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Nonlinear Structural Analysis of Suspended Cables Made of Natural Fibers Used in Traditional Andean Bridges: A Comparison of Numerical Formulations

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Abstract. This study analyzes the nonlinear structural behavior of a suspended cable made of natural vegetal fiber, representative of the main structural components of traditional Andean suspension bridges. The analysis is conducted using the finite element method within the Abaqus/CAE environment, incorporating geometric nonlinearity and mechanical properties characteristic of materials with low axial stiffness. Two types of finite elements are compared: truss elements (pure axial response) and beam elements (flexural-axial response), both subjected to the same geometric configuration and equivalent self-weight loading. The response of the truss element model shows a high degree of agreement with the analytical solution of the inextensible catenary, whereas the beam element model exhibits significant deviations, particularly in the estimation of the maximum midspan deflection and the distribution of internal forces. Additionally, the numerical convergence of the truss model is assessed, identifying an optimal discretization range that ensures computational stability and result accuracy. Finally, the influence of variations in the cable's physical and mechanical properties on its structural response is examined, revealing that the low axial stiffness of natural fibers leads to significant differences in the overall structural behavior. These findings highlight the importance of accurate mechanical characterization of the materials used in traditional structural systems.

Keywords: finite elements, suspended cable, natural fibers, nonlinear analysis, Abaqus/CAE.

1 Introduction

The structural behavior of suspended cables made from natural fibers has been scarcely studied, both through experimental approaches and numerical modeling. Historically, these cables were used in the construction of pedestrian suspension bridges designed to cross large rivers, particularly in the central Andean region of Peru [1]. These structures played a strategic role in connecting the main routes of the Inca road system, known as Qhapaq Ñan [2]. Recent experimental studies on ropes made from *ichu* and *agave* fibers have demonstrated their low strength and axial stiffness, as well as considerable variability in mechanical properties depending on the rope diameter and braiding pattern, in comparison with metallic cables [3][4]. These systems, intended for pedestrian and livestock traffic, may exhibit visible deformations under load. Their structural analysis is relevant from both a functional and a heritage conservation perspective. In this context, the finite element formulation must accurately represent the dominant tensile regime, which poses a methodological challenge regarding the selection of element type and the numerical stability of the model.

Finite element modeling of suspended cables requires an accurate definition of geometry, loading conditions, and, most importantly, the type of structural element employed. This decision directly affects the global response under localized loads, especially in systems with low axial stiffness [5]. One of the main challenges in cable-

supported structures is the geometric distortion produced under external loads [6], which has led to the use of stabilizing components such as decks, hanger configurations, longitudinal beams, or transverse frames.

In systems governed by axial tension, truss elements are generally more suitable due to the predominance of axial forces in suspended cables. However, in some applications, beam or frame elements with reduced flexural stiffness are used to improve numerical stability, particularly under geometrically nonlinear conditions, even if this introduces additional degrees of freedom [7].

This study presents a direct comparison between truss and beam/frame formulations implemented in Abaqus/CAE under identical geometric and loading conditions, applied to a suspended cable made of natural fiber with properties consistent with traditional Andean configurations, based on experimental data reported in the recent literature. The objective is to evaluate the influence of element formulation on the structural response under self-weight, in order to establish suitable modeling criteria for lightweight cable systems with low axial stiffness made from natural materials.

2 Analytical Model: Inextensible Catenary

To provide a theoretical benchmark for comparison, this study adopts the classical inextensible catenary model, widely developed in structural mechanics [8]. This formulation assumes a perfectly flexible, inextensible cable under uniform self-weight, with no bending or shear resistance and constant cross-section along the span.

The equilibrium shape is described by the equation:

$$y(x) = \frac{F_H}{w}\left[\cosh\left(\frac{wx}{F_H}\right) - 1\right] \tag{1}$$

where y(x) is the vertical displacement, F_H the horizontal component of the internal force, w the linear weight, and x the horizontal coordinate. For a known span L and midspan sag f, the horizontal tension F_H is obtained by solving the transcendental equation:

$$f = \frac{F_H}{w}\left[\cosh\left(\frac{wL}{F_H}\right) - 1\right] \tag{2}$$

This expression is solved numerically. Once F_H is known, the total cable length Lc is computed as:

$$Lc = \frac{2F_H}{w}\sinh\left(\frac{wL}{2F_H}\right) \tag{3}$$

and the vertical reaction at each support becomes:

$$F_V = \frac{wLc}{2} \tag{4}$$

This idealized formulation provides a closed-form approximation that serves as a consistent analytical baseline for comparing the structural response obtained from finite element simulations using truss and beam elements.

3 Computational Model

3.1 Finite Element Implementation

A two-dimensional computational model was developed in Abaqus/CAE [9] to simulate the structural behavior of a suspended cable system with geometric and mechanical characteristics representative of vegetal fiber ropes. Two different element formulations were implemented for comparison: truss elements (T2D2), which transmit only axial forces, and beam elements (B21), which incorporate both axial and flexural stiffness through three degrees of freedom per node [10]. Both models were subjected to self-weight and evaluated under different property configurations, with geometric nonlinearity activated via the NLGEOM option. The cable span was pinned at both ends, and identical material properties and cross-sectional areas were used to ensure comparability.

The baseline parameters used in the simulations are summarized in Table 1.

Table 1. Geometric and material parameters used in the finite element model

Parameter	Nomenclature	Value
Span length	L	20.0 m
Initial sag	f_0	2.0 m
Cross-sectional area	A	0.0314 m²
Material density	ρ	300 kg/m³
Elastic modulus	E	100 MPa
Gravity acceleration	g	9.81 m/s²
Number of elements	-	400

These values are representative of structural configurations composed of braided vegetal fibers with low axial stiffness, as reported in prior studies [3],[4], [11].

3.2 Modeling Strategy in Abaqus/CAE

The modeling strategy followed a conventional finite element procedure within Abaqus/CAE, involving geometry definition, assignment of mechanical properties, boundary conditions, nonlinear static analysis, and mesh generation. The process was applied consistently to both truss and beam element formulations, ensuring comparability under identical conditions.

The full modeling sequence is illustrated in Figure 1, summarizing the logical steps from geometry definition to postprocessing.

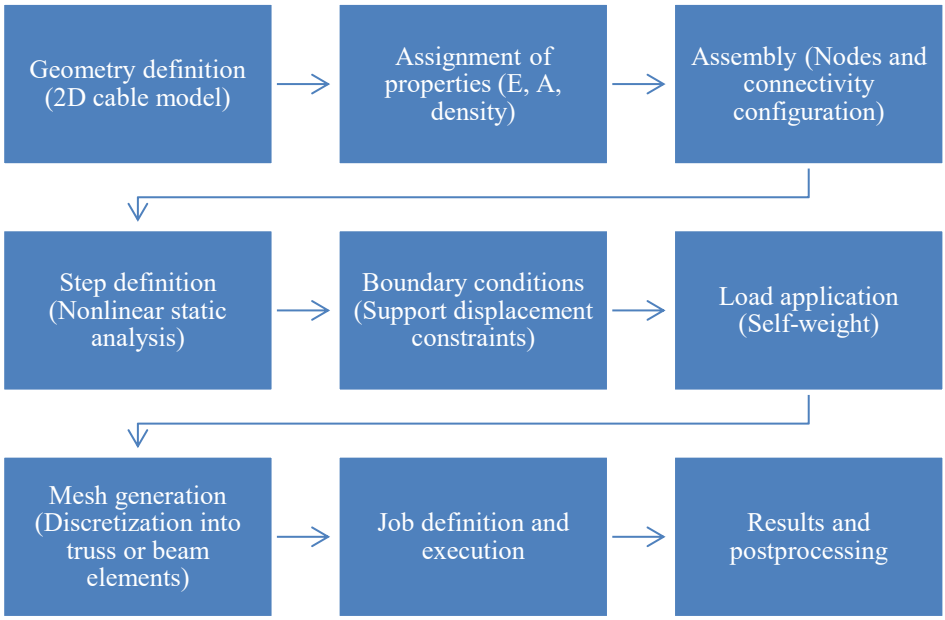


Figure 1. Workflow diagram implemented in Abaqus/CAE for the suspended cable model.

The computational results are presented and discussed in the following section, including both benchmark comparisons with the analytical solution and parametric variations in the cross-sectional area.

4 Results

This section presents the results obtained from finite element simulations. Two element formulations were analyzed, truss (T2D2) and beam (B21), under identical geometric and loading conditions. The results are organized into three stages:

(i) determining the appropriate number of elements through mesh convergence analysis,

(ii) comparing the structural response under self-weight against the analytical solution of the inextensible catenary, and

(iii) evaluating the effect of variations in mechanical properties under self-weight conditions.

All simulations were performed using the reference parameters listed in Table 1. The total cable length used in the numerical models was 20.508 m to reproduce the initial sag.

4.1 Numerical Model Convergence

An initial cable length of 20.508 m was used for all simulations. To assess mesh convergence, the number of elements was progressively increased from 20 to 800, corresponding to element lengths ranging from 1.0254 m to 0.03418 m. For each discretization, the vertical midspan displacement (δz) was obtained for both truss and beam formulations under self-weight.

The results in Table 2 indicate that differences in computed displacements become negligible beyond 400 elements, where the relative variation with respect to the reference solution is less than 1×10^{-4} for both formulations. Figure 2 illustrate the convergence trend for the truss and beam models, respectively. Based on these results, a discretization of 400 elements was adopted for subsequent analyses as it provides a representative balance between accuracy and computational efficiency.

Table 2. Mesh convergence in the finite element model: variation of midspan sag for truss and beam elements

Number of Elements	Element Length (m)	Midspan Sag δz (Truss) (m)	Relative Difference (Truss)	Midspan Sag δz (Beam) (m)	Relative Difference (Beam)
20	1.0254	-2.00237	-0.121%	-2.02752	-0.126%
40	0.5127	-2.00054	-0.030%	-2.02560	-0.032%
80	0.25635	-2.00009	-0.007%	-2.02512	-0.008%
200	0.10254	-1.99996	-0.001%	-2.02499	-0.001%
400	0.05127	-1.99994	0.000%	-2.02497	0.000%
600	0.03418	-1.99994	0.000%	-2.02496	0.000%

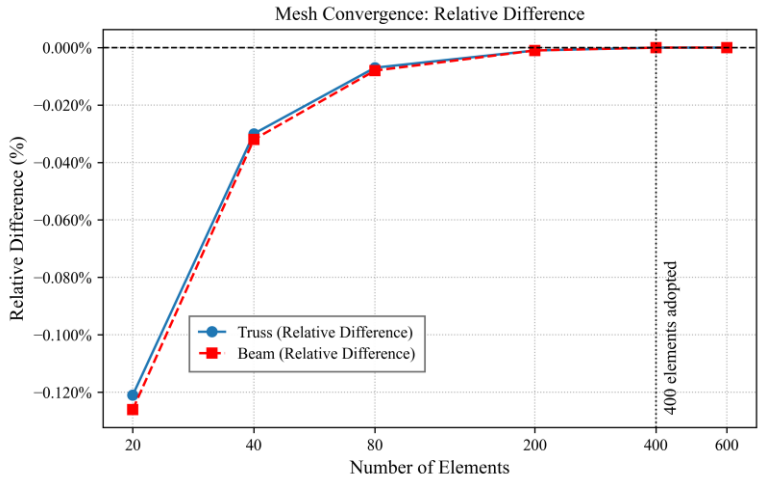


Figure 2. Mesh convergence: relative difference in midspan sag for truss and beam elements.

4.2 Comparison under Self-Weight

Table 3 presents the structural response of the suspended cable under self-weight, comparing the analytical solution based on the inextensible catenary formulation with finite element models using TRUSS and BEAM elements in Abaqus/CAE. Figure 3 illustrates the deflected shape corresponding to the analytical solution. For this loading condition, differences are minimal in vertical reactions and sag, whereas the deviation in horizontal reaction with BEAM elements is attributable to flexural stiffness. Given the scope of this study, only TRUSS elements will be used in the subsequent examples.

Table 3. Comparison of structural response under self-weight: analytical vs. finite element models

Quantity	Analytical	Truss	Difference Truss (%)	Beam	Difference Beam (%)
Vertical reaction F_V [N]	948.301	948.027	-0.03%	948.055	-0.03%
Horizontal reaction F_H [N]	2,340.426	2,339.850	-0.02%	2,149.79	8.15%
sag f [m]	-2.000	-2.000	0.00%	-2.025	1.25%

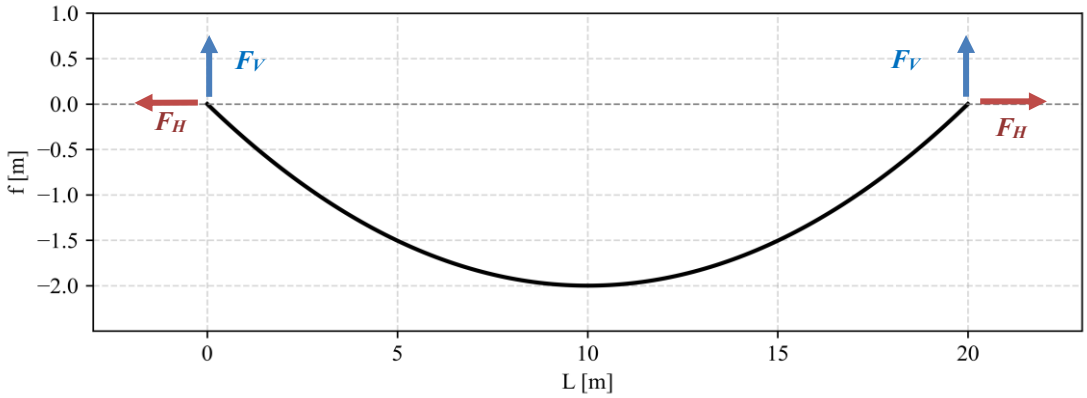


Figure 3. Deflected shape of the cable under self-weight.

4.3 Influence of cross-sectional area on the response to self-weight loads

Following the comparison under self-weight with fixed geometric parameters, this section investigates the influence of cross-sectional area variations on the structural response of the cable. The analysis employs the TRUSS formulation to isolate the effect of changes in axial stiffness, introduced through modifications in the cross-sectional area, on both the initial sag and the subsequent vertical displacement. The total cable length was kept constant in all cases to ensure direct comparability of results. Table 4 shows the corresponding results.

Table 4. Effect of cross-sectional area variation on cable deformation under self-weight loads

Cross-sectional Area	Self-weight sag [m]	Cable deformation [mm]	Δ Deformation [%]
Base Area (A)	-2.000	15.0	-
A+10%	-1.997	14.2	-5.33%
A-10%	-2.003	17.3	15.33%

4.4 Influence of elastic modulus on the response to self-weight loads

In Table 5, the elastic modulus E was varied following the same procedure as in Section 4.3. The deformation pattern matches that obtained for cross-sectional area variation, reflecting the dependence on EA.

Table 5. Effect of elastic modulus variation on cable deformation under self-weight loads

Elastic Modulus	Self-weight sag [m]	Cable deformation [mm]	Δ Deformation [%]
Base elastic modulus (E)	-2.000	15.0	-
E+10%	-1.997	14.2	-5.33%
E-10%	-2.003	17.3	15.33%

4.5 Influence of density on the response to self-weight loads

In Table 6, the density ρ was varied following the same parametric procedure, while keeping the cable length constant. An increase in density resulted in greater sag and vertical deformation, whereas a reduction produced the opposite effect.

Table 6. Effect of density variation on cable deformation under self-weight loads

Density	Self-weight sag [m]	Cable deformation [mm]	Δ Deformation [%]
Base density (ρ)	-2.000	15.0	-
ρ +10%	-2.003	17.3	15.33%
ρ -10%	-1.997	14.2	-5.33%

Figure 4 presents the axial deformation variation obtained from finite element simulations under self-weight for ±10% changes in A, E, and ρ. Reductions in axial stiffness result in a greater increase in maximum sag than the decrease produced by equivalent positive variations, indicating the expected nonlinear behavior of the system.

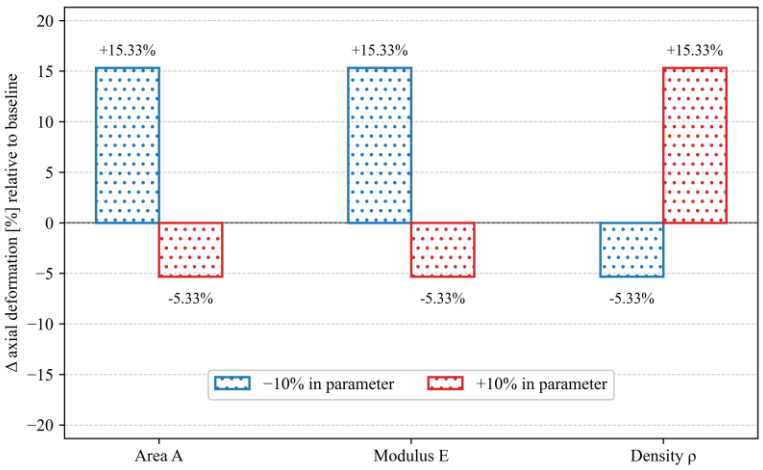


Figure 4. Axial deformation variation under ±10% changes in A, E, and ρ.

5 Conclusions

The analytical solution (inextensible catenary) is consistent with the TRUSS (T2D2) finite element model under self-weight, using the initial parameters listed in Table 1. In the comparison of reactions and sag (Table 3), the TRUSS model reproduces the response with a minimal relative error (0.00–0.03%). In contrast, the BEAM model exhibits discrepancies in the horizontal reaction (approximately 8.15%), attributable to flexural stiffness (EI) and the rotational degrees of freedom inherent to this element type, effects incompatible with the pure axial behavior of a cable.

The TRUSS formulation is physically more suitable for suspended cables, as it directly captures the axial state. The BEAM formulation would only be acceptable with moment releases at the nodes (hinges or releases imposing M=0) or with a significantly reduced moment of inertia (negligible EI). Either approach requires

verification and calibration against the analytical reference solution to avoid flexural contamination of the response.

With constant initial length, variations in effective cross-sectional area (A), elastic modulus (E), and density (ρ) influence the initial sag under self-weight. Tables 4 and 5 show that increasing A or E by 10% reduces deformation by 5.33%, while decreasing them by 10% increases deformation by up to 15.33%, evidencing an inverse relationship with axial stiffness (EA). For ρ (Table 6), the effect is directly proportional: higher density results in greater sag and greater deformation.

Accurate determination of A, E, and ρ is critical to predicting the global response of suspended cables, especially in systems with low axial stiffness and low density, such as Andean bridges constructed from vegetable fiber ropes, in contrast to conventional steel cables.

6 Discussion

The specific literature on natural-fiber cables, such as *Festuca dolichophylla* or agave, used in traditional Andean suspension bridges remains scarce and fragmented. Recent studies have focused on uniaxial tensile tests to determine tensile strength, but their structural application requires modeling methodologies adapted to the mechanical behavior of these materials.

The results obtained here confirm that effective A, E, and ρ have a significant impact on the response of suspended systems with low EA and hygroscopic materials. Unlike steel cables, where the effective load-bearing section has been extensively studied, including considerations of helical geometry, interstitial voids, and non-linear stress–strain behavior, vegetable-fiber braided cables still lack a consolidated methodology for accurately determining their effective load-bearing area.

Therefore, structural analysis must be integrated with material characterization studies that consider, among others, the braiding angle, degree of compaction, internal porosity, fiber-to-fiber adhesion, and moisture variation. Only through this systematic integration (structural model + material characterization) is it possible to reliably predict the behavior of these typologies while ensuring their preservation and guaranteeing structural safety.

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