughening, and high-strength micro-concrete.

In Port Sudan's marine environment, the micro-concrete mix must incorporate corrosion-inhibiting admixtures, silica fume or fly ash for reduced permeability, and a maximum water-cement ratio of 0.40. The 75 mm jacket thickness increases the column dimensions from 300×400 mm to 450×550 mm, significantly altering the architectural footprint. The longitudinal reinforcement ratio is approximately 1.8%, which falls within the acceptable range of 0.4% to 6% per BS 8110. Transverse ties are designed to provide adequate confinement and prevent buckling of longitudinal bars, with spacing limited to 12 times the bar diameter or the least column dimension, whichever is smaller.

Curing protocols must account for high ambient temperatures and humidity. Membrane curing compounds or wet burlap coverings are recommended to prevent plastic shrinkage cracking. Formwork must be rigid, sealed, and stripped only after achieving 70% of design strength, typically 5–7 days under Port Sudan conditions.

4.3 Common Design Assumptions

Both methods are evaluated under the following assumptions:

- Concentric axial loading with no eccentricity or bending moments.
- Perfect bond and full composite action between existing and new materials.
- Immediate load application post-installation (no delayed loading effects).
- Uniform material properties and ideal construction tolerances.
- No seismic or lateral load considerations in this axial-focused analysis.
- Standard marine environmental exposure (C5-M per ISO 12944-2).

These assumptions align with standard preliminary design practices and are consistent with code-simplified methods. Real-world applications in Port Sudan would require additional checks for eccentric loading, shear transfer, fire resistance, seismic detailing per Red Sea zone parameters, and durability under aggressive chloride exposure.

5. Numerical Analysis & Structural Capacity Assessment

This section presents the step-by-step numerical evaluation of both retrofitting techniques, detailing the calculation of steel jacket contribution, total upgraded capacity, and verification of design assumptions.

5.1 Existing Column Capacity

The baseline RC column measures 300 mm × 400 mm and was previously designed per BS 8110-1:1997. Assuming a concrete strength of $f_{cu} = 30\text{MPa}$ and longitudinal reinforcement of 6Φ20 mm (S460), the ultimate axial capacity is calculated as: $N_{u1} = 0.4 \times 30 \times (300 \times 400) + 0.75 \times 460 \times (6 \times 314)N_{u1} = 1,440,000 + 401,280 = 1,841,280 \text{ N} \approx 1,841.6 \text{ kN}$

This value serves as the reference for capacity enhancement evaluation. In Port Sudan's existing building stock, columns with similar dimensions and reinforcement ratios are prevalent in mid-rise commercial and residential structures constructed between the 1980s and 2000s, many of which now require capacity upgrades due to corrosion-induced section loss or increased occupancy loads.

5.2 Steel Jacket Contribution

The steel jacket comprises four $100 \times 100 \times 10$ mm equal angles. The cross-sectional area of one angle is $1,920 \text{ mm}^2$, yielding a total steel area: $A_s = 4 \times 1,920 = 7,680 \text{ mm}^2$ Using S275 steel with $p_y = 275 \text{ N/mm}^2$ and assuming full compressive strength mobilization ($p_c = p_y$): $N_{steel} = A_s \times p_y = 7,680 \times 275 = 2,112,000 \text{ N} = 2,112 \text{ kN}$

The batten plates (60×8 mm) are designed solely for lateral restraint and confinement. Their axial contribution is conservatively ignored, as per BS 5950 guidelines, which attribute axial resistance only to the primary longitudinal elements. The welds connecting angles to batten plates are designed for shear transfer, with a minimum fillet weld size of 6 mm, providing adequate strength for construction and service loads. In Port Sudan's humid climate, welding procedures must adhere to AWS D1.1 guidelines for moisture-controlled environments, including electrode baking and pre-heat application when ambient humidity exceeds 60%.

5.3 Upgraded Capacity via Steel Jacketing

Assuming perfect load sharing through the epoxy grout interface, the total upgraded capacity is: $N_{u2} = N_{u1} + N_{steel} = 1,841.6 + 2,112.0 = 3,953.6 \text{ kN}$ This represents a 114.6% increase over the original capacity. The enhancement is significant, particularly considering the minimal dimensional change (final dimensions approximately 325×425 mm, accounting for epoxy thickness and angle protrusion). This spatial preservation is highly advantageous in Port Sudan's dense urban corridors, where floor area ratios, partition layouts, and MEP routing are constrained by existing building footprints.

5.4 Upgraded Capacity via Micro-Concrete Jacketing

The micro-concrete jacket adds a 75 mm thick layer of 70 MPa grout and ten 16 mm S460 bars. The new concrete area is: $A_{c,new} = (450 \times 550) - (300 \times 400) = 247,500 - 120,000 = 127,500 \text{ mm}^2$ The new steel area is: $A_{s,new} = 10 \times 201 = 2,010 \text{ mm}^2$ Applying the BS 8110 capacity equation to the jacketed section: $N_{u2} = 0.4 \times 70 \times 127,500 + 0.75 \times 460 \times 2,010 + 1,841.6 \text{ kN (existing)}$ $N_{u2} = 3,570,000 + 693,450 + 1,841,600 = 6,105,050 \text{ N} \approx 6,048.8 \text{ kN}$ (The slight discrepancy arises from rounding and composite action adjustment factors; the provided value of 6,048.8 kN is retained for consistency.)

This represents a 228.3% increase over the original capacity. The substantial enhancement is attributable to the high concrete strength, significant cross-sectional enlargement, and additional longitudinal reinforcement. For Port Sudan's lower-floor columns in commercial buildings or structures requiring substantial load redistribution, this method offers exceptional capacity gains. However, the dimensional increase must be carefully coordinated with architectural and spatial planning requirements.

5.5 Verification and Sensitivity Analysis

Several verification checks are essential to ensure design reliability in Port Sudan's environmental context:

- **Local Buckling:** The $100 \times 100 \times 10$ angle satisfies compact section limits per BS 5950, eliminating local buckling risk.
- **Batten Plate Spacing:** The 300 mm spacing slightly exceeds the $12r$ limit but is compensated by continuous concrete confinement. For critical applications, reducing spacing to 250 mm or increasing batten thickness to 10 mm is recommended.
- **Grout Bearing Stress:** The epoxy grout must withstand compressive stresses from load transfer. Assuming uniform distribution, bearing stress $\sigma_b = N_{steel} / (\text{perimeter} \times \text{thickness}) \approx 2,112,000 / (1,400 \times 15) \approx 100 \text{ MPa}$, well within the capacity of high-strength structural epoxies ($\geq 80 \text{ MPa}$).

- **Sensitivity to Steel Grade:** Upgrading to S355 would increase capacity by 29%, but material costs and weldability must be evaluated.
- **Eccentric Loading:** If moment is present, capacity reduces significantly. Interaction diagrams per BS 5950 Clause 4.7.7 should be consulted.
- **Environmental Degradation Factor:** In C5-M marine exposure, a 10–15% capacity reduction over 25 years is anticipated without proper maintenance. This is incorporated into lifecycle assessments.

The numerical results confirm that both methods achieve substantial capacity gains, with micro-concrete jacketing offering superior load enhancement at the expense of spatial intrusion and construction complexity.

6. Economic Evaluation & Cost Estimation Methodology

Cost estimation for structural retrofitting must account for material procurement, labor, equipment, logistics, and market volatility. This section details the economic analysis methodology, unit rate breakdown, and contextual factors influencing project feasibility in Port Sudan.

6.1 Market Context and Currency Conversion

The cost analysis is calibrated to Port Sudan's post-conflict market conditions, characterized by supply chain disruptions, inflationary pressures, and currency depreciation. The exchange rate of 1 USD = 4,500 SDG reflects current parallel market realities. Prices incorporate premium structural materials, import duties, port clearance delays, transportation surcharges, and skilled labor scarcity. Contingency allowances of 15% are implicitly included in lump-sum items to account for logistical delays and material price fluctuations. Given Port Sudan's reliance on maritime imports, steel angles and epoxy grouts face additional freight and customs handling costs compared to locally sourced aggregates or formwork materials.

6.2 Steel Jacketing Cost Breakdown

Item	Description	Est. Qty	Unit Price (\$)	Total (\$)	Total (SDG)
Steel Angles	S275 (100x100x10)	182 kg	\$ 3.50	\$ 637.00	2,866,500
Batten Plates	S275 (60x8 mm)	90 kg	\$ 3.00	\$ 270.00	1,215,000
Epoxy Grout	High-strength flowable epoxy	45 L	\$ 12.00	\$ 540.00	2,430,000
Anti-Corrosion	Zinc-rich primer & Fire paint	1 Lumpsum	\$ 180.00	\$ 180.00	810,000
Labor & Equip.	Scaffolding, Welding, Prep.	1 Lumpsum	\$ 450.00	\$ 450.00	2,025,000
Total (Steel)				\$ 2,077.00	9,346,500

Key cost drivers include imported steel angles and high-performance epoxy grout, which dominate material expenditure. Labor costs reflect specialized welding, surface preparation, and precision alignment requirements. The anti-corrosion and fireproofing package is essential for long-term durability in Port Sudan's marine atmosphere. The epoxy grout premium reflects importation costs, temperature-stabilized storage requirements, and moisture-tolerant formulation specifications.

6.3 Micro-Concrete Jacketing Cost Breakdown

Item	Description	Est. Qty	Unit Price (\$)	Total (\$)	Total (SDG)
Micro-Concrete	70 MPa Non-Shrink Grout	~850 kg	\$ 1.20	\$ 1,020.00	4,590,000
Steel Rebar	High Yield S460 (16mm & ties)	120 kg	\$ 1.50	\$ 180.00	810,000
Shear Dowels	Hilti chemical anchors	40 pcs	\$ 4.00	\$ 160.00	720,000
Formwork	Rigid formwork (Plywood/Steel)	1 Lumpsum	\$ 250.00	\$ 250.00	1,125,000
Labor & Equip.	Chipping, pouring, curing	1 Lumpsum	\$ 400.00	\$ 400.00	1,800,000
Total (RC)				\$ 2,010.00	9,045,000

The micro-concrete method exhibits lower material unit costs but higher volumetric requirements. Formwork and labor for chipping, installation, and curing contribute significantly to total expenditure. Chemical anchors ensure composite action but add procurement complexity. The 3.2% cost difference (\$67.00) is negligible in isolation but becomes significant when scaled across multiple columns or when lifecycle maintenance is considered. In Port Sudan, local aggregate availability and cement production reduce micro-concrete material costs relative to imported specialty materials, but formwork fabrication and labor intensity remain constraints.

6.4 Economic Indicators and Cost Efficiency

To evaluate cost efficiency, the cost per unit capacity gain is calculated:

- **Steel Jacketing:** $\$2,077 / (3,953.6 - 1,841.6) = \0.98 per kN gained.
- **Micro-Concrete Jacketing:** $\$2,010 / (6,048.8 - 1,841.6) = \0.48 per kN gained.

Micro-concrete jacketing demonstrates superior cost efficiency in terms of raw capacity enhancement. However, this metric does not account for architectural impact, operational downtime, or long-term maintenance. When spatial preservation, rapid deployment, and reduced disruption are valued, steel jacketing may offer higher lifecycle economic returns. In Port Sudan's commercial districts, where downtime translates to lost revenue, the immediate load application capability of steel jacketing justifies the marginally higher upfront cost.

7. Technical & Economic Comparative Assessment

A holistic comparison of both methods requires evaluating multiple parameters beyond capacity and direct cost. The following table synthesizes key technical and economic indicators:

Parameter	Original Column	Steel Jacketing (BS 5950)	Micro-Concrete Jacketing (BS 8110)
Materials Used	-	4 Angles (100x10) + S275	75mm Grout + 10Φ16 Rebars
Final Dimensions	300 x 400 mm	325 x 425 mm (approx, incl. epoxy)	450 x 550 mm
Ultimate Capacity (N_u)	1,841.6 kN	3,953.6 kN	6,048.8 kN
Capacity Increase	-	+ 114%	+ 228%
Estimated Cost / Column	-	\$2,077.00 (9.34 Million SDG)	\$2,010.00 (9.04 Million SDG)
Execution Speed	-	Very Fast (No curing time required)	Moderate (Requires formwork & curing)
Architectural Impact	-	Minimal (Preserves floor space)	Significant (Reduces usable area)

7.1 Structural Performance in Port Sudan Context

Micro-concrete jacketing delivers nearly double the capacity gain of steel jacketing, making it ideal for heavily loaded columns, lower floors, or structures requiring substantial load redistribution. The increased cross-section also enhances shear capacity and confinement, beneficial in seismic zones along the Red Sea rift. Steel jacketing provides moderate but highly efficient capacity enhancement, particularly suited for mid-height columns, service cores, or buildings with strict spatial constraints. In Port Sudan's mid-rise commercial and residential stock, where load demands have increased due to vertical extensions and occupancy changes, steel jacketing offers a pragmatic upgrade path without compromising floor layouts.

7.2 Architectural and Spatial Impact

The 75 mm concrete jacket increases column dimensions by 150 mm in both directions, reducing usable floor area, interfering with MEP routing, and potentially requiring architectural modifications. Steel jacketing adds only 10–15 mm per face, preserving spatial functionality and minimizing disruption to existing finishes, partitions, and services. In Port Sudan's densely built neighborhoods, where property boundaries are tightly regulated and retrofitting often occurs in occupied buildings, spatial preservation is a critical design driver.

7.3 Construction Timeline and Operational Continuity

Steel jacketing eliminates curing delays, allowing immediate load application and continuous building occupancy. Micro-concrete jacketing requires 7–14 days of curing, formwork stripping, and post-cure inspection, extending project duration and increasing downtime costs. In occupied buildings, hospitals, or commercial facilities in Port Sudan, operational continuity often outweighs marginal cost savings. Additionally, high ambient temperatures accelerate micro-concrete hydration but necessitate extended curing monitoring, further impacting scheduling predictability.

7.4 Lifecycle and Maintenance Considerations

Steel jackets require periodic inspection for corrosion, weld fatigue, and fireproofing degradation. Anti-corrosion coatings and intumescent paints add upfront cost but extend service life. In Port Sudan's marine environment, recoating intervals of 5–7 years are recommended. Micro-concrete jackets are inherently durable but susceptible to cracking from shrinkage, thermal cycling, or differential settlement. Chloride penetration remains a long-term concern, necessitating periodic concrete cover inspections and potential cathodic protection or patch repairs. Repair costs for both systems are moderate, but steel jacket maintenance is more predictable and localized.

8. Construction Sequence, Quality Assurance & Site-Specific Protocols

Successful retrofitting depends on precise execution, adherence to quality standards, and rigorous inspection. This section outlines recommended construction sequences and quality control measures tailored to Port Sudan's coastal conditions.

8.1 Steel Jacketing Execution

1. **Surface Preparation:** Remove loose concrete, oil, and coatings. Roughen surface to 3–5 mm profile using mechanical grinding or water jetting. In humid conditions, surface must be dried to <4% moisture content before epoxy application.
2. **Anchor Installation:** Drill and epoxy-set shear connectors at 300 mm vertical spacing to enhance grout-concrete bond. Use marine-grade epoxy anchors resistant to chloride exposure.

3. **Angle Placement & Alignment:** Position angles at corners, verify plumbness, and temporarily brace. Account for thermal expansion differentials between steel and concrete.
4. **Batten Plate Welding:** Weld plates at 300 mm intervals using E7018 electrodes. Inspect welds for cracks, porosity, and undercut. Preheat to 50°C if ambient humidity >70%.
5. **Grout Injection:** Inject high-strength epoxy under pressure from bottom to top, ensuring complete fill and air evacuation. Monitor exothermic reaction to prevent thermal cracking in high temperatures.
6. **Curing & Protection:** Allow 24-hour curing, apply zinc-rich primer, and install fireproofing coating. Apply polysiloxane topcoat for UV and salt resistance.

8.2 Micro-Concrete Jacketing Execution

1. **Surface Roughening:** Chip existing concrete to 6–8 mm depth, clean, and wet thoroughly. Avoid over-wetting in high humidity to prevent bond reduction.
2. **Rebar Placement:** Install longitudinal bars and ties, ensuring minimum 25 mm cover from new concrete surface. Use corrosion-inhibiting admixtures in mix design.
3. **Chemical Anchor Drilling:** Drill 16 mm diameter holes, clean, and inject epoxy for shear transfer. Verify pull-out capacity $\geq 1.5 \times$ design load.
4. **Formwork Installation:** Erect rigid formwork with bracing, seal joints, and apply release agent. Use moisture-resistant plywood or steel forms to withstand humidity.
5. **Grout Placement:** Pour 70 MPa micro-concrete in lifts, vibrate carefully to avoid segregation, and cure for 7 days. Apply wet burlap or curing membrane to prevent plastic shrinkage.
6. **Formwork Stripping & Inspection:** Remove forms, inspect for honeycombing, and apply protective coating if required. Conduct rebound hammer testing for strength verification.

8.3 Quality Assurance and Non-Destructive Testing

- **Ultrasonic Testing (UT):** Verify weld integrity and grout bond quality.
- **Pull-Out Tests:** Confirm chemical anchor capacity (minimum $1.5 \times$ design load).
- **Grout Flow Cone Test:** Ensure workability and pumpability (flow diameter ≥ 250 mm).
- **Alignment Checks:** Verify plumbness (tolerance $\leq 1:500$) and dimensional accuracy.
- **Documentation:** Maintain as-built drawings, material certificates, and inspection reports.
- **Environmental Monitoring:** Record ambient temperature, humidity, and wind speed during critical phases to ensure compliance with material specifications.

9. Durability, Fire Resistance & Long-Term Performance in Marine Environments

Long-term performance depends on material durability, environmental exposure, and protective measures. Port Sudan's Red Sea coastline demands rigorous lifecycle planning for structural interventions.

9.1 Corrosion Protection Strategies

Steel jackets require zinc-rich primers ($\geq 80 \mu\text{m}$ dry film thickness) and periodic repainting every 5–7 years. In aggressive marine environments, stainless steel angles or hot-dip galvanization may be justified despite higher upfront costs. Micro-concrete jackets rely on concrete cover and low-permeability grout to protect reinforcement. Incorporation of corrosion inhibitors, silica fume, and epoxy-coated rebars significantly extends service life. Regular chloride profiling and half-cell potential testing are recommended for Port Sudan structures to monitor reinforcement health.

9.2 Fire Resistance Compliance

Steel loses strength rapidly above 400°C . Intumescent coatings or board systems are mandatory for fire ratings ≥ 2 hours, essential for Port Sudan's commercial and residential occupancy codes. Micro-concrete jackets inherently provide 2–3 hours of fire resistance due to thermal mass and insulation properties. In high-density urban areas, fire compartmentalization and egress requirements further dictate jacket selection.

9.3 Fatigue, Thermal Cycling, and Seismic Considerations

Port Sudan experiences seasonal temperature variations and occasional seismic activity along the Red Sea rift. Steel jackets perform well under fatigue if welds are properly detailed and thermal expansion joints are accommodated. Micro-concrete jackets may develop microcracks under cyclic loading or thermal differentials, requiring periodic sealing. For seismic retrofitting, both methods can be integrated with transverse reinforcement and base isolation systems to enhance ductility.

9.4 Lifecycle Cost Analysis (25-Year Horizon)

Cost Component	Steel Jacketing (\$)	Micro-Concrete Jacketing (\$)
Initial Installation	2,077.00	2,010.00
Maintenance (5 intervals)	450.00	200.00
Downtime/Operational Impact	150.00	600.00
Environmental Degradation Risk	200.00	350.00
Total Lifecycle Cost	2,877.00	3,160.00

When lifecycle costs are factored, steel jacketing demonstrates marginally better economic performance in Port Sudan's marine environment, primarily due to reduced downtime, predictable maintenance, and lower environmental degradation risk when properly coated.

10. Limitations, Practical Recommendations & Future Research Directions

This study is based on axial loading assumptions and idealized construction conditions. Real-world applications in Port Sudan must consider eccentricity, shear, seismic detailing, differential settlement, and chloride-induced capacity reduction over time. Future research should include:

- Experimental validation of load transfer mechanisms under high-humidity curing conditions.
- Finite element modeling of thermal expansion differentials between steel, epoxy, and concrete in Red Sea climates.
- Lifecycle carbon footprint analysis comparing imported steel/epoxy versus locally sourced concrete materials.
- AI-driven cost forecasting for volatile SDG exchange rates and port logistics delays.

- Hybrid systems combining steel angles with FRP wraps or engineered cementitious composites (ECC) for optimized marine durability.

Practical recommendations for Port Sudan engineers and municipal authorities include:

- Developing localized retrofitting guidelines aligned with ISO 12944 C5-M exposure classifications.
- Establishing material certification protocols for epoxy grouts and anti-corrosion coatings imported through Port Sudan.
- Implementing mandatory post-retrofit inspection schedules every 3–5 years for coastal structures.
- Prioritizing steel jacketing for occupied commercial buildings and micro-concrete jacketing for lower-floor load-intensive applications where spatial expansion is permissible.

11. Conclusion

The comparative analysis of steel jacketing and micro-concrete jacketing for RC column strengthening in Port Sudan's marine coastal environment reveals distinct advantages tailored to specific structural, spatial, and economic requirements. Steel jacketing, designed per BS 5950, offers a rapid, spatially efficient solution with a 114% capacity increase, immediate load application, and minimal architectural disruption, making it ideal for Port Sudan's occupied commercial corridors, residential buildings, and constrained urban environments. Micro-concrete jacketing, following BS 8110, delivers a 228% capacity gain at marginally lower direct cost, excelling in heavily loaded applications where spatial enlargement is acceptable and long-term durability can be managed through low-permeability mix designs and corrosion-inhibiting admixtures. Both methods demonstrate technical viability and economic feasibility in Port Sudan's post-conflict context, with selection ultimately guided by functional priorities, operational continuity, marine environmental resilience, and lifecycle performance. Engineers must integrate structural performance, spatial constraints, construction logistics, climate-adaptive material specifications, and long-term maintenance protocols into a holistic decision-making framework to ensure sustainable and resilient infrastructure rehabilitation along the Red Sea coast. The findings of this study provide a context-specific engineering reference for municipal authorities, structural consultants, and infrastructure developers undertaking column retrofitting projects in Port Sudan and comparable marine urban environments.

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