An Engineering Study of the Last Inca Suspension Bridge

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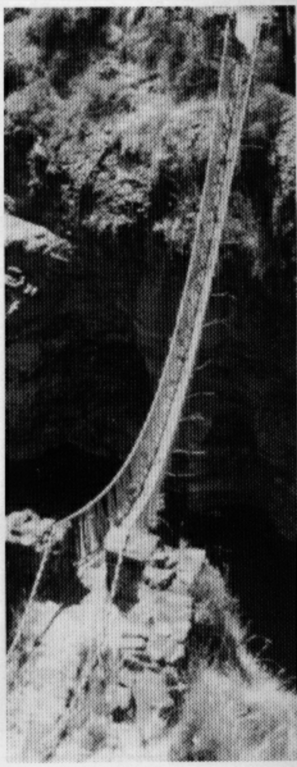
Suspension bridge construction in the Andes Mountains flourished 500 to 1000 years ago, reaching its height under the Inca Empire. The Inca Empire stretched from the Southern tip of South America into modern day Colombia, and relied on a network of roads which totaled over 14,000 miles in length. Building in the Andes, Inca engineers were forced to tunnel through rock and build bridges across some of the world's deepest canyons. When the Spanish arrived in South America in 1532, they marveled at over 200 natural-fiber suspension bridges which were essential to the workings of the Inca Empire. As testimony to their practicality, many of these suspension bridges survived the Spanish conquest, and continued to meet the transportation needs of Peru well into the 19th century.

The most famous Inca bridge—the Apurimac Bridge—was used as a literary device by Thornton Wilder in "The Bridge of San Luis Rey," a popular novel of the 1930's. Although they are much more than a romantic setting for a novel, the suspension bridges of the Andes have never received much attention from engineers or archaeologists. This, despite the fact that in constructing the bridge over the Apurimac River, the Inca had to span a 150-foot wide canyon and tunnel through 200 feet of solid rock in building the approach to the bridge. The Apurimac Bridge was capable of supporting Spanish horses and cannons, as well as people. It survived for 300 years after the Spanish invasion, until it finally collapsed in the 1890's. During its reign, the Inca State controlled the Apurimac Bridge and others like it, charging tolls and performing ongoing maintenance. The State also ordered local villages to build and repair secondary suspension bridges as part of their annual tax to the Inca.

Fortunately, one of these secondary bridges has survived to the present in a remote region of Peru. It is this bridge, at Huinchiri, that became the focus of the author's study.

The Bridge Festival at Huinchiri, Peru

Using only their hands and 18-inch long strands of grass, the villagers of Quehue and Huinchiri construct the Keshwa-chaka ("grass-bridge") which spans the 100-foot wide canyon over the Apurimac River between these villages. Because the typical lifespan for a bridge made of grass is less than two years, this bridge is rebuilt each year during an important festival. In this three-day bridge festival, five hundred people from both villages come together to rebuild the bridge.



The festival begins with all members of the community working together to produce over 50,000 feet of grass cord. This is accomplished by cutting grass from the local mountainside and twisting it by hand into cords approximately 3/8-inch thick. These cords are laid out in bundles of 24 and are then twisted into ropes which are 2 inches in diameter. Finally, three of these 2-inch diameter ropes are braided into a large, 150-foot cable which will become one of the main structural elements of the bridge. By the end of the first day of the festival, six of these cables have been completed.

Braiding the main cable

On Day 2, only adult male members of the community work on constructing the bridge, and the women and children carry on with the activities of the festival. At the start of the day, workers cut the old bridge and let it fall into the canyon. Only the stone abutments remain, to serve as supports for the new bridge. Next, the workers

The main structural system of the bridge.

send the new cables across the canyon using a traveler rope, and in this way they lay out four large cables for the bridge deck and two cables to serve as handrails. For the next eight hours, crews of men pull on the cables, gradually reducing the sag. As the sag is removed, the cables are tied to the stone abutments. The workers continue to tension the cables until the maximum sag is only several feet at the center. This method of construction removes most of the slippage that can occur in braided rope cables, and keeps the sag to a minimum.

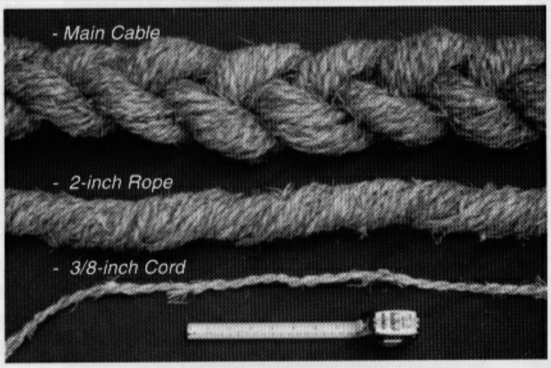
On Day 3, the final details of the bridge construction are performed solely by one person—the *Chakacamayoc* or "Bridge-keeper"—who inherits this role from his father. Moving out across the bridge, he completes the walkway by lashing a wooden floor to the cables, while at the same time tying vertical cords between the walkway and the handrails. When the Bridge-keeper reaches the opposite side, the bridge is complete.

The Link Between Huinchiri and Cornell

In August 1994, a NOVA television production on Inca technology documented the bridge festival at Huinchiri. Mr. Edward Franquemont, a Harvard-trained anthropologist (and an advisor to the author on cultural and archeological aspects) who lives and works in Ithaca, New York, coordinated the filming of the bridge construction for the NOVA documentary. He was able to bring samples of the cable back to Ithaca, and he subsequently contacted Professor M. J. Sansalone in structural engineering at Cornell University. She coordinated funding for an advisee—the author—to pursue the topic as an undergraduate research project.

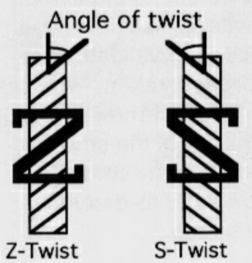
Laboratory Testing

The author conducted the experimental study in the George Winter Laboratory for Experimental Research in Structural Engineering at Cornell University. The goal of the laboratory testing was to understand the strength and stiffness characteristics of the grass cables, and to evaluate their behavior as a structural component in a tension structure. The samples brought back from Peru included one piece each of 3/8-inch diameter cord, 2-inch diameter rope, and the braided cable. Each piece was approximately six feet in length. To gain information about the strength and stiffness of the most basic component of the braided cables, the 2-inch diameter rope was taken apart so that the 24 component cords could be tested individually.



The samples of rope available for testing.

The four main properties which determine the strength of a rope are: 1) the strength of its individual strands; 2) the number of strands; 3) the angle of twist (or helix angle) of each strand; and, 4) the age of the rope. In addition, the direction of twist is a distinguishing characteristic of rope and is identified as either a Z-twist or an S-twist corresponding to the diagonal of each letter. Thus, the first stage of the laboratory testing was to carefully measure and record the important characteristics of each cord.



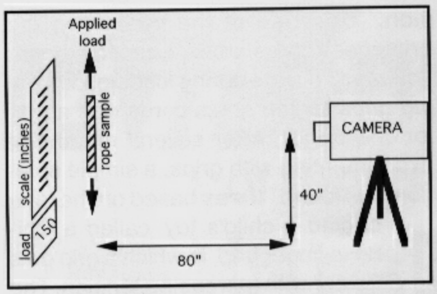
Geometric properties

Because the individual cord samples were produced by many different people, there was a tremendous amount of variation in the characteristics of each cord. The diameter of the cords ranged from 0.2 inches up to 0.5 inches, with an average diameter of 0.3 inches. Similarly, the angle of twist varied from 10 degrees to 40 degrees, with an average angle of 25 degrees. All of the cords were produced with an S-twist. In addition to documenting their physical properties, the author tested all of the cords when each was one-year old. This age was selected to coincide with the age of the bridge just before replacement.

With only a limited number of test samples, a reliable gripping system was needed to test the cords to failure in tension. Because of the variability, the brittleness of the grass, and the elongation which occurs during loading, designing grips for the grass cords was a major challenge. After several months of experimenting with grips, a simple solution was found. It was based on the idea behind a child's toy, called a Chinese finger trap, in which a grip gets tighter with increasing tension. The finger trap idea was applied by wrapping straps (in this case nylon shoelaces) around a cord in a helical pattern. By gradually increasing the helix angle, it was possible to reach 100% coverage at the top of the grip. This method actually strengthened the cord within the grip region and almost guaranteed failure would occur within the region between the grips.

Grass rope grip

The next challenge was to find a way to measure the applied load versus the elongation of the cords during testing. As it was not possible to attach any type of instrumentation or extensometer to the grass, an indirect approach was used. A scale with an accuracy of more than 1/8 inch was placed behind, but not attached to, the test specimen. One of the grips was also attached to a load cell, which measured the applied force. The load cell was connected to a data-acquisition system which displayed the actual force values on a digital screen. Each test was recorded on video. In this way, it was possible to obtain load versus elongation data at all stages during the test.



Schematic diagram of test set-up

When this set-up had been assembled and proof tested, it was possible to begin testing the cords. Each of the twenty four samples taken from the 2-inch diameter rope was loaded to failure.

Results of Cord Testing

As anticipated, the wide variation in properties among the cords resulted in a wide range of breaking strengths. The average cord strength was 115 pounds, with a standard deviation of 20 pounds. The strongest cord broke at 182 pounds, and the weakest cord broke at 37 pounds.

For the grass cord, the average strain at failure was 3.1%, or 3/8-inch elongation for a 12-inch specimen length. By calculating the slope of the stress-strain curve for grass cord, it is possible to determine the modulus of elasticity for the material. A typical stress-strain curve for a cord is characterized by an initially flat slope (low stiffness), when the fibers slip in relation to one another, and subsequently, a region of steeper slope (higher stiffness) as the fibers become rigid and the cord stiffens, enabling it to pick up additional load more quickly. In the region characterized by a higher stiffness, the modulus of elasticity was obtained from the slope of the curve. The stiffness of a typical grass cord is 60,000 pounds per square inch.

Comparing this modulus of elasticity with that of other modern rope materials reveals that the grass cord is actually 20% stiffer than cotton cord, and is equal to 90% of the stiffness of henequen and 60% of the stiffness of nylon.

Laboratory Testing of Main Cable

The knowledge gained from testing the grass cords made it possible to predict the behavior of the large cable. An approximation for the strength of any rope can be made by multiplying the total strength of all strands by the cosine of the angle at which they are twisted or:

- *Rope strength = (# of strands) (strength of each strand) (cos Φ)*

In our case, the strands were twisted approximately 45 degrees two separate times: once to form the 2-inch rope, and once more to braid the large cable. With 72 strands (cords), at an average strength of 115 pounds, our equation becomes:

- *Rope strength = (72 cords) (115 lbs./cord) (cos 45^0) (cos 45^0)*
  Rope strength = 4140 lbs.

To test the large cable, a testing system with a 5000-pound capacity was constructed. This test set-up was similar in principle to the previous set-up, except that the shoelaces were replaced with high-strength polyester straps for gripping the rope.

The behavior of the large cable as it was loaded to failure is as follows. There was a long period when the cable picked up load slowly, due to the initial slippage in the components of the cable. When the applied load reached 3000 pounds, the load-elongation behavior became much stiffer and in a matter of a few seconds the load exceeded 4000 pounds. The failure was sudden, occurring at a load of 4020 pounds. This result compares well to the cable's estimated strength of 4140 pounds. In fact, the actual capacity was within 3% of the predicted capacity. This close prediction of capacity was possible due to the extensive testing which was carried out on the grass cords. This result validates the experimental approach taken, which concentrated on understanding and quantifying the behavior of the smallest component of the cable - the cord. This result could now be used to determine the capacity of the bridge.

Fieldwork in Peru

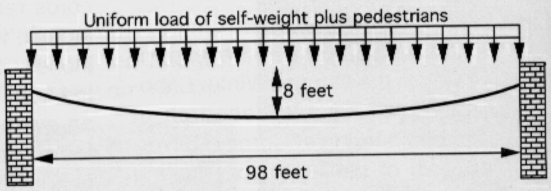
The bridge dimensions were needed before an analysis of the Huinchiri bridge could be performed. In August of 1995, the author visited a total of five Inca suspension bridge sites. Two days were spent at the Huinchiri Bridge site, where measurements were taken of the overall bridge dimensions, including the stone abutments. The clear span was found to be 98 feet and the maximum sag at the center was found to be 8 feet. These were the two most important measurements for the purpose of performing structural analysis of the bridge.

As mentioned earlier, the strength of grass ropes is a function of age, with strength decreasing over time. In addition, creep occurs, and the sag of the bridge increases. Thus it was important to know the sag of the bridge, when the bridge was at the same age as the age of the laboratory test samples. This way the strength of the cables and the geometry of the bridge correlated in time, and an accurate analysis could be performed.

Structural Analysis

All of the loading on the bridge, including self-weight, is carried by the four main floor cables. Although there are two handrails connected to the floor by vertical cords, they serve only as a safety device and are not used to suspend the walkway. Thus, the structure is fundamentally different from the modern suspension bridge form, where the deck is suspended from the main cables.

In the equilibrium analysis, the bridge was modeled as a cable under a uniform load. Based on the measured dimensions of the span and sag, a parabolic shape was assumed and the length of the bridge deck was calculated to be 100 feet. Knowing these dimensions and the strength of a single cable, it was possible to calculate the maximum uniform load that could be supported by each cable. From static equilibrium, a uniform load of 25 pounds per linear foot caused a maximum tension force in each cable (at the location of the supports) of 4100 pounds. This load is equal to the self-weight of the cable and the decking, plus the load of 14 people (each weighing 150 pounds) spread along the length of the cable. Therefore, with four cables, the ultimate capacity of the bridge, at one year of age, is four times this amount, or 56 people.



Inca Bridge modeled as a single cable under uniform load

The capacity of the Huinchiri bridge is well above the normal loads imposed upon it. Rarely does the bridge need to support more than one or two people at any one time. In fact, this Inca bridge has survived for cultural reasons alone, because less than 500 yards upstream a modern steel truss bridge, built in 1967, serves all of the local transportation needs.

Modern Uses of the Inca Suspension Bridge Form

Whatever happens to the Huinchiri bridge, the Inca suspension bridge form will remain alive into the 21st century, in the shape of stressed ribbon pedestrian bridges. This European bridge design is based on the Inca principles, but is built using modern materials. In the Autumn of 1992, Concrete Quarterly described stress ribbon design as "innovative" and "exemplified by slender beauty."[2] The first stress ribbon design pedestrian bridge that was built in the United States, in 1990 in Redding, CA is easily identified as a modern version of the Inca suspension bridge form.

The key features of both bridge designs are:

- *1) Cables that are anchored on either end of the bridge and are tensioned to reduce the sag at the center.*
- *2) A bridge deck that rests directly on top of the cables so the cables themselves function as the bridge deck.*
- *3) Railings which are not load-carrying, but are merely meant to form a net to protect the users of the bridge.*

Although the principle behind the stress ribbon design is considered to be "innovative," a person who has studied Inca bridge technology realizes that it is merely a modern version of a bridge form created by the Inca over 500 years ago. One wonders how many other engineering ideas and designs remain to be rediscovered in the works of the Inca and other pre-industrial civilizations.

The author hopes to pursue his rediscovery of the works of ancient "engineers" in his graduate studies in structural engineering and in his future career as an engineer.

John Ochsendorf is a Senior at Cornell University. In the College of Engineering's College Program, he is pursuing a Major in Structural Engineering and a Minor in Archaeology. He will pursue graduate studies in structural engineering at Princeton University beginning in the fall of 1996.

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Stress ribbon design in Redding, California (413-foot span) [2]

References

1) Franquemont, E.M., The Inca Bridge at Huinchiri. Presented at the 35th Annual Meeting of the Institute of Andean Studies, Berkeley, CA, January 1995.

2) Redfield, Charles and Strasky, Jiri, "Sacramento Ribbon," Concrete Quarterly, Autumn 1992, pps. 22-25.