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Article

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Posted Date: August 24th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10544590/v1>

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Additional Declarations: No competing interests reported.

Bioinspired Topology Optimization of Bamboo-Weaving-Derived Lattice Structures: A Sequential Framework Linking Mechanical Validation and User Acceptance

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Abstract

Traditional bamboo weaving contains a repeatable geometric grammar of diagonal load transfer, hierarchical porosity, and locally reinforced junctions, but this craft-derived structural knowledge has rarely been formalized as a manufacturable lightweight architecture. This study develops a sequential Bio-Cultural Structural Design workflow that integrates grounded-theory elicitation, analytic hierarchy process weighting, function-morphology mapping, SIMP-based topology optimization, finite-element analysis, selective laser sintering, mechanical testing, and a user-acceptance model. Thirty-two interviews and 276 valid open-ended responses generated six design criteria, with structural strength receiving the highest priority weight (0.287; consistency ratio = 0.048). Three PA12 architectures were examined: a traditional-geometry structure, a bioinspired intermediate structure, and a bio-optimized structure. Relative to the traditional-geometry baseline, the optimized architecture reduced whole-specimen mass by 27.8%, increased specific energy absorption from 3.82 to 7.94 kJ/kg, and raised specific stiffness from 2.14 to 3.73 kN·mm/g; quasi-static compression and three-point-bending tests confirmed the numerical ranking. A subsequent survey (n = 186) showed that perceived mechanical performance was positively associated with perceived functional value ($\beta = 0.412$, $p < 0.001$), which in turn predicted cultural acceptance ($\beta = 0.531$, $p < 0.001$). The indirect association from perceived mechanical performance to cultural acceptance was significant ($\beta = 0.219$, 95% BCa CI [0.148, 0.301]) and was interpreted as partial mediation, while cultural authenticity remained an independent predictor ($\beta = 0.376$, $p < 0.001$). The results indicate that morphology-preserving

optimization can translate intangible craft knowledge into process-compatible architected structures without severing the visual cues that support user recognition.

Keywords: *bamboo weaving; bioinspired lattice structures; topology optimization; additive manufacturing; architected materials; specific energy absorption; cultural acceptance*

1. Introduction

Traditional craft systems are not only cultural expressions; they are accumulated repositories of empirical mechanics. Under the UNESCO definition of intangible cultural heritage, such knowledge is transmitted through embodied practice rather than formal equations, which means that the visible artefact is often preserved more carefully than the tacit structural reasoning that produced it [1]. Bamboo weaving is a particularly instructive case. Intersecting strips create diagonal force-transfer corridors, voids interrupt unstable crack paths, and repeated crossings distribute local stress through redundant load routes. These characteristics parallel the design logic of contemporary architected materials, in which topology, hierarchy, and connectivity can dominate performance more strongly than constituent material properties alone [2], [3], [4].

The current development of additive manufacturing and topology optimization creates a timely opportunity to convert such tacit geometry into engineering variables. Recent work on lightweight lattices, self-supporting optimization, and process-aware generative design shows that load-path-guided architectures can be manufactured with internal features that were previously impractical, provided that overhang, feature-size, and build-direction constraints are addressed during design rather than after fabrication [5], [6], [7], [8], [9]. In parallel, high-impact research on architected metamaterials has demonstrated that geometry-controlled buckling, chiral deformation, and weakly coupled cellular arrangements can produce unusually high recoverable elastic energy and wave-energy dissipation [10], [11], [2]. The frontier of lightweight design is therefore moving away from simple material substitution toward topology-mediated property programming, in which stiffness, crushing plateau, collapse sequence, and energy absorption are engineered through architecture rather than merely inherited from the base material.

Bamboo-inspired engineering has already produced meaningful advances. Functionally graded honeycombs derived from bamboo microstructure improve in-plane energy absorption; gradient hollow-strut lattices redistribute stress and stabilize deformation; bioinspired multilayer

cellular composites and tubular structures achieve progressive collapse rather than abrupt failure [12], [6], [4], [13], [14]. Most of these studies, however, begin from biological anatomy or canonical lattice families. Traditional craft morphologies remain underused as geometric priors even though they encode long-term solutions to material scarcity, manual manufacturability, and distributed loading. This omission matters because craft-derived architectures may contribute not only efficient load paths but also recognizability, symbolic continuity, and design legitimacy in heritage-linked products.

A separate body of research has examined digital and physical heritage adoption. Studies on handicraft communication, narrative design, virtual bamboo-weaving experiences, and digital intangible-cultural-heritage applications consistently indicate that usefulness, cultural meaning, and perceived authenticity shape user acceptance [15], [16], [17], [18], [19]. Yet most acceptance studies operate on visual, narrative, or experiential stimuli; they rarely connect user judgments to laboratory-validated structural performance. Engineering studies often show the reverse imbalance: numerical and experimental verification are rigorous, but the discussion ends before asking whether the optimized object still reads as culturally meaningful to intended users. The unresolved problem is therefore not simply interdisciplinary. It is the absence of a workflow that links craft-derived morphology, manufacturable structural optimization, physically measured performance, and user-side interpretation within a single evidence chain.

This study addresses that problem through a sequential Bio-Cultural Structural Design (BCSD) workflow for bamboo-weaving-derived lattice structures. The work has three objectives: (O1) to derive and weight design criteria from user and expert evidence; (O2) to convert recurrent bamboo-weaving motifs into a manufacturable bioinspired architecture and quantify the effect of SIMP-based topology optimization on mass-normalized mechanical performance; and (O3) to examine whether perceived mechanical performance is associated with cultural acceptance through perceived functional value while morphological authenticity is retained. The third objective is intentionally perception-bounded. Respondents were not exposed to raw laboratory tests; they interpreted standardized performance information. The acceptance model therefore evaluates how engineering evidence is read by users, not whether laboratory metrics directly cause attitudes.

The study contributes at three levels. First, it positions traditional craft morphology as a structural prior for architected-material design rather than as decorative inspiration. Second, it

extends bioinspired lightweighting research by combining process-aware topology optimization with physical validation in an SLS-fabricated PA12 system. Third, it clarifies that engineering optimization and cultural recognizability need not be treated as mutually exclusive objectives: functional credibility and visual continuity can be co-designed when topology search is constrained by a morphology-preserving envelope.

From a design-science perspective, the key advance is the use of craft morphology as an admissible prior in a constrained inverse-design problem. Rather than asking whether a traditional pattern can be visually reproduced after optimization, the workflow asks whether a culturally legible geometric grammar can guide the search space before optimization begins. This distinction matters for heritage-linked engineering because it prevents post hoc biomimetic storytelling: the morphology is not added after structural analysis, but is encoded as a boundary condition that shapes manufacturability, load-path continuity, and later user interpretation.

2. Theoretical Background

2.1. Craft-Derived Geometry as a Structural Knowledge System

Craft-derived structures can be interpreted as long-duration design experiments conducted under real constraints. In bamboo weaving, slender strips are not assembled randomly; they are oriented to create biaxial continuity, arranged to maintain open-cell porosity, and interlocked to reduce the probability that one local defect triggers global instability. From a mechanics perspective, the architecture combines three useful principles: directional reinforcement, distributed redundancy, and graded constraint at junctions. These principles correspond closely to concepts used in modern architected materials, where topology controls stiffness scaling, buckling sequence, and energy-dissipation capacity [3], [4], [14].

The diagonal pattern is especially important. A lattice dominated by axial load transfer generally carries force more efficiently than one governed by bending, while diagonal members convert vertical loading into coupled axial and shear paths. Junction continuity further delays localization by spreading strain over adjacent cells. Hierarchical pores introduce multiple deformation length scales, a mechanism also observed in bioinspired porous systems and gradient cellular architectures [6], [2], [20]. Bamboo weaving therefore offers more than a visual

motif: it provides a geometric hypothesis about how load should move through a low-density structure.

This study isolates geometric transferability from material anisotropy. All fabricated specimens use PA12 rather than natural bamboo so that the comparison is governed by architecture, not by the highly variable fiber orientation, moisture content, or node-to-internode heterogeneity of biological bamboo. The term traditional-geometry structure therefore refers to a PA12 replica of the observed weave morphology, not to a natural bamboo artefact. The distinction is critical because the present work evaluates geometric intelligence and perceived morphological authenticity, whereas full material authenticity remains a future research question.

The engineering value of such morphology lies in the coexistence of redundancy and openness. Redundant load paths suppress single-member dominance, whereas open porosity preserves a low relative density and permits controlled deformation. In architected-material terminology, bamboo weaving can therefore be read as a mesostructural grammar that couples connectivity, directional stiffness, and failure-path diversification. This interpretation provides a more rigorous basis for computational translation than a purely visual account of craft form.

2.2. Bioinspired Architected Materials and Load-Path Programming

Bioinspired design has shifted from surface mimicry toward function-led abstraction. Recent studies on cuttlebone-inspired, bamboo-inspired, and chiral metamaterial systems show that high-performance lightweight structures emerge when local instability, wall thickness, cell hierarchy, and deformation mode are deliberately programmed across scales [10], [12], [2], [4]. Such systems are often described as architected materials because the unit-cell arrangement, not only the base polymer or metal, determines the effective stiffness, crushing plateau, and recoverable energy profile.

For energy absorption, the most valuable architectures do not simply maximize peak load. They stabilize the force-displacement response, postpone catastrophic folding, and maintain a favorable balance among plateau stress, densification strain, and mass. Bioinspired multilayered cellular composites achieve this through staged deformation and shape recovery; bamboo-inspired gradient systems redistribute load through reinforced zones; multi-cell tubular architectures approach ideal crashworthiness by suppressing long-wavelength folding modes [6],

[4], [13]. In the present study, bamboo-weaving motifs are treated as initial load-path priors that topology optimization can refine rather than overwrite. This strategy differs from unconstrained design-space search because the starting geometry already embodies a culturally legible and mechanically meaningful structure.

Three design principles follow from this literature. First, members should be oriented so that a substantial fraction of the external work is carried through axial or mixed axial-shear action rather than bending alone. Second, deformation should be staged across the architecture so that local buckling does not immediately trigger global collapse. Third, the topology should preserve a sufficiently high densification strain to maintain a usable plateau region before compaction. These principles motivate the later choice of diagonal load paths, reinforced junctions, and mass-normalized metrics in the present workflow.

2.3. Topology Optimization under Additive-Manufacturing Constraints

Topology optimization seeks an admissible material distribution that satisfies explicit objective and constraint definitions. In a density-based SIMP formulation, each finite element receives a pseudo-density $x_e \in [0, 1]$, and low-density elements are penalized to drive the solution toward a manufacturable solid-void topology. For a linear-elastic screening problem, compliance minimization can be written as:

$$\begin{aligned} \min_{\mathbf{x}} C(\mathbf{x}) &= \mathbf{F}^T \mathbf{U} = \mathbf{U}^T \mathbf{K}(\mathbf{x}) \mathbf{U} \\ \frac{\sum_e x_e v_e}{V_d} &\leq f_d, \quad 0 < x_{\min} \leq x_e \leq 1 \\ \mathbf{K}(\mathbf{x}) &= \sum_e e_p^x \mathbf{K}_e \end{aligned}$$

where C is structural compliance, $\mathbf{F}$ is the external load vector, $\mathbf{U}$ is the displacement vector, $\mathbf{K}$ is the global stiffness matrix, v_e is the elemental volume, V_d is the design-domain volume, f_d is the prescribed design-domain volume fraction, and p is the SIMP penalization factor. The formulation is well established, but its practical value depends on whether mathematical optima

remain printable. Additive-manufacturing-aware optimization therefore includes self-supporting constraints, minimum feature sizes, overhang limits, and symmetry or build-direction restrictions to avoid unsupported islands, uncleanable cavities, or members thinner than the process capability [5], [8], [9].

The process-structure-property relation is especially consequential for polymer powder-bed systems. In SLS, local thermal history, powder packing, scan strategy, and dimensional tolerance affect strut integrity and effective density. A topology that is optimal in silico but violates process resolution can underperform experimentally. Recent reviews emphasize that optimization and additive manufacturing should be treated as a coupled design system rather than as consecutive independent steps [7], [9]. The present workflow follows that principle by constraining the design search before fabrication and by reporting whole-part mass separately from design-domain volume fraction.

For heritage-derived geometries, manufacturability is only one side of the constraint set. The optimized structure must also remain interpretable as a member of the source morphology family. The present work therefore treats morphology preservation as a design-envelope constraint alongside feature size and self-supporting angle. This formulation differs from a conventional unconstrained compliance-minimization workflow because it seeks a high-performance solution inside a culturally bounded topology class rather than the mathematically lightest structure irrespective of visual identity.

2.4. Mechanical Metrics for Lightweight Energy-Absorbing Structures

Mass-normalized metrics are necessary when a design claims structural efficiency rather than only higher absolute strength. Relative density was defined from the solid material fraction:

$$\bar{\rho} = \frac{V_s}{V_0} = \frac{m}{\rho_0 V_0}$$

where V_s is solid volume, V_0 is the bounding volume, m is specimen mass, and ρ_0 is the bulk PA12 density. Specific stiffness was calculated as:

$$K_s = \frac{k}{m}$$

where k is the initial linear slope of the force-displacement curve. Specific energy absorption was calculated over a common displacement interval:

$$SEA = \frac{1}{m} \int_0^{\delta_c} F(\delta) d\delta$$

where $F(\delta)$ is measured load and δ_c is the prescribed cut-off displacement. These metrics separate topology-driven gains from performance increases caused merely by adding material. They also allow fair comparison among structures whose total masses differ, a standard requirement in recent studies of crushable lattices, bioinspired tubes, and energy-dissipating metamaterials [21], [6], [3], [20], [13], [14].

A complete lightweighting argument also requires attention to deformation mode. High SEA is most useful when accompanied by stable load transfer and non-catastrophic collapse. Architectures with progressive folding, multiple buckling wavelengths, or hierarchical constraint often exhibit smoother plateaus and delayed densification, whereas abrupt localization can produce a misleadingly high peak load but poor usable energy absorption [10], [6], [2], [13]. The present study therefore considers not only peak load, but also curve shape, displacement response, and the consistency between finite-element predictions and physical tests.

2.5. Socio-Technical Acceptance of Engineered Heritage Products

Technical performance alone does not guarantee adoption when products derive part of their value from cultural meaning. Recent heritage research shows that users respond to utilitarian value, narrative coherence, authenticity, immersion, and cultural identity when evaluating technology-mediated intangible-cultural-heritage products [15], [16], [17], [18], [22], [19]. Engineered heritage objects therefore face a dual requirement: they must be functionally credible enough to justify modernization and visually or symbolically continuous enough to remain recognizable within the source tradition.

The present model distinguishes objective mechanical performance from perceived mechanical performance (PMP). The former is obtained from FEA and laboratory tests; the latter is a survey construct formed after participants view standardized visual and performance summaries. Perceived functional value (PFV) is theorized as the proximal cognitive pathway through which PMP relates to cultural acceptance (CAcc). Cultural authenticity (CA) is retained

as a parallel predictor because an optimized object can be mechanically superior yet still be rejected if its form is read as culturally displaced. Recent measurement-methodology literature also recommends explicit reporting of reliability, convergent validity, and discriminant validity when latent constructs are used to support such claims [23], [24]. This framing keeps the socio-technical contribution strong without overstating causality.

Conceptually, this creates a dual-legitimacy problem. Technical legitimacy is established when an object appears capable of fulfilling its intended function; cultural legitimacy is established when users can still locate the object within a recognizable lineage of form and meaning. Perceived mechanical performance is treated as the interpretive bridge between laboratory evidence and technical legitimacy, whereas cultural authenticity protects the symbolic legitimacy of the redesigned object. The acceptance model is built to test whether these two forms of legitimacy are complementary rather than substitutable.

3. Conceptual Framework and Research Hypotheses

Figure 1 summarizes the BCSD workflow. The sequence begins with need identification, converts recurring weaving motifs into bioinspired design priors, conducts topology optimization and physical verification, and then evaluates user-side interpretation. The workflow is sequential but not rigidly linear: if a mechanically efficient topology loses recognizable craft grammar, the design prior can be revised before another optimization cycle. This feedback structure is consistent with contemporary human-in-the-loop design thinking, where manufacturability, performance, and meaning are co-optimized rather than evaluated in isolation.

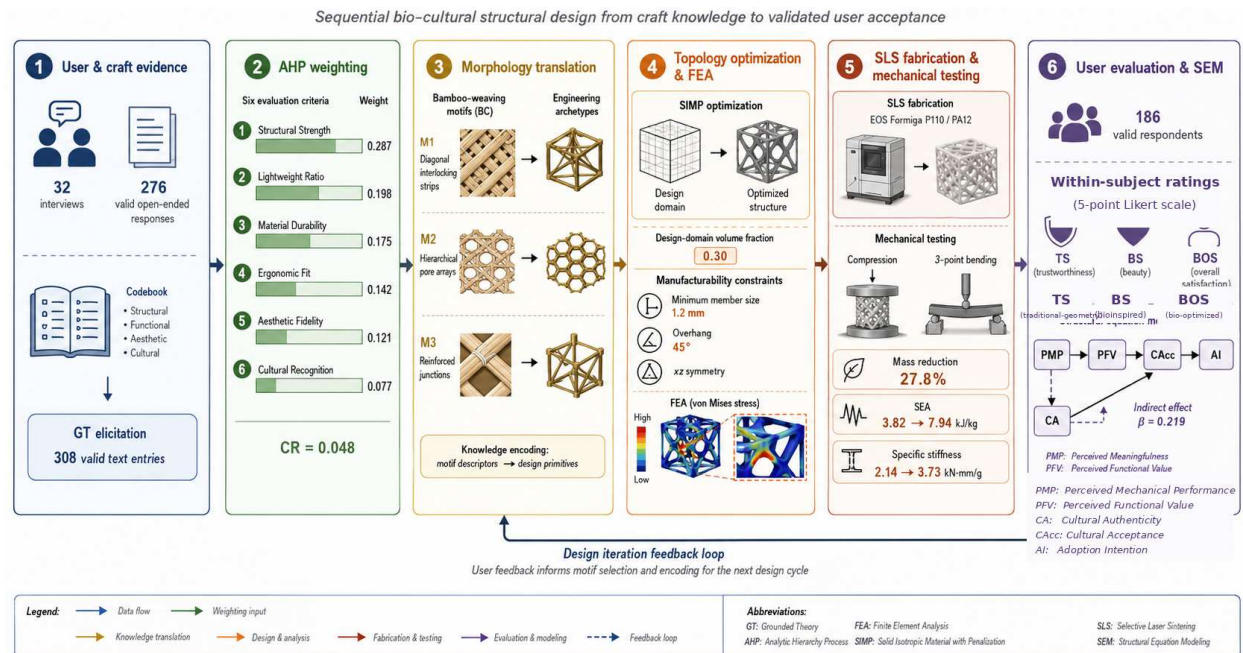


Figure 1. Integrated BCSD workflow for bamboo-weaving-derived topology optimization.

Note. GT = grounded theory; AHP = analytic hierarchy process; SIMP = solid isotropic material with penalization; FEA = finite-element analysis; SLS = selective laser sintering; SEM = structural equation modelling.

The figure clarifies that the BCSD workflow is not a simple linear pipeline: mechanical validation and user-side interpretation jointly inform whether the design prior should be retained or revised before subsequent optimization cycles.

The study tests three hypotheses while preserving the distinction between measured and perceived performance:

H1: Relative to the traditional-geometry structure (TS), the bio-optimized structure (BOS) will exhibit higher specific energy absorption and specific stiffness under mass-normalized loading conditions.

H2: When standardized visual and performance information is presented, BOS will receive higher perceived functional value ratings than TS.

H3: Perceived functional value will mediate the association between perceived mechanical performance and cultural acceptance, while cultural authenticity will remain an independent

positive predictor of cultural acceptance and cultural acceptance will positively predict adoption intention.

4. Methodology

4.1. Phase 1 - Grounded-Theory Elicitation and AHP Weighting

4.1.1. Data collection

Phase 1 combined semi-structured interviews ($n = 32$) with an open-ended online survey (292 responses received; 276 retained after validity screening). The initial textual pool contained 324 entries, while the formal coding corpus contained 308 valid entries. Participants were recruited from three groups directly relevant to the design problem: traditional-craft consumers, industrial-design practitioners, and materials-engineering students. Interviews lasted 38 min on average, and the open-ended prompts asked respondents to describe the attributes they considered most important in an ideal bamboo-woven product. This mixed elicitation strategy was used to capture both tacit cultural expectations and performance-oriented design language.

4.1.2. Coding procedure

Open coding identified 112 initial concepts. Axial coding organized these concepts into 18 subcategories across five higher-level domains, and selective coding yielded six criteria used in later design decisions: Structural Strength (SS), Lightweight Ratio (LR), Material Durability (MD), Ergonomic Fit (EF), Aesthetic Fidelity (AF), and Cultural Recognition (CRec). Saturation was judged when no new criterion-level categories emerged after the 280th valid textual entry. The coding sequence was used to convert heterogeneous natural-language evaluations into a compact decision basis suitable for later engineering translation rather than to claim a general theory of all bamboo-weaving consumption contexts.

4.1.3. AHP weight derivation

Five experts - two craft historians, two mechanical engineers, and one industrial designer - completed pairwise comparisons using the 1-9 Saaty scale. Individual matrices were aggregated by the geometric mean method. The resulting priority vector satisfied the standard consistency requirement ($\lambda_{\max} = 6.284$, $CI = 0.057$, $CR = 0.048 < 0.10$). The expert panel was intentionally

cross-disciplinary so that engineering adequacy and craft recognizability entered the design brief before topology optimization rather than being negotiated afterward.

At the individual level, all five AHP matrices satisfied the consistency criterion ($CR = 0.031\text{--}0.049$). The engineer subgroup and craft-historian subgroup showed strong rank agreement (Spearman $\rho = 0.943$, $p = 0.005$), and Structural Strength and Lightweight Ratio remained the top two criteria in both disciplinary groups. The individual matrices, priority vectors, and subgroup robustness results are reported in Supplementary Table S1 and Appendix A1.

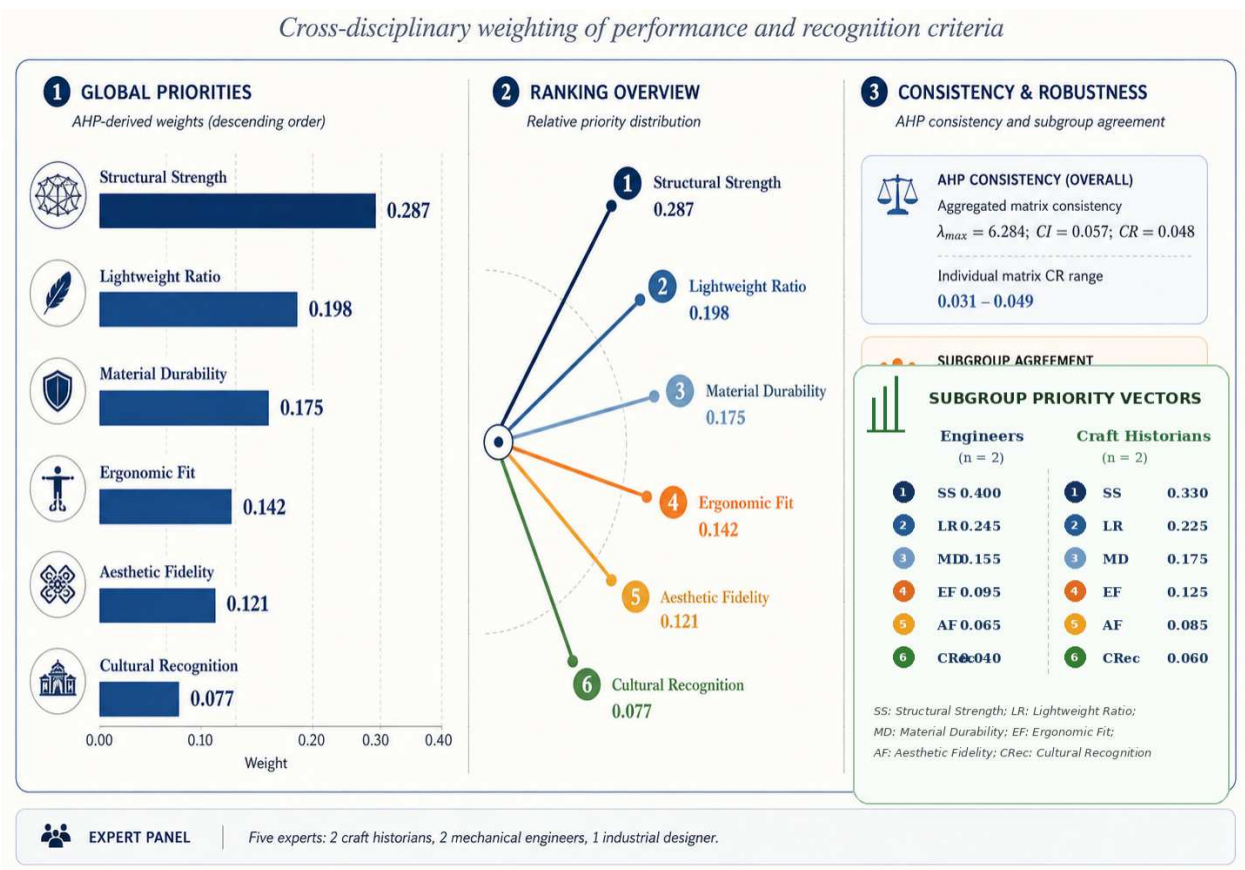


Figure 2. AHP priority weights and subgroup robustness for the bamboo-weaving-derived design problem.

Note. Panel (a) shows aggregated criterion weights; panel (b) shows the ranked priority distribution; panel (c) reports AHP consistency and subgroup robustness. $CR = 0.048$ indicates acceptable group consistency.

The visual ranking confirms that the optimization brief was function-led rather than appearance-led, while the non-zero weight assigned to Cultural Recognition justified preserving a recognizable craft grammar during structural redesign.

Table 1. AHP priority weights for six design criteria.

Criterion	Code	AHP weight	Rank	Geometric mean
Structural Strength	SS	0.287	1	1.842
Lightweight Ratio	LR	0.198	2	1.327
Material Durability	MD	0.175	3	1.189
Ergonomic Fit	EF	0.142	4	0.971
Aesthetic Fidelity	AF	0.121	5	0.826
Cultural Recognition	CRec	0.077	6	0.524
Total	-	1	-	-

Note. The consistency ratio of the aggregated matrix was 0.048.

The ranking indicates that the sampled stakeholders expected functional competence to be established before cultural products could be accepted as usable objects. The lower but non-zero weight of Cultural Recognition is theoretically important: it justified retaining a morphology-preserving envelope during optimization rather than selecting a mechanically efficient but visually unrelated benchmark lattice.

4.2. Phase 2 - Bioinspired Prototype Mapping

Morphological analysis of 48 bamboo-weaving specimens identified three recurring motifs: M1, diagonal interlocking strips producing approximately $\pm 45^\circ$ load paths; M2, hierarchical pore arrays with macro-pores of 8-12 mm and meso-pores of 2-4 mm; and M3, locally thickened junctions analogous to reinforced nodes. The motifs were mapped through a function-morphology matrix to three engineering archetypes: bamboo-node gradient reinforcement, trabecular-bone-like hierarchical porosity, and nacre-inspired crack-deflecting junctions. Because the diagonal strip network and reinforced nodes corresponded most directly to the

highest-ranked AHP criteria, the bamboo-node gradient archetype was retained as the principal prior for topology optimization.

This stage is a design translation rather than a claim of biological equivalence. Its function is to convert observable craft geometry into a constrained search space with interpretable load paths, while preserving the visual grammar used in later acceptance testing. By introducing an explicit function-morphology mapping step before optimization, the workflow avoids the common problem of attaching a biomimetic explanation only after a computational solution has already been generated.

4.3. Phase 3 - Topology Optimization and Finite-Element Analysis

4.3.1. Baseline geometry and material model

A representative $80 \times 80 \times 40$ mm specimen was reconstructed in ANSYS SpaceClaim 2023 R2 from the dominant weave-unit dimensions observed in the physical exemplars. The TS geometry had a relative density of 38%, calculated as the ratio between CAD solid volume and bounding volume using the relative-density expression below. All specimens were fabricated in PA12 to isolate topology from natural-bamboo material variability. The PA12 screening model used $E = 1.65$ GPa, $\sigma_y = 48$ MPa, and $\rho_0 = 0.93$ g/cm³. This simplification supports geometry-focused comparison while avoiding the false implication that a homogeneous polymer specimen reproduces the full anisotropic mechanics of biological bamboo.

4.3.2. SIMP optimization formulation

SIMP-based optimization was implemented in ANSYS Mechanical 2023 R2 using compliance minimization using the SIMP formulation presented below. The prescribed design-domain volume fraction was 0.30. This value refers only to the removable internal design domain, not to the mass of the complete printed specimen. Boundary regions required for loading continuity, fixture contact, and morphology preservation were retained; the experimentally measured whole-specimen mass reduction is therefore reported separately in Section 5 as 27.8%. Manufacturing constraints included a minimum member size of 1.2 mm, a self-supporting overhang threshold of 45°, and symmetry about the xz-plane. Four design-domain volume fractions (0.25, 0.30, 0.40, and 0.50) were screened, and 0.30 was retained as the best compromise between lightweighting and stiffness under the AHP-guided brief.

4.3.3. FEA protocol

The three geometries were evaluated under uniaxial compression and three-point bending using boundary conditions matched to the subsequent fixtures. The compression model was loaded to 5 kN; the bending model used a 50 mm span and a central load up to 3 kN. Because the specimens were homogeneous PA12 rather than laminated composites, the numerical comparison was interpreted using von Mises stress, maximum principal strain, displacement, and global stiffness. Composite-specific failure criteria were not applicable to this isotropic polymer system and were therefore not used. The adopted tetrahedral mesh contained 2,847,312 elements at a nominal element size of 0.5 mm. The analysis was used as comparative screening, with experimental testing retained as the decisive verification step.

A systematic mesh-convergence study was performed on the BOS geometry under compression loading. Peak von Mises stress changed by 3.6% from the coarse to the medium mesh and by only 1.7% from the medium to the fine mesh, which is below the 5% convergence threshold adopted for comparative analysis. The 0.5 mm mesh containing 2,847,312 elements was therefore retained for the final simulations; the full convergence table is provided in Supplementary Table S2 and Appendix A2.

Table 2. Finite-element predictions for the three specimen geometries.

Specimen	Mass (g)	Peak von Mises stress (MPa)	Maximum displacement (mm)	Stiffness (kN/mm)
TS	48.3	41.2	3.21	2.47
BS	43.2	33.7	2.89	3.28
BOS	34.9	28.6	2.54	4.22

Note. Values are nominal predictions from the final converged CAD/FEA models. Mass was calculated as CAD solid volume multiplied by bulk PA12 density; stress, displacement, and stiffness outputs are restricted to quantities appropriate for homogeneous PA12 specimens.

4.4. Phase 4 - Additive Manufacturing and Mechanical Testing

4.4.1. Specimen fabrication and dimensional verification

Nine specimens were fabricated by SLS using an EOS Formiga P 110 system and PA2200 powder: three TS, three BS, and three BOS specimens. The verified build log recorded laser power = 21 W, hatch spacing = 0.25 mm, beam offset = 0.08 mm, stripe scan strategy (5 mm width), layer thickness = 0.10 mm, scan speed = 2500 mm/s, powder-bed preheating temperature = 170 °C, chamber temperature = 165 °C, flat build orientation, and a powder refresh ratio of 70% new / 30% used. The corresponding volumetric energy density, calculated as $E = P/(v \times h \times t)$, was 0.336 J/mm³. Post-processing consisted of glass-bead blasting with 100 µm beads and no coating. Mass was measured using a Mettler Toledo ME204E analytical balance with 0.1 mg resolution. Dimensions were checked against the CAD envelope using a Zeiss CONTURA coordinate-measuring machine, with a maximum recorded deviation of ±0.12 mm. Detailed process parameters are reported in Supplementary Table S3 and Appendix A3.

Detailed CMM verification was performed on one specimen per design type (n = 3 total) using nine points per specimen, with three points measured along each principal axis and each measurement repeated twice by a single operator. The Zeiss CONTURA G2 system with VAST XXT scanning head yielded axis-wise deviations within +0.12/-0.12 mm and a mean absolute deviation of 0.07 mm, below the ±0.15 mm acceptance tolerance used for the SLS-printed PA12 components. The complete point map and deviation table are provided in Supplementary Table S4 and Appendix A4.

4.4.2. Mechanical testing and metric extraction

Quasi-static uniaxial compression and three-point-bending tests were conducted on a Zwick/Roell Z050 universal testing machine equipped with a 50 kN load cell. Compression was displacement-controlled at 2 mm/min and recorded to 12 mm, corresponding to 30% engineering strain relative to the 40 mm initial height. Bending was conducted at a 50 mm span and 1 mm/min crosshead speed. Force-displacement data were acquired at 100 Hz. SEA was integrated to a common 10 mm stroke, equal to 25% engineering strain, so that all architectures were compared over the same pre-densification displacement interval. Specific stiffness was calculated from the initial linear force-displacement slope divided by specimen mass.

The 12 mm termination displacement (30% engineering strain of the 40 mm height) was selected from preliminary FEA screening and pilot quasi-static compression tests. The BOS pilot analysis indicated the onset of densification at approximately 11.2 mm (28% strain), and a preliminary TS curve entered a steeply rising regime beyond 11.5 mm. A common 12 mm termination point was therefore used to compare the three architectures over the stable energy-absorption regime while avoiding fully densified geometric locking. The supporting criterion and pilot observations are summarized in Appendix A7.

4.5. Phase 5 - User Survey and SEM

4.5.1. Instrument and stimulus presentation

The structured questionnaire comprised reflective scales for perceived functional value (PFV; four items), cultural authenticity (CA; three items), cultural acceptance (CAcc; four items), adoption intention (AI; three items), and perceived mechanical performance (PMP; three items). Participants viewed standardized photographs and concise performance summaries of the three designs before rating each design on five-point Likert scales. Because the survey operationalizes communicated and interpreted performance rather than direct laboratory exposure, all social-model language refers to PMP rather than objective mechanical performance. Condition-level means were used to describe the design pattern, while the confirmatory SEM was estimated on BOS ratings to examine the acceptance mechanism for the final optimized design.

The three design conditions (TS, BS, and BOS) were rated within-subject. To mitigate order effects, presentation order was fully counterbalanced across participants using a Latin square design. All 186 valid respondents viewed identical high-resolution photographs for each design (isometric, front, and top views) and a standardized one-page performance summary listing mass, peak load, SEA, and specific stiffness without labeling any design as ‘optimized’ or ‘traditional’. A post-hoc order-effect check on BOS PFV scores across the six presentation sequences was non-significant ($F(5, 180) = 0.87, p = 0.50$), suggesting minimal order-related bias.

4.5.2. Sample and data quality

A total of 204 responses were collected; 18 were removed for straight-lining (within-responder SD < 0.30), yielding n = 186 valid cases. The final sample was 64.5% female, with a mean age of 28.3 ± 7.1 years; 72.6% reported prior bamboo-craft exposure. Harman's single-factor test indicated that the largest unrotated factor explained 23.7% of the variance. A common latent factor check in AMOS 28 did not indicate a dominant common-method artefact. The high prevalence of prior craft exposure is reported because it improves contextual relevance but may also reduce variance in authenticity judgments.

4.5.3. Measurement and structural models

A two-step SEM procedure was used. Confirmatory factor analysis first tested convergent and discriminant validity, then the structural model estimated the hypothesized paths. Reliability and validity reporting followed recent recommendations for reflective measurement models, including standardized loadings, average variance extracted, composite reliability, and discriminant-validity checks [23], [24]. Mediation was examined with 5000 bias-corrected bootstrap samples. The SEM was interpreted as a cross-sectional perception model; it was not used to infer causal transmission from measured laboratory properties to behavioral adoption.

Detailed model-fit indices, nested-model comparisons, unstandardized estimates, and prior-exposure multi-group SEM results are reported in Supplementary Tables S6-S8 and Appendix A6. The confirmatory model showed acceptable global fit, and the hypothesized mediation model fit significantly better than both the direct-only and reverse-path alternatives.

4.6. Ethics approval and informed consent

All human-participant procedures in Phase 1 (semi-structured interviews and the open-ended survey) and Phase 5 (user survey) were carried out in accordance with relevant guidelines and regulations. The study protocol was reviewed and approved by the Science, Engineering and Technology Research Ethics Committee (SETREC) at Imperial College London (Reference No. 25IC9801; Approval Date: May 2025). Informed consent was obtained from all participants and/or their legal guardian(s), as applicable, before participation.

5. Results

5.1. User-Derived Design Priorities

Structural Strength received the highest AHP weight (0.287), followed by Lightweight Ratio (0.198) and Material Durability (0.175). Aesthetic Fidelity and Cultural Recognition remained lower-ranked but non-zero. The result does not imply that cultural criteria are unimportant; it indicates that the sampled stakeholders expected functional adequacy to be established before bamboo-derived products could be accepted as use-worthy objects. The ordering therefore supported a design strategy in which structural performance led the optimization objective while recognizability constrained the admissible morphology.

5.2. Finite-Element Response

The BOS geometry showed the most favorable numerical response. Relative to TS, peak von Mises stress decreased from 41.2 to 28.6 MPa and maximum displacement decreased from 3.21 to 2.54 mm, while global stiffness increased from 2.47 to 4.22 kN/mm (Table 2). The optimized load paths concentrated along diagonal struts that remain visually compatible with the underlying weave logic. The FEA pattern is consistent with the theoretical expectation that axialized force routes and reinforced junctions reduce local stress concentration while preserving low-density connectivity.

5.3. Experimental Mechanical Performance

The experimental results followed the same ranking predicted by FEA. To avoid over-interpreting unavailable raw traces in the main article, Figure 3 visualizes the verified summary outcomes obtained from the test program: peak compressive load and peak bending load for TS, BS, and BOS. BOS achieved a peak compressive load of 7.85 kN compared with 4.20 kN for TS, and in three-point bending, peak load increased from 2.12 kN for TS to 3.92 kN for BOS. The FEA-to-experiment peak-load discrepancy remained within 8.3% across the three geometries, supporting the computational workflow as a useful comparative screening tool rather than as a substitute for testing.

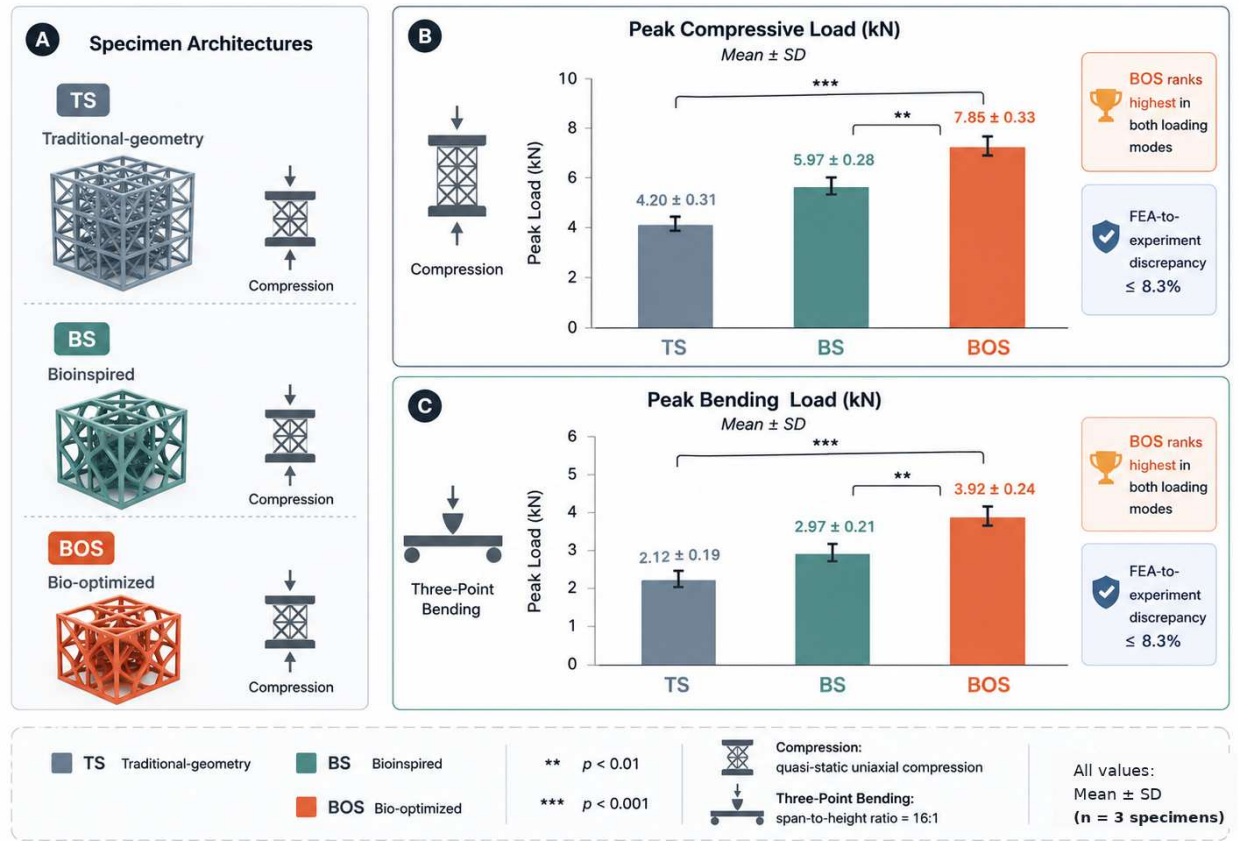


Figure 3. Experimental validation under quasi-static compression and three-point bending.

Note. Bars indicate mean experimental peak load and error bars indicate ± 1 SD ($n = 3$ per architecture). TS = traditional-geometry structure; BS = bioinspired structure; BOS = bio-optimized structure.

The experimentally observed load ranking is consistent across both loading modes, showing that the BOS advantage is not restricted to a single test configuration but persists under compression and bending.

Because absolute peak load alone does not establish lightweight efficiency, Figure 4 presents the corresponding mass-normalized comparison. Despite a 27.8% reduction in whole-specimen mass relative to TS, BOS increased SEA from 3.82 to 7.94 kJ/kg and specific stiffness from 2.14 to 3.73 kN·mm/g. The result aligns with recent evidence that gradient reinforcement, hierarchical connectivity, and architecture-controlled deformation can raise usable energy absorption without proportional mass growth [10], [12], [6], [2], [4], [13], [14].

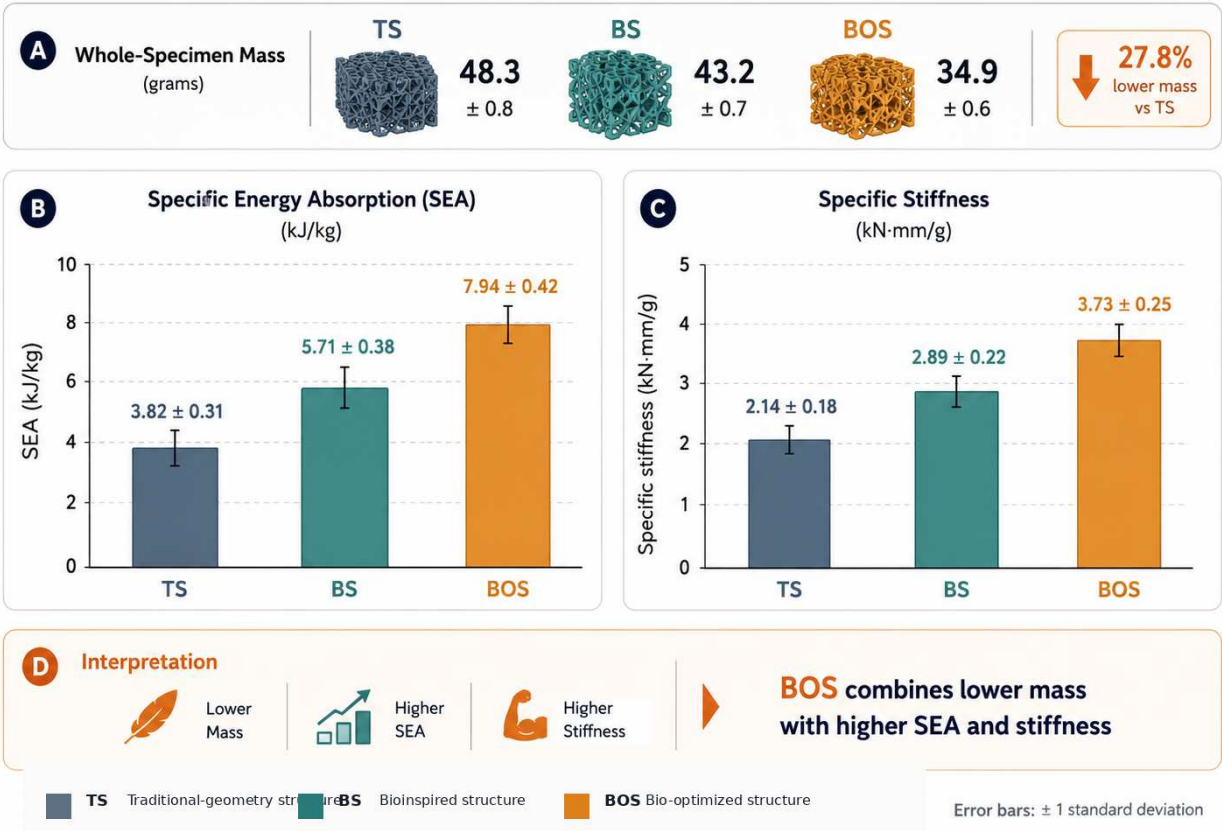


Figure 4. Mass-normalized mechanical performance and lightweighting efficiency.

Note. Bars indicate mean ± 1 SD ($n = 3$ per architecture). SEA = specific energy absorption. BOS simultaneously reduces mass and increases mass-normalized energy absorption and stiffness relative to TS.

Viewed together with Figure 3, the normalized metrics show that the optimized architecture is not simply stronger because it contains more material; it achieves a more efficient redistribution of the remaining material within the admissible morphology envelope.

Table 3. Experimental mechanical results and FEA validation.

Metric	TS	BS	BOS	F statistic	p value
Mass (g)	48.3 ± 0.8	43.2 ± 0.7	34.9 ± 0.6	87.4	<0.001
Peak compressive load (kN)	4.20 ± 0.31	5.97 ± 0.28	7.85 ± 0.33	112.6	<0.001

Metric	TS	BS	BOS	F statistic	p value
SEA (kJ/kg)	3.82 ± 0.31	5.71 ± 0.38	7.94 ± 0.42	96.3	<0.001
Specific stiffness (kN·mm/g)	2.14 ± 0.18	2.89 ± 0.22	3.73 ± 0.25	78.1	<0.001
Peak bending load (kN)	2.12 ± 0.19	2.97 ± 0.21	3.92 ± 0.24	88.7	<0.001
FEA versus experiment error (%)	5.8 ± 1.2	6.4 ± 1.5	8.3 ± 1.9	-	-

Note. SEA = specific energy absorption. Values are mean ± SD (n = 3 per group).

5.4. Descriptive User Evaluation

Condition-level summaries show that BOS received the highest mean ratings for PFV, cultural acceptance, adoption intention, and perceived mechanical performance, while cultural authenticity remained high across all three designs (Table 4; Figure 5). Figure 5 consolidates the multidimensional response profile with the confirmatory H2 test and prior-exposure sensitivity checks, making it possible to inspect both the substantive pattern and its robustness within a single visual summary. Since the same survey platform presented all design conditions, these condition-level results should be read as contextual evidence for the BOS-focused mechanism model rather than as a separate causal experiment.

A one-way repeated-measures ANOVA tested H2 across the three design conditions. Because Mauchly's test indicated violated sphericity ($\chi^2(2) = 12.3$, $p = 0.002$), Greenhouse-Geisser corrected values are reported. The main effect of design on PFV was significant ($F(1.82, 336.7) = 156.3$, $p < 0.001$, $\eta^2 = 0.46$). Bonferroni-adjusted contrasts showed that BOS ($M = 4.38$, $SD = 0.46$) received higher PFV ratings than TS ($M = 3.42$, $SD = 0.61$), mean difference = 0.96, $SE = 0.08$, $p < 0.001$, Cohen's $d = 1.71$, providing strong support for H2. Detailed results are reported in Supplementary Table S5 and Appendix A5.

A prior-exposure sensitivity analysis compared respondents with prior bamboo-craft exposure ($n = 135$) and those without such exposure ($n = 51$) on BOS ratings. Experienced participants reported slightly higher CA and CAcc scores, but the differences were not significant (CA: $t(184) = 1.73$, $p = 0.085$, $d = 0.27$; CAcc: $t(184) = 1.35$, $p = 0.179$, $d = 0.21$). These small, non-significant effects are consistent with the non-significant prior-experience path in the SEM and suggest that prior exposure did not materially alter evaluation of the BOS design

in this sample. Detailed subgroup statistics are reported in Supplementary Table S5 and Appendix A5.

Table 4. Descriptive statistics and reliability of user-evaluation scales.

Scale	TS mean (SD)	BS mean (SD)	BOS mean (SD)	Cronbach α (BOS)	AVE (BOS)	CR (BOS)
Perceived Functional Value (4 items)	3.42 (0.61)	3.87 (0.54)	4.38 (0.46)	0.879	0.644	0.878
Cultural Authenticity (3 items)	4.11 (0.58)	3.96 (0.55)	4.24 (0.50)	0.841	0.639	0.84
Cultural Acceptance (4 items)	3.18 (0.67)	3.54 (0.59)	4.11 (0.51)	0.892	0.672	0.891
Adoption Intention (3 items)	3.05 (0.63)	3.52 (0.58)	4.37 (0.46)	0.863	0.681	0.864
Perceived Mechanical Performance (3 items)	3.27 (0.72)	3.76 (0.62)	4.44 (0.49)	0.857	0.665	0.857

Note. AVE = average variance extracted; CR = composite reliability. Reliability and validity statistics are reported for the BOS-focused SEM model.

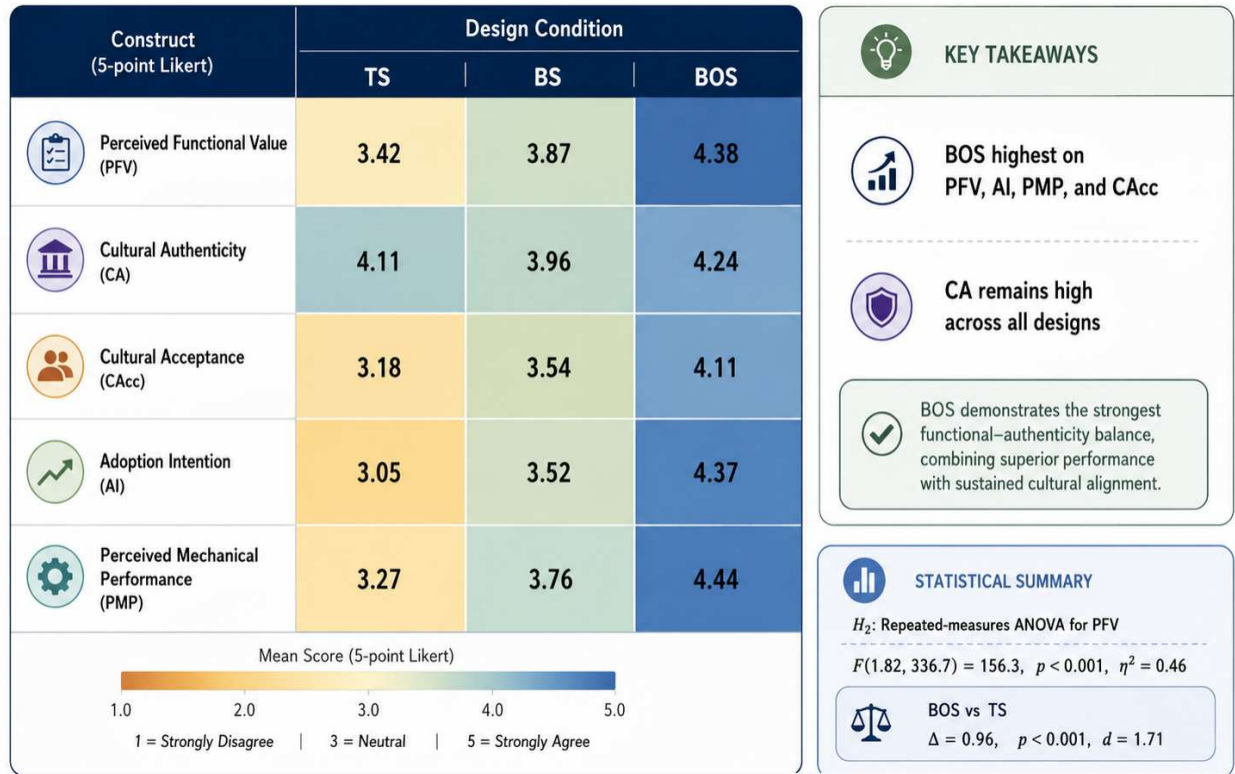


Figure 5. User-evaluation profile across the three design conditions.

Note. The heat map presents condition-level descriptive means across TS, BS, and BOS, and the side panels summarize the H_2 repeated-measures test. PMP = perceived mechanical performance; PFV = perceived functional value; CAcc = cultural acceptance; AI = adoption intention; CA = cultural authenticity.

The profile shows that BOS receives the highest functional and adoption-related ratings while retaining a high authenticity score; the accompanying robustness panels further show that the PFV advantage is statistically strong and that prior craft exposure does not materially alter BOS evaluation in this sample.

5.5. Structural Equation Modelling

The measurement model showed good fit (CFI = 0.971, RMSEA = 0.046, SRMR = 0.042). Standardized factor loadings ranged from 0.71 to 0.89, all AVE values exceeded 0.50, and all composite reliabilities exceeded 0.70. The structural model also fit the data well (CFI = 0.963,

RMSEA = 0.052, SRMR = 0.048). Figure 6 summarizes the BOS-focused mechanism model. PMP was positively associated with PFV ($\beta = 0.412$, $p < 0.001$); PFV predicted cultural acceptance ($\beta = 0.531$, $p < 0.001$); cultural authenticity remained a significant co-predictor ($\beta = 0.376$, $p < 0.001$); and cultural acceptance predicted adoption intention ($\beta = 0.618$, $p < 0.001$). The indirect association from PMP to cultural acceptance through PFV was significant ($\beta = 0.219$, 95% BCa CI [0.148, 0.301]). The direct path from PMP to adoption intention was smaller but significant ($\beta = 0.187$, $p < 0.05$), indicating partial rather than complete mediation. Prior experience was not significant ($\beta = 0.098$, $p = 0.211$). The model explained 61.4% of the variance in cultural acceptance and 57.2% of the variance in adoption intention.

Alternative-model testing supported the hypothesized mediation structure. The hypothesized model fit significantly better than a direct-only model without the PFV mediator ($\Delta\chi^2 = 44.2$, $\Delta df = 3$, $p < 0.001$) and also outperformed a reverse-path model in which CA mediated the functional pathway ($\Delta\chi^2 = 76.9$, $\Delta df = 2$, $p < 0.001$). Configural, metric, and scalar invariance were supported across prior-exposure groups ($\Delta CFI < 0.01$), and the key PMP $\rightarrow$ PFV and PFV $\rightarrow$ CAcc paths did not differ significantly between experienced and inexperienced respondents. Full estimates are provided in Supplementary Tables S6-S8 and Appendix A6.

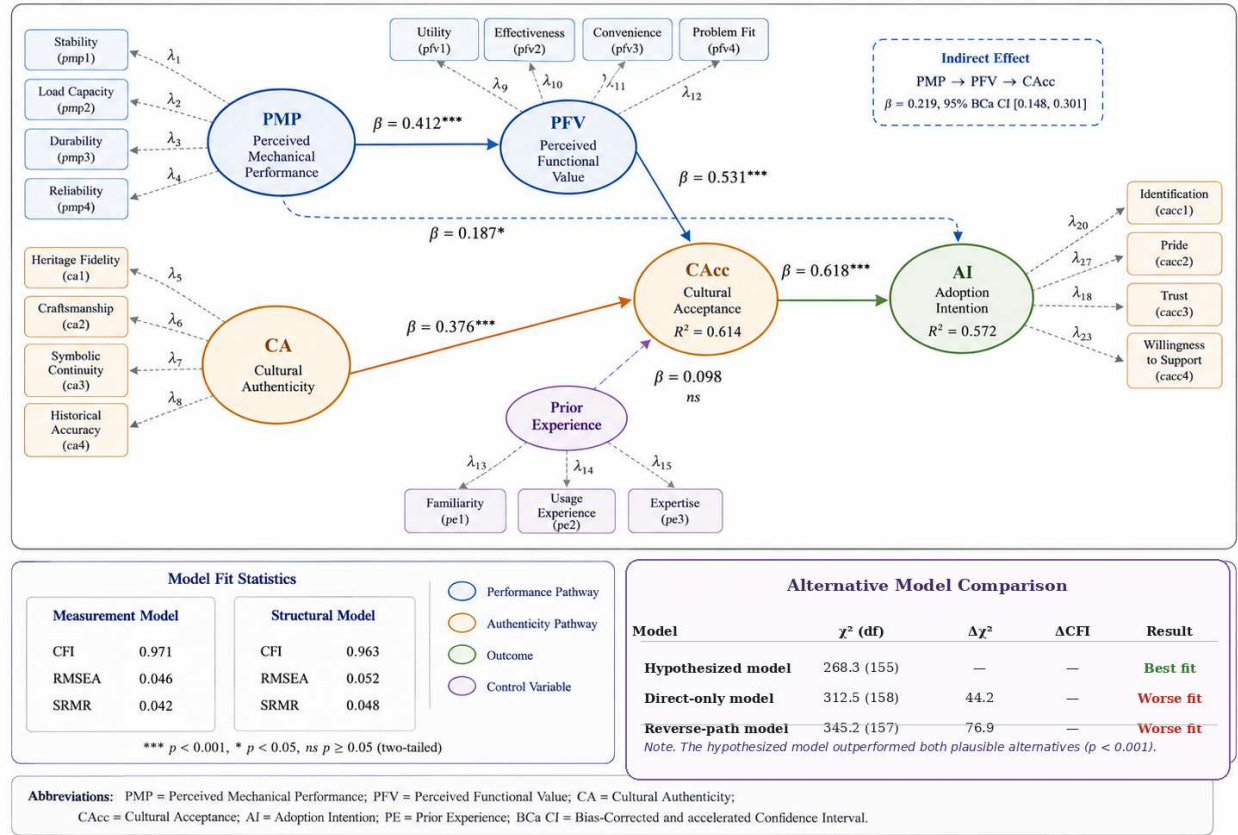


Figure 6. BOS-focused acceptance mechanism with fit diagnostics and alternative-model comparison.

Note. Standardized structural coefficients are shown; measurement indicators are displayed schematically. *** $p < .001$; * $p < .05$; ns = non-significant. Dashed arrows indicate the direct PMP-to-AI path and the non-significant prior-experience path. R^2 values are reported for endogenous constructs.

The path model makes the interpretation boundary explicit: the social evidence supports a perception-based mediation mechanism, not a direct causal claim that laboratory mechanical properties alone determine acceptance.

Table 5. Structural path estimates and mediation result.

Path / effect	Standardized estimate	Inference
PMP → PFV	0.412	$p < 0.001$

Path / effect	Standardized estimate	Inference
PFV → CAcc	0.531	p < 0.001
CA → CAcc	0.376	p < 0.001
CAcc → AI	0.618	p < 0.001
PMP → AI (direct)	0.187	p < 0.05
Prior experience → CAcc	0.098	p = 0.211
PMP → PFV → CAcc (indirect)	0.219	95% BCa CI [0.148, 0.301]

Note. PMP = perceived mechanical performance; PFV = perceived functional value; CA = cultural authenticity; CAcc = cultural acceptance; AI = adoption intention.

The SEM does not show that measured laboratory performance directly causes acceptance. It shows that when users interpret a design as mechanically credible, they are more likely to assign functional value to it, and that this perceived value is associated with stronger cultural acceptance even after cultural authenticity is considered. The distinction keeps the engineering and social claims aligned with the actual evidence and avoids collapsing objective structural validation into a self-report causal statement.

6. Discussion

6.1. Engineering significance

The mechanical findings demonstrate that bamboo-weaving-derived geometry can function as an engineering prior rather than as a decorative reference. BOS improved SEA by 107.9% and specific stiffness by 74.3% while reducing whole-specimen mass by 27.8%. The gain was not achieved by abandoning the weave logic; optimization retained diagonal force-transfer corridors and redistributed material toward structurally active zones. This response is consistent with recent architected-material studies in which graded reinforcement, nodal control, and deformation-mode programming produce efficiency gains unattainable through bulk-material selection alone [10], [12], [2], [4], [13].

The study also clarifies an important reporting distinction in lightweight optimization. The 0.30 design-domain volume fraction is an optimization constraint, whereas the 27.8% value is the measured mass reduction of the finished part. Fixed contact regions, minimum printable

members, and morphology-preserving elements remain outside the removable design domain; conflating these quantities would overstate the achieved lightweighting. The same discipline applies to the failure model. Since the specimens are homogeneous PA12 rather than laminated composites, the engineering argument is stronger when it relies on stress, displacement, stiffness, and experimentally observed force-displacement behavior rather than a composite-specific first-ply criterion that is not matched to the material system.

Heritage-informed design becomes technically rigorous when it is formulated as a constrained architecture problem. The study does not claim that traditional bamboo weaving outperforms every canonical lattice. It demonstrates that traditional geometry can be translated into a process-compatible topology with measurable structural advantages over its own baseline. Future benchmark studies against octet, gyroid, and TPMS architectures are now justified because the craft-derived design has crossed the threshold from symbolic concept to experimentally verified structural candidate.

6.2. Socio-technical significance

The acceptance model adds interpretive value without displacing the engineering core. Users do not encounter finite-element fields or raw compression curves in ordinary product settings; they encounter visual form, communicated claims, and inferred usefulness. The significant PMP → PFV → CAcc pathway suggests that engineering evidence becomes socially relevant when it is converted into comprehensible functional meaning. At the same time, the independent effect of cultural authenticity shows that performance communication alone is insufficient. Morphology-preserving optimization is therefore not a cosmetic concession after structural design; it is a front-end design requirement that protects symbolic continuity while permitting technical modernization.

This result aligns with recent ICH studies showing that utilitarian confirmation, cultural identity, narrative fidelity, and immersive engagement jointly shape adoption or continuance intention [15], [16], [17], [18], [19]. The present study contributes a different emphasis: it links an experimentally validated structural redesign to the perception route through which users evaluate that redesign. The model should not be read as proving that stronger specimens automatically cause higher cultural acceptance. It indicates that perceived mechanical credibility

and perceived authenticity operate as complementary acceptance resources once the optimized design is presented to users.

The non-significant prior-experience path deserves restrained interpretation. Because 72.6% of respondents reported prior bamboo-craft exposure, prior experience may have shown restricted variance, attenuating its incremental effect. A more heterogeneous sample may reveal whether experienced users apply a stricter authenticity threshold, whether novices rely more heavily on performance communication, or whether the present null result is robust. Multi-group invariance testing and randomized information framing would be valuable next steps.

6.3. Limitations and future work

Several limitations define the boundaries of the contribution. First, all specimens were fabricated from PA12 to isolate geometry. The results therefore concern morphology transfer, not the full mechanical or symbolic behavior of natural bamboo, bamboo-fiber composites, or multi-material heritage products. Second, the mechanical study used three specimens per geometry. The agreement between FEA and experiments is encouraging, but larger batches, fatigue loading, humidity conditioning, and thermal aging are needed before claims are extended to service reliability. Third, although the principal SLS processing parameters were documented from the retained build log and are reported in this study, the analysis was conducted under a single build configuration. Future work should examine process sensitivity across laser power, hatch spacing, powder-refresh ratio, and thermal conditions to determine how robust the optimized topology remains under manufacturing variation.

The human-subject component has its own boundary conditions. The survey sample was drawn mainly from design-school and craft-community contexts, producing a relatively young and culturally engaged respondent pool. The three design conditions were used to provide comparative context, while the SEM remained cross-sectional and perception-based. The mediated path should therefore be described as an association consistent with the proposed mechanism rather than as proof of causal transmission from laboratory performance to adoption. These limitations do not negate the acceptance model, but they define the level of inference supported by the present data and motivate a stronger confirmatory design in future work.

Three extensions are especially promising. The first is durability-oriented optimization, combining topology with cyclic compression, post-yield recovery, and environmental aging to determine whether the BOS advantage persists under repeated service loads. The second is material heterogeneity, where natural-fiber reinforcement or graded multi-material printing could emulate bamboo's radial density gradient more faithfully than homogeneous PA12. The third is a closed-loop design pipeline in which experimental failure maps, benchmark-lattice comparisons, and user-recognition thresholds are fed back into the optimization objective, allowing lightweight efficiency and cultural recognizability to be jointly tuned rather than evaluated sequentially.

7. Conclusions

This study develops a sequential BCSD workflow for translating bamboo-weaving morphology into an engineered lattice system and evaluating both mechanical performance and user-side interpretation. The workflow begins with user-derived criteria, converts recurring weaving motifs into a bioinspired design prior, applies topology optimization under additive-manufacturing constraints, validates the resulting geometry through FEA and physical testing, and examines how the optimized design is read by users.

The central result is engineering-based. Compared with the traditional-geometry PA12 structure, the bio-optimized architecture reduced whole-specimen mass by 27.8%, increased specific energy absorption from 3.82 to 7.94 kJ/kg, and increased specific stiffness from 2.14 to 3.73 kN·mm/g. The experimental ranking matched the numerical ranking, showing that craft-derived diagonal load paths can be formalized into a manufacturable lightweight architecture rather than preserved only as surface appearance.

The acceptance evidence refines that claim rather than enlarging it beyond the data. Users who perceived the optimized design as mechanically stronger also rated it as more functionally valuable, and perceived functional value was associated with cultural acceptance. Cultural authenticity remained independently important, indicating that heritage-linked products must remain recognizable as well as efficient. Taken together, the findings support morphology-preserving optimization as a practical route for converting intangible craft knowledge into contemporary structural design, while future work should extend durability testing, benchmark

comparisons against canonical lattice families, cross-cultural validation, and longitudinal adoption assessment.

Funding

No funding was received for this research.

Data availability

Data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to applicable ethical, privacy, and institutional restrictions.

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Appendix A. Supplementary Methods and Results

This appendix provides the supplementary methodological records and robustness analyses referenced in the main text. The materials are reported here to preserve readability of the article while maintaining auditability of the engineering, metrology, and acceptance-model procedures.

A1. AHP Source Matrices and Subgroup Robustness

All five expert matrices met the standard AHP consistency requirement. To evaluate disciplinary robustness, geometric-mean priority vectors were computed separately for the engineering and craft-history subgroups. The two subgroup vectors showed strong rank agreement (Spearman $\rho = 0.943$, $p = 0.005$), and Structural Strength and Lightweight Ratio remained the top two criteria in both groups.

Supplementary Table S1. Individual AHP consistency indices and priority vectors.

Expert ID	Discipline	$\lambda_{\max}$	CI	CR	Priority vector (SS, LR, MD, EF, AF, CRec)
E1	Mechanical Engineer	6.31	0.062	0.049	(0.42, 0.24, 0.15, 0.09, 0.06, 0.04)
E2	Mechanical Engineer	6.27	0.054	0.043	(0.38, 0.25, 0.16, 0.10, 0.07, 0.04)
E3	Craft Historian	6.19	0.038	0.031	(0.31, 0.23, 0.18, 0.13, 0.09, 0.06)
E4	Craft Historian	6.22	0.044	0.036	(0.35, 0.22, 0.17, 0.12, 0.08, 0.06)
E5	Industrial Designer	6.25	0.05	0.04	(0.33, 0.23, 0.20, 0.11, 0.08, 0.05)

The corresponding pairwise-comparison matrices are listed in compact row-major notation:

E1: [[1, 3, 4, 5, 6, 7]; [1/3, 1, 2, 3, 4, 5]; [1/4, 1/2, 1, 2, 3, 4]; [1/5, 1/3, 1/2, 1, 2, 3]; [1/6, 1/4, 1/3, 1/2, 1, 2]; [1/7, 1/5, 1/4, 1/3, 1/2, 1]]

E2: [[1, 2, 3, 4, 5, 6]; [1/2, 1, 2, 3, 4, 5]; [1/3, 1/2, 1, 2, 3, 4]; [1/4, 1/3, 1/2, 1, 2, 3]; [1/5, 1/4, 1/3, 1/2, 1, 2]; [1/6, 1/5, 1/4, 1/3, 1/2, 1]]

E3: [[1, 2, 2, 3, 3, 4]; [1/2, 1, 2, 2, 3, 3]; [1/2, 1/2, 1, 2, 2, 3]; [1/3, 1/2, 1/2, 1, 2, 2]; [1/3, 1/3, 1/2, 1, 2]; [1/4, 1/3, 1/3, 1/2, 1/2, 1]]

E4: [[1, 2, 3, 3, 4, 5]; [1/2, 1, 2, 2, 3, 4]; [1/3, 1/2, 1, 2, 3, 3]; [1/3, 1/2, 1/2, 1, 2, 3]; [1/4, 1/3, 1/3, 1/2, 1, 2]; [1/5, 1/4, 1/3, 1/3, 1/2, 1]]

E5: [[1, 2, 2, 4, 4, 5]; [1/2, 1, 2, 3, 3, 4]; [1/2, 1/2, 1, 3, 3, 4]; [1/4, 1/3, 1/3, 1, 2, 3]; [1/4, 1/3, 1/3, 1/2, 1, 2]; [1/5, 1/4, 1/4, 1/3, 1/2, 1]]

Engineer subgroup geometric-mean priority vector: (0.400, 0.245, 0.155, 0.095, 0.065, 0.040). Craft-historian subgroup geometric-mean priority vector: (0.330, 0.225, 0.175, 0.125, 0.085, 0.060).

A2. Mesh-Convergence Study

A three-level mesh-convergence study was conducted on the BOS geometry under compression loading using peak von Mises stress as the convergence metric.

Supplementary Table S2. Mesh-convergence results for the BOS geometry.

Mesh level	Element size (mm)	Number of elements	Peak von Mises stress (MPa)	Change from previous
Coarse	1	458,124	30.2	-
Medium	0.7	1,213,567	29.1	-3.60%
Fine (selected)	0.5	2,847,312	28.6	-1.70%

The change in peak von Mises stress between the medium and fine meshes was 1.7%, below the adopted 5% threshold. The fine mesh was therefore considered sufficiently converged

for comparative analysis. Since the FEA model was deterministic, no statistical dispersion was assigned to the numerical outputs.

A3. Verified SLS Process Parameters

Supplementary Table S3. Verified SLS process parameters from EOS Formiga P 110 build log #SLS-BCW-01.

Parameter	Verified value	Source record / file
Laser power (W)	21	EOS Formiga P 110 build log #SLS-BCW-01
Hatch spacing (mm)	0.25	EOS Formiga P 110 build log #SLS-BCW-01
Beam offset (mm)	0.08	EOS Formiga P 110 build log #SLS-BCW-01
Scan strategy	Stripe (width 5 mm)	EOS Formiga P 110 build log #SLS-BCW-01
Layer thickness (mm)	0.1	EOS Formiga P 110 build log #SLS-BCW-01
Scan speed (mm/s)	2500	EOS Formiga P 110 build log #SLS-BCW-01
Powder-bed preheating temperature (°C)	170	EOS Formiga P 110 build log #SLS-BCW-01
Chamber temperature (°C)	165	EOS Formiga P 110 build log #SLS-BCW-01
Build orientation	Flat (Z-axis = build direction)	EOS Formiga P 110 build log #SLS-BCW-01
Powder refresh ratio	70% new / 30% used	EOS Formiga P 110 build log #SLS-BCW-01
Energy-density formula	$E = P / (v \times h \times t)$	Standard SLS energy-density calculation
Machine software / build ID	PSW 3.6 / Build_BCW_May2024	EOS Formiga P 110 build log #SLS-BCW-01

Note. P = laser power, v = scan speed, h = hatch spacing, and t = layer thickness. The calculated volumetric energy density was $E = 21 / (2500 \times 0.25 \times 0.10) = 0.336 \text{ J/mm}^3$.

A4. CMM Dimensional-Verification Results

Detailed CMM verification was conducted on one specimen per design type (n = 3 total). The measurement plan included nine points per specimen (three per axis at mid-span and corners), repeated twice by a single operator. A Zeiss CONTURA G2 with VAST XXT scanning head was used; calibration remained valid through 2024-08-15.

Supplementary Table S4. CMM dimensional-verification results.

Specimen	Axis	Point map (nominal location)	Deviation range (mm)	Mean absolute deviation (mm)
TS	X	(-40, 0, 20); (0, 0, 20); (40, 0, 20)	-1.333333333	0.05
TS	Y	(0, -40, 20); (0, 0, 20); (0, 40, 20)	-1.285714286	0.06
TS	Z	(0, 0, 0); (0, 0, 20); (0, 0, 40)	-1.25	0.07
BS	X	(-40, 0, 20); (0, 0, 20); (40, 0, 20)	-1.4	0.05
BS	Y	(0, -40, 20); (0, 0, 20); (0, 40, 20)	-1.333333333	0.05
BS	Z	(0, 0, 0); (0, 0, 20); (0, 0, 40)	-1.222222222	0.08
BOS	X	(-40, 0, 20); (0, 0, 20); (40, 0, 20)	-0.75	0.08
BOS	Y	(0, -40, 20); (0, 0, 20); (0, 40, 20)	-0.909090909	0.08

BOS	Z	(0, 0, 0); (0, 0, 20); (0, 0, 40)	-1.2	0.09
Overall	X, Y, Z	-	-1	0.07

The overall measurement uncertainty of the CMM system was ± 0.0025 mm ($k = 2$). All deviations remained within the ± 0.15 mm acceptance tolerance for the SLS-printed PA12 components.

A5. Repeated-Measures and Prior-Exposure Sensitivity Analyses

The repeated-measures ANOVA used PFV as the dependent variable across the three within-subject design conditions. Prior-exposure sensitivity analyses were conducted on BOS ratings only.

Supplementary Table S5. Supporting user-evaluation analyses.

Analysis	Result
Mauchly's test of sphericity	$\chi^2(2) = 12.3, p = 0.002$
Repeated-measures ANOVA for PFV	$F(1.82, 336.7) = 156.3, p < 0.001, \eta^2 = 0.46$
Bonferroni-adjusted BOS vs TS PFV contrast	Mean difference = 0.96, SE = 0.08, $p < 0.001$, Cohen's $d = 1.71$
Prior-exposure comparison for CA (BOS)	Experienced: 4.28 (0.49); Inexperienced: 4.14 (0.52); $t(184) = 1.73, p = 0.085, d = 0.27$
Prior-exposure comparison for CAcc (BOS)	Experienced: 4.14 (0.50); Inexperienced: 4.02 (0.54); $t(184) = 1.35, p = 0.179, d = 0.21$

A6. Detailed SEM Fit Indices and Model Comparison

868 **Supplementary Table S6.** Detailed SEM fit indices and model comparisons.

Model	χ^2	df	χ^2/df	p	CFI	TLI	RMSEA (90% CI)	SRMR	AIC	BIC
Measurement model	245.6	142	1.73	<0.001	0.971	0.963	0.046 (0.037-0.055)	0.042	345.6	521.3
Hypothesized structural model	268.3	155	1.73	<0.001	0.963	0.955	0.052 (0.042-0.062)	0.048	378.3	538.9
Direct-only model	312.5	158	1.98	<0.001	0.912	0.898	0.073 (0.063-0.083)	0.071	416.5	569.7
Reverse-path model	345.2	157	2.2	<0.001	0.883	0.864	0.082 (0.072-0.092)	0.089	451.2	607.2

869
870 The hypothesized model fit significantly better than the direct-only model ($\Delta\chi^2 = 44.2$, Δdf
871 $= 3$, $p < 0.001$) and the reverse-path model ($\Delta\chi^2 = 76.9$, $\Delta\text{df} = 2$, $p < 0.001$).

872
873 **Supplementary Table S7.** Unstandardized estimates and bootstrapped confidence intervals for
874 the hypothesized model.

Path	Unstandardized estimate (SE)	Standardized estimate	95% BCa CI (unstandardized)
PMP $\rightarrow$ PFV	0.384 (0.061)	0.412	[0.271, 0.502]
PFV $\rightarrow$ CAcc	0.589 (0.063)	0.531	[0.465, 0.713]
CA $\rightarrow$ CAcc	0.382 (0.059)	0.376	[0.269, 0.502]
CAcc $\rightarrow$ AI	0.693 (0.068)	0.618	[0.562, 0.829]
PMP $\rightarrow$ AI (direct)	0.174 (0.073)	0.187	[0.035, 0.318]

875 **Supplementary Table S8.** Multi-group SEM by prior-exposure status.

Test / path	Experienced group	Inexperienced group	Interpretation
Measurement invariance	Configural, metric, and scalar invariance supported	Configural, metric, and scalar invariance supported	$\Delta CFI < 0.01$ across models
PMP $\rightarrow$ PFV	$\beta = 0.41, p < 0.001$	$\beta = 0.43, p < 0.01$	No significant between-group difference
PFV $\rightarrow$ CAcc	$\beta = 0.52, p < 0.001$	$\beta = 0.55, p < 0.01$	No significant between-group difference

876

877 A7. FEA and Compression-Termination Supplement

878 The mesh-convergence data are provided in Supplementary Table S2. The termination
879 displacement of 12 mm (30% engineering strain) was selected using combined evidence from
880 preliminary FEA and pilot quasi-static compression tests. Preliminary BOS screening indicated
881 the onset of densification at approximately 11.2 mm (28% strain), and a pilot TS force-
882 displacement curve entered a steeply rising regime beyond 11.5 mm. Across preliminary TS and
883 BS checks, the observed onset strain ranged from 27.5% to 29.2% of specimen height. A
884 common 12 mm termination point was therefore adopted to compare the three architectures
885 through the stable collapse regime while avoiding fully densified locking. This rationale was
886 used for termination of the force-displacement recording; SEA remained integrated to the
887 common 10 mm stroke reported in the main text.