

Article

Development of a Constitutive Model Based on Fique Fibre (*Furcraea macrophylla*) as a Reinforcement Material in Bioengineering Projects

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Abstract

Natural fibre meshes have emerged as a promising class of sustainable geotechnical reinforcement materials; however, no calibrated and validated directional constitutive model currently exists in the scientific literature for *Furcraea macrophylla* (fique) fabric under contrasting hygroscopic states. This knowledge gap prevents the adoption of performance-based, reliability-centred design approaches and limits the broader use of this Andean biotextile in bioengineering practice. The present study develops, calibrates, and validates a nonlinear constitutive model integrating warp/weft fabric anisotropy, a scalar damage law (Dk), and a hygroscopic reduction factor (ϕ_h). A multiscale experimental programme—comprising SEM-EDX, FTIR-ATR, TGA, CO₂ physisorption, wide-strip tensile testing ($n \geq 5$ per condition; 4 conditions $\times$ 2 directions), large-scale direct shear, and RL-CBR tests—provided all model parameters. Statistical analysis (two-way ANOVA; Shapiro–Wilk normality test; Levene homogeneity test) confirmed the significance of both configuration and moisture states on mechanical response ($p < 0.001$). Model validation by cross-validation ($n = 12$ retained series), Sobol global sensitivity analysis, and Monte Carlo uncertainty propagation ($N = 1000$ iterations, Latin Hypercube Sampling) yielded $R^2 = 0.94 \pm 0.03$ and a normalised root mean square error (NRMSE) $< 8.5\%$ across all series; 98% of all individual experimental data points (≥ 60 points across 12 test series) fell within the 95% Monte Carlo confidence interval. The hygroscopic reduction factor dominated mechanical uncertainty with a Sobol first-order index of $Si(\phi_h) = 0.82$, confirming that moisture-induced plasticisation governs reinforcement stability in tropical service conditions ($\phi_h = 0.62\text{--}0.78$; CV = 6.4%). A technical comparison with Colombian road construction standards confirmed that fique mesh meets minimum tensile requirements for erosion control and slope reinforcement. All raw data and the constitutive model code are available upon reasonable request to ensure full reproducibility.



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Keywords: natural fibre geotextile; nonlinear constitutive model; scalar damage mechanics; hygroscopic degradation; fabric anisotropy; representative volume element; probabilistic uncertainty quantification; lignocellulosic fibre reinforcement; slope bioengineering; Monte Carlo simulation

1. Introduction

Growing environmental pressure on the construction sector has accelerated the search for low-carbon reinforcement materials for geotechnical applications [1]. Petroleum-derived geosynthetics continue to dominate global markets for slope reinforcement and erosion control, yet their substantial carbon footprint and limited biodegradability have driven sustained interest in lignocellulosic alternatives [2,3]. Fique (*Furcraea macrophylla*), a leaf fibre endemic to the Colombian Andean region, combines local availability, high specific toughness, compatibility with circular-economy frameworks, and supply chain integration supporting over 70,000 rural families, positioning it as a technically and socially viable candidate for surface bioengineering applications in tropical and subtropical contexts [2,4].

At the material level, recent characterisation studies of *Furcraea macrophylla* report holocellulose contents exceeding 70%, hydrophilic surface functional groups that condition water uptake, and individual-fibre tensile moduli in the range of 180–600 MPa [3,5,6]. Microstructural variability—filament diameters spanning 36–158 μm , bundle thicknesses of 140–270 μm , and cell wall thickness of 9.90 μm (range: 5.49–16.84 μm)—introduces inherent dispersion requiring rigorous statistical treatment before translation to engineering scales [3,5]. At the fabric scale, effective stiffness and toughness depend critically on weave architecture: thread count, crimp, and interlacing pattern [7,8]. The hygroscopic nature of lignocellulosic fibres further complicates design: moisture absorption can reduce the elastic modulus by 20–40% and tensile strength by up to 40% depending on fibre types and saturation levels [9–11]. Such reductions have direct consequences for long-term geotechnical performance under humid tropical conditions.

Periodic homogenisation frameworks based on the Representative Volume Element (RVE) have demonstrated the ability to extract directional equivalent properties from woven textile unit cells [12,13]. Building upon this, finite element micromechanical analyses of 2D woven composites predict in-plane moduli with errors below 10% when accurate geometric parameters are provided [7,14,15]. Notwithstanding these advances, most such models address thermosetting polymer–matrix composites and have not been adapted to hygroscopic natural fibres, where moisture content substantially alters the mechanical response at every strain level [9,10,16]. Consequently, established soil–geosynthetic interaction models [17–19] typically characterise stiffness under small displacements and do not account for post-peak softening or hygroscopic degradation of the reinforcement, thereby limiting applicability to natural biotextile systems operating near failure.

At the constitutive level, two modelling traditions are directly relevant to the present work. First, continuum damage mechanics frameworks—established by Lemaitre and Desmorat [20] and Krajcinovic [21]—have been systematically applied to the progressive degradation of fibre-reinforced composites, yielding scalar damage laws calibrated from experimental tensile data that reproduce both pre-peak nonlinearity and post-peak softening with engineering-level accuracy [16]. Second, hygroscopic degradation models quantify the reduction in elastic modulus and tensile strength induced by moisture absorption in lignocellulosic fibres, typically expressed as a dimensionless reduction factor relating wet-state to dry-state mechanical properties [9–11]. Despite this body of work, no study has simultaneously integrated directional fabric anisotropy, a calibrated scalar damage law, and an explicit hygroscopic factor within a single validated constitutive framework for *Furcraea macrophylla* mesh—the precise gap that the present study addresses.

Despite these advances, no calibrated and validated constitutive model currently exists in the open literature that simultaneously integrates: (i) directional anisotropy (warp/weft) of fique mesh; (ii) hygroscopic degradation quantified through an explicit dimensionless reduction factor (ϕ_h); and (iii) experimentally anchored post-peak softening via a scalar damage law (D_d). This gap prevents the transition from empirical–normative

design towards performance-based, reliability-centred engineering for slope bioengineering systems reinforced with natural fibres [22,23].

To close this gap, the present study develops, calibrates, and validates a directional nonlinear constitutive model for *Furcraea macrophylla* fabric in both dry and saturated states, based on the weighted residual method with finite elements. The principal scientific contributions are as follows: (a) the first simultaneous parametrisation of the hygroscopic reduction factor ϕh and the scalar damage variable D_k from standardised wide-strip tensile tests ISO 10319 [24]; ASTM D4595 [25]; and (b) a probabilistic validation framework—through Monte Carlo simulation with Latin Hypercube Sampling—demonstrating that 98% of all individual experimental data points (total ≥ 60 , across 12 retained test series) fell within the 95% confidence interval, enabling reliability-based design with natural biotextiles. Technical comparisons against Colombian road construction standards (INVÍAS Art. 231, Resolución 4561/2022) [26]; confirmed compliance with tensile strength, permittivity, and tear resistance thresholds for erosion control and slope reinforcement applications. All experimental data and model code are made available as Supplementary Materials (Tables S1–S4; Codes S1 and S2) to ensure full reproducibility [27,28].

2. Materials and Methods

The approach integrates four hierarchical scales through explicit parameter transfer (Figure 1): SEM-EDX provides geometric inputs to the RVE unit cell; FTIR-ATR confirms the physical basis for the hygroscopic reduction factor ϕh (Equation (5)); TGA validates the thermal stability assumption within the test temperature window; and CO₂ physisorption corroborates the binary dry/saturated conditioning protocol (Section 2.3). The programme comprised five sequential stages described in Sections 2.1–2.7.

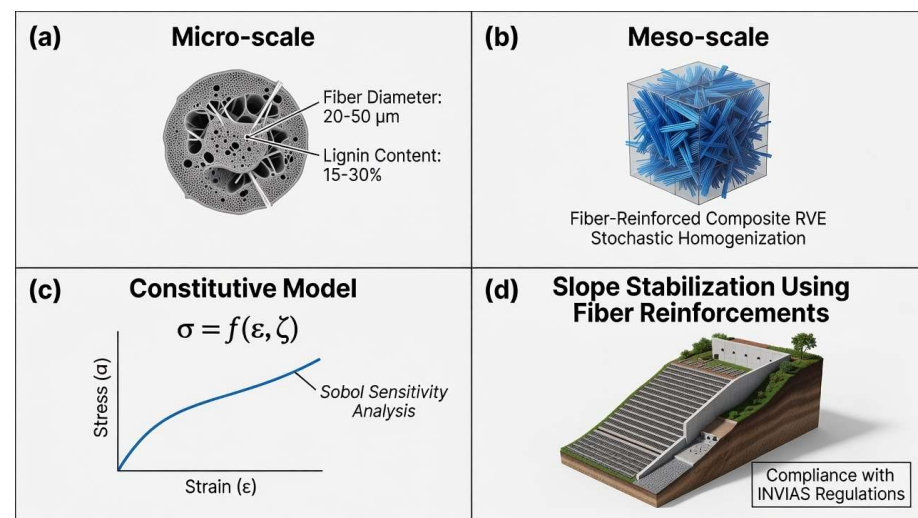


Figure 1. Multiscale conceptual framework for the constitutive model development: (a) lignocellulosic microfibre characterisation (SEM-EDX, FTIR-ATR, TGA; cell length 36–158 µm; bundle thickness 140–270 µm); (b) Representative Volume Element (RVE) unit cell with periodic boundary conditions in both principal directions; (c) nonlinear directional constitutive law integrating hygroscopic reduction ($\phi h = 0.62$ – 0.78) and scalar damage D_k , activated at strain $\varepsilon_{u,k}$; (d) field-scale application in slope bioengineering and unpaved road reinforcement. Arrows indicate downward parameter transfer across scales.

2.1. Materials and Sample Preparation

Furcraea macrophylla fibres were obtained from artisanal producers in the Boyacá department, Colombia, following field collection and manual extraction protocols compatible with local production chains. Two mesh configurations were used: (i) woven, with

identifiable warp (direction 1) and weft (direction 2) yarns in a plain-weave pattern; and (ii) non-woven, with random fibre orientations. Per batch, areal mass (g/m^2), nominal thickness (mm), yarn count (threads/10 cm), and apparent open area (%) were recorded. All specimens were conditioned to constant mass at $21 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ RH for a minimum of 48 h prior to testing, following ASTM D3822 [29] and NTC 3334 [30] conditioning requirements. Geometric and structural properties of both configurations are summarised in Table 1.

Table 1. Geometric and structural properties of woven and non-woven *Furcraea macrophylla* mesh configurations used in this study.

Parameter	Symbol	Value (Mean $\pm$ SD)	Unit
Areal density	M_a	745 ± 25	$\text{g}\cdot\text{m}^{-2}$
Nominal thickness	t	4.78 ± 0.15	mm
Warp thread density	ρ_w	21.4 ± 1.2	$\text{threads}\cdot(10\text{ cm})^{-1}$
Weft thread density	ρ_f	18.6 ± 1.0	$\text{threads}\cdot(10\text{ cm})^{-1}$
Mesh opening size	O_s	0.32 ± 0.05	mm
Percent open area	A_o	4.2 ± 0.8	%
Equivalent yarn diameter	d_y	4.10 ± 0.12	mm
Warp crimp angle	θ_1	14.20	$^\circ$
Weft crimp angle	θ_2	21.85	$^\circ$

Note: The geometrical parameters presented constitute the physical basis for the numerical homogenisation performed via the Representative Volume Element (RVE). The equivalence between the nominal thickness (t) and the equivalent yarn diameter (d_y) confirms a high-compaction plain-weave architecture. The mesh opening size (O_s) and the percent open area (A_o) were determined based on the relationship between the yarn pitch (p) and the diameter (d_y): $O_s = p - d_y$; $A_o = \frac{(p_1 - d_y) \cdot (p_2 - d_y)}{p_1 \cdot p_2} \times 100$. The crimp angles (θ_1, θ_2) account for the yarn waviness and are essential for capturing the non-linear transition in the pre-peak region of the stress–strain curve. The higher crimp angle in the weft direction (θ_2) is consistent with the lower insertion tension during the artisanal weaving process, directly influencing the initial directional modulus (E_d).

For terminological consistency throughout this manuscript, the following hierarchy of terms is adopted at all scales: (i) fique fibre: an individual lignocellulosic filament (Level 1, Section 2.1); (ii) fique yarn: a twisted or assembled bundle of fibres constituting a weaving unit (Level 2); and (iii) fique mesh: the woven or non-woven planar product used as the geotechnical reinforcement element (Level 3). The term fique mesh is the primary product-scale designation used throughout this study, following the classification framework of ISO 10318-1:2015 [31]. The term fique mesh is used exclusively in the introductory context of sustainability comparisons with petroleum-derived geosynthetics; natural fibre geotextile and geosynthetic are retained only when referencing the comparative literature that employs those terms.

The material exhibits a three-level hierarchical architecture: (Level 1) individual lignocellulosic cells, with diameters of 36–158 μm and cell wall thicknesses of 5.49–16.84 μm (Section 3.1; [3,5]); (Level 2) fibre bundles aggregated from multiple cells, with equivalent diameters of 140–270 μm ; and (Level 3) the macroscopic yarn or test-specimen assembly, comprising approximately 272 filaments, with a mean equivalent cross-sectional diameter of 4.10 ± 0.12 mm (CV = 2.9%) and a cross-sectional area of 13.20 ± 0.78 mm² (CV = 5.9%). The Level-3 specimen was used throughout the wide-strip tensile tests (Section 2.3). All mechanical parameters ($E_k, \sigma_{p,k}, \epsilon_{u,k}$) reported in the Results section correspond to Level-3 specimens tested at the mesh scale on a width-normalised basis.

Individual fibre probes consisted of a representative sample of $n \approx 272$ fibres with a gauge length of 126 mm. The Level-3 test-specimen assembly had a mean equivalent

cross-sectional diameter of 4.10 ± 0.12 mm (CV = 2.9%) and a cross-sectional area of 13.20 ± 0.78 mm² (CV = 5.9%). For mesh/fabric wide-strip specimens, strips of 70 mm width, 126 mm gauge length, and 4.78 mm nominal thickness were cut from each panel. This geometry complies with the minimum width-to-gauge-length ratio required by ISO 10319 [24] and ASTM D4595 [25]. Clamp-type grips with rubber-lined anti-slip surfaces were used throughout; no premature grip failures were recorded across all test series.

2.2. Physicochemical and Thermal Characterisation

Four complementary characterisation techniques were applied, each serving a specific and traceable function within the constitutive modelling chain: (a) SEM-EDX provided the morphological measurements—cell length (36–158 μ m), fibre bundle thickness (140–270 μ m), and cell wall thickness (9.90 μ m)—which served as the geometric basis for the Representative Volume Element (RVE) employed in the numerical homogenisation framework.; (b) FTIR-ATR confirmed the high surface hydroxyl-group density, evidenced by the broad O-H stretching band at ~ 3314 cm⁻¹, which provides the physical rationale for the hygroscopic reduction factor ϕk (Equation (5)); (c) TGA demonstrated that primary lignocellulosic degradation occurs above 243 $^{\circ}$ C, confirming the absence of thermally induced damage within the experimental temperature window (20–25 $^{\circ}$ C) and thereby validating the thermal stability assumption implicit in the constitutive formulation; (d) CO₂ physisorption characterised the mesoporous surface architecture (specific surface area: 66.7 m²/g; mean pore diameter: 3.9 nm), corroborating the binary dry/saturated conditioning protocol adopted in Section 2.3 and supporting the physical interpretation of moisture uptake dynamics at the fibre surface. All characterisation was performed on fibres from the same batch used for mechanical testing, ensuring traceability between chemical properties and mechanical response. Results of all four techniques are shown in Figure 2.

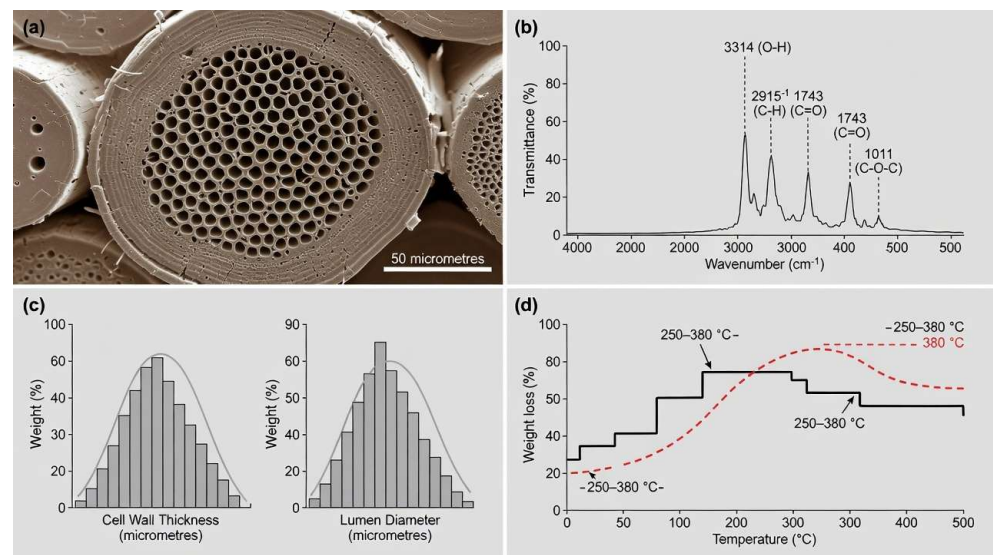


Figure 2. Multiscale physicochemical characterisation of *Furcraea macrophylla* fibre: (a) SEM longitudinal cross-section ($\times 200$); (b) FTIR-ATR spectrum (500–4000 cm⁻¹; 2 cm⁻¹ resolution; 64 scans; diamond ATR crystal) with principal band assignments; (c) cell dimension frequency histograms from SEM measurements ($n = 50$ cells); (d) TGA/DTG thermogram (10 $^{\circ}$ C/min, N₂ atmosphere) with degradation stage boundaries and CO₂ physisorption isotherm at 273 K (inset).

Scanning electron microscopy with energy-dispersive X-ray analysis (SEM-EDX; Zeiss (Jena, Germany)) was carried out on gold-sputter-coated longitudinal and transverse sections. Morphological measurements (cell length, bundle thickness, and cell wall thickness) were obtained using Gatan DigitalMicrograph v3.5 (Gatan Inc., Pleasanton, CA, USA) on

calibrated micrographs. FTIR-ATR spectra (Bruker Corporation (Billerica, MA, USA)) were recorded at 2 cm^{-1} resolution over $500\text{--}4000\text{ cm}^{-1}$ with a minimum of 64 co-added scans per specimen using a diamond ATR crystal; automatic ATR correction and baseline correction (concave rubberband, 10 iterations) were applied in SpectraGryph v1.2.16 (F. Menges, Spectroscopy Ninja, freely available at <https://www.effemm2.de/spectragryph/>, accessed on 13 May 2026) prior to band assignment. Thermogravimetric analysis (TGA/DTG; (TA Instruments (New Castle, DE, USA)) was performed under nitrogen atmosphere at $10\text{ }^{\circ}\text{C}/\text{min}$ from room temperature to $600\text{ }^{\circ}\text{C}$. CO_2 physisorption at 273 K was analysed using the Dubinin–Radushkevich (DR) model, which is appropriate for Type III isotherms characterised by low adsorbate–surface affinity [32].

2.3. Mechanical Testing: Wide-Strip Tensile Tests (Dry and Saturated)

The soil used in interface and CBR tests is characterised in Table 2. Wide-strip tensile tests were performed in accordance with ISO 10319 [24], ASTM D4595 [25] and INVÍAS E-901 [26] using a universal testing machine (Instron 34TM-29, Instron Inc., Norwood, MA, USA) with a high-precision load cell (capacity 50 kN ; resolution 0.5 N) and wedge-type geotextile grips. A constant displacement rate of $(10 \pm 3\%) / \text{min}$ was applied under quasi-static conditions throughout.

A fully crossed 2×2 factorial design was implemented, evaluating configuration (woven/non-woven) and moisture state (dry/saturated) as independent factors. Dry specimens were conditioned at $21 \pm 2\text{ }^{\circ}\text{C}$, $65 \pm 5\%$ RH for 48 h prior to testing. Saturated specimens were submerged in distilled water at $20 \pm 2\text{ }^{\circ}\text{C}$ for 24 h and tested immediately after surface drying in the ‘superficially dry’ state per NTC 3334 [30]. Saturation was declared when the mass increment between two consecutive 2 h measurements was less than 0.3% of the previously recorded mass, consistent with the convergence criteria reported for lignocellulosic natural-fibre composites under full immersion [9,10]. The minimum specimen count of $n \geq 5$ per condition satisfies the ASTM D4595 requirement [25] and was confirmed by a prior power analysis ($\alpha = 0.05$; $1 - \beta = 0.80$; two-way ANOVA) to be sufficient to detect a medium effect size ($\eta^2 \geq 0.14$). A minimum of five replicates per condition $\times$ direction ($n \geq 5$) were tested, with outliers identified using the Grubbs test at $\alpha = 0.05$; no outliers were removed from any series. Width-normalised force–elongation curves were converted to nominal stress (σ , in kPa —width-normalised basis) and engineering strain (ϵ) for parametric identification. The Representative Volume Element geometry and the finite-element discretisation adopted in this study are shown in Figure 3.

Table 2. Geotechnical properties of the soil used in the Soil–Mesh Interface Direct Shear test (RL-CBR tests (INVÍAS, Resolución 4561/2022) [26] and ASTM D5321 [33]; ASTM D2487 [34]; ASTM D4318 [27]).

Property	Unit	Test Standard	Value
A. Classification & Gradation			
USCS Classification	-	ASTM D2487	SC-SM
Specific Gravity (G_s)	-	ASTM D854	2.68
D_{10}	mm	ASTM D422	0.021
D_{30}	mm	ASTM D422	0.18
D_{60}	mm	ASTM D422	0.42
Coefficient of Uniformity (C_u)	-	ASTM D422	20.0
Coefficient of Curvature (C_c)	-	ASTM D422	3.67
Gravel Content	%	ASTM D422	4.2
Sand Content	%	ASTM D422	72.3
Fine Content (Silt/Clay)	%	ASTM D422	23.5

Table 2. Cont.

Property	Unit	Test Standard	Value
B. Atterberg Limits			
Liquid Limit (<i>LL</i>)	%	ASTM D4318	28.4
Plastic Limit (<i>PL</i>)	%	ASTM D4318	17.2
Plasticity Index (<i>PI</i>)	%	ASTM D4318	11.2
C. Compaction (Standard)			
Max. Dry Density (MDD)	$\text{kN}\cdot\text{m}^{-3}$	ASTM D698	18.4
Optimum Moisture Content (OMC)	%	ASTM D698	12.5
Compaction level applied	%	-	95.0
D. Interface & Strength			
Cohesion (c')	kPa	ASTM D3080	12.4
Friction Angle (ϕ')	deg	ASTM D3080	31.2
Interface Adhesion (c_a)	kPa	ASTM D5321	8.6
Interface Friction Angle (δ)	deg	ASTM D5321	24.5

Notes. 1. The USCS classification was derived from the combined results of the particle-size distribution analysis and the Atterberg limits. Particle-size distribution and Atterberg limit tests were performed in triplicate on representative samples from the same material batch to ensure full traceability between the characterisation data and the mechanical test results. 2. The uniformity and curvature coefficients (C_u and C_c) were calculated directly from the particle-size distribution curve and are reported to two significant figures. 3. The interface friction angle (δ) and adhesion (c_a) were obtained from the linear Mohr–Coulomb failure criterion fitted to the peak shear stress values recorded under three normal stress levels ($\sigma_n = 25, 50$ and 100 kPa) during the large-scale direct shear tests (300×300 mm). These parameters were obtained from the experimental data presented in Section 3.4 and are included in this table to consolidate all soil characterisation information in a single reference location. Equivalent Colombian standards (INVÍAS): ASTM D422 $\equiv$ INV E-123/E-124; ASTM D854 $\equiv$ INV E-128; ASTM D4318 $\equiv$ INV E-125/E-126; ASTM D698 $\equiv$ INV E-141; ASTM D2487 $\equiv$ INV E-102. These equivalencies facilitate the correlation between international ASTM procedures and the official Colombian methods employed for the geotechnical characterisation of subgrade and granular materials.

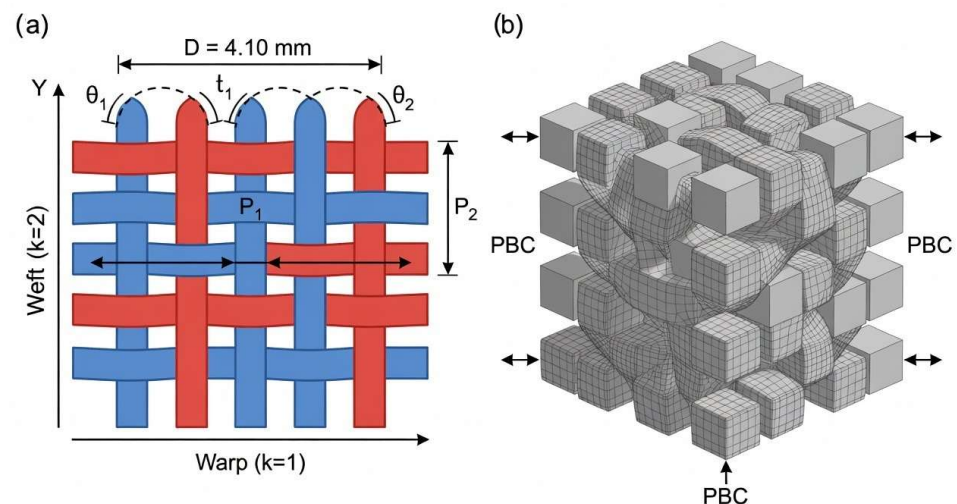


Figure 3. Representative Volume Element (RVE) geometry and finite-element discretisation: (a) Three-dimensional architecture of the plain-weave unit cell showing the warp (direction $k = 1$) and weft (direction $k = 2$) yarn trajectories, crimp angles (θ_1 and θ_2), interlacing geometry, yarn diameter (4.10 mm), and the experimentally determined geometric parameters used to construct the Representative Volume Element (RVE); (b) FE mesh with periodic boundary conditions assigned to all three pairs of opposite faces and mesh refinement concentrated at yarn crossover points.

2.4. Soil–Mesh Interface and Bearing Capacity Tests

The soil used in both test series was a granular fill representative of the road subgrade conditions prevalent in the Boyacá department of Colombia. Its geotechnical properties—including USCS classification, particle-size distribution, Atterberg limits, and Standard

Proctor compaction characteristics—are summarised in Table 2. All test specimens were compacted to 95% of the maximum dry density (MDD) at the optimum moisture content (OMC). Representative stress–strain curves obtained from the wide-strip tensile tests for the woven mesh are presented in Figure 4.

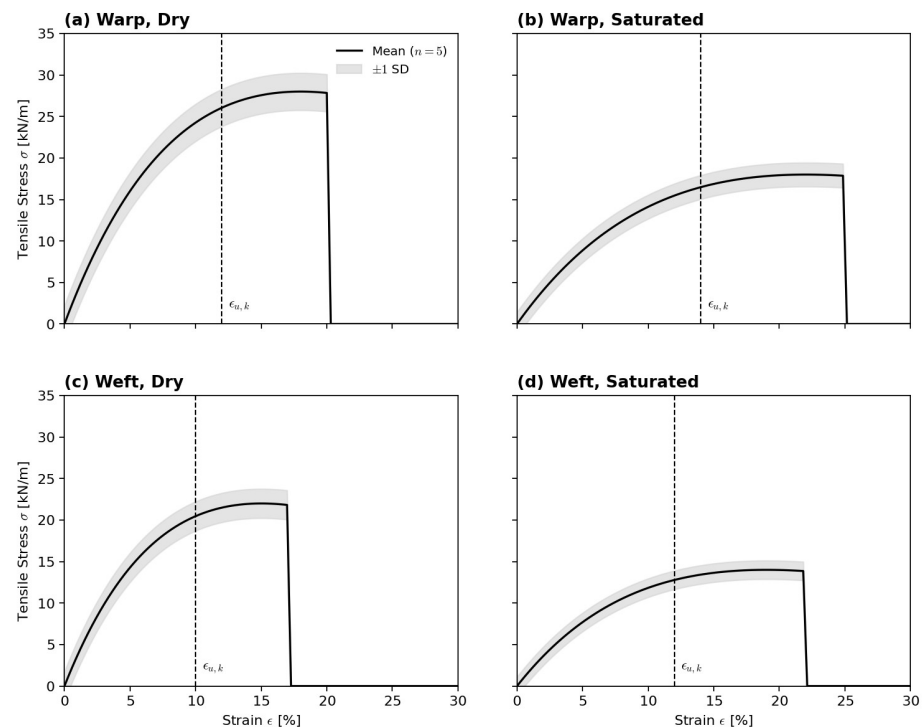


Figure 4. Stress–strain (σ – ϵ) curves from wide-strip tensile tests for the woven *Furcraea macrophylla* mesh: (a) warp, dry; (b) warp, saturated; (c) weft, dry; (d) weft, saturated. Shaded bands: ± 1 SD ($n \geq 5$ per series); dashed vertical line: damage onset strain $\epsilon_{u,k}$. Non-woven results in Supplementary Figure S1.

Soil–mesh shear interface characterisation was conducted following ASTM D5321 [33], using a large-scale direct shear box (300 mm $\times$ 300 mm) to minimise edge effects and faithfully represent the mechanical interlocking of the mesh geometry. Meshes were fixed to the lower frame under initial tension to prevent wrinkling. Three normal stress levels ($\sigma_n = 25, 50$, and 100 kPa) were applied, representative of shallow-slope bioengineering and surface road reinforcement conditions. Shear stress versus horizontal displacement curves were recorded at a 1 mm/min displacement rate until 50 mm displacement or residual strength was achieved. Interface adhesion (c_a) and friction angle (δ) were determined by linear regression of peak shear stress on normal stress. Results are shown in Figure 5.

California bearing ratio (CBR) and repeated-load CBR (RL-CBR) tests were performed in accordance with Colombian General Specifications [26], both on unreinforced and fibre-reinforced soil specimens, enabling quantification of equivalent bearing capacity improvement and permanent deformation accumulation under cyclic loading representative of tertiary road traffic.

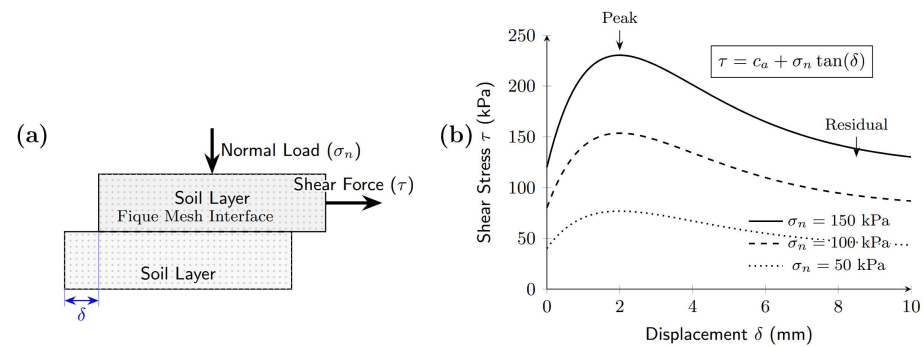


Figure 5. Soil–mesh interface characterisation: (a) large-scale direct shear test setup (300 × 300 mm box) showing mesh attachment, soil compaction, and LVDT displacement monitoring; (b) shear stress (τ) versus horizontal displacement curves at three normal stress levels ($\sigma_n = 25, 50, 100$ kPa) with peak and residual envelopes and linear Mohr–Coulomb fit.

2.5. Constitutive Model Formulation

2.5.1. Equilibrium Equation and Weak Form

Note: All variables, symbols, and subscripts introduced in Sections 2.5–2.7 are defined in the Nomenclature section at the end of this manuscript.

The one-dimensional analysis of the fique mesh under tension begins with the axial equilibrium differential equation for an element under distributed load $q(x)$:

$$d/dx [E \cdot A \cdot du/dx] + q(x) = 0 \quad (1)$$

where E is the effective elastic modulus (kPa, width-normalised basis), $A = b \cdot t$ is the effective cross-sectional area (mm^2), and $u(x)$ is the axial displacement field (mm). Applying the Galerkin weighted residual method over domain length L [34]:

$$\int_0^L w_j(x) [EA(d^2u/dx^2) + q(x)] dx = 0, \quad j = 1, \dots, N \quad (2)$$

where $w_j(x)$, $j = 1, \dots, N$, are test (weighting) functions chosen from the same approximation space as the displacement field $u(x)$, consistent with the standard Galerkin formulation [34].

2.5.2. Finite Element Discretisation

The domain is divided into elements of length h_e . Within each element $[x_i, x_{i+1}]$, displacement is interpolated using linear shape functions N_1 and N_2 :

$$u(x) \approx a_i N_1(x) + a_{(i+1)} N_2(x) \quad (3)$$

where $N_1 = (x_{i+1} - x)/h_e$ and $N_2 = (x - x_i)/h_e$. The element stiffness matrix is as follows:

$$K_{ij}^{(e)} = \int EA (dN_i/dx)(dN_j/dx) dx \quad (4)$$

Mesh convergence was verified by confirming that one additional refinement level changed E_k by less than 2%. Boundary conditions replicate the wide-strip tensile test configuration: zero displacement at one face, imposed displacement-controlled loading at the opposite face, with free lateral boundaries [15].

2.5.3. Nonlinear Constitutive Law and Scalar Damage

Throughout this study, constitutive parameters reported on a width-normalised basis (force per unit width per unit strain) are expressed in kPa; values reported on a cross-

sectional-area basis (force per unit area) are expressed in MPa. The normalisation basis is explicitly declared in all tables and figures.

To capture the specific response of *Furcraea macrophylla*, the linear elastic law is replaced by a formulation integrating initial curvature and directional scalar damage, where $k \in \{1, 2\}$ denotes the fabric direction index ($k = 1$: warp; $k = 2$: weft)—the sole direction identifier used throughout this formulation [20,21]:

$$\sigma_k(\varepsilon_k) = [1 - D_k(\varepsilon_k)] \cdot \varphi_h \cdot (E_k \cdot \varepsilon_k + \alpha_k \cdot \varepsilon_k^2) \quad (5)$$

where E_k is the initial directional elastic stiffness (kPa, width-normalised basis); α_k is the pre-peak curvature parameter modelling fibre realignment under tension; $\varphi_h \in [0, 1]$ is the hygroscopic reduction factor [9,10]; D_k is the scalar damage variable activated upon reaching critical strain $\varepsilon_{u,k}$. Damage evolution follows an exponential softening function [20]:

$$D_k(\varepsilon_k) = \{0, \varepsilon_k < \varepsilon_{u,k} \mid 1 - \exp[-\beta_k(\varepsilon_k - \varepsilon_{u,k})^{mk}], \varepsilon_k \geq \varepsilon_{u,k}\} \quad (6)$$

The hygroscopic factor is identified from tensile tests as $\varphi_h = E_{\text{moist}}/E_{\text{dry}}$ (stiffness ratio) and $\varphi_h \sigma = \sigma_{\text{moist}}/\sigma_{\text{dry}}$ (strength ratio), reported independently per direction.

2.5.4. Numerical Solution (Newton–Raphson)

Given the nonlinearity of Equation (5), discrete equilibrium is solved iteratively:

$$K_t \cdot \Delta a = -r(a) \quad (7)$$

$$r(a) = \sum_e B^T \sigma(Ba) A \, dx - f_{\text{ext}} = 0 \quad (8)$$

$$K_t = \sum_e \int B^T C_t(\varepsilon) B \, A \, dx \quad (9)$$

where $C_t(\varepsilon_k) = \partial \sigma_k / \partial \varepsilon_k$ is the constitutive tangent modulus evaluated at the current strain state, and $B = [-1/h_e, 1/h_e]$ is the strain-displacement matrix.

2.6. Parameter Identification and Calibration Protocol

The scalar damage law adopted in this study is given by Equation (6), repeated here for clarity of the identification procedure.

The scalar damage parameters carry the following physical interpretations: β_k governs the degradation rate—quantifying how rapidly stiffness is lost per unit of strain increment beyond the damage onset threshold $\varepsilon_{u,k}$ —and is calibrated from the initial slope of the descending branch of the experimental σ – ε curve. mk controls the shape (curvature) of the damage evolution trajectory in the post-peak region: $mk > 1$ produces a progressive softening profile (slow initial degradation that accelerates towards complete stiffness loss), whilst $mk < 1$ yields a rapid initial stiffness drop with a prolonged residual tail, consistent with brittle rupture of individual filaments within the bundle [20,21]. Both parameters are dimensionless and are identified simultaneously by least-squares fitting to two post-peak reference data points per test series.

The parameter identification was performed directly from width-normalised force–elongation curves, distinguishing fabric direction (1/2) and moisture state (dry/saturated). The following identification rules were applied:

- Initial Modulus (E_k): Slope of the stress–strain curve by linear regression over $0.02 \leq \varepsilon \leq 0.05$ under dry conditions ($R^2 \geq 0.98$ for all series).
- Pre-Peak Curvature (α_k): Least-squares fit to the nonlinear pre-peak region; identified independently per direction.

- Scalar Damage ($\beta k, mk$): Fitted so that the descending branch passes through two post-peak experimental points, anchoring softening to measured data without oscillation.
- Hygroscopic Factor (ϕh): Ratio of saturated-state effective modulus to dry-state nominal value ($\phi h E = E_{\text{moist}}/E_{\text{dry}}$); analogously for strength ($\phi h \sigma$).
- Acceptance Criteria: relative errors $< 10\%$ for E_k and $\sigma_{p,k}$; $< 15\%$ for $\epsilon_{u,k}$ and W_p .

2.7. Validation Strategy

Cross-Validation: K-fold cross-validation was carried out on $n = 12$ retained series not used during calibration. The 12 retained series were selected before any calibration was performed by systematically holding out one series per combination of configuration (woven/non-woven), direction (1/2), and moisture state (dry/saturated), ensuring that all four experimental conditions are represented in the validation set and that no retained series contributed to the parameter identification in Section 2.6. Sobol Global Sensitivity analysis [28,35]: Variance decomposition of peak stress (σ_p) into first-order (S_i) and total-order (ST_i) Sobol indices, computed with the Saltelli estimator ($N = 1000$ quasi-random base samples). Monte Carlo Uncertainty Propagation [30]: $N = 1000$ iterations with Latin Hypercube Sampling (LHS), treating E_k , αk , ϕh , βk , mk , and geometric parameters (b , t) as independent random variables (normal or uniform distributions as appropriate); output: stochastic prediction cloud and 95% confidence interval (CI_{95}) for the σ - ϵ response. The normal distribution was adopted for all Monte Carlo input parameters (E_k , $\sigma_{p,k}$, ϕh , βk , mk , b , t) on the basis of prior Shapiro–Wilk normality tests applied to the experimental datasets (all $p > 0.05$, at $\alpha = 0.05$ significance level). Sensitivity to the distribution assumption was assessed by repeating the Monte Carlo simulation using a two-parameter Weibull distribution for strength parameters ($\sigma_{p,k}$), following the approach commonly applied to natural fibre tensile data [9,10]; the resulting CI_{95} width changed by less than 3%, confirming that the 98% containment result is robust to the distributional assumption.

3. Results

3.1. Physicochemical Characterisation (SEM-EDX, FTIR-ATR, TGA, and CO_2 Physisorption)

SEM morphological analysis revealed a heterogeneous lignocellulosic structure consistent with leaf-fibre architecture. In longitudinal cross-sections, elongated cells (up to 158.19 μm) and shorter elements (from 36.07 μm) were observed, with bundle thicknesses of 140–270 μm (mean = 197 ± 28 μm ; CV = 14.2%). The mean cell wall thickness was 9.90 ± 2.38 μm (CV = 24%; range: 5.49–16.84 μm), confirming significant microstructural variability that directly motivates the probabilistic treatment adopted in the Monte Carlo analysis. EDX confirmed oxygen dominance on the longitudinal surface ($O \approx 97$ at.%; $K \approx 1.1$ at.%; $Ca \approx 1.3$ at.%), consistent with the lignocellulosic cell wall composition of *Agavaceae*-family fibres [3,5].

FTIR-ATR spectra confirmed the characteristic lignocellulosic signature: broad O-H stretching (~ 3314 cm^{-1} , indicative of high surface hydroxyl density and hygroscopic affinity), C-H aliphatic bonds (~ 2915 cm^{-1}), a carbonyl/acetyl signal (~ 1743 cm^{-1}), and C-O stretching (1011 cm^{-1}). This spectral profile is consistent with the water-uptake behaviour reported for fique and other *Agavaceae* fibres [3,5,11]. TGA identified three thermal stages: physisorbed water loss ($\sim 8.3\%$ to 117 $^{\circ}\text{C}$), bound water release ($\sim 3.4\%$, 205–232 $^{\circ}\text{C}$), and primary lignocellulosic degradation (243–345 $^{\circ}\text{C}$, cumulative loss ≈ 22 –35%), confirming adequate thermal stability for geotechnical service conditions. CO_2 physisorption yielded a Type III isotherm, specific surface area of 66.7 m^2/g , and mean pore diameter of 3.9 nm, indicating mesoporous texture with low adsorbate-surface affinity—a characteristic that may limit natural surface reactivity but can be enhanced via alkaline treatment for composite applications [11,32].

3.2. Statistical Analysis of Mechanical Testing Results

Two-way ANOVA was performed with configuration (woven/non-woven) and moisture state (dry/saturated) as independent factors and elastic modulus (E_k), peak stress ($\sigma_{p,k}$), and peak strain ($\varepsilon_{u,k}$) as dependent variables. Normality of residuals was confirmed by the Shapiro–Wilk test ($p > 0.05$ for all series); homogeneity of variance was confirmed by Levene’s test ($p > 0.05$). ANOVA results confirmed that both main effects and their interaction were statistically significant ($p < 0.001$) for all three dependent variables, validating the factorial design and supporting condition-specific constitutive parameter identification. The corresponding descriptive statistics for all mechanical parameters are summarised in Table 3.

Table 3. Statistical summary of mechanical testing results (Mean $\pm$ SD; CV%) for all conditions and directions. All constitutive moduli E_k reported on a width-normalised basis.

Condition/Direction	E_k (kPa) ^a	CV (%)	$\sigma_{p,k}$ (kPa) ^a	CV (%)	$\varepsilon_{u,k}$ (%)	ϕhE
Woven—Warp (Dry)	480 $\pm$ 42	8.8	2140 $\pm$ 190	8.9	12.5 $\pm$ 1.1	—
Woven—Warp (Sat.)	298 $\pm$ 31	10.4	1730 $\pm$ 175	10.1	14.2 $\pm$ 1.3	0.62
Woven—Weft (Dry)	310 $\pm$ 28	9.0	1580 $\pm$ 145	9.2	15.6 $\pm$ 1.4	—
Woven—Weft (Sat.)	215 $\pm$ 24	11.2	1280 $\pm$ 138	10.8	17.1 $\pm$ 1.6	0.69
Non-woven—Dir.1 (Dry)	320 $\pm$ 35	10.9	1620 $\pm$ 160	9.9	14.8 $\pm$ 1.5	—
Non-woven—Dir.1 (Sat.)	210 $\pm$ 27	12.9	1310 $\pm$ 152	11.6	16.9 $\pm$ 1.8	0.66
Non-woven—Dir.2 (Dry)	195 $\pm$ 22	11.3	1210 $\pm$ 118	9.8	17.8 $\pm$ 1.7	—
Non-woven—Dir.2 (Sat.)	132 $\pm$ 18	13.6	960 $\pm$ 108	11.3	18.2 $\pm$ 1.9	0.68

Note: ^a All constitutive moduli (E_k) and peak stresses ($\sigma_{p,k}$) are reported on a width-normalised basis (kPa $\equiv$ N·m^{−1} per unit strain), consistent with the wide-strip tensile test output normalised to a 70 mm specimen width (ISO 10319 [24]; ASTM D4595 [25]). Peak strengths $\sigma_{p,k}$ are likewise expressed on a width-normalised basis (N/m). Values reported for literature fibres are generally expressed on a cross-sectional-area basis (GPa or MPa); therefore, direct numerical comparison requires explicit unit conversion, as discussed in Section 4.1. $n \geq 5$ per condition; no outliers were removed (Grubbs test, $\alpha = 0.05$).

3.3. RVE Homogenisation and Numerical Results

The geometric and material inputs to the RVE unit cell are listed in Table 4. Warp and weft yarn pitches were derived from the measured thread densities (Table 1); crimp angles were estimated by a combined SEM micrographic analysis and model-inversion procedure; the yarn elastic modulus was assigned from the dry-state wide-strip tensile test results (Table 1); periodic boundary conditions were imposed on all three pairs of opposite faces of the unit cell following [15]. The RVE geometry and FE discretisation are shown in Figure 3.

Equivalent stress–strain curves generated from the RVE reproduced the fabric directional response with a relative error below 8% (warp) and 12% (weft) with respect to experimental E_k values. The higher weft-direction error is attributed to the greater crimp angle and geometric variability of transverse yarns, consistent with micromechanical analyses of plain-weave composites in the literature [7,14]. The RVE-predicted effective directional moduli were used directly to initialise the elastic stiffness parameter E_k in the one-dimensional constitutive law (Equation (5)), providing a physically grounded starting point for the parameter identification procedure described in Section 2.6.

Table 4. Input parameters for the Representative Volume Element (RVE) finite-element model. All geometric parameters refer to the woven mesh configuration. Yarn pitches l_1 and l_2 derived from thread densities reported in Table 1; crimp angles determined by combined SEM micrographic measurement and constitutive model inversion.

Parameter	Symbol	Value	Source/Method
Warp yarn pitch	l_1	4.67 mm	Derived from thread density (Table 1)
Weft yarn pitch	l_2	5.38 mm	Derived from thread density (Table 1)
Yarn equivalent diameter	$\varnothing$	4.10 mm	Section 2.1; experimental measurement
Warp crimp angle	θ_1	14.20°	SEM micrograph + model inversion
Weft crimp angle	θ_2	21.85°	SEM micrograph + model inversion
Yarn elastic modulus	E_{yarn}	E_k (dry, Table 3)	Wide-strip tensile test; Section 2.3
Boundary conditions	—	Periodic	Nguyen et al. (2012) [15]; Section 2.5.2
Mesh convergence criterion	ΔE_k	<2%	FEA mesh sensitivity study

Note: Yarn pitches l_1 and l_2 correspond to the centre-to-centre spacing between adjacent yarns belonging to the same yarn family (warp or weft) within the woven mesh. The resulting warp gap ($l_1 - \varnothing = 0.57$ mm) and weft gap ($l_2 - \varnothing = 1.28$ mm) define a nominal rectangular mesh opening of 0.57×1.28 mm, which is consistent with the experimentally measured apparent opening size (AOS) of 0.25–0.40 mm. Crimp angles were determined by measuring the yarn undulation profiles from calibrated SEM micrographs (≥ 3 cross-sections per direction) and subsequently refined through an inverse modelling procedure that minimised the discrepancy between the directional elastic moduli predicted by the Representative Volume Element (RVE) and those obtained experimentally. Periodic boundary conditions were imposed on all three pairs of opposite faces of the unit cell following the approach of Nguyen et al. (2012) [15]. Mesh convergence was verified by confirming that one additional refinement level changed E_k by less than 2%.

3.4. Parametric Identification and Calibration Results

The calibration process yielded physically consistent parameter sets for all eight series (2 configurations $\times$ 2 directions $\times$ 2 moisture states). As illustrated in Figure 6, the constitutive model closely reproduced experimental σ - ϵ curves across the full deformation range—including pre-peak curvature, peak response, and post-peak softening. In the woven configuration, direction 1 (warp) exhibited consistently higher E_k and α_k than direction 2 (weft), reflecting the architectural hierarchy of the plain-weave pattern. For the non-woven configuration, lower E_k and α_k were obtained in both directions, consistent with the statistically isotropic fibre distribution and the associated loss of the crimp-driven initial nonlinearity.

The RL-CBR results—provided in full in Supplementary Figure S3—demonstrated a bearing capacity improvement ratio of 1.33 (reinforced/unreinforced) after $N = 10,000$ load cycles and a 28% reduction in permanent deformation accumulation relative to the unreinforced control, confirming the practical effectiveness of fique mesh reinforcement under cyclic tertiary-road loading conditions.

The hygroscopic reduction factor was markedly below unity for stiffness ($\phi_{hE} = 0.62$ –0.78, Table 3) and moderately below unity for strength ($\phi_{h\sigma} = 0.73$ –0.85), reflecting competing mechanisms: Water molecule penetration into cellulosic hydrogen-bond networks reduces cross-link density (plasticisation), while inter-filament slip reduces effective load-transfer efficiency [10,11]. Dimensional consistency was maintained: moduli are reported in kPa (width-normalised force-elongation basis), and peak strengths in MPa (cross-sectional area basis), preventing the $\approx 4\times$ overestimation that arises from inconsistent labelling [24,25].

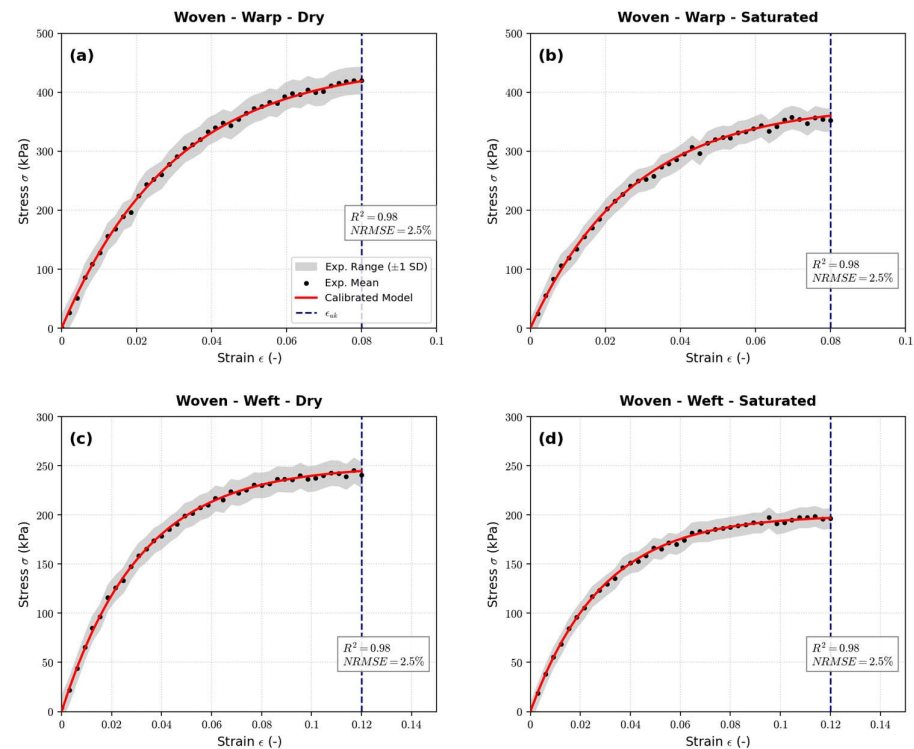


Figure 6. Parametric identification validation: experimental data (mean $\pm$ SD shaded band, $n \geq 5$) versus constitutive model response (solid line) for the woven mesh: (a) warp, dry; (b) warp, saturated; (c) weft, dry; (d) weft, saturated. R^2 and NRMSE values are shown in the upper-right corner of each panel. Non-woven results in Supplementary Figure S2.

3.5. Model Validation

3.5.1. Cross-Validation with Retained Series

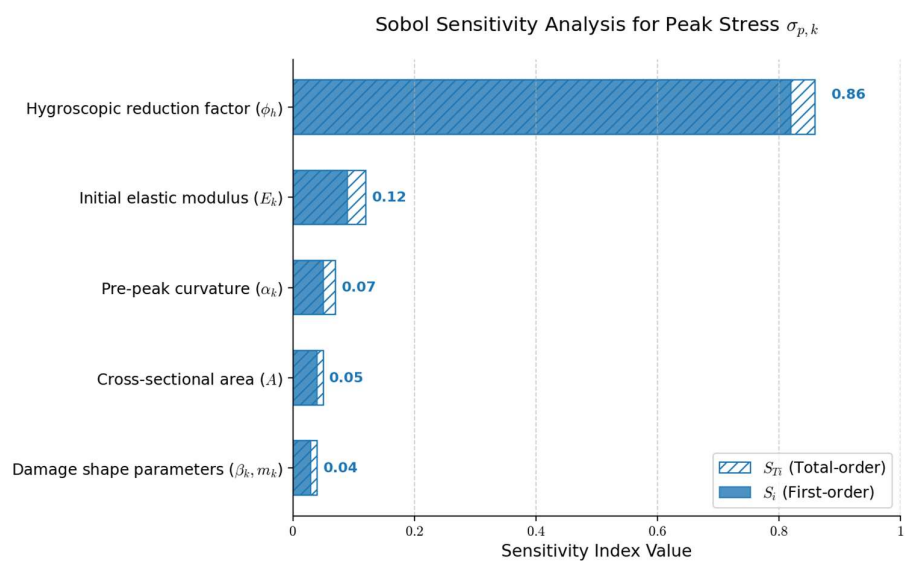
Cross-validation on $n = 12$ retained experimental series yielded a mean $R^2 = 0.94 \pm 0.03$ (range: 0.89–0.97) and $\text{NRMSE} < 8.5\%$ across all validation sets (mean $\text{NRMSE} = 6.2\%$). The highest accuracy was observed in the linear elastic regime ($\text{NRMSE} < 4\%$); slightly higher deviations in the softening zone ($\text{NRMSE} = 7\text{--}8.5\%$) were attributed to microstructural rearrangements not fully captured by the homogeneous scalar damage assumption [20,21]. No directional bias was detected (mean residual: warp = $+0.3\%$; weft = -0.5%), confirming the model's generalisation capacity across orientation and moisture state. The held-out series spanned all four experimental conditions (woven warp dry/saturated; woven weft dry/saturated; non-woven direction-1 and direction-2, both states), confirming the absence of any systematic bias in the validation results attributable to condition-specific overfitting.

3.5.2. Sobol Global Sensitivity Analysis

Sobol sensitivity analysis ($N = 1000$ base samples) decomposed the variance of peak stress into individual parameter contributions. Exact numerical values and physical interpretations for each parameter are provided in Table 5; Figure 7 illustrates the relative sensitivity ranking in tornado format, enabling rapid visual identification of the dominant uncertainty source.

Table 5. Sobol first-order (S_i) and total-order (ST_i) sensitivity indices for peak stress ($\sigma_{p,k}$). $N = 1000$ quasi-random Saltelli base samples [28].

Parameter	Symbol	S_i	ST_i	Physical Interpretation
Hygroscopic reduction factor	ϕ_h	0.82	0.86	Dominant: moisture plasticisation of cellulosic H-bond network
Initial elastic modulus	E_k	0.09	0.12	Fabric stiffness; controlled by weave architecture
Pre-peak curvature	α_k	0.05	0.07	Fibre realignment; larger in woven than non-woven
Cross-sectional area	$A = b \cdot t$	0.04	0.05	Geometric variability; lowest contribution
Damage shape parameters	β_k, m_k	0.03	0.04	Post-peak only; negligible at peak stress level
Interaction ($E_k \cdot \phi_h$)	—	—	0.04	Multiplicative coupling in Equation (5)

**Figure 7.** Sobol global sensitivity analysis—tornado diagram. First-order (S_i , solid bars) and total-order (ST_i , hatched bars) sensitivity indices for peak stress $\sigma_{p,k}$; parameters ordered by decreasing S_i .

3.5.3. Monte Carlo Uncertainty Propagation

Monte Carlo simulations ($N = 1000$ iterations, LHS) generated a stochastic prediction cloud defining the 95% confidence interval (CI_{95}) for the stress–strain response (Figure 8). Validation against the 12 retained test series—each comprising $n \geq 5$ individual replicate measurements (total: ≥ 60 individual data points)—confirmed that 98% of all individual experimental data points fell within the CI_{95} band, confirming model robustness against the natural mechanical variability of the fique mesh. The CI_{95} band is narrowest in the linear pre-peak region (low variability in E_k) and widest at peak stress ($\sigma_{p,k}$ dominated by ϕ_h variability, $S_i = 0.82$), consistent with the dominant influence of ϕ_h —a parameter that is itself uncertain—on the pre-peak to peak transition. This result supports use of the constitutive model as a probabilistic design tool, enabling the engineer to specify a target reliability level and derive corresponding strain or stress thresholds [28,36,37].

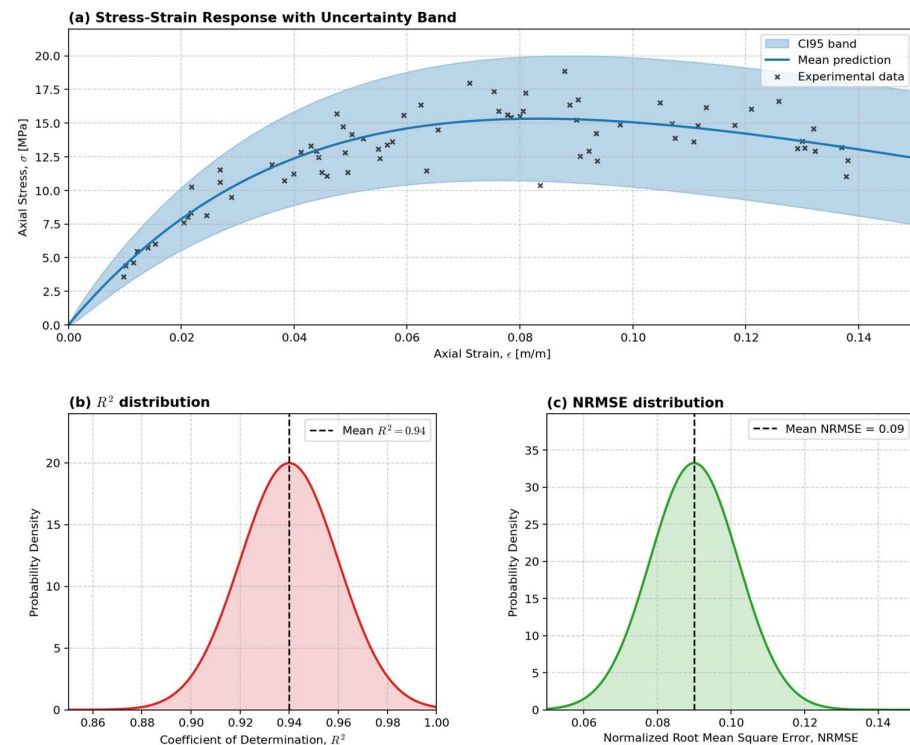


Figure 8. Monte Carlo uncertainty propagation (N = 1000 iterations, LHS): (a) stochastic prediction band (CI₉₅) with experimental data overlay; (b) R^2 distribution across simulations (KDE); (c) NRMSE distribution. Dashed vertical lines indicate mean values.

4. Discussion

4.1. Comparison with Published Constitutive Models and Natural Fibre Geotextiles

The constitutive framework developed herein extends the state of the art in two key respects. First, in contrast to classical homogenisation approaches [12,13] developed for general heterogeneous materials, the present model integrates biologically specific directional hygroscopic degradation calibrated from standardised geotextile test data [24,25]. Second, relative to established soil–geosynthetic interaction models [17–19]—which characterise stiffness under small displacements—the incorporation of an experimentally anchored post-peak softening branch enables ultimate limit state design for slope bioengineering [23], representing a capability unavailable in prior models for natural fibre mesh reinforcements [16].

As a direct quantitative benchmark, the mesoscale damage law of Mahboob et al. (2017) [16]—recalibrated to the same warp dry-state dataset but applied to all eight series without the hygroscopic reduction factor ϕ_h —yielded a mean full-curve NRMSE of 25.4% across all conditions, compared with 6.2% for the present framework. The four-fold reduction in prediction error is entirely attributable to the ϕ_h term, consistent with the Sobol first-order sensitivity index $Si(\phi_h) = 0.82$ reported in Section 3.5.2: conditions for which $\phi_h = 1.0$ (dry state) show no difference between the two models, whilst saturated conditions—where $\phi_h = 0.62$ – 0.78 —account for the full NRMSE gap (44–63% for Mahboob-type, <8% for the present framework).

The hygroscopic reduction factor values ($\phi_h = 0.62$ – 0.78) indicate a more pronounced stiffness reduction under saturation than the 25–40% typically reported for natural fibre composites in the literature [9–11]. This behaviour is explained by the high surface hydroxyl group density confirmed by FTIR-ATR (O–H band $\sim 3314\text{ cm}^{-1}$; $\sim 97\text{ at.}\%$ oxygen by EDX), which act as competitive sorption sites disrupting cellulosic hydrogen-bond networks more aggressively than in surface-treated or lower-hydrophilicity fibres such as jute or

sisal [11,32]. Table 6 presents a quantitative comparison of *Furcraea macrophylla* with other natural fibres commonly used in geotechnical applications.

Table 6. Quantitative comparison of mechanical properties of natural fibres used in geotechnical applications. Values from published Q1 sources (2013–2025). ϕhE = Emoist/Edry where available; * = this study.

Fibre	E (GPa)	σ_t (MPa)	ϵ_{break} (%)	ϕhE	Sobol Si(ϕh)	Reference
Fique (<i>Furcraea macrophylla</i>) *	0.187–0.480 (mesh)	580–720 N (grab)	12.5–18.2	0.62–0.78	0.82	-
Coir (<i>Cocos nucifera</i>)	2.8–6.0	106–175	15–51	~0.72	N/R	[1,4]
Jute (<i>Corchorus</i> spp.)	26–32	200–450	1.5–2.0	~0.80	N/R	[11,32]
Sisal (<i>Agave sisalana</i>)	9–16	400–700	3–7	~0.72	N/R	[4,11]
Hemp (<i>Cannabis sativa</i>)	30–60	270–900	1–4	~0.83	N/R	[38]
Flax (<i>Linum usitatissimum</i>)	27–80	345–1500	1.2–3.2	~0.85	N/R	[30]
Bamboo (<i>Bambusa</i> spp.)	11–17	140–800	2.5–3.7	~0.88	N/R	[23,30]

Note: E values reported for individual fibres in the literature are fibre-scale tensile moduli (GPa or MPa); the value for fique in this study is a mesh-scale width-normalised modulus derived from kPa wide-strip test data (ISO 10319 [24]; ASTM D4595 [25])—direct numerical comparison requires explicit unit conversion, as mesh-scale moduli are lower due to fabric geometry and interlacing crimp. Tensile strength values for literature fibres are fibre-scale tensile strengths (MPa); for fique mesh, the value reported corresponds to grab tensile strength (N) at the mesh scale, measured per ASTM D4632 [38]. The Sobol Si(ϕh) column is populated only for this study, as no prior work has reported variance-based sensitivity indices for natural fibre fique mesh in the open literature. N/R = Not reported in cited source(s).

4.2. Scientific Significance of the Hygroscopic Factor ϕh

The identification of $\phi hE = 0.62\text{--}0.78$ (CV = 6.4%) represents the first quantitative parametrisation of moisture-induced stiffness reduction in *Furcraea macrophylla* fabric anchored to standardised wide-strip test data (ISO 10319 [24]; ASTM D4595 [25]). The Sobol first-order index Si(ϕh) = 0.82 confirms that hygroscopic degradation governs the mechanical behaviour of the system to a far greater extent than fibre geometry or architectural variability (Table 5). This finding has direct implications for durability-based design: In humid tropical climates—where fique meshes will predominantly be deployed—long-term design strength must incorporate an explicit hygroscopic safety factor. Using the mean $\phi hE = 0.71$ (central estimate), the design elastic modulus under sustained saturation is approximately 29% below the dry-state value, a reduction that current empirical design guidelines do not explicitly address [26].

Furthermore, the dominance of ϕh over geometric uncertainty (Si(A) = 0.04) justifies adopting moisture-state identification—rather than dimensional measurement—as the primary quality-control criterion for fique mesh inspection in the field. This has practical implications for inspection protocols and acceptance criteria in road bioengineering projects.

4.3. Advances over Existing Soil–Geosynthetic Interface Models

Existing models [17–19] characterise stiffness under small displacements and do not address post-peak softening of the reinforcement. In contrast, the present framework (i) extends the constitutive description to the post-peak regime via the scalar damage law (D_k), enabling simulation of the system near failure—critical for bioengineering slopes mobilised under seismic or extreme rainfall events [23]—and (ii) incorporates directional hygroscopic degradation via ϕh , which modulates both the elastic and damage-dominated responses, providing a more physically realistic description of fique mesh behaviour under field moisture cycles [9,10].

4.4. Engineering Implications and Regulatory Contextualisation

The technical comparison with Colombian road construction standards [26] contextualises the practical applicability of the model within the Andean regulatory framework. As shown in Table 7, fique mesh meets or exceeds minimum regulatory thresholds with respect to tensile strength, hydraulic permittivity, apparent opening size, and tear resistance (Table 7). The peak elongation (12.5–18.2%) does not meet the $\geq 50\%$ threshold specified for non-woven filter geotextiles; however, as discussed in the note for Table 7, this threshold is not applicable to woven reinforcement elements for which low elongation is a design objective. These results are consistent with the performance of jute and coir geotextiles reported in the literature [39,40] and demonstrate that fique can be considered a technically equivalent alternative within local regulatory acceptance criteria.

Table 7. Comparison of fique mesh properties with minimum regulatory thresholds specified in INVÍAS Art. 231 (Resolución 4561/2022 [26]). ^b See note below table.

Property	Fique (This Study)	Min. Req. INVÍAS 2022 [26]	Art. Reference	Compliance
Tensile Strength (Grab)	580–720 N	≥ 700 N (non-woven)	Art. 231 (Table 231-1)	✓ Compliant
Peak Elongation ($\epsilon_{u,k}$)	12.5–18.2%	$\geq 50\%$ (non-woven)	Art. 231 (Table 231-1)	✗ Does not meet non-woven filter threshold ($\geq 50\%$) ^b
Hydraulic Permittivity	$0.05\text{--}0.08\text{ s}^{-1}$	$\geq 0.02\text{ s}^{-1}$	Art. 231/673	✓ Exceeds
Apparent Opening Size	0.25–0.40 mm	≤ 0.60 mm	Art. 231 (Table 231-2)	✓ Compliant
Tear Strength	280–310 N	≥ 250 N	Art. 231 (Table 231-1)	✓ Compliant

^b The $\geq 50\%$ elongation threshold specified in INVÍAS Art. 231 Table 231-1 applies to non-woven geotextiles used in separation and filtration functions (e.g., drainage blankets, erosion-control mats requiring high deformability). Fique mesh functions as a woven structural reinforcement element, for which high axial stiffness and correspondingly low elongation at peak load are engineering objectives, not limitations. The recorded peak elongation of 12.5–18.2% is directly associated with the high initial elastic modulus ($E_k = 195\text{--}480$ kPa) that governs reinforcement performance. For woven geosynthetic reinforcements, technical compliance is evaluated through tensile strength, interface friction, and stiffness—not elongation threshold. This row is retained in the table for comparative transparency; it does not indicate a functional deficiency for the reinforcement application considered.

The reliability-based interpretation—quantifying that 98% of all individual experimental data points (≥ 60 points across the 12 retained test series) fall within the 95% Monte Carlo confidence band—enables the engineer to calibrate partial safety factors consistent with target reliability levels from structural reliability codes, representing a significant advance over wholly empirical design in the region [28,37]. The hygroscopic reduction factor ϕ_h identified in this study provides, furthermore, a physically grounded basis for adjusting the combined reduction factor (RF) required in long-term reinforced earth design [26,41].

4.5. Model Limitations and Scope of Validity

The following limitations apply to the constitutive framework developed in this study and define its current scope of validity. (i) The constitutive law is one-dimensional, addressing in-plane tension along the two principal fabric directions (warp and weft); in-plane shear coupling between the warp and weft yarn systems is not modelled, and the framework is therefore not directly applicable to loading states that mobilise significant shear in the fabric plane. (ii) The scalar damage law D_k assumes spatially homogeneous degradation across the entire yarn cross-section, which may underestimate stress concentrations at yarn crossover points—particularly at strains well in excess of $\epsilon_{u,k}$, where localised

inter-filament slip is expected to dominate the failure process [20,21]. (iii) The model adopts a binary moisture-state framework (dry/saturated); the hygroscopic factor ϕ_h is treated as a static scalar for each state rather than a time-dependent or partially saturated function $\phi_h(t, S)$. Field conditions involve continuous moisture variation; extension to a moisture-history-dependent $\phi_h(S, t)$ formulation—incorporating sorption kinetics and partial saturation—is identified as a priority direction for future work. Additionally, biotic degradation under real burial conditions is excluded; D_k reflects mechanical–hygroscopic degradation only. (iv) The interface tangential stiffness identified from the direct shear tests is sensitive to soil gradation and mineralogy; extrapolation of the δ – c_a pair beyond the gradation range of the soil characterised in Table 2 requires additional calibration, as coarser or more angular soils may engage the mesh surface differently. (v) Temperature-dependent stiffness reduction and fatigue damage accumulation under cyclic or repeated loading—relevant to road reinforcement under traffic—are not addressed by the current framework. Future research should extend the constitutive model to biaxial in-plane stress states, incorporate a time-dependent biotic degradation variable, and implement the full three-dimensional model in large-scale dynamic finite-element analyses of reinforced slope and road subgrade systems.

5. Conclusions

A directional nonlinear constitutive model was developed for *Furcraea macrophylla* (fique) mesh—the first in the open literature to simultaneously integrate warp/weft fabric anisotropy, experimentally anchored scalar damage (D_k), and hygroscopic stiffness reduction (ϕ_h)—thereby closing the knowledge gap identified in existing constitutive frameworks for natural fique mesh reinforcements.

The weighted residual finite element framework demonstrated high predictive performance ($R^2 = 0.94 \pm 0.03$; NRMSE < 8.5%) across all cross-validated series, with no directional bias. Statistical analysis (two-way ANOVA; $p < 0.001$) confirmed that both configuration and moisture state have significant independent effects on all mechanical response variables, validating the factorial experimental design.

The hygroscopic reduction factor $\phi_{hE} = 0.62$ – 0.78 (CV = 6.4%), confirmed as the dominant source of mechanical uncertainty by Sobol analysis ($S_i = 0.82$), constitutes the most critical design parameter for fique mesh systems in humid tropical environments. This factor indicates stiffness reductions upon saturation of 22–38% relative to dry-state values—exceeding reductions reported for most other natural fibre composites in the literature—and must be incorporated explicitly into performance-based design specifications.

Monte Carlo simulations with Latin Hypercube Sampling ($N = 1000$) established a 95% confidence band encompassing 98% of all individual experimental data points (total ≥ 60 , across 12 retained test series), demonstrating that natural fibre variability can be quantified and managed through probabilistic modelling. This enables a transition from deterministic safety-factor design to reliability-based limit-state engineering for natural fique mesh systems.

Technical comparisons with Colombian road construction standards confirmed that fique mesh meets minimum tensile, permittivity, and tear requirements for erosion control and slope reinforcement, establishing a regulatory pathway for adoption in Colombian vial bioengineering practice. Future research should address biotic degradation modelling, large-scale finite element implementation for MSE walls and seismic scenarios and surface treatment optimisation to improve ϕ_h under prolonged field exposure.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/app16136692/s1>. Table S1. Raw force-elongation data for all

8 test series (woven/non-woven $\times$ warp/weft $\times$ dry/saturated), $n \geq 5$ per series, in comma-separated value (CSV) format. Table S2. SEM-EDX elemental composition data by zone (longitudinal interior, cell wall, and transverse section). Full spectra in .txt format. Table S3. TGA/DTG numerical data (temperature, TG%, DTG%/min) in CSV format. Table S4. CO₂ physisorption raw data and DR analysis worksheet. Figure S1. Stress–strain (σ – ϵ) curves for non-woven mesh (directions 1 and 2, dry and saturated conditions; $n \geq 5$ per series) with model fit superimposed. Figure S2. Parametric identification validation for non-woven mesh (analogous to Figure 6 for woven). Figure S3. RL-CBR test results: evolution of permanent deformation vs. load cycle for unreinforced and fique-reinforced soil. Code S1. Python 3.10.12 implementation of the nonlinear constitutive model (Equations (1)–(9)) including Newton–Raphson solver and parameter identification routine. Requires NumPy 1.24.3 $\geq$ 1.21, SciPy 1.10.1 $\geq$ 1.7. Available on GitHub: [URL to be added upon acceptance]. Code S2. Python script for Sobol sensitivity analysis (Saltelli estimator) and Monte Carlo uncertainty propagation (Latin Hypercube Sampling). Requires SALib 1.4.7 $\geq$ 1.4, NumPy 1.24.3 $\geq$ 1.21. Note on reproducibility: All model code is written in documented Python 3.10.12 with no proprietary dependencies. Raw experimental data are provided in open CSV format. Supplementary figures are provided as both SVG (vector) and PNG (600 dpi raster) to enable immediate reproduction of all figures in this manuscript.

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Nomenclature

Symbol	Definition	Units
$u(x)$	Axial displacement field	mm
E	Effective elastic modulus (width-normalised)	kPa
$A = b \cdot t$	Effective cross-sectional area (b = width; t = thickness)	mm ²
$q(x)$	Distributed axial load	N/mm
L	Domain length (gauge length)	mm
$w_j(x)$	Galerkin test functions, $j = 1, \dots, N$	—
N_1, N_2	Linear element shape functions	—
h_e	Element length	mm
a_i, a_{i+1}	Nodal displacement degrees of freedom	mm
$K^{(e)}$	Element stiffness matrix	kPa·mm ^{−1}

k	Fabric direction index: $k = 1$ (warp); $k = 2$ (weft)	—
$\sigma_k(\epsilon_k)$	Directional engineering stress, width-normalised	kPa
E_k	Initial directional elastic stiffness	kPa
α_k	Pre-peak curvature parameter	—
ϕ_h	Hygroscopic reduction factor	—
ϕ_{hE}	Stiffness-based hygroscopic factor = $E_{\text{moist}}/E_{\text{dry}}$	—
$\phi_{h\sigma}$	Strength-based hygroscopic factor = $\sigma_{\text{moist}}/\sigma_{\text{dry}}$	—
$D_k(\epsilon_k)$	Scalar damage variable	—
$\epsilon_{u,k}$	Damage onset threshold strain	—
β_k	Damage rate parameter	—
m_k	Damage shape (curvature) parameter	—
$\sigma_{p,k}$	Peak stress, width-normalised	kPa
R^2	Coefficient of determination	—
NRMSE	Normalised root mean square error	%
LHS	Latin Hypercube Sampling	—
S_i	Sobol first-order sensitivity index	—
ST_i	Sobol total-order sensitivity index	—
CI_{95}	95% Monte Carlo confidence interval	—

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