Mechanical characterization of natural fiber ropes used in the construction of the Q'eswachaka suspension bridge

Adonai E. Banda[1], Elvis M. Vargas[1], Eliot P. Zegarra[1], Zenón J. Del Prado[2], Luis F. Muñoz[3]

[1]*Academic Department of Civil Engineering, Universidad Andina del Cusco, Peru*
Urb. Ingeniería Larapa Grande A-7, Cusco, Peru
adonaies19@gmail.com, emamaniv@gmail.com, eliotpz@hotmail.com
[2]*School of Civil and Environmental Engineering, Federal University of Goiás*
Avenida Universitária, Quadra 86, Lote Área 1488 - Setor Leste Universitário, Goiânia - GO, 74605-220
zenon@ufg.br
[3]*Departamento de Engenharia Civil e Ambiental, Pontifícia Universidade Católica do Rio de Janeiro*
Rua Marquês de São Vicente, 225, Gávea, Rio de Janeiro, Brazil, CEP 22451 -900
lfpm21@gmail.com

Abstract. In this work, the mechanical characterization of natural fiber ropes is studied. For this, *festuca dolichophylla* fibers are used to manufacture ropes used to build a 28 m span historical hanging bridge called Q'eswachaka Bridge. The structure is located in the district of Quehue, department of Cusco, Peru, and is yearly rebuilt with ancient lnka's technology. In order to quantify the material parameters Linear Elastic material models were adopted, twelve simple tensile tests were performed on samples made with diverse diameters, ranging from 30 mm up to 50 mm. The resulting stress-strain curves show that the initial part of these curves fit very close to hyperplastic material and can be applied to future modelling of real structures.

Keywords: mechanical properties, tensile tests, nonlinear materials, *festuca dolichophylla*, historical bridge.

1 Introduction

The Q'eswachaka pedestrian suspension bridge shown in Fig. 1 is located in the district of Quehue, province of Canas, Cusco, Peru. According to Bauer [1], the original construction of the bridge occurred during the Inca empire. Currently, the renovation (reconstruction) of the bridge is carried out annually, following the ancestral Inca traditions and techniques. Four communities neighboring the bridge (Ccollana Quehue, Huinchiri, Chaupibanda, and Choccayhua) participate in the renovation. The hanging structure of the Q'eswachaka bridge has a span of 28 m and consists of four lower main cables called Duros and two upper main cables called Maquis, the Maqui is made of approximately 72 smaller diameter ropes known as Q'eswaska, while the Duro comprises around 108 similar ropes. The diameters of the Duro and Maqui are approximately 15 cm and 10 cm, respectively. The main cables are made entirely of ropes based on vegetable fibers of the Festuca dolichophylla species, locally known as Q'oya.

Over the years, numerous studies have been developed to understand the physical and mechanical behavior of natural fibers used for structural purposes. Vega and Villanueva [2] conducted tests to obtain the tensile strength of individual fibers of Stipa Ichu, Mori et al. [3] and Candiotti et al. [4] conducted tests to obtain mechanical properties of individual fibers of Stipa Obtusa. In addition, some authors have conducted studies to understand the mechanical behavior of ropes based on plant fibers. Nunura et al. [5] analyzed the results of tensile tests on the ropes of a suspension bridge made of Ichu and agave-based ropes with the objective of characterizing the mechanical resistance of the ropes under different conditions (dry ropes and ropes moistened with water). On the other hand, there are some studies to estimate the properties of the Q'eswachaka suspension bridge, such as the work done by Palomo [6] that considered properties of plant fibers from previous studies and by means of mathematical approximations obtained certain mechanical properties. The aforementioned studies have important contributions, however, there are still technical aspects that require a more detailed analysis, especially regarding the mechanical properties of ropes made with *Festuca dolichophylla* used in the construction of the Q'eswachaka bridge. At present, no previous studies have been identified on the mechanical properties of *Festuca dolichophylla* fibers or ropes made from this material.

Figure 1. Panoramic view (left) and cross-sectional view (right) of the Q'eswachaka bridge.

The present investigation focuses on the mechanical characterization of the tensile behavior of the main ropes of the Q'eswachaka bridge. The main objective is to obtain the stress-strain curves of the main chords made with *Festuca dolichophylla*, crucial information to understand their behavior under different loading conditions. For this purpose, tensile tests were carried out using ropes made with the same species of natural fiber used in the bridge. The specimens simulating the Duro and Maqui type ropes are manufactured at a reduced scale of 1:12 of the cross-sectional area. These tests allow the determination of essential parameters such as maximum stress, unit strain and modulus of elasticity of the ropes.

The study of the mechanical properties of the Q'eswachaka bridge chords has both practical and theoretical relevance. From a practical perspective, the results can contribute to the development of better procedures for the conservation and renovation of the bridge, ensuring its longevity and safety. Furthermore, this knowledge can be applied in current engineering, especially in the design of structures that seek to combine sustainability and traditional techniques.

This paper describes the technique used for the manufacture of the ropes, the methodology used in the preparation of the samples and the performance of the tensile tests. Subsequently, the results obtained are analyzed. Finally, conclusions and recommendations for future research and conservation practices are offered. This research, by combining ancestral knowledge with modern techniques of analysis, not only seeks to preserve an invaluable cultural heritage, but also to contribute to the advancement of contemporary engineering.

2 Materials and Methods

2.1 Rope manufacturing

For this research, the elaboration of the ropes was carried out using weaving techniques identical to those used in the annual renovation of the Q'eswachaka bridge. For this, ropes made from the Q'oya plant (Festuca dolichophylla) fiber were used, which is native to the Peruvian Andes and is the main raw material in the construction of the Q'eswachaka bridge (upper left of Fig. 2). The collection of these fibers was carried out in January and February 2024 in Quehue, Canas, Cusco, Peru. Once extracted, the coarser fibers were manually selected. Subsequently, the fibers were stored in a dry environment, extending them to complete the drying process for a period of 5 days on average. Next, the previously prepared Q'oya fibers were soaked in water and gently beaten with a rounded stone to improve their workability. The weaving of the Q'eswa-type ropes (upper right of Fig. 2) was done by twisting two groups of fibers to form a two-strand rope. When the length of the fibers is exhausted, another group of fibers of similar quantity is added and overlapped by twisting to continue weaving. This process is continued until ropes of approximately 20 meters in length were obtained.

The weaving process of the Maqui type ropes (lower left of Fig. 2), consisted of taking three units of the Q'eswa type ropes and twisting them to form a larger rope, then twisting them again together with another rope of the same diameter. This process was carried out by seven people who, together, twisted the ropes clockwise until they formed a single rope of greater diameter called Maqui, consisting of a total of 6 Q'eswaskas.

The weaving process of the Duro type ropes (lower right of Fig. 2), consisted of braiding three groups of ropes, each group being made up of 3 twisted Q'eswaskas, they formed a single rope of greater diameter called Duro, consisting of a total of 9 Q'eswaskas, this technique has been used in various parts of the world since prehistoric times [7].

Figure 2. Q'oya fibers (upper left), Q'eswa type rope (upper right), Maqui type rope (lower left) and Duro type rope (lower right).

2.2 Sample preparation

For each sample, the eye splice is made at both ends as shown on the left of Fig. 3. The eye splice consists of interlacing the ropes as if they were a continuation of themselves, the minimum length of the overlap zone must be equivalent to four times the pitch of the rope [8]. Each specimen has a minimum effective test length L of 2 m, excluding containment zones of at least 3 times the diameter d at each end, the nominal diameter being the largest dimension of the rope cross section [9]. The specimen placed in the tensile machine (Figure 3 right) includes some attachments that compensate for the freedom of rotation that the rope has at the time of testing and the thread sensor that performs the data collection of the elongation [10].

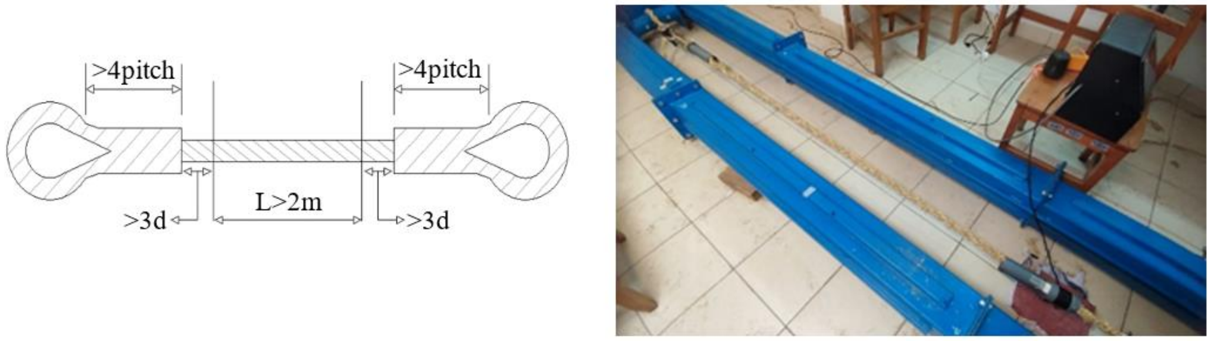

Figure 3. Minimum dimensions of a specimen (left) and tensile testing machine (right).

2.3 Tensile test

The tensile load was applied by displacement control at a speed of 2 mm/s [10]. The elongation was measured with a wire-type displacement sensor, being recorded the force values P(N) and the displacement values d (mm) [10]. The stress-strain curve was plotted from the values of stress $\sigma = P/A$ and strain $\varepsilon = \delta/L$, where A is the nominal area obtained from the nominal diameter δ and L is the initial effective length [10]. For each of the curves a second-degree polynomial fit was performed according to Eq. (1) using the OriginPro program, an average curve was obtained from these curves [11].

$$y = \beta_0 + \beta_1 x + \beta_2 x^2. \tag{1}$$

In Eq. (1) β_i are adjustment coefficients of the polynomial of degree 2.

2.4 Constitutive law of the material

The mechanical behavior of materials is defined mainly by the ratio of the applied stress and the deformation experienced in the material, generally called structural material constitutive ratio, in which the mechanical behavior of the material can be appreciated graphically. For the case under study, two types of behavior will be obtained: for small deformations a linear behavior expressed through an initial tangent modulus of elasticity and an initial secant modulus of elasticity. And for large deformations a non-linear behavior expressed through a non-linear constitutive relation [9].

3 Numerical Results

This section shows the results obtained from tensile tests on ropes made from natural fiber of the Festuca dolichophylla species. Figure 4 shows the results of the stress-strain relationship obtained for the Maqui (left) and Duro (right) type ropes considered as valid. Results are considered valid when the rupture of the rope occurs within the effective length. For the Maqui type ropes, 4 tests are considered as valid results, and for the Duro type ropes, 5 valid results are considered out of the 6 initial samples. In Fig. 4 it can be observed that both Maqui and Duro type ropes present an initial linear zone, followed by a hardening zone and finally a final linear zone until reaching the breakage which occurs in a brittle form. Likewise, it can be observed that the three stress-strain curves are particularly close to each other in the case of the Maquis, the curve of sample 0 being the one that presents the greatest difference from the rest of the curves. In the case of the Duro, there is a homogeneous separation between the results of all the samples.

Figure 5 shows the average stress-strain curves fitted with a second degree polynomial for the Maqui and Duro rope types together with the data of the respective fits. It can be noted that there is an optimally correlated fit for both cases. Figure 5 also shows that the Maqui rope presents an average ultimate tensile strength of 4.31 MPa. This resistance is higher than the average resistance obtained for Duro rope, which registers a value of 2.61 MPa. Also,it can be noted that Maqui ropes have an average maximum unit deformation of 0.144 mm/mm, which is lower than the unit deformation of Duro type rope, which registers 0.187 mm/mm.

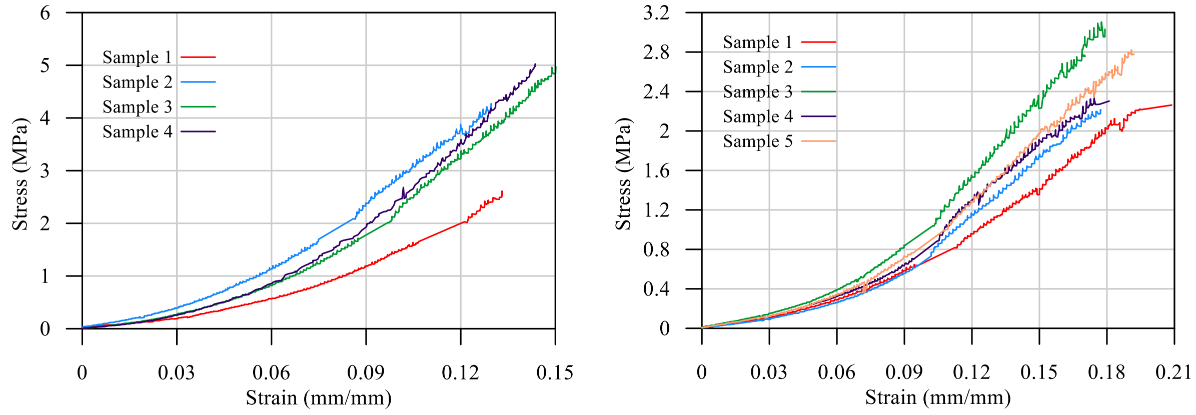

Figure 4. Tensile stress-strain curves of Maqui type (left) and Duro type (right) ropes.

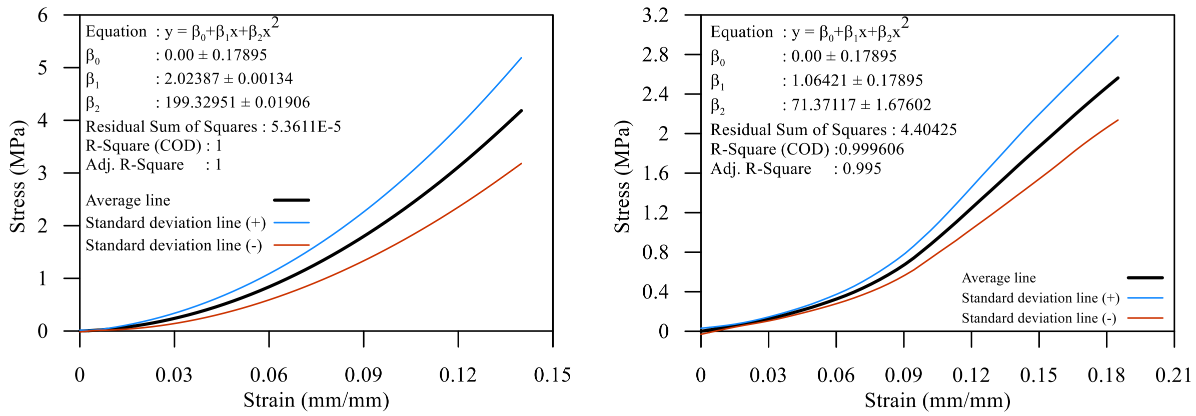

Figure 5. Stress-strain curves fitted with a polynomial approximation of Maqui (left) and Duro (right) ropes.

Figure 6 shows the approximation of the linear modulus of elasticity and the slope of non-linear behavior for the Maqui and Duro rope types. Figure 6 shows that the initial tangent, initial secant and non-linear secant modulus of the Maqui type rope higher than those of the Duro type rope by 64.6 %, 83.05 % and 122 %, respectively. The Maqui type rope is more rigid due to the twisted form it presents, this twist has a smaller angle of deviation in relation to the hard typebraided ropes, which generates a smaller rearrangement of the fibers when tractioned.

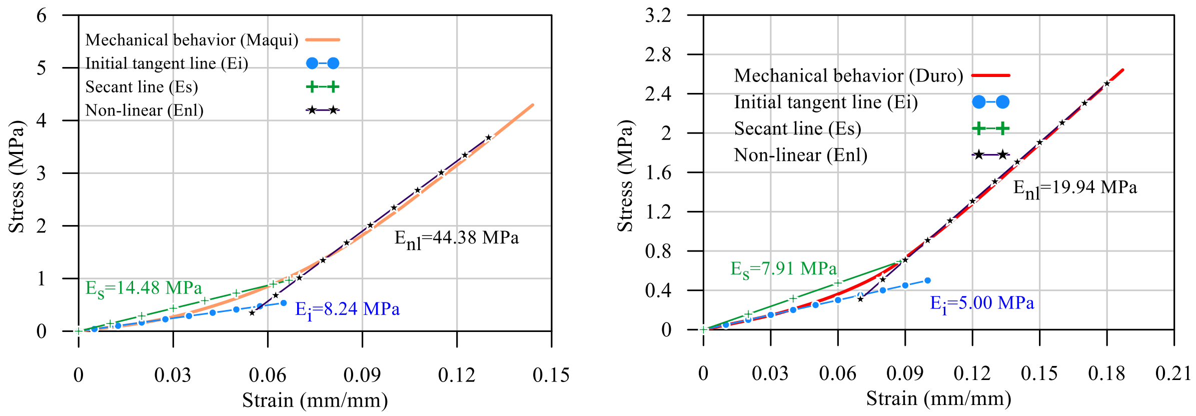

Figure 6. Modulus of elasticity of Maqui (left) and Duro (right) ropes.

4 Conclusions

The present study on the mechanical properties of the Q'eswachaka bridge ropes has provided valuable information on their behavior under tension. The main conclusions are presented below:

The stress-strain curves obtained provided an effective tool to characterize the mechanical properties of the ropes when subjected to tensile stress. A hardening process was evidenced in both Maqui and Duro ropes. Maqui ropes showed a higher tensile strength and higher modulus of elasticity compared to Duro ropes, showing higher stiffness. The origin of this difference is identified in the way the ropes are manufactured, the Maqui type ropes having a lower deflection angle than the Duro type ropes.

The use of normative methodologies to perform the tensile tests ensured that accurate and reproducible data were obtained. This reinforces the validity of the results and their applicability in future research and in the conservation of the bridge. Likewise, the findings can serve as a basis for the development of conservation and maintenance strategies that guarantee the preservation of this Inca cultural heritage, ensuring its functionality and safety in the long term.

It is suggested to continue this study by conducting tensile tests on Maqui and Duro type ropes with different moisture contents, at different diameter scales and with cyclic loading and unloading processes; thus obtaining a numerical model that represents the non-linear behavior of the hanging structure of theQ'eswachaka bridge, and thus obtaining the levels of safety in service and resistance.

This study addresses a significant gap in the existing literature by offering original insights into the mechanical properties of *Festuca dolichophylla* ropes utilized in the Q'eswachaka bridge. The findings have practical implications, as they enable the development of numerical models that predict the bridge's behavior under different conditions. The proposed modeling approach has the potential to reduce the necessity for future experimental studies and to enhance conservation strategies, thereby ensuring the long-term safety and preservation of the bridge.

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