World Journal of Engineering and Technology
www.worldengineerjournal.com
Online ISSN:
Received: 14-10-2025, Accepted: 13-11-2025, Published: 28-11-2025
Volume 1, Issue 2, Oct-Dec, 2025, Page No. 11-16

Seismic performance and durability assessment of bamboo-reinforced concrete structures in coastal engineering applications

Budianto Sastrowardoyo
Department of Civil and Structural Engineering Nusantara Maritime Technical University, Indonesia

Abstract
The incorporation of sustainable reinforcement materials in structural engineering presents an opportunity to reduce environmental impact while maintaining structural integrity in marine environments. This study investigates the seismic performance and long-term durability of bamboo-reinforced concrete (BRC) composites subjected to cyclic loading, salt-spray exposure, and wave action conditions characteristic of coastal regions. A total of 120 reinforced concrete specimens were manufactured using three reinforcement types: conventional steel rebars (control), treated bamboo strips, and hybrid bamboo-steel composite reinforcement. Specimens underwent 500 hours of accelerated salt-spray testing (ASTM B117) and cyclic loading simulations at 0.5g, 0.75g, and 1.0g peak ground acceleration. Compressive strength retention after durability testing was 94.2% (±2.3%) for BRC specimens and 91.6% (±3.1%) for hybrid composites, compared to 88.5% (±4.2%) for steel-reinforced controls. Flexural capacity under seismic loading showed that BRC structures exhibited superior damping characteristics with a 23.4% increase in energy dissipation relative to conventional reinforcement. Cracking patterns indicated delayed crack initiation in BRC specimens, with maximum crack width of 0.28 mm (±0.05 mm) compared to 0.41 mm (±0.07 mm) for steel controls after 1.0g seismic simulation. Durability assessment revealed that treated bamboo composites maintained structural coherence in high-chloride environments, with corrosion-induced strength loss of only 4.8% over 18 months of simulated marine exposure. The findings demonstrate that properly treated and engineered bamboo reinforcement offers comparable or superior performance to conventional materials in coastal applications while providing significant environmental and economic advantages. This research establishes design guidelines for BRC structures in seismic and corrosive environments, contributing to sustainable construction practices in vulnerable coastal regions.

Keywords: Bamboo-reinforced concrete, seismic performance, coastal durability, composite materials, sustainable construction, salt-spray corrosion, energy dissipation

Introduction

Background and Context

Coastal regions worldwide face compounding challenges of seismic activity, environmental degradation, and the need for sustainable infrastructure development. Approximately 600 million people live in low-elevation coastal zones, with many residing in seismically active regions where conventional reinforced concrete remains the predominant structural material [1]. However, the production of Portland cement and steel reinforcement accounts for approximately 16% of global CO_2 emissions, creating an urgent imperative to develop alternative reinforcement systems that maintain structural performance while reducing environmental burden [2].

Bamboo, a rapidly renewable resource that reaches maturity in 3–5 years compared to 50+ years for timber, has been recognized by the United Nations as a sustainable material with significant structural potential [3]. The tensile strength of bamboo (150–200 MPa) rivals that of mild steel (250 MPa), while its lower density (600–900 kg/m³) offers advantages in seismic design through reduced inertial forces [4]. Despite these promising characteristics, the application of bamboo reinforcement in coastal engineering remains limited, primarily due to concerns regarding durability in chloride-rich environments and insufficient understanding of performance under cyclic seismic loading.

Literature Review and Research Gaps

Previous studies have demonstrated the feasibility of bamboo as reinforcement in concrete structures under static loading conditions. Verma *et al.* (2019) [5] showed that bamboo-reinforced concrete beams achieved comparable flexural capacity to steel-reinforced specimens when reinforcement ratios were appropriately adjusted [5]. Similarly, Yamaguchi *et al.* (2020) [6] documented that properly treated bamboo maintained tensile strength retention of 85–92% after one year of outdoor exposure in humid subtropical climates [6].

However, critical research gaps persist. First, the behavior of bamboo reinforcement under cyclic seismic loading—particularly at amplitude levels relevant to high-hazard coastal zones—remains poorly characterized. Second, while general durability assessments exist, the specific mechanisms of degradation in high-chloride marine environments have not been thoroughly investigated. Third, the interaction between concrete matrix and bamboo under combined seismic and corrosive conditions lacks systematic experimental documentation. Most prior research has focused on temperate climates or short-term exposure periods (less than 12 months), limiting applicability to long-term coastal infrastructure design.

Research Objectives and Hypotheses

This study was designed to address these gaps through comprehensive experimental assessment. The primary objectives were:

1. To quantify the seismic performance of bamboo-reinforced concrete under cyclic loading representative of Design Basis Earthquakes in coastal regions;
2. To evaluate durability of treated bamboo composites in simulated marine salt-spray environments;
3. To establish comparative performance metrics between bamboo-reinforced, steel-reinforced, and hybrid composite systems;
4. To develop evidence-based design guidelines for coastal structures utilizing bamboo reinforcement.

We hypothesized that: (H_1) properly treated bamboo reinforcement would maintain structural performance comparable to steel across seismic loading scenarios; (H_2) specialized preservation treatments would significantly enhance durability in chloride-rich environments, reducing strength loss to less than 5% over 18 months of simulated marine exposure; and (H_3) the lower modulus of elasticity in bamboo would result in superior energy dissipation characteristics and reduced cracking patterns under cyclic loading.

Novelty and Contribution

This research represents the first comprehensive investigation combining seismic performance assessment with marine durability evaluation of engineered bamboo reinforcement. The study advances the field through: systematic experimental protocol integrating ASTM salt-spray testing with cyclic loading simulation; quantification of damping and energy dissipation mechanisms; and development of practical design guidelines for coastal applications. The findings directly support the integration of sustainable reinforcement materials in climate-vulnerable regions where economic constraints limit conventional reconstruction capacity.

Article Organization

This article is structured as follows: Section 2 details the experimental methodology, including material specifications, specimen preparation, and testing procedures. Section 3 presents quantitative results with statistical analysis. Section 4 interprets findings within the context of existing literature and discusses implications for design practice. Finally, Section 5 concludes with recommendations for future research and practical implementation.

Methods

1. Research Design

This study employed a mixed-method experimental design integrating quantitative mechanical testing with durability assessment. The research combined controlled laboratory experiments with accelerated environmental conditioning to simulate long-term coastal exposure. A factorial design was implemented with three categorical factors: (1) reinforcement type (steel, bamboo-treated, hybrid); (2) seismic loading intensity (0.5g, 0.75g, 1.0g peak ground acceleration); and (3) environmental conditioning (baseline, salt-spray exposure). This design allowed systematic evaluation of individual and interactive effects.

2. Material Specifications and Sample Preparation

Concrete mixtures were designed to achieve a target compressive strength of 30 MPa, representative of common coastal structural applications. All concrete was manufactured using Type I Portland cement, naturally graded fine sand (fineness modulus 2.8), coarse aggregate (19 mm nominal), and potable water with water-cement ratio of 0.55. Three reinforcement types were evaluated:

Control Group (Steel): Conventional deformed steel reinforcing bars (Grade 60, 12 mm diameter, nominal yield strength 420 MPa)

Treatment Group 1 (Bamboo-Treated): Culm strips harvested from mature Phyllostachys edulis bamboo, processed into 12 mm × 8 mm rectangular elements. Treatment protocol involved: (a) mechanical splitting and smoothing; (b) hot-water extraction at 90°C for 4 hours to remove extractives; (c) immersion in 10% borax/boric acid solution for 24 hours; (d) copper-chromium-arsenic (CCA) preservation (1.3% dry salt content by mass); (e) air-drying to equilibrium moisture content of 12–15%.

Treatment Group 2 (Hybrid Composite): Steel reinforcement (primary tensile resistance) with bamboo strips configured as supplementary reinforcement and stirrup elements.

3. Specimen Fabrication

A total of 120 rectangular concrete specimens (150 mm × 150 mm × 300 mm) were cast. Specimen distribution by treatment group and loading condition is presented in Table 1. Reinforcement was centered in wooden formwork with 25 mm concrete cover. Concrete was placed by gravity with minimal vibration to ensure uniform fiber distribution without fiber segregation. All specimens were cured under standard laboratory conditions (23°C ± 2°C, 65% ± 5% relative humidity) for 28 days prior to testing.

4. Durability Testing Protocol

Environmental conditioning was conducted using accelerated salt-spray testing (ASTM B117) in a neutral salt-fog chamber. The chamber was maintained at 35°C with continuous mist of 5% NaCl solution. Two exposure durations were implemented: (1) short-term: 500 hours (approximately 2 months equivalent to 18 months natural coastal exposure); (2) extended: 1,500 hours for selected specimens. Post-exposure specimens were sectioned to examine corrosion propagation depth and reinforce-concrete interface degradation using optical microscopy and scanning electron microscopy (SEM).

Surface chloride penetration was quantified using acid-soluble chloride extraction at depths of 10 mm, 20 mm, and 30 mm, analyzed by potentiometric titration (ASTM C1218). Corrosion current density (icorr) was measured using a three-electrode potentiodynamic system (Gamry Reference 3000 potentiostat) at potential sweep rate of 1 mV/s.

5. Seismic Performance Testing

Cyclic loading was applied using a servo-hydraulic materials testing system (MTS 810) configured for sinusoidal displacement-controlled loading. Three peak ground acceleration scenarios were simulated:

- **Low Seismicity (0.5g):** Applied displacement amplitude ± 3.2 mm
- **Moderate Seismicity (0.75g):** Applied displacement amplitude ± 4.8 mm
- **High Seismicity (1.0g):** Applied displacement amplitude ± 6.4 mm

Each loading scenario consisted of 100 cycles at 1 Hz frequency, followed by post-cycle static failure testing. Load-displacement hysteresis curves were recorded continuously. Energy dissipation (area enclosed by hysteresis loops) was calculated from load-displacement data using numerical integration. Crack development was monitored using digital image correlation (DIC) with high-resolution cameras (16 megapixel, 0.01 mm spatial resolution).

6. Post-Testing Analysis

Following durability exposure and cyclic loading, specimens underwent static compression testing to failure using a universal testing machine (Shimadzu Autograph AGS-X) at displacement rate of 1.3 mm/min. Compressive strength was calculated from maximum load divided by specimen cross-sectional area. Modulus of elasticity was determined from the linear elastic region of the stress-strain curve (between 5% and 33% of maximum stress).

Cracking patterns were documented through: (1) visual inspection with magnifying glass and crack-width gauge; (2) high-resolution photography; (3) digital image analysis for automated crack detection. Maximum crack width and total crack length were quantified.

7. Statistical Analysis

Data were analyzed using SPSS (Version 27.0) and R (Version 4.1.2). Descriptive statistics (mean, standard deviation, coefficient of variation) were calculated for all mechanical properties. Normality was assessed using Shapiro-Wilk test. Homogeneity of variance was confirmed using Levene's test. Two-way ANOVA was performed to evaluate main effects of reinforcement type and loading condition, with Tukey's honest significant difference (HSD) post-hoc test for pairwise comparisons. Linear regression analysis was conducted to model relationships between exposure duration and strength retention. Statistical significance was set at $\alpha = 0.05$.

Multivariate analysis of variance (MANOVA) was used to examine simultaneous effects on dependent variables (compressive strength, flexural capacity, energy dissipation). Effect sizes were reported using eta-squared (η^2) and partial eta-squared ($\eta^2 p$) metrics.

8. Ethical Considerations

This study involved no human subjects or animal testing. All experimental work was conducted in accordance with institutional laboratory safety protocols. Disposal of hazardous materials (CCA-treated bamboo remnants, chloride solutions) followed environmental regulations outlined by the Environmental Protection Agency (40 CFR Part 261).

Results

1. Baseline Compressive Strength

Baseline compressive strength at 28 days (prior to durability exposure or cyclic loading) was: Steel control: 31.2 ± 1.4 MPa; Bamboo-treated: 29.8 ± 1.6 MPa; Hybrid composite: 30.5 ± 1.3 MPa (Figure 1A). ANOVA revealed no significant difference in baseline strength among groups ($F_{2,117} = 2.31$, $p = 0.104$), confirming comparable initial material properties. Coefficient of variation ranged from 4.1% to 5.4%, indicating acceptable concrete quality consistency across batches.

2. Durability Assessment: Salt-Spray Exposure

Chloride penetration depths at 500 hours of salt-spray exposure are presented in Table 2. Mean penetration at 10 mm depth was: Steel 8.2% ± 0.9%; Bamboo-treated 7.1% ± 1.1%; Hybrid 7.8% ± 1.0% of chloride content relative to total cement mass. Penetration decreased with depth, with values at 30 mm depth approximately 30–35% of surface concentrations.

Corrosion current density measurements (Table 2) revealed significant differences. Steel control specimens exhibited $i_{corr} = 2.34 \pm 0.47$ μA/cm², indicative of moderate corrosion activity. Bamboo-treated specimens showed substantially lower values ($i_{corr} = 0.18 \pm 0.09$ μA/cm²), approaching passive state threshold (<0.1 μA/cm²). Hybrid composites intermediate values ($i_{corr} = 1.21 \pm 0.35$ μA/cm²).

Strength retention after 500-hour salt-spray exposure is shown in Figure 1B. Steel control specimens retained 88.5% ± 4.2% of baseline strength. Bamboo-treated specimens demonstrated superior durability, retaining 94.2% ± 2.3% (difference = 5.7 percentage points, 95% CI: 2.1–9.3%). Hybrid composites retained 91.6% ± 3.1%, intermediate to the other groups. Two-way ANOVA identified significant main effects for both reinforcement type ($F_{2,117} = 18.42$, $p < 0.001$, $\eta^2 = 0.24$) and exposure duration ($F_{1,117} = 52.17$, $p < 0.001$, $\eta^2 = 0.31$).

Extended exposure (1,500 hours) data from a subset of specimens (n = 20) showed strength retention of 82.4% ± 5.6% (steel), 88.3% ± 3.9% (bamboo-treated), and 85.1% ± 4.7% (hybrid). Linear regression analysis of strength retention versus exposure duration demonstrated significant negative trend for all groups ($R^2 = 0.87$, $p < 0.001$), with bamboo-treated specimens maintaining steeper retention slope relative to steel controls.

3. Seismic Performance: Cyclic Loading Response

Energy dissipation results across loading intensities are presented in Table 3. At moderate seismicity (0.75g), bamboo-treated specimens dissipated 3.18 ± 0.42 kJ per 100 cycles, compared to 2.58 ± 0.39 kJ for steel controls—a 23.4% increase (95% CI: 15.2–31.6%, $p < 0.001$). Hybrid composites dissipated 2.89 ± 0.41 kJ (12.0% increase relative to steel, $p = 0.008$).

Energy dissipation increased progressively with loading intensity. At 1.0g, values were: Steel 4.12 ± 0.58 kJ; Bamboo-treated 5.24 ± 0.71 kJ; Hybrid 4.68 ± 0.63 kJ. Linear regression analysis showed energy dissipation as function of loading intensity (g-level) was statistically significant for all groups ($p < 0.001$), with similar slopes (approximately 2.8 kJ per 0.1g increment).

Hysteresis loop characteristics (Figure 2) demonstrate the difference in material behavior. Steel-reinforced specimens showed sharper, more angular loops with abrupt stiffness changes at crack propagation. Bamboo-reinforced specimens exhibited broader, rounded hysteresis loops characteristic of materials with higher internal damping and gradual stiffness degradation.

4. Crack Development and Width Analysis

Maximum crack widths under seismic loading are summarized in Table 4. At 1.0g loading, steel control specimens developed average maximum crack width of 0.41 ± 0.07 mm, while bamboo-treated specimens showed significantly smaller cracks (0.28 ± 0.05 mm, reduction =

31.7%, $p < 0.001$). Hybrid composites produced intermediate crack widths (0.35 ± 0.06 mm). Figure 3 presents crack width distributions, indicating that bamboo-reinforced specimens had proportionally more specimens with crack widths below 0.25 mm (the ACI 440 limit for environmental exposure conditions).

Crack initiation occurred at earlier loading cycles in steel controls compared to bamboo-reinforced specimens. Initiation typically occurred at cycle 18–24 for steel controls, cycle 32–41 for bamboo-treated, and cycle 25–33 for hybrid composites at 1.0g loading ($F_{2,117} = 34.51$, $p < 0.001$). Total crack length per specimen (sum of all cracks >0.1 mm width) was: Steel 287 ± 64 mm; Bamboo-treated 156 ± 48 mm; Hybrid 218 ± 56 mm ($p < 0.001$ for pairwise comparisons).

5. Residual Strength and Stiffness

Specimens tested at high seismic intensity (1.0g) followed by static compression showed residual strength degradation. Steel controls retained 76.4% ± 6.2% of pre-cyclic compression strength. Bamboo-treated specimens retained 83.1% ± 5.1% (difference = 6.7 percentage points, 95% CI: 2.1–11.2%, $p = 0.006$). Hybrid composites retained 79.8% ± 5.8%.

Initial tangent stiffness (from compression testing) was reduced following cyclic loading. Stiffness reduction was proportional to loading intensity: 8–12% at 0.5g, 14–19% at 0.75g, 22–28% at 1.0g. Bamboo-treated specimens consistently showed lower stiffness degradation (mean reduction 4.2 percentage points less than steel controls, $p = 0.021$).

6. Combined Effects: Durability Plus Seismic Loading

Specimens exposed to both salt-spray (500 hours) and subsequent cyclic loading (1.0g) showed interactive effects. Compressive strength of these specimens was:

- **Steel (durability + seismic):** 24.8 ± 2.1 MPa (20.5% reduction from baseline)
- **Bamboo-treated (durability + seismic):** 26.2 ± 1.8 MPa (12.1% reduction from baseline)
- **Hybrid (durability + seismic):** 25.5 ± 1.9 MPa (16.4% reduction from baseline)

Two-way ANOVA with factors of reinforcement type and environmental condition (control vs. durability+seismic) showed significant interaction effect ($F_{2,117} = 8.74$, $p < 0.001$, $\eta^2 p = 0.13$), indicating that durability exposure affected reinforcement types differentially. Bamboo-treated composites showed the smallest combined effect, supporting hypotheses H_1 and H_2.

Discussion

Interpretation of Durability Findings

The superior performance of bamboo-reinforced concrete in salt-spray environments (94.2% ± 2.3% strength retention vs. 88.5% ± 4.2% for steel) can be attributed to multiple factors. First, bamboo exhibits lower electrical conductivity than steel, resulting in reduced galvanic coupling and slower corrosion propagation. The measured corrosion current density for bamboo-treated specimens (0.18 ± 0.09 μA/cm²) was approximately 13-fold lower than steel controls, indicating near-passive electrochemical state even in high-chloride environments.

Second, the CCA preservation treatment effectively mitigated both biological degradation and chemical attack. The boron and copper components inhibit fungal and bacterial activity, while the arsenic component provides resistance to localized corrosion mechanisms. Literature supports this interpretation; previous studies by Barbosa *et al*. (2020) [7] documented similar preservation efficacy in tropical marine environments, though their findings were limited to shorter exposure periods (6 months) [7].

Third, the lower modulus of elasticity of bamboo (approximately 8–12 GPa vs. 200 GPa for steel) may reduce stress concentration at the reinforcement-concrete interface, distributing loads more gradually across the composite. This distribution mechanism reduces microcracking propagation pathways that typically accelerate chloride ingress in steel-reinforced systems.

However, strength retention decreased more steeply with extended exposure (1,500 hours), with bamboo-treated specimens declining from 94.2% to 88.3% (5.9 percentage point decrease). This suggests that while initial protection is excellent, long-term degradation mechanisms may eventually emerge. Further investigation of failure mechanisms at the bamboo-concrete interface during extended exposure is warranted.

Seismic Performance Analysis

The enhanced energy dissipation in bamboo-reinforced specimens (23.4% increase at 0.75g loading) reflects fundamental differences in material behavior under cyclic stress. Bamboo exhibits viscoelastic response characterized by gradual energy absorption through internal friction and fiber sliding mechanisms. This contrasts with steel's primarily elastic behavior until yield, followed by plastic deformation. The broader hysteresis loops observed in bamboo-reinforced specimens (Figure 2) are consistent with higher structural damping ratios estimated at 6.2% ± 1.1% for bamboo versus 2.8% ± 0.9% for steel controls.

Enhanced damping provides practical benefits in seismic design. Higher damping reduces peak displacement demands and accelerations transmitted to building contents and non-structural systems. For equivalent structural systems, bamboo reinforcement could theoretically allow 10–15% reductions in design forces under seismic loading, potentially permitting more economical member sizing or greater architectural flexibility.

The delayed crack initiation in bamboo-reinforced specimens (initiation at cycles 32–41 vs. 18–24 for steel controls at 1.0g) indicates superior cracking control. Smaller crack widths (0.28 mm vs. 0.41 mm, 31.7% reduction) have significant implications for durability, as chloride penetration rates increase non-linearly with crack width. ACI 440 guidance suggests that for reinforced concrete exposed to chloride environments, crack width should be limited to 0.13–0.25 mm depending on exposure classification. Bamboo-reinforced systems achieved better compliance with these criteria (87% of specimens below 0.25 mm vs. 63% of steel controls).

The cracking behavior likely results from three mechanisms: (1) distributed microcracking rather than localized macrocracks due to bamboo's lower elastic modulus; (2) superior bonding characteristics (bamboo's surface roughness and cellular structure provide mechanical interlock); and (3) the absence of corrosion-induced expansion that creates additional tensile stresses in steel-reinforced systems.

Residual Strength and Combined Environmental-Seismic Effects

Residual strength degradation after high-intensity seismic loading was substantial (22–24% reduction for steel controls), reflecting cumulative damage from microcracking and reinforcement-concrete interface degradation. Bamboo-reinforced specimens retained 6.7 percentage points more strength (83.1% vs. 76.4%), suggesting better crack control prevents secondary damage mechanisms from propagating during seismic cycles.

The interactive effects of durability exposure and seismic loading are particularly significant. The 20.5% strength reduction for steel specimens exposed to both conditions substantially exceeded the additive effect of individual stressors (expected ~28% reduction for combined effect). This synergistic degradation likely reflects chloride-induced corrosion expanding cracks initiated during seismic loading, creating preferential pathways for accelerated chloride ingress.

Bamboo-treated specimens showed the smallest combined effect (12.1% total reduction), supporting the hypothesis that superior durability characteristics in corrosive environments provide protective benefits that extend to complex loading scenarios. This finding has direct relevance to seismic-prone coastal zones where structures experience simultaneous environmental and mechanical stressors.

Comparison with Existing Literature

These findings align with and extend prior research. Yamaguchi *et al.* (2020) [6] reported 85–92% strength retention for bamboo after one-year outdoor exposure; our results showing 94.2% retention after 500 hours of accelerated testing suggest effective preservation treatments can achieve comparable long-term performance within shorter evaluation timeframes [6]. However, their study did not incorporate seismic loading, limiting applicability to dynamic situations.

The energy dissipation enhancement (23.4%) is consistent with damping characteristics reported by Kumar & Sharma (2021) [8], who measured approximately 18–25% damping improvements in bamboo-fiber reinforced polymers [8]. Our values are slightly higher, possibly reflecting the difference between bamboo as primary reinforcement (our study) versus secondary fiber reinforcement (their study).

Crack width reduction aligns with findings by Gao *et al.* (2019) [9], who documented 25–35% crack width reduction in bamboo-reinforced beams under static loading [9]. Our finding of 31.7% reduction under cyclic loading extends this to dynamic conditions.

Practical Implications for Coastal Engineering

These findings support feasibility of bamboo-reinforced concrete in coastal structures, particularly in developing nations and remote regions where conventional reinforcement logistics and costs are prohibitive. In countries like Indonesia, Philippines, and Bangladesh—all highly seismic and vulnerable to coastal flooding—bamboo grows abundantly and locally, potentially enabling distributed manufacturing of structural elements.

Design guidelines emerging from this research suggest: (1) bamboo reinforcement can be specified for structures in high-chloride environments if proper preservation treatment is applied, achieving performance equivalent to or better than steel in marine conditions; (2) the enhanced damping characteristics support application in seismic-design specifications, potentially enabling equivalent performance with reduced overall structural mass; (3) crack width control is superior, supporting potential for longer service lives before chloride-induced degradation of reinforcement in the case of any steel components in hybrid systems.

For structures designed for 50-year service life in coastal high-seismic zones, bamboo reinforcement may reduce life-cycle costs compared to steel, particularly when accounting for the logistics of steel production and transportation in remote island nations. Environmental benefits include embodied energy reduction of approximately 70–80% compared to steel reinforcement [10].

Limitations and Uncertainties

Several limitations should be noted. First, specimens in this study were relatively small (150 × 150 × 300 mm), and scaling effects for larger structural members remain unknown. Larger members experience different stress distributions and concrete curing patterns that may affect performance.

Second, salt-spray testing (ASTM B117) provides accelerated exposure but may not perfectly replicate all mechanisms of natural marine deterioration (wave action, thermal cycling, biological colonization). Extended field validation in actual coastal environments would strengthen conclusions.

Third, the bamboo treatment protocol (CCA preservation) involved arsenic compounds now restricted or prohibited in some jurisdictions due to environmental concerns. Alternative preservation treatments (copper-azole, alkaline copper quaternary) should be evaluated for applicability.

Fourth, this study employed a single bamboo species (Phyllostachys edulis). Performance differences with other bamboo species have not been characterized, limiting generalizability to different geographic regions.

Fifth, cost analysis was beyond the scope of this research. While qualitative arguments suggest economic advantages in bamboo-abundant regions, comprehensive life-cycle cost analysis including preservation treatment, reinforcement placement labor, and long-term maintenance would strengthen practical recommendations.

Future Research Directions

Several avenues warrant investigation: (1) Characterization of performance in actual field conditions through long-term monitoring of coastal test structures; (2) Evaluation of alternative preservation treatments compatible with environmental regulations; (3) Assessment of multiple bamboo species and hybrid systems optimized for specific geographic and climatic conditions; (4) Development of design models incorporating damage evolution and residual strength degradation during combined seismic-environmental loading; (5) Investigation of bamboo-polymer composite systems combining bamboo with epoxy or polyester matrices for enhanced durability; (6) Life-cycle assessment and cost-benefit analysis for various coastal regions and development contexts.

Conclusion

This comprehensive experimental study demonstrates that properly treated bamboo can serve as an effective primary reinforcement material in coastal structures exposed to simultaneous seismic and marine corrosive conditions. Key findings are:

1. **Durability Excellence:** Bamboo-treated specimens retained 94.2% of baseline compressive strength after 500-hour salt-spray exposure, significantly exceeding steel controls (88.5%). Corrosion current density measurements confirmed near-passive electrochemical state in bamboo composites.

2. **Enhanced Seismic Performance:** Bamboo-reinforced systems dissipated 23.4% more energy under cyclic seismic loading and exhibited 31.7% smaller maximum crack widths compared to conventional steel reinforcement.

3. **Superior Cracking Control:** Delayed crack initiation and reduced crack propagation in bamboo systems provide superior environmental performance by limiting chloride ingress pathways.

4. **Favorable Combined Effects:** Under simultaneous durability exposure and seismic loading, bamboo-treated specimens showed the smallest combined strength degradation (12.1% vs. 20.5% for steel controls), suggesting protective synergies between material properties.

5. **Practical Applicability:** The findings establish technical feasibility of bamboo reinforcement in seismic-prone coastal regions, with potential environmental and economic advantages for vulnerable developing nations.

These results contribute to the emerging field of sustainable structural materials and provide evidence-based design guidelines for practitioners. Proper implementation requires careful material selection, appropriate preservation treatment, and integration into building codes specific to coastal high-seismic environments.

For future implementation, we recommend: (1) validation through field testing in actual coastal conditions; (2) development of simplified design procedures for practicing engineers; (3) evaluation of complementary hybrid systems combining bamboo and minimal steel reinforcement; (4) extension to larger-scale structural components and complete buildings; and (5) integration into building codes in seismic-prone developing nations where this technology offers maximum impact.

Bamboo-reinforced concrete represents a paradigm shift toward sustainable structural engineering that maintains performance standards while reducing environmental burden—a critical imperative for climate-vulnerable coastal communities worldwide.

References

1. McGranahan G, Balk D, Anderson B. The rising tide: assessing the risks of climate change and human settlements in low elevation coastal zones. Environ Urban,2007:19(1):17–37.
2. International Energy Agency. Technology Roadmap: Low-Carbon Transition in the Cement Industry. Paris: IEA Publications, 2018.
3. Sharma B, Harries KA, Ghavami K. Methods of improving mechanical performance of bamboo and its composites: a review. J Reinf Plast Compos,2013:32(6):371–385.
4. Ghavami K. Bamboo as reinforcement in structural concrete elements. Cem Concr Compos,2005:27(6):637–649.
5. Verma VK, Jain AK, Singh SP. Experimental investigation of bamboo as reinforcement in concrete beams. Constr Build Mater,2019:225:234–247.
6. Yamaguchi M, Sato H, Koshitaka T. Durability assessment of treated bamboo strips in humid subtropical environments. J Wood Sci,2020:66(1):18.
7. Barbosa AL, Silva JV, Carvalho DC. Marine durability of bamboo-reinforced concrete: accelerated testing and field validation. Sustainable Struct,2020:4(2):89–104.
8. Kumar S, Sharma R. Mechanical and damping characteristics of bamboo fiber reinforced polymer composites. Compos Part B Eng,2021:218:108912.
9. Gao D, Zhang M, Wang Z, Han Y. Crack control behavior of bamboo reinforced concrete beams under flexural loading. Constr Build Mater,2019:203:612–625.
10. Miller SA, Horvath A, Monteiro PJM. Impacts of