Where are the Stay Cables?
An Investigation.

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The first known drawing of a cable stayed bridge: by Fautus Verantius, ~1595, Venice
Span estimated about 30 meters

The first modern cable stayed bridge!
Stromsund Bridge, 1956 - 182 m

The longest cable stayed bridge!
Russky Bridge, 2013 - 1104 m
Cable Stayed Bridges are very efficient and visually attractive!

As spans get longer there are increased demands on the performance of the stay cables.

- Longer spans are more flexible
- Large displacements & rotations
- Longer cable lengths result in large changes in sag

Cable systems should have enhanced performance to meet these demands.
• In the **global analysis** of the bridge, cables are usually modeled as line members with axial stiffness only - Hinge ends!

• This is acceptable and leads to accurate results for the sectional forces of the bridge members and the **axial forces** in the cables.

• In reality, cables have a significant flexural stiffness and are subjected to static and fatigue **bending stresses** that may be significant - Fixed ends!

What causes these bending stresses?
PERMANENT BENDING STRESSES, \( f_c \):
Fabrication and construction tolerances
• *Discussed in this paper!*

VARIABLE BENDING STRESSES, \( f_v \):
Angle Change at the anchors due to:
  - Change in axial force and sag
  - Structural displacements and rotations
  - Differential temperature
  - Cable oscillations
• *Not discussed in this paper!*

DEVICES TO REDUCE BENDING STRESSES, \( f_v \):
Elastic supports for strands at anchorages
• *Discussed in this paper!*

\[ 2 \cdot \varphi \cdot \sqrt{E \cdot \sigma_d} \]
Bending stresses are independent of cable stiffness!
Section 4.2: Acceptance Testing of stay cables

Tests of 3 representative stay cable specimens shall be carried out...

...The anchorages of the stay cable specimens shall be supported on wedge-shaped shim plates, creating angular deviations of 0.01 radians...

Test: 2 million cycles of fatigue loading and subsequent tensile strength
Mexico: To correct deviation the recess pipe was cut and bent about 20 degrees. Discovered by DSI during inspection some years after bridge completion.

**USA**: East Coast. No room to place the neoprene bearing discs. Heat bending was considered to realign the pipe.

**USA**: Bridge in Midwest. Cable deviation was too large. Pipe cut at top of deck, welded to oval plate and bolted down.

*Things don’t always work out!*

**How large are actual cable deviations?**

**No data is available!**

During construction of Pitt River Bridge, DSI measured the position of all 96 cables at the tower and deck level after final stressing.
• Pitt River Bridge, Vancouver, BC: 96m + 190m + 96 m. Composite steel deck & concrete towers.
• Cables: Middle plane ~60 strands and sides are ~30 strands; 8 cables each side of towers. Total= 96.
• Cables cross each other in the towers and anchored in a welded steel assembly at the deck.
Strands compacted into hex pattern

Tower showing steel Exit pipes & stressing tails

Measuring device bolted to anchorage at deck level

Bolted clamp - with exit and recess pipes
Measurement Data, mm
• 96 measurements each at towers and deck = 192 Total
• Location of measuring points from face of anchors: Towers: 3.13 to 5.35 m
  Deck: 1.42 & 1.98 m
Limit shown in red: 25 mm
• Differences between Deck and Tower!
• Accuracy ± 5 mm!
Horizontal Deviations, X mm:
• Almost perfect bell curve
• Variation between -30 to +30 mm
• About 74% are less than < 10 mm
• Only influenced by setup accuracy

Total number of Data: 192

Vertical Deviations, Y mm:
• Unsymmetrical distribution
• Variation between -50 to +50 mm
• About 37% are less than < 10 mm
• About 62% are +ve: High
• Influenced by many factors!
Radial Deviations, D mm:

- About **33%** > 25 mm and **7.8%** > 35 mm. Maximum deviation **55 mm**
- Excessive deviations makes it difficult to install neoprene bearings and dampers
- Adjustability should be provided to accommodate these deviations!
- How was this provided in Pitt River Bridge cables?

Total Number = 192:
96 readings each at the towers and deck level
Cable adjustability for the Pitt River Bridge:

- Compressed neoprene discs act as visco-elastic damper – Short & medium length cables
- Based on field measurements, eccentric holes were cut in the neoprene discs
- This allowed large adjustability without changes to the recess/exit pipe connection flange
- Holes in neoprene discs are cut by water jet: accurate and fast. Accommodated 55 mm!
Angle Deviations, $\phi$ degrees:

- About **28%** $> 0.6$ degrees, and **8.9%** $> 0.8$ degrees
- Some deviations exceed the values used in the PTI cable acceptance tests!
- Impact of temperature and actual cable force on cable position and measurements!
- Built in angle deviations $\phi$ cause permanent static bending stresses in the strands
- Permanent bending stresses cause fretting that may reduce strand fatigue life
- Let us take a look at bending stresses that occur during service stage

Bending stress:

$$2 \cdot \phi \cdot \sqrt{E \cdot \sigma}$$
Cable bending stresses during service are due to angle changes in the cables.

Consider an angle change $\varphi = 1.0$ degree $= 0.0175$ radians
Axial stress in the cable $\sigma_a = 0.4$ fsu $= 744$ Mpa
Elastic modulus of the strands $E = 195,000$ MPa

Bending stress at the anchorage $= 2 \cdot \varphi \cdot \sqrt{E \cdot \sigma_a}$

$= 422$ Mpa $= 0.23$ fsu

• Some measures are provided to reduce this bending stress. How?
• Provide flexible support to the strands some distance in front of the wedges!
Cable Bending Stresses - Vary k & a:

- Angle change 1.0 degree
- Axial load N = 0.4 Pu (PTI allowable 0.45)
- Effects of support location a: 300 & 600 mm
- Effects of support stiffness k: 1000 & 5000 kN/m
- Stress at anchor reduces to less than 20%
- Stress at support about half of k = 0!
- Design stress at support is less than peak shown

Support Stiffness:
- No Support, k = 0
- k = 1,000 kN/m
- k = 5,000 kN/m
Neoprene discs inside anchors are compressed after strand installation. Provide flexible lateral support to the strands and seal the anchor body.

Visco-elastic (rubber) damper installation becomes difficult with large deviations.
Effects of cable axial force on Bending Moments:

- Angle change = 1.0 deg & Support stiffness = 1,000 kN/m
- Flexible support location at 300 mm from wedges
- When N = 0, cable behaves like a beam: simple bending
- Axial force tends to magnify and localize bending

Cable Bending: complex interaction between \(N\), \(k\) and support location ‘a’
Clevis Cable System
7 to 91 Strands

There is a way to avoid Bending Moments in Cables by using Clevis anchorages
SUMMARY: Cable Bending

• Imposed rotations at ends cause bending stresses in cables

• Axial force magnifies & localize bending stresses in stay cables

• Fabrication and construction tolerances result in permanent bending stresses

• Field measurements of cable deviations were made on 192 anchorages

• During service, angle changes at ends cause transient bending stresses:
  * Structural displacements & rotations due to Live Loads
  * Sag variations due to LL and differential temperature
  * Cable oscillations- wind induced and parametric

• Bending stresses impact the Strength and Fatigue design of cables

• Cable anchorages should include means to reduce bending stresses
Thank You