

Image-based modelling approaches for the mechanical assessment of natural-fibre coreless filament wound structures

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Abstract

Coreless filament winding (CFW) enables lightweight and customizable composite structures but introduces significant geometric and material variability, especially when using natural fibres and bio-based resins. This variability strongly affects local stiffness and stress distributions, particularly near joints and anchoring regions. This paper presents an image-based workflow for reconstructing finite element beam models directly from photogrammetric scans of loop-shaped flax composite specimens tested in tension. High-resolution meshes are processed to extract centrelines, cross-sectional geometries, and spatially varying mechanical properties. These data are integrated into a parametric FE workflow combining Rhinoceros 3D, Grasshopper, Python and SOFiSTiK. The method was applied to 15 specimens and 1200 reconstructed cross-sections, enabling the evaluation of variability in sectional and stiffness-related properties. Results confirm substantial dispersion in geometric parameters. The study demonstrates the potential of photogrammetry-based reconstruction for the characterisation and numerical idealisation of heterogeneous natural-fibre CFW components, and establishes a basis for future digital twin approaches coupling physical testing and FE calibration.

Keywords: Coreless filament winding; Natural fibre composites; Flax fibres; Image-based characterisation; Photogrammetry; Finite element modelling; Material heterogeneity; Data-driven structural analysis.

1. Introduction

1.1. Research context

Coreless filament winding (CFW) is a robotic fabrication method in which resin-impregnated fibres are deposited along paths between individual anchor points, producing free-form structures without the need for elaborate moulds or formwork. While enabling efficient structural systems, the process induces significant uncertainty in local cross-sections and fibre architecture due to variations in impregnation and fibre interaction during deposition. These uncertainties are further amplified when natural fibres replace conventional synthetic composites, as grown materials introduce an inherent variability. Since neither CFW nor natural fibre are covered by current composite design standards for building construction, experimental characterisation is required to assess stiffness, strength and failure behaviour. These parameters are essential for numerical simulations used in design and structural verification, while experimental scatter informs appropriate safety factors. Developing more geometrically rigorous models and increasing the fidelity of material parameters could ultimately reduce reliance on physical testing, which is both time- and resource-intensive.

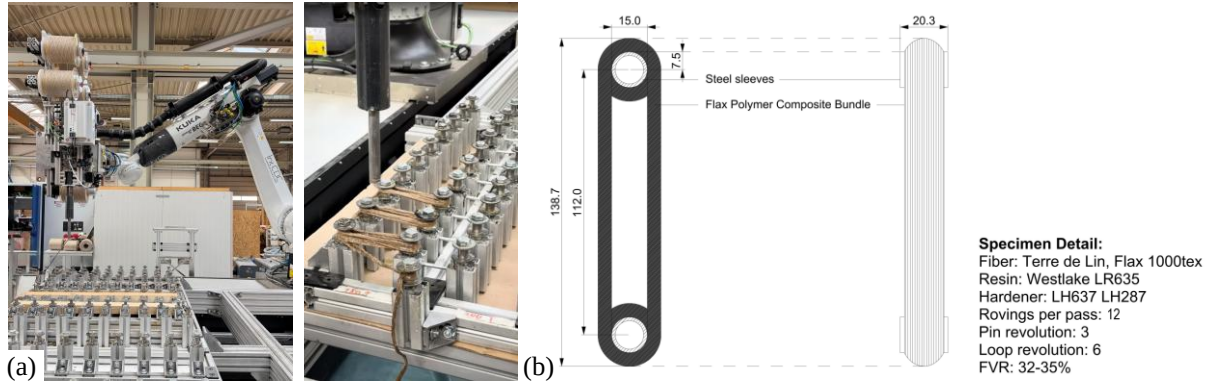


Figure 1: (a) Robotic winding of the specimen: (b) loop design drawing

In this context, the material is tested on a universal testing machine using loop specimens [1]. Here, “material” refers to the composite directly resulting from the CFW fabrication process, as the specimens are produced using the same setup as the actual structural components. The loop-shaped specimens are shown and described in Figure 1. In the present paper, these specimens serve as a proof of concept for an image-based method that reconstructs a finite element model from photogrammetric scans. The FE model can then be used to create a digital twin of the physical tension test.

Applying the method is not only useful as a proof of concept for larger specimens, but also helps analyse the material-testing results themselves for two reasons. First, part of the mechanical dispersion originates from geometric variability. Second, testing a loop does not directly provide the axial stiffness properties of the material itself. Instead, it measures the stiffness of a specific loop geometry, in which factors such as the transverse behaviour at the winding pins, the leg length and the leg spacing all introduce additional biases. For these reasons, the method forms part of a broader engineering workflow described in Figure 2. The present paper focuses on the capture of static specimens and the post-processing of the mesh into cross-sectional properties, exploring its potential for FE applications and future matching with physical test results.

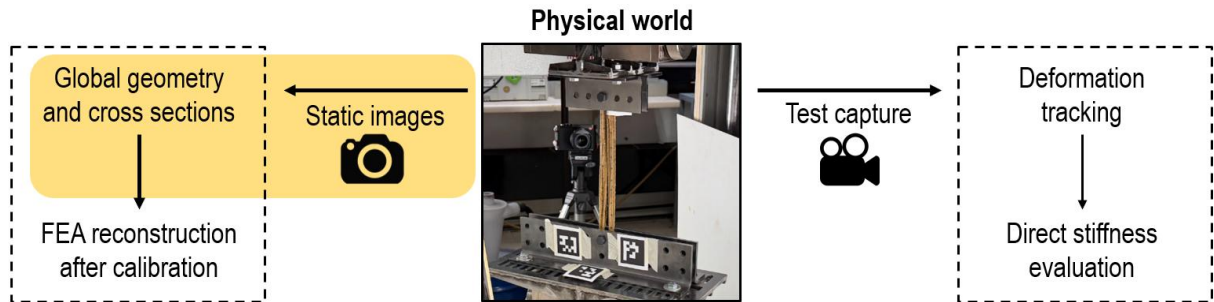


Figure 2: Larger framework of the method (the object of the paper is highlighted in yellow)

1.2. State of the art

The use of photogrammetry to reconstruct geometries for finite element models spans a wide range of disciplines and scales. For example, F. Mancini [2] explores the use of photogrammetry to build geophysical FE models, while B. Zhao [3] uses photogrammetry to calibrate geometrical models of inflatable structures based on membrane equations. This becomes particularly relevant when fabrication defects lead to discrepancies in mechanical properties. For example, K. Woloszyk [4] reconstructs FE models of imperfectly welded steel plates and investigates how fabrication-induced geometric scatter affects local stiffness responses. Similar approaches are also relevant when natural materials are involved: P. Guindos [5] reconstructs FE models of timber beams accounting for knots and local grain orientation to digitally reproduce bending tests. Results show that locally heterogeneous material

properties can improve predictions of large-scale stiffness responses while also identifying failure locations and loads.

In the specific context of CFW, methods based on physical measurement for accessing fibre positions and cross-sections also have precedents. In L. Balangé [6], the fibre production process is monitored through repeated terrestrial laser scanning during fabrication, enabling the geometric characterization of both fibre axes and cross-sections. Two complementary processing strategies are investigated: (i) a segmentation-based approach relying on straight-line fitting between intersections and convex-hull estimation of projected cross-sections, and (ii) a continuous representation using best-fit B-spline curves for both fibre centrelines and cross-sectional boundaries.

In M. Gil Pérez and P. Mindermann [7], the same scanning method is applied to evaluate bundle positions and cross-sections. Laser-scanned cross-sections (a) are compared with process-simulation convex hulls (b), calliper measurements (c), physical cuts (d), and area estimations derived from fibre content and resin quantity, assuming a target fibre volume ratio (e). In the example presented in that study, the (e) method provides the closest area estimate (5% error compared to ground truth (d)), although it does not account for the material's geometric distribution (the shape of the cross-section). Other methods show estimation errors ranging from 35% (c) to 212% (a), with laser scanning being the least accurate due to a mismatch between the resolution of geodesic-based methods and the scale of the fibre bundles under investigation.

So far, the integration of these theoretical and experimental cross-sectional values has been part of the data-management workflows developed within co-design methods for CFW, as described in M. Gil Pérez and C. Zechmeister [8]. Yet, the limitations mentioned above highlight the need for higher-resolution image-based approaches, as the accuracy of existing methods remains insufficient for reliable structural-performance assessment. Photogrammetry therefore appears as a promising alternative for integrating computer-vision approaches into NFRP structural-engineering workflows.

2. Methods

2.1. Image capture

A custom timber capture rig was constructed for the photogrammetric acquisition of the loop-shaped specimens (Figure 3). The setup consisted of a timber base plate with a central mounting point used for suspending the specimens during image acquisition. The specimens were stabilised using fishing line tensioned through a turnbuckle in order to prevent motion during capture and to elevate the geometry from the background, thereby improving visibility and reducing occlusion. A rotating timber arm fitted with a camera mount enabled image capture around the specimen along a circular trajectory.

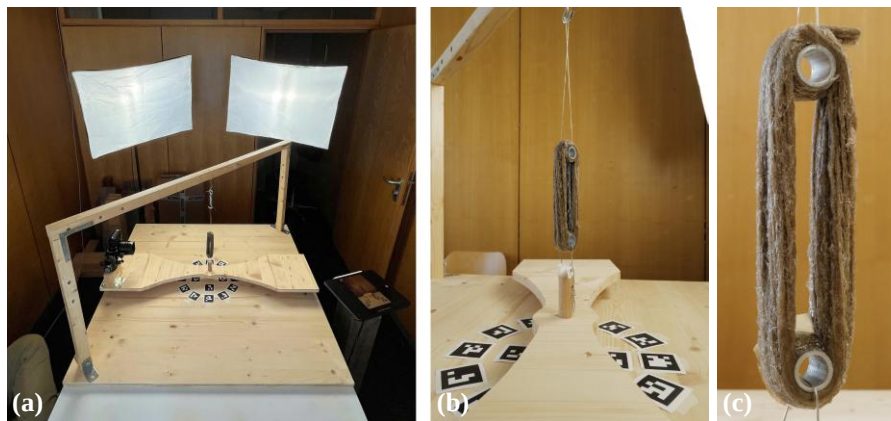


Figure 3: (a) Overview of the image capturing rig setup, (b) suspended test specimen from the view of the camera and (c) cropped view of mounted specimen

Fiducial markers were attached to the base plate surrounding the specimen. These markers served both as high-contrast visual features for structure-from-motion (SfM) reconstruction and as reference features for camera pose estimation during photogrammetric alignment.

Images were captured using a Leica Q2 camera equipped with a 47.3 megapixel full-frame Bayer-array sensor, producing images with a native resolution of 8368×5584 pixels. The camera was fitted with a fixed 28 mm f/1.7 lens and mounted in portrait orientation on the rotating arm, yielding an approximate spatial sampling density of 15.5 px/mm at the specimen plane.

Camera settings were kept fixed throughout acquisition to ensure photometric consistency between images. Constant shutter speed, aperture, ISO sensitivity, white balance, and focal distance were maintained for all captures. Images were recorded in JPEG format.

Lighting was provided by a combination of diffuse daylight and two LED continuous light sources, each equipped with a softbox, positioned opposite the window side of the setup. This arrangement reduced hard shadows while maintaining sufficient surface contrast for feature detection and mesh reconstruction.

Approximately 40 images were captured for each specimen. Images were manually spaced along the capture trajectory to ensure a roughly even angular spacing and sufficient overlap between neighbouring views. Remote shutter actuation was used to minimise camera vibrations during exposure.

2.2. Image processing

Camera alignment and mesh reconstruction were performed in RealityScan [9] using a structure-from-motion and multi-view stereo reconstruction pipeline (Figure 4). Camera poses were estimated automatically from the captured image sets without explicit fiducial marker detection.

The intrinsic camera parameters were constrained to remain shared across all images within each capture session. Initial intrinsic estimates were derived from the camera metadata and subsequently refined during bundle adjustment using the software's approximate calibration mode.

Dense mesh reconstruction was performed using the software's "Normal quality" preset. The selected reconstruction settings provided sufficient geometric fidelity for the subsequent finite element simulations while maintaining manageable mesh complexity. Reconstruction quality was later evaluated through comparison with flatbed scans of specimen cross-sections (Section 3.1).

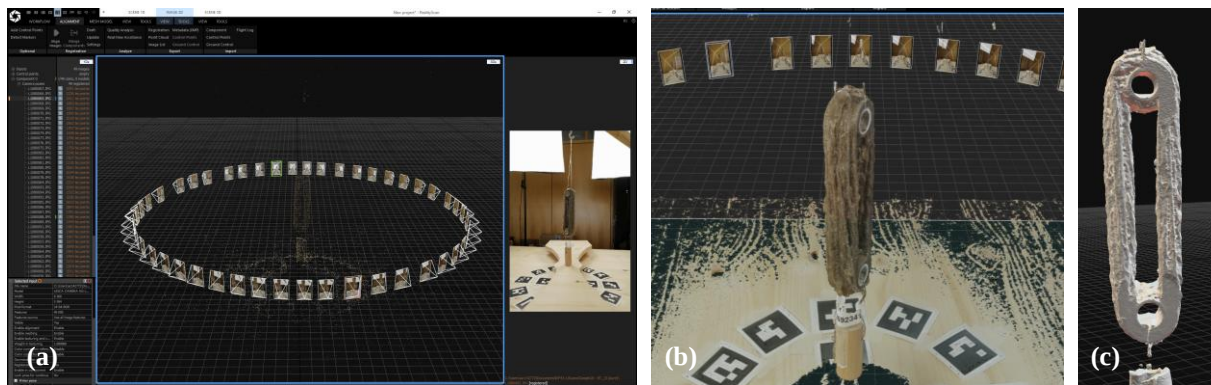


Figure 4: Screenshots of RealityScan (a) pose reconstruction; (b) textured mesh; (c) shaded mesh

2.3. Mesh post-processing

The photogrammetric reconstruction produces a triangulated surface mesh that serves as the geometric basis for the generation of an equivalent beam-type structural model. The post-processing workflow happens in Rhinoceros 3D [10] and focuses on extracting robust centreline and cross-sectional information directly from the scanned geometry, while remaining sufficiently generic to accommodate

different specimen topologies. Although the methodology is illustrated here on loop specimens, the same principles can be extended to more complex geometries.

The workflow begins with a preparation stage in which the raw mesh is isolated, scaled, and simplified. Sleeve regions, corresponding to the metallic anchoring sleeves used during fabrication and testing, are automatically identified through colour-based vertex filtering and used as geometric references to calibrate the specimen dimensions and define the global loading axis. Once the mesh is properly aligned and cleaned, the sleeve volumes are removed to retain only the composite geometry that is relevant for the subsequent analysis (Figure 5 (a)).

The neutral axis extraction relies on an iterative sectional approach. Successive cuts orthogonal to the loading direction are used to identify the dominant geometric branches of the specimen and reconstruct preliminary centrelines (Figure 5 (b)). These curves are then refined through repeated local re-sectioning, progressively converging toward stable representations of the specimen's neutral axes (Figure 5 (c)). This iterative strategy incorporates robustness against local geometric noise and irregularities inherent to photogrammetric meshes.

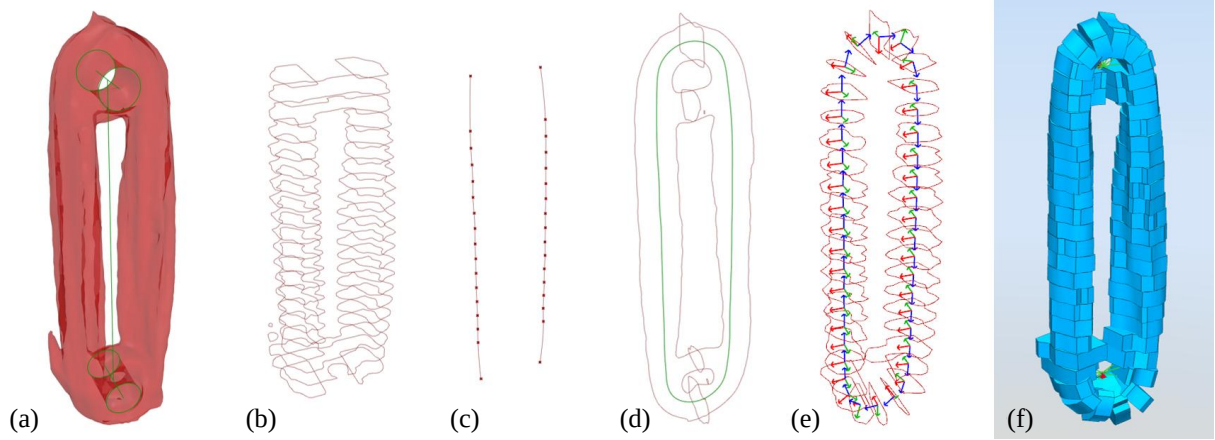


Figure 5: Steps in the workflow (a) clean remeshed specimen with sleeves outlines and main axis; (b) first iteration of cuts along the main axis; (c) intermediate interpolation between centre points; (d) complete and smoothed neutral axis and long section cuts; (e) final cross sections with local axis; (f) FE software screenshot

A global reconstruction step is subsequently performed to recover the continuous geometry around the sleeve regions and ensure smooth connectivity between branches. Reference planes derived from the extracted centrelines are used to generate larger sectional cuts, from which the complete specimen trajectory can be reconstructed and regularised into a continuous global centreline suitable for structural idealisation (Figure 5 (d)).

Finally, the continuous centreline is discretised into beam elements through a series of local cross-sectional extractions performed normal to the reconstructed axis (by definition, cross-sections are perpendicular to the neutral axis). The extracted contours are simplified and reoriented in their plane within a consistent local reference frame (Figure 5 (e)), enabling the direct generation of beam sections compatible with finite element implementations in the FE software (Figure 5 (f)).

2.4. Structural modelling workflow

Based on the local coordinates of points defining the cross-section polylines, a commercial FE software computes the mechanical properties listed in Table 1. Additionally, based on the reconstructed geometry, mechanical properties can then be assigned to each cross-section individually. Indeed, each cross-section i can be assigned a specific set of material properties values (E_i, G_i) corresponding to the Young's modulus and the shear modulus.

Table 1: Cross-section parameters that are computed in the FE software

Parameter	Unit	Description
A	m ² or mm ²	Cross-sectional area
A_{yy}, A_{zz}	m ² or mm ²	Effective shear area for force in Y and Z direction
A_{yz}	m ² or mm ²	Coupling shear area
I_{yy}, I_{zz}	m ⁴ or mm ⁴	Second moment of area about centroidal Y and Z axes
I_{yz}	m ⁴ or mm ⁴	Product of inertia about centroidal axes
I_t	m ⁴ or mm ⁴	Saint-Venant torsion constant

According to the Rule of Mixtures [11] and if FVR is the fibre volume ratio:

$$E_i = FVR_i * E_{fibre} + (1 - FVR_i) * E_{resin} \quad (1)$$

Local FVR can be deduced geometrically from the known quantity of fibres defined during specimen fabrication. The following example is given for a 1000 tex roving (1000 g/km):

$$m_{1\text{ kg}} = \rho_{flax} * L_{1\text{ km}} * A_{1\text{ roving}} \quad (2)$$

$$FVR_i = \frac{N_{loops} * N_{rovings} * A_{1\text{ roving}}}{A_i} \quad (3)$$

Where N_{loops} is the number of loops that are wound for the specimen and $N_{rovings}$ the number of rovings that are wound simultaneously for each loop. To account for manufacturing-induced voids, a void ratio R_{voids} can be introduced. Voids replace only resin, while the fibre content remains unchanged. Consequently, the axial stiffness of a cross-section is affected both by the reduction of the E_{resin} contribution and by a global reduction of effective cross-section. Instead of applying this global reduction to A , this factor is reported on the Young's modulus. Therefore Equation (1) becomes:

$$E'_i = (1 - R_{voids}) * (FVR_i * E_{fibre} + (1 - FVR_i - R_{voids}) * E_{resin}) \quad (4)$$

R_{voids} is not measurable at the cross-section level and is therefore estimated at specimen scale. This is done through a global mass balance using the fibre mass ratio (FMR). Again, since the total length of fibre is known from the manufacturing process, so is the fibre mass. The fibre mass ratio is thus defined as fibre mass divided by the total specimen mass (excluding the two sleeves). In the end, R_{voids} is the result of the following equation:

$$(\rho_{flax} * FMR + \rho_{resin}(1 - FMR - R_{voids})) * V_{mesh} = m_{sample} - 2 * m_{1\text{ sleeve}} \quad (5)$$

And finally, according to literature [12]:

$$G_i = 0,35 * E_i \quad (6)$$

Figure 6 illustrates the data exchange between Grasshopper, the FE software, and a custom Python post-processing script. If appropriate boundary conditions and load cases reproducing the physical test are also defined, the FE model can provide the resulting internal forces (Axial force N , Bending moment about Y and Z axis M_y and M_z , Shear force along Y axis and Z axis V_y and V_z , torsional moment M_t).

Combining those with the cross-sectional properties, the script enables the computation and visualization of local stresses along the specimen. Stresses are evaluated directly at the control points defining the perimeter using generalized Navier–Swain formulation for normal stress, Timoshenko theory and Saint-Venant approximation for shear stresses.

The selected FE software (SOFiSTiK [13]) does not readily support full-field stress evaluation at arbitrary points in non-symmetric sections, which is more flexibly implemented in Python.

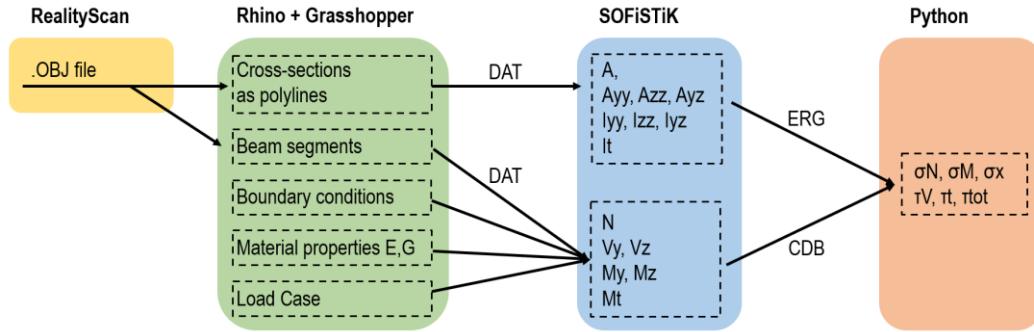


Figure 6: Data exchange between environments

3. Results

3.1. Validation of reconstructed cross-sections

Figure 7 compares digital cross-sectional cuts obtained with the present method to four physical cuts of the specimens. Comparison includes a few biases: flatbed scanning was performed on already tested specimens (which may have slightly altered their original cross-sectional geometry through transverse contraction and residual deformation after testing); manual cutting may result in slight offsets from the intended mid-plane section; spline reconstruction in CAD remains operator-dependent. The new proposed method significantly improves resolution, using typically ~500 control points (CP) per section for the initial mesh produced in RealityScan, compared to ~100 CP for intermediate geometry manipulation in Grasshopper and ~25 CP for the simplified polyline that is sent to the FE software. This dense discretization enables a more faithful reconstruction of the geometry, but the examples show that some large cavities remain hidden to photogrammetry. In the examples, the area estimation error is limited to 6,3%, confirming higher accuracy than previously reported approaches (see Section 1.2). With ~500 vertices over a ~50 mm perimeter (~10 vertices/mm) and a scan resolution of ~15 px/mm, the representation corresponds to ~1.5 pixels per vertex.

Image	Image contour	~ 500 vertices Full-res. mesh	~ 100 vertices Work mesh	~ 20 vertices SOF polyline
	224 mm ²	235 mm ²	234 mm ²	232 mm ² +3,5% error
	173 mm ²	187 mm ²	187 mm ²	184 mm ² +6,3% error
	161 mm ²	163 mm ²	162 mm ²	158 mm ² -1,8% error
	171 mm ²	186 mm ²	185 mm ²	181 mm ² +5,8% error

Figure 7: Digital and physical cross-sectional cuts comparison

3.2. Variability of cross-sectional properties

The method was applied to 15 samples with 80 cross-sections per sample, resulting in a total of 1200 cross-sections for comparison. Table 2 summarizes the main results across all samples. Figure 8 presents the dispersion of A , A_{yy} , A_{zz} , I_t , I_{yy} , I_{zz} across the full dataset. The box edges correspond to the 25–75% percentiles, while the whiskers extend from the 10–90% range. The central line represents the median.

To better distinguish variability occurring within individual samples from variability occurring between samples, two additional statistics were computed in : CVi (“internal variability within each specimen”) and CVcs (“cross-specimen variability”). For the latter, the coefficient of variation is computed only across the 15 specimen-average values rather than the complete set of 1200 values. Results in Table 2 show that variability between specimens is consistently lower. However, because cross-sectional property variations are coupled with neutral-axis variations within the FE model, these values cannot be directly translated into equivalent levels of dispersion in the global structural response. In addition, impregnation quality variations are not captured by the image-based approach.

Table 2: Statistics of key parameters across the whole set

Parameter (unit)	Mean value	Standard deviation	Min	Max	Coefficient of variation	Min CVi	Max CVi	CVcs
A (mm ²)	168,0	24,8	113,5	279,3	14,8%	12,0%	19,4%	4,8%
A_{yy} (mm ²)	136,9	21,2	72,4	232,4	15,5%	12,1%	21,4%	5,2%
A_{zz} (mm ²)	140,2	20,8	93,7	239,5	14,9%	12,2%	19,4%	4,6%
I_t (mm ⁴)	3828	1289	1332	11390	33,7%	26,3%	44,9%	10,4%
I_{yy} (mm ⁴)	3191	1212	736	7352	38,0%	29,2%	40,7%	13,9%
I_{zz} (mm ⁴)	2105	920	554	8154	43,7%	33,7%	52,6%	12,7%
E' (GPa)	6,9	0,7	4,6	9,3	11,2%	9,1%	15,8%	3,4%
$E'A$ (kN)	1155	65	660	1645	5,7%	2,7%	12,1%	2,8%

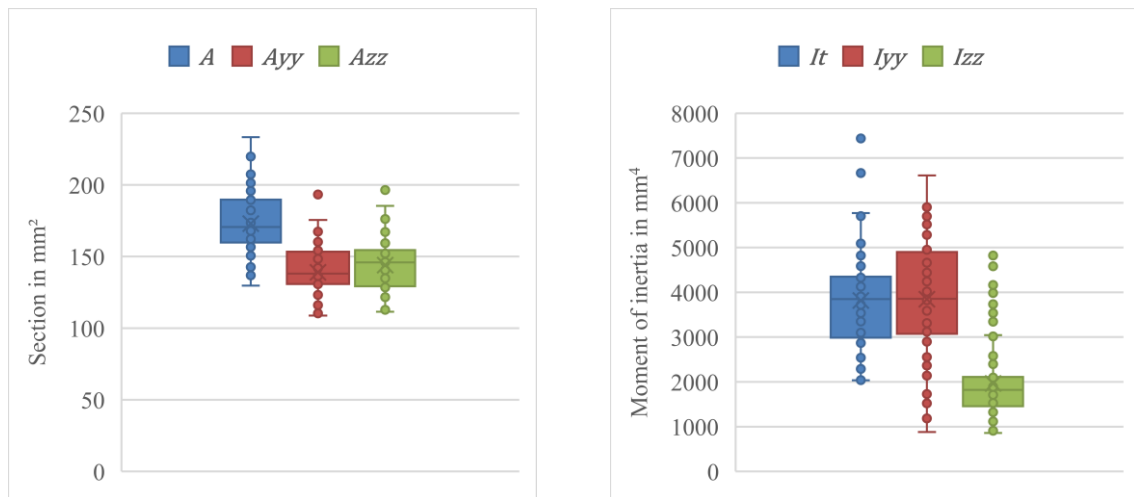


Figure 8: Sections and moments of inertia dispersion of 15 samples x 80 cross-sections

Because the axial stiffness $E'A$ is the primary parameter governing axial deformation, it was included among the evaluated variables. Since E' and A vary in opposite directions with changes in geometry, their product remains more stable (5.7%) than either factor individually (14.8% and 11.2%, respectively).

From a strength perspective, A varies significantly (14.8%) while the fibre quantity remains constant. Under pure axial tension, this means the tensile resistance should not vary to the same extent, even if the average stress on the composite total area changes. In contrast, under compression loading, variations in A would directly affect axial compression resistance, assuming the influence of void-ratio variations (affecting local resin quantity) is distributed homogeneously. Likewise, I_{yy} and I_{zz} would significantly influence buckling resistance. In this context, voids introduce a dual effect: on one hand, they may increase bending stiffness by redistributing material farther from the centroid; on the other hand, they reduce material continuity and thus compromise composite cohesion, which can negatively impact stability and hence failure resistance. If this holds, tensile designs appear less sensitive to manufacturing uncertainties than compression- or stability-driven cases.

4. Discussion and outlook

The present beam-based formulation offers computational efficiency but does not natively capture the transverse composite behaviour at the winding pins. Two alternative modelling strategies could address this: using the photogrammetric mesh directly within a 3D finite element framework, with fibre orientations assigned to each volumetric element, or generating longitudinal mesh cuts to produce a 2D structural model in which each element receives a fibre orientation and a thickness derived from the out-of-plane geometry. However, such high-fidelity 2D or 3D models are computationally expensive and should primarily be regarded as intermediate tools for understanding material behaviour rather than as end-use predictive models. The approach currently being pursued retains beam elements while separately modelling pin-region transverse behaviour through parametric spring elements.

The local stress evaluation framework is implemented but not yet validated against physical test results; once matched, it will enable identification of critical cross-sections and failure-prone locations along the specimen. More broadly, if the reconstructed geometry is assumed correct, material properties become the primary free variable, opening the path to inverse calibration of composite stiffness by iteratively matching FE predictions to experimental load-displacement responses. Finally, the method is intended to scale beyond loop specimens: image acquisition during large-scale structural testing is a natural next step. Furthermore, the static photogrammetric capture could also be enriched with fabrication-time scanning to capture fibre orientations throughout the full cross-section, or with X-ray tomography to reveal internal void distributions — both remaining inaccessible to surface-based methods alone.

5. Conclusion

This work presented an image-based workflow for reconstructing beam-type finite element models from photogrammetric scans of natural-fibre coreless filament wound specimens. The proposed method enables the extraction of spatially varying geometric and sectional properties directly from fabricated components, capturing variability that is typically neglected in simplified descriptions. Application to 15 loop specimens highlighted significant dispersion in local geometric properties, while also showing that global axial stiffness remains comparatively stable. Importantly, the numerical cross-sectional quantities derived from the scan-based reconstruction show good agreement with direct physical measurements of the cross-sections, supporting the fidelity of the imaging and processing pipeline. The study demonstrates that photogrammetry can provide a practical bridge between fabrication, experimental testing, and structural modelling for heterogeneous composite systems. Although the local stress evaluation framework and the application of the method to material stiffness evaluation remain under development, the presented workflow establishes a robust basis for future digital twin approaches integrating FE simulations with physical testing and image-based calibration of material behaviour.

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