Where are the Stay Cables?
An Investigation.

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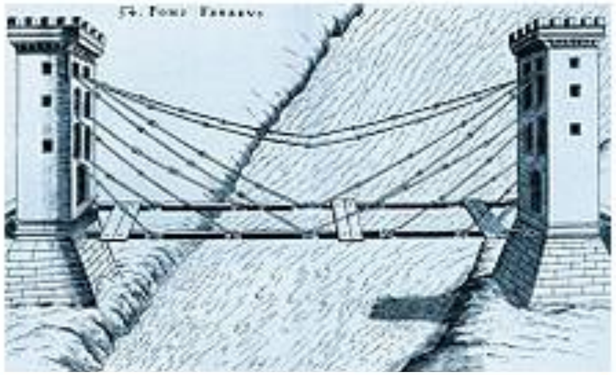


The first known drawing of a cable stayed bridge: by Fautus Verantius, ~1595, Venice
Span estimated about 30 meters

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 !

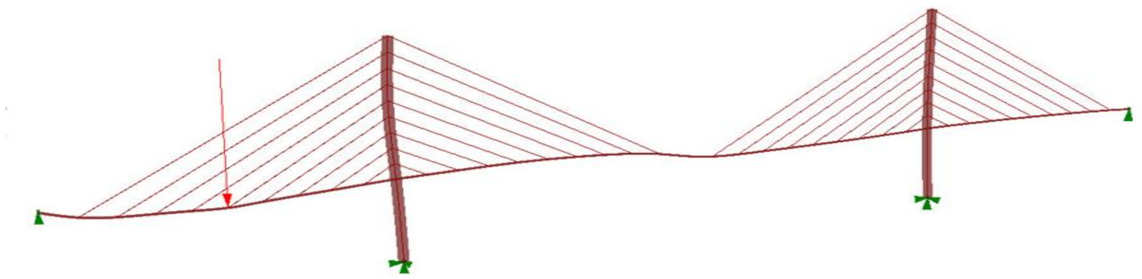
As spans get longer there are increased demands on the performance of the stay cables

Longer spans are more flexible

Large displacements & rotations

Longer cable lengths result in large changes in sag

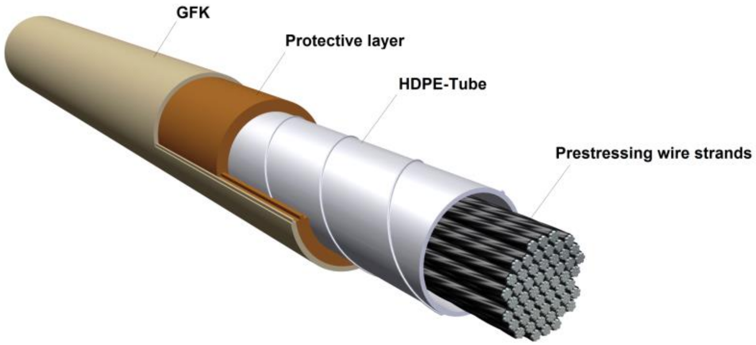
Cable systems should have enhanced performance to meet these demands



- 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 !

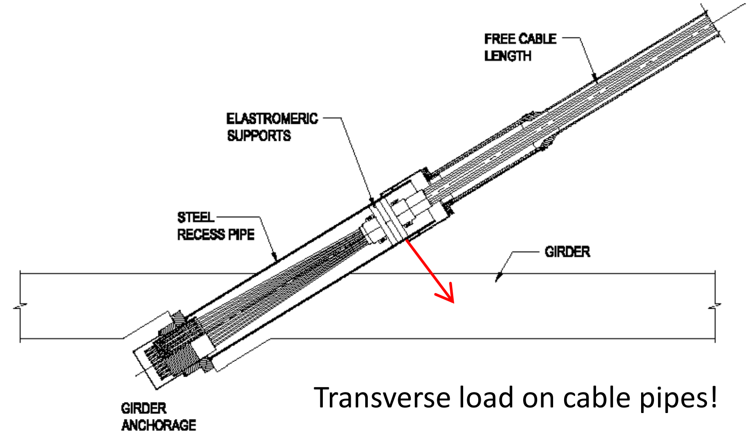


What causes these bending stresses?

PERMANENT BENDING STRESSES, fc:

Fabrication and construction tolerances

- *Discussed in this paper!*



Transverse load on cable pipes!

VARIABLE BENDING STRESSES, fv:

Angle Change at the anchors due to:

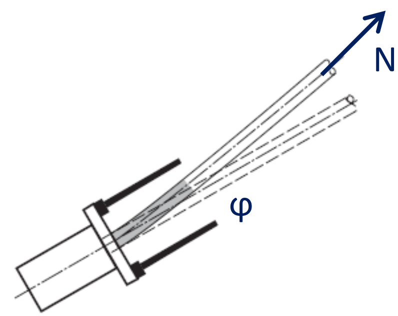
Change in axial force and sag

Structural displacements and rotations

Differential temperature

Cable oscillations

- *Not discussed in this paper!*

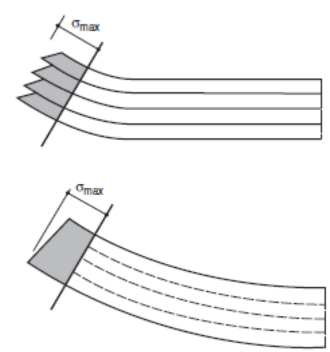


Fixed Support !
Bending stresses:
local and depend
on N , φ and E

DEVICES TO REDUCE BENDING STRESSES fv:

Elastic supports for strands at anchorages

- *Discussed in this paper!*



$$2 \cdot \varphi \cdot \sqrt{E \cdot \sigma_a}$$

Bending stresses
are independent
of cable stiffness!

PTI DC45.1-12

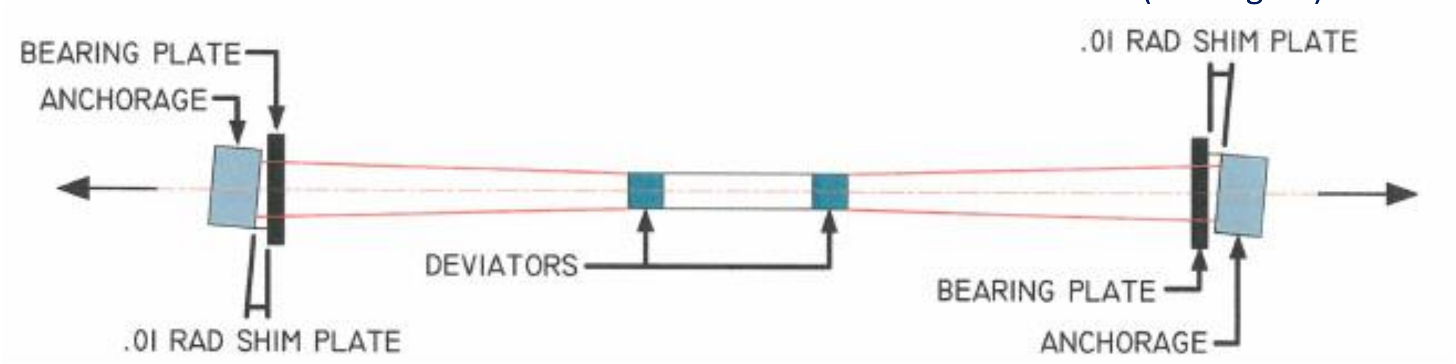
Recommendations for Stay Cable Design, Testing and Installation

Section 4.2: Acceptance Testing of stay cables

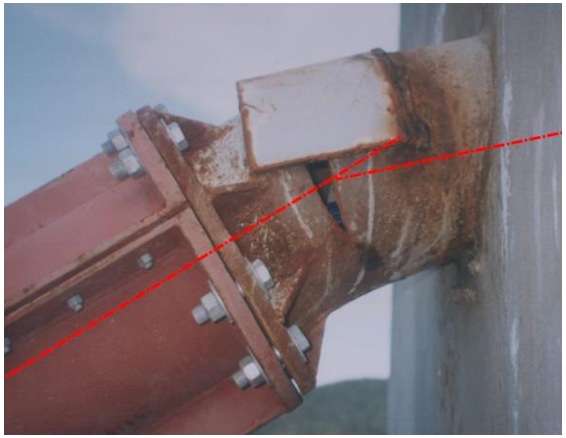
Tests of 3 representative stay cable specimens shall be carried out…

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

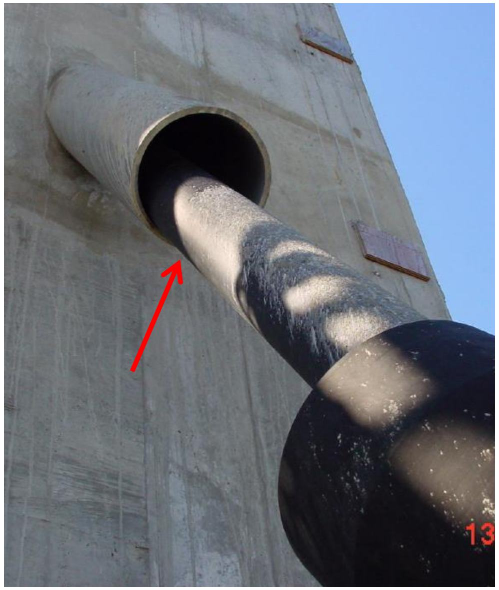
(0.6 degree)



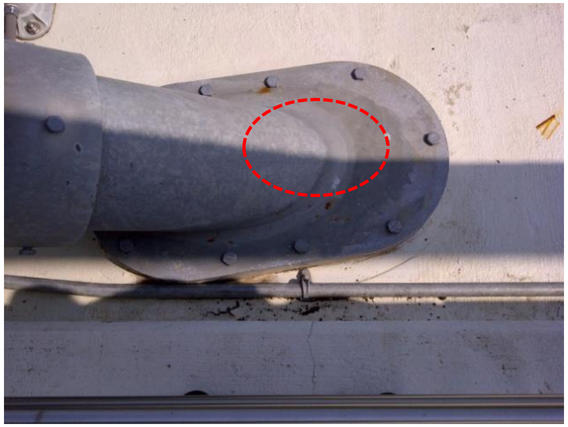
Test: 2 million cycles of fatigue loading and subsequent tensile strength



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.



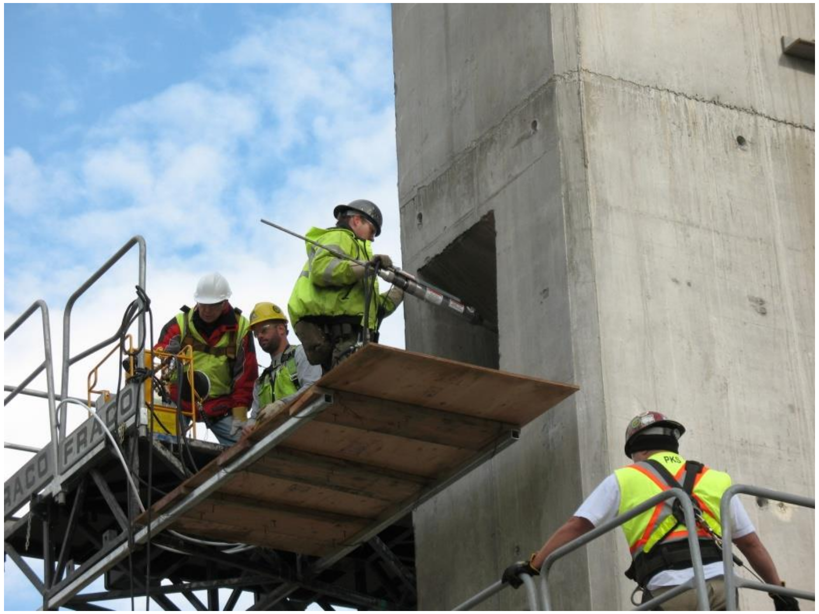
USA: Bridge in Midwest. Cable deviation was too large. Pipe cut at top of deck, welded to oval plate and bolted down.

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.

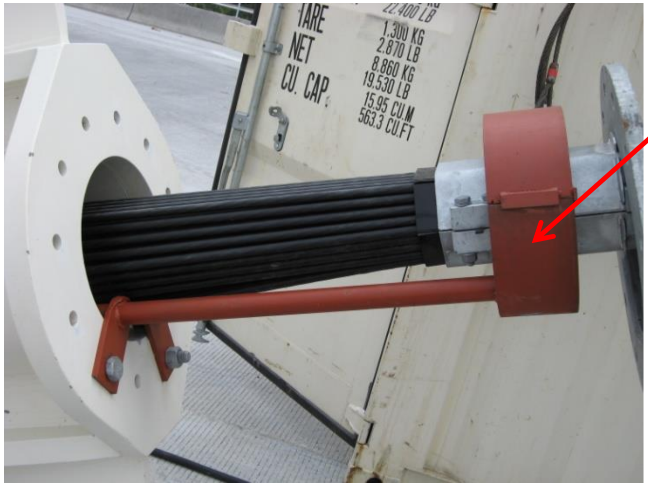


Cable Installation

Finished Cables

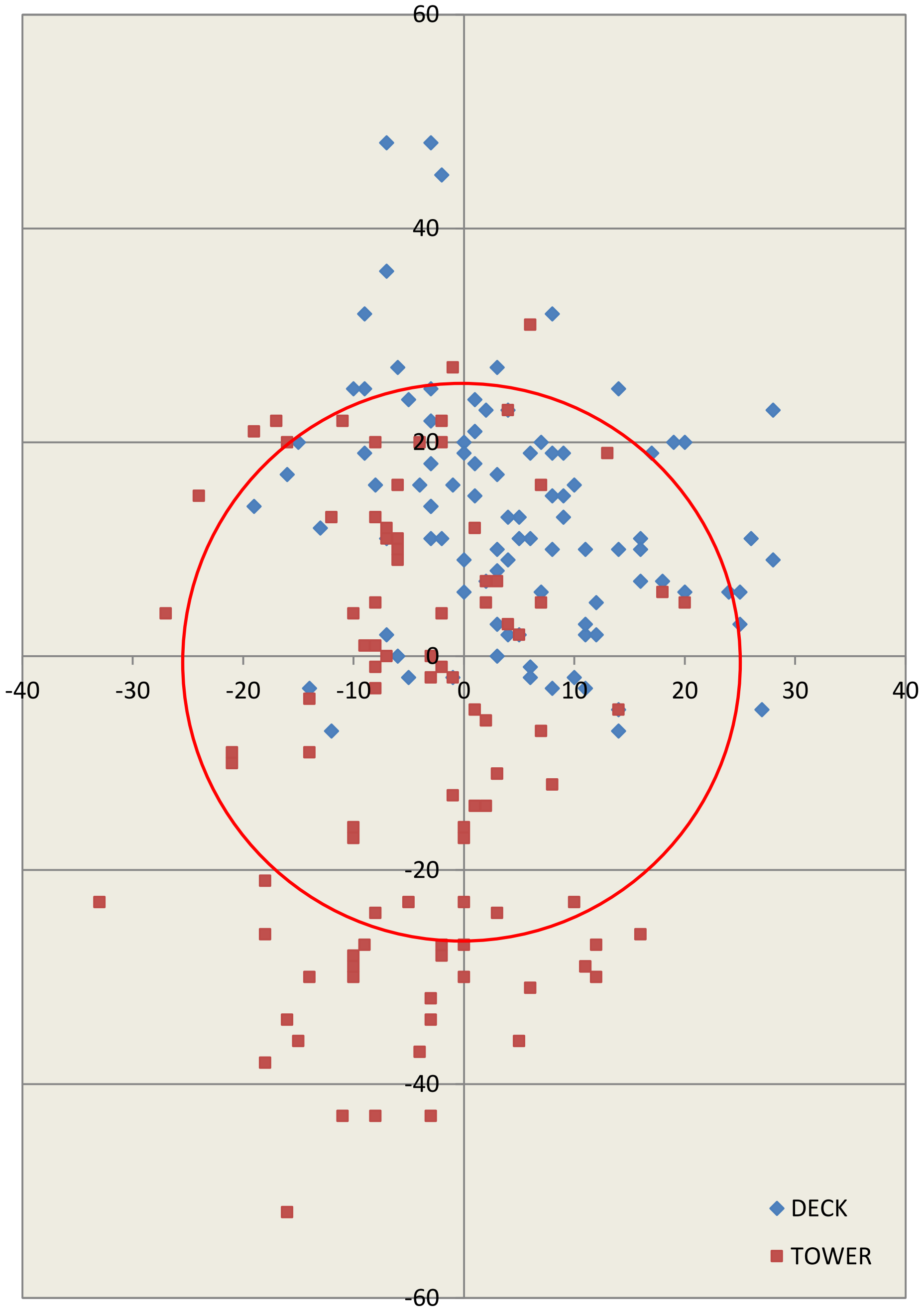
Tower showing
steel Exit pipes
& stressing tails

Strands compacted
into hex pattern



Measuring device
bolted to anchorage
at deck level

Bolted clamp- with exit
and recess pipes

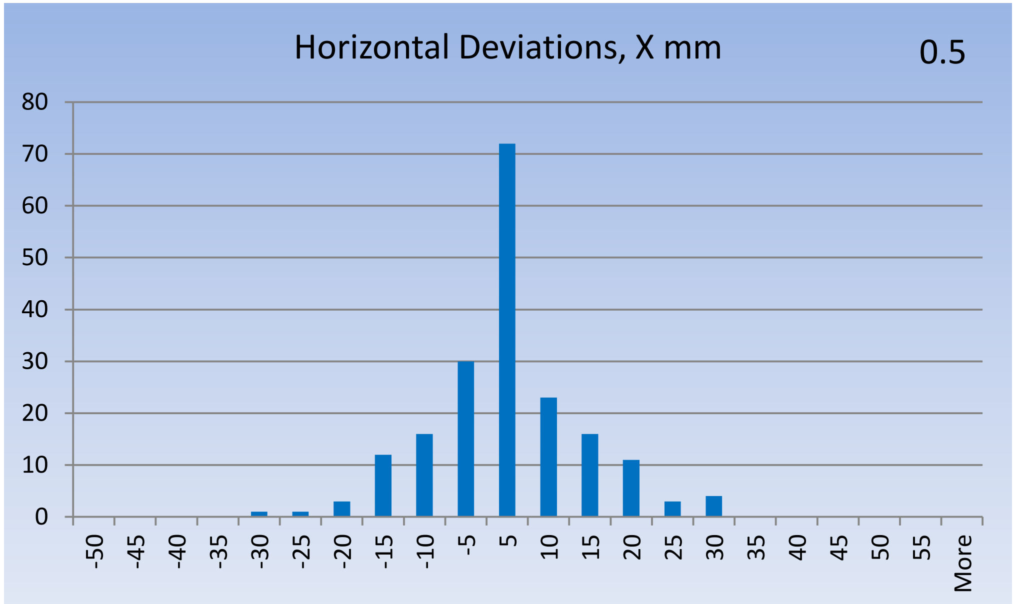


Measurement Data, mm

- 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

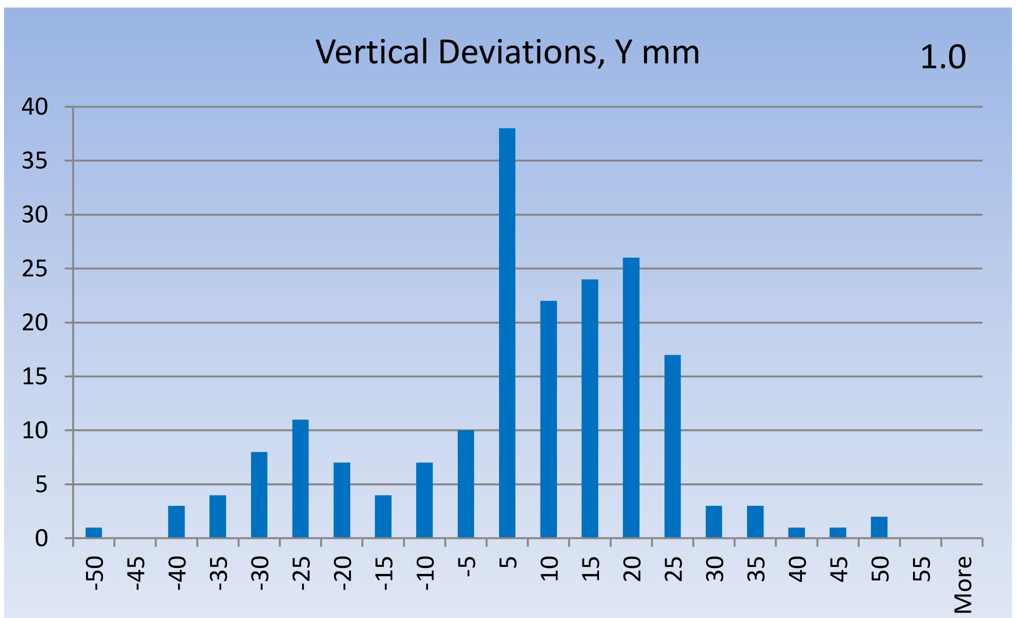
- Differences between Deck and Tower !
- Accuracy ± 5 mm !



Horizontal Deviations, X mm:

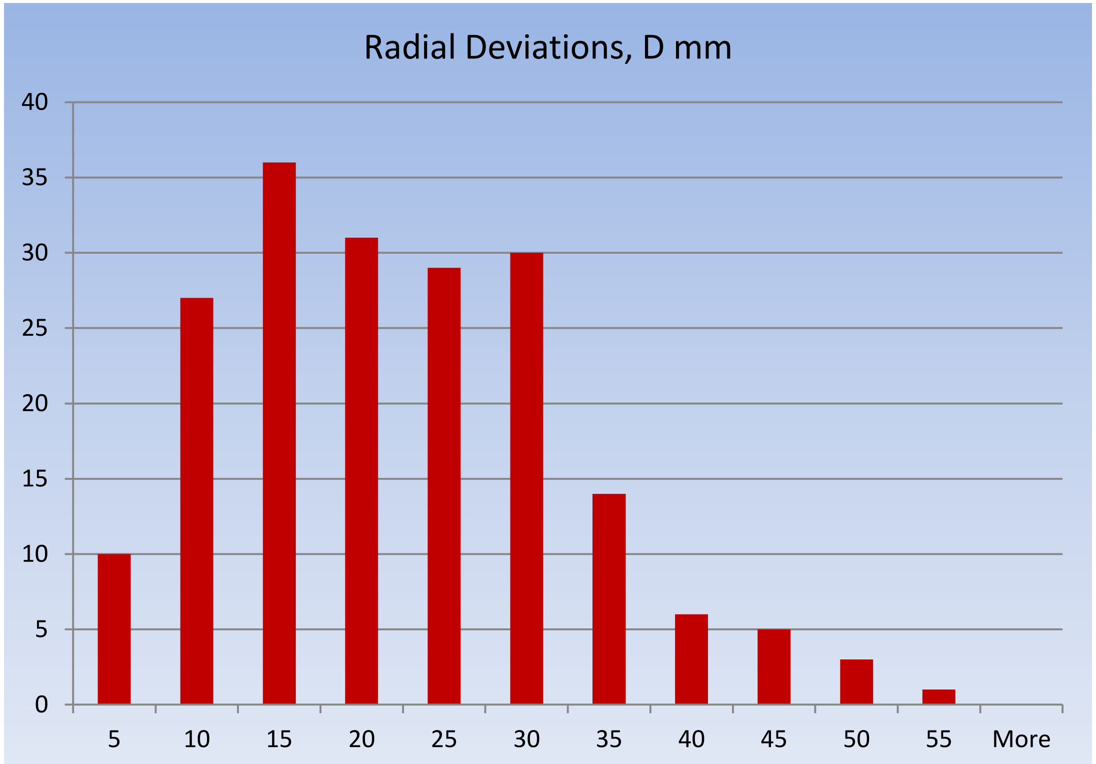
- Almost perfect bell curve
- Variation between -30 to +30 mm
- About **74%** are less than < 10 mm
- Only influenced by setup accuracy

Total number of Data: 192



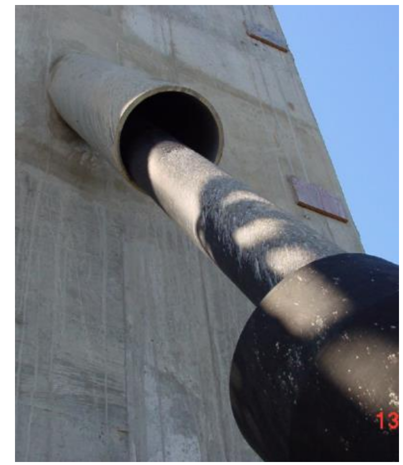
Vertical Deviations, Y mm:

- Unsymmetrical distribution
- Variation between -50 to +50 mm
- About **37%** are less than < 10 mm
- About 62% are +ve: High
- Influenced by many factors !



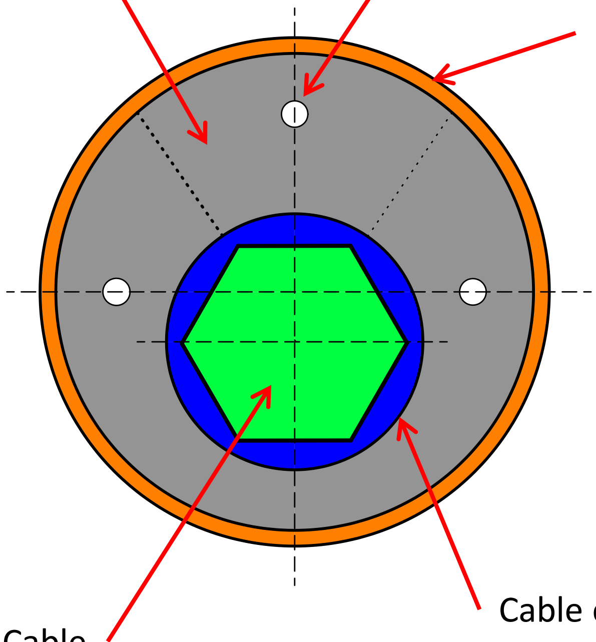
Total Number = 192:

96 readings each at the towers and deck level



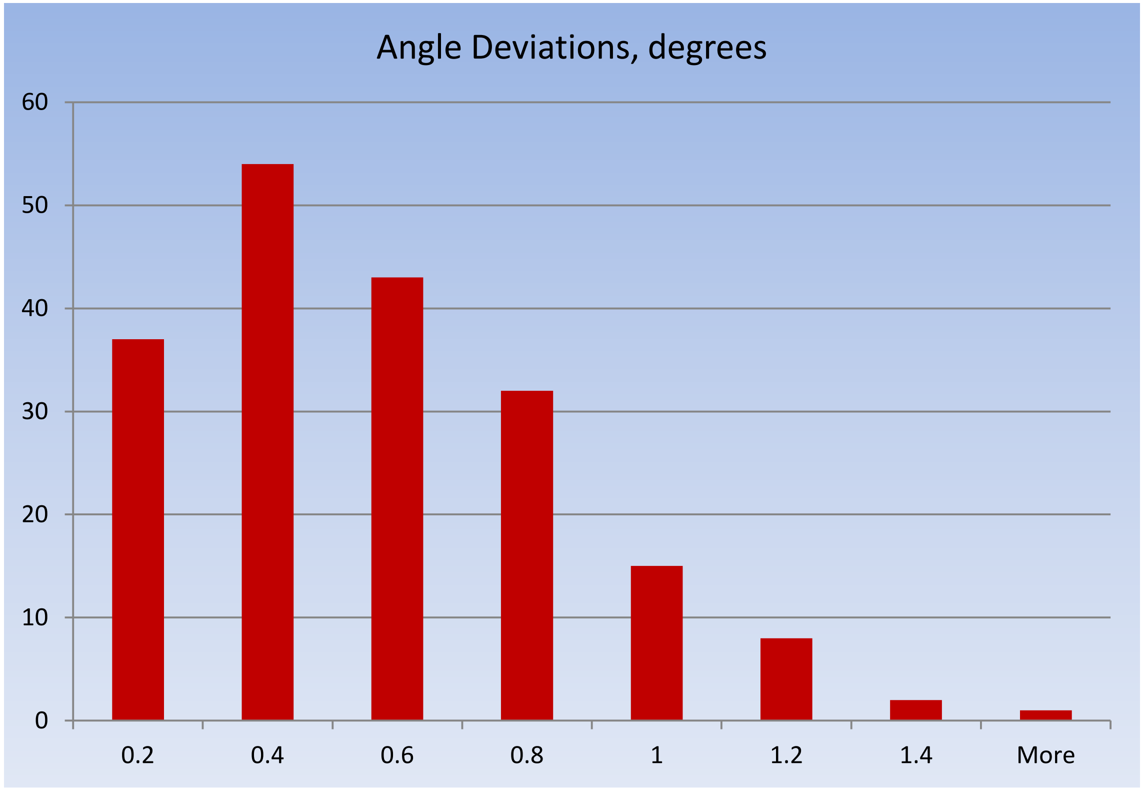
Radial Deviations, D mm:

- 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?



<u>Cable adjustability for the Pitt River Bridge:</u>

- Compressed neoprene discs act as visco-elastic damper – Short & medium length cables
- Based on field measurements, <u>eccentric holes</u> 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!



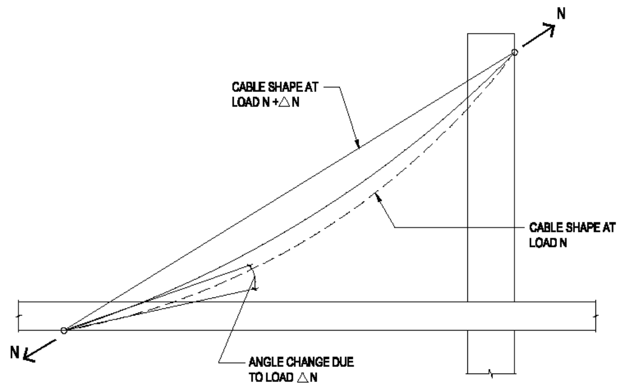
Total Number = 192:
96 readings each at the towers and deck level

Bending stress:

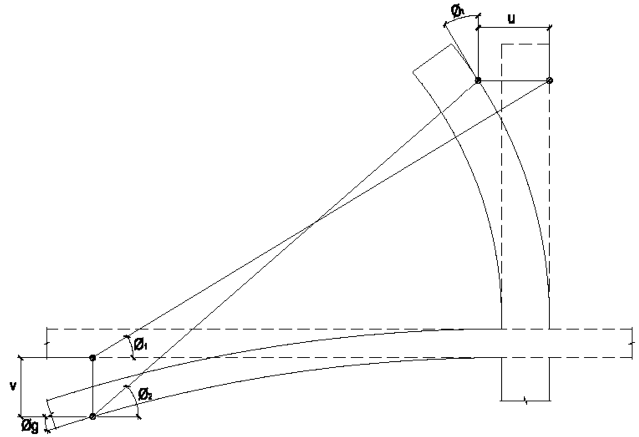
$$2 \cdot \varphi \cdot \sqrt{E \cdot \sigma_a}$$

Angle Deviations, φ 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 **φ** 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



CHANGE OF CABLE SAG
DUE TO FORCE CHANGE △N



STRUCTURAL DISPLACEMENTS & ROTATIONS

Cable bending stresses during service are due to angle changes in the cables

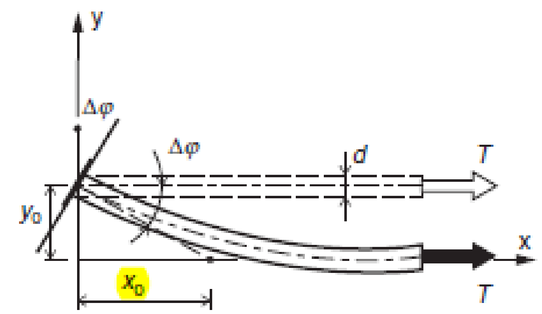
Consider an angle change φ = 1.0 degree = 0.0175 radians

Axial stress in the cable σa = 0.4 fsu = 744 Mpa

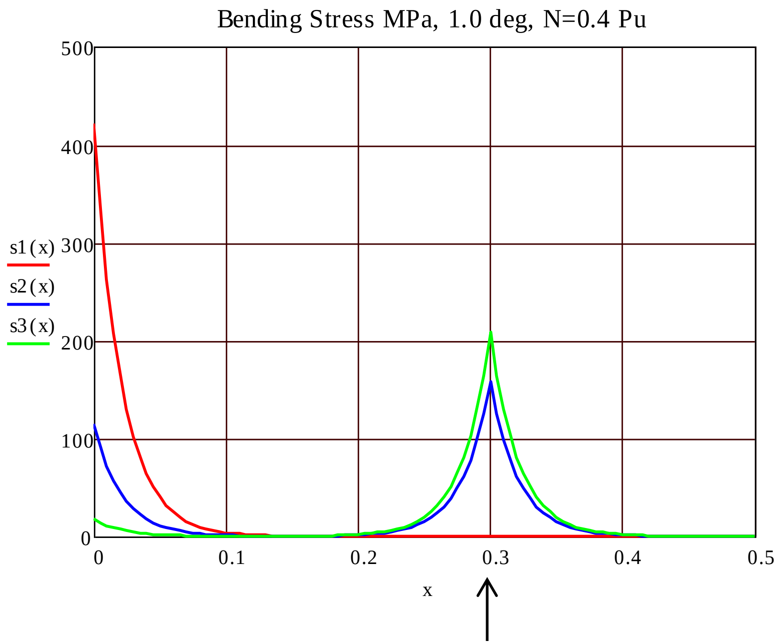
Elastic modulus of the strands E = 195,000 MPa

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

= **422** Mpa = 0.23 fsu !

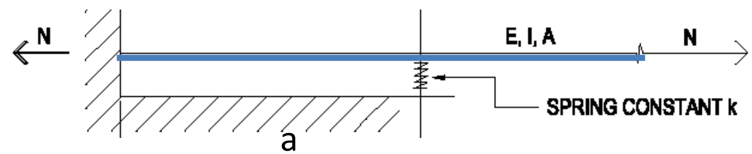


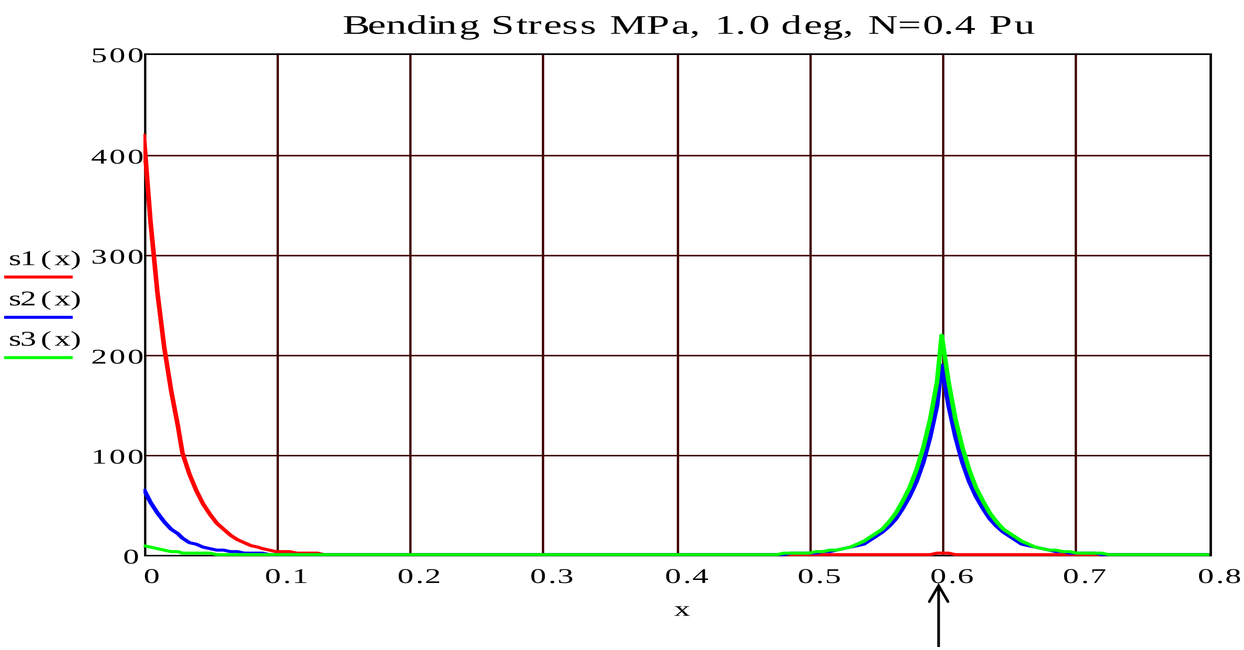
- Some measures are provided to reduce this bending stress. **How?**
- Provide flexible support to the strands some distance in front of the wedges !



Cable Bending Stresses- Vary k & a:

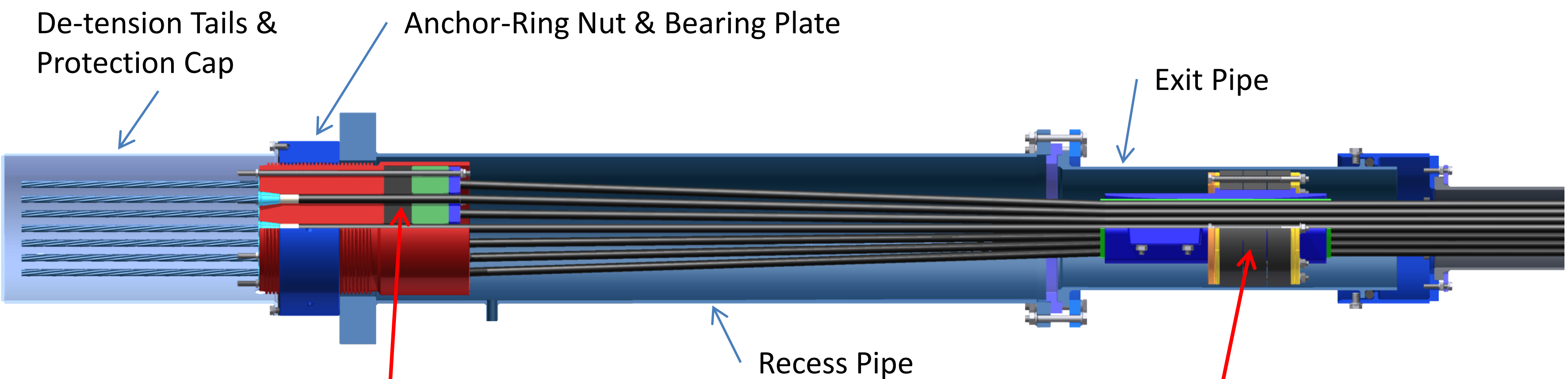
- Angle change 1.0 degree
- Axial load N= 0.4 Pu (PTI allowable 0.45)
- Effects of support location a: 300 & 600 mm
- Effects of support stiffness k: 1000 & 5000 kN/m
- Stress at anchor reduces to less than 20%
- Stress at support about half of k = 0 !
- Design stress at support is less than peak shown

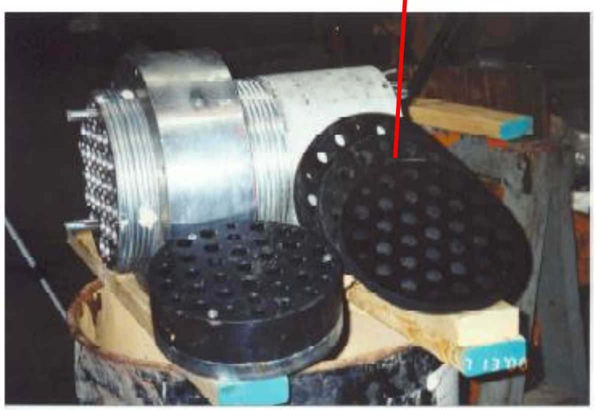




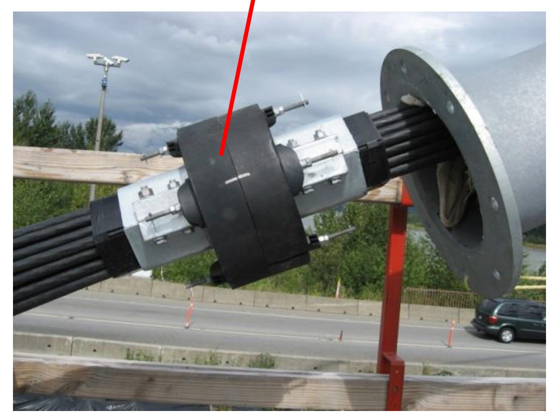
Support Stiffness:

- No Support, k = 0
- k = 1,000 kN/m
- k = 5,000 kN/m



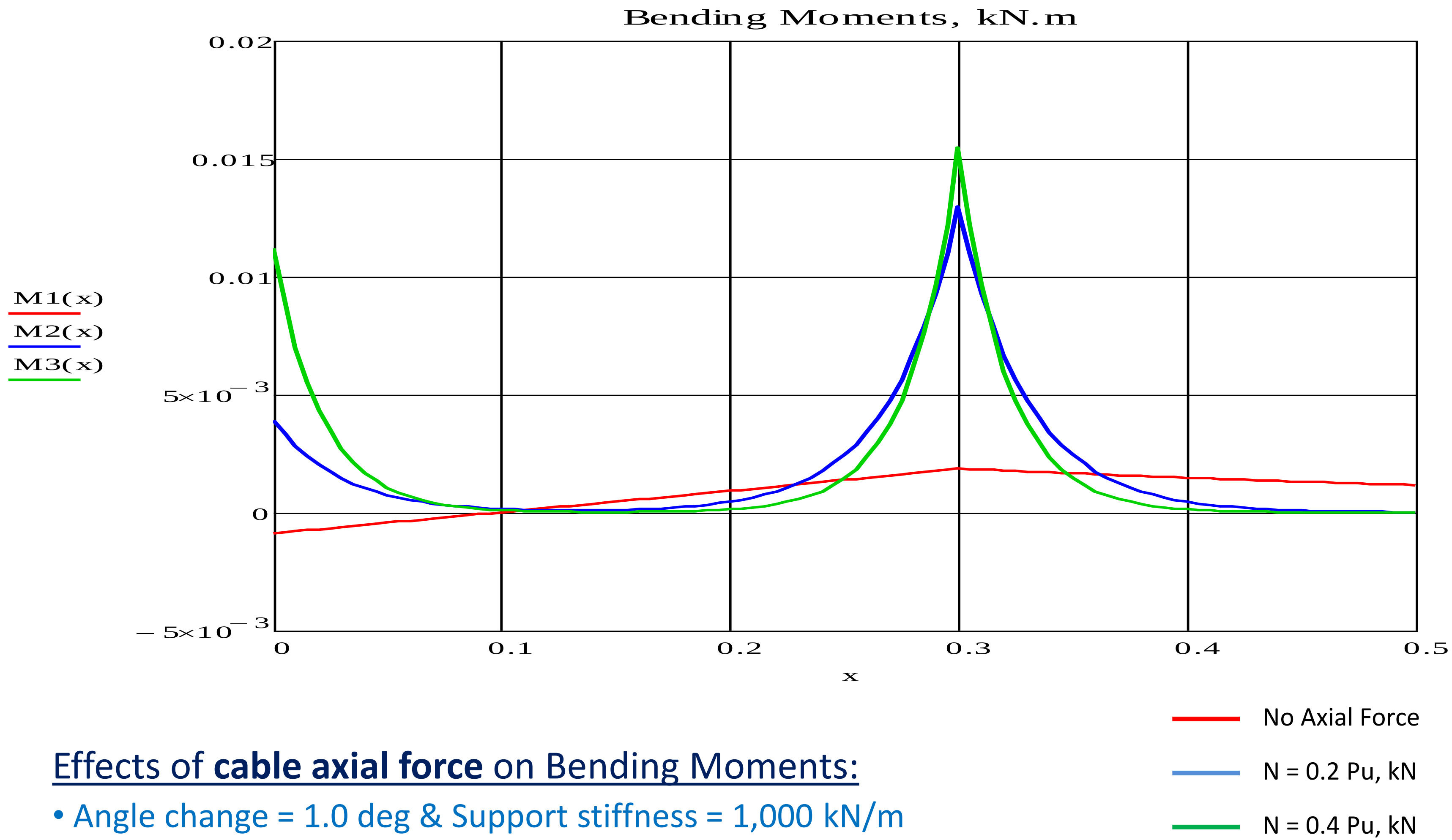


Cable System



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

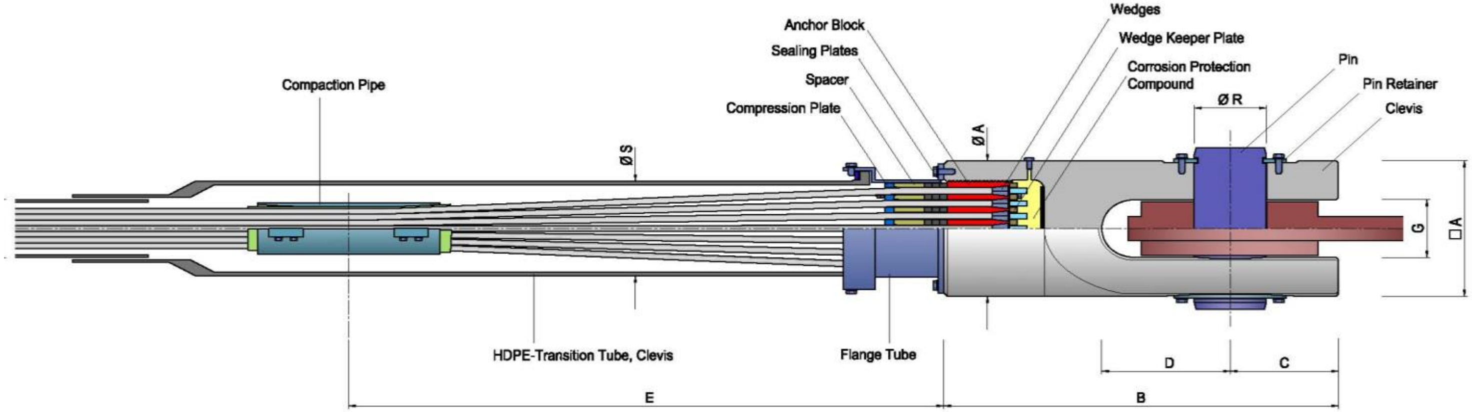


Effects of **cable axial force** on Bending Moments:

- 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 <u>permanent</u> bending stresses
- Field measurements of cable deviations were made on 192 anchorages
- During service, angle changes at ends cause <u>transient</u> 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