Wind Induced Vibration of Cable Stay Bridges Workshop

St. Louis 2006 April 25-27

Application of Aerodynamic Design Guidelines to Recent Cable Stay Bridges

Andreas Felber, Don Bergman and Peter Taylor

BUCKLAND & TAYLOR LTD.
Bridge Engineering

Overview

- Current Design Guidelines
- Dynamic Characteristics of Stay Cables
- Cable Vibration Mechanisms
- Mitigation Measures
- Case Studies
- Further Research Needs

Current Design Guidelines

- **PTI Recommendations for Stay Cable Design, Testing and Installation**
  4th edition 2001 Feb.
- **SETRA Cable Stays Recommendations of French Interministerial Commission on Prestressing**
  June 2002
- **Publications from Recent Conferences and Literature**
  - **6th International Symposium on Cable Dynamics, Sept 2005**
  - **FHWA-RD-02-Draft, 2002 Wind Induced Vibration of Stay Cables HNTB, John Hopkins, RWDI, B&T**
- **Project Specific Studies and Experience**

Dynamic Characteristics of Stay Cables

Key parameters:

- m mass (kg/meter)
- T Tension (N)
- L Length (meter)

- D Diameter (meter)
- ζ Critical Damping Ratio

- Densities (kg/meter)^3
  - ρ_{Air} Air
  - ρ_{Avg} Average for Stay
  - ρ_S Density of Steel

Vibration Frequency:

- Taut String Theory

$$f_i = [i\,(T/m)^{1/2}]\,/(2\,L)$$

For Strand Cables with

DL Tension=(0.35-0.4) GUTS

$(T/m)^{1/2}$~ 270-290m/s

Rough Estimate

$$f_i = (i*140\text{m/s})\,/L$$

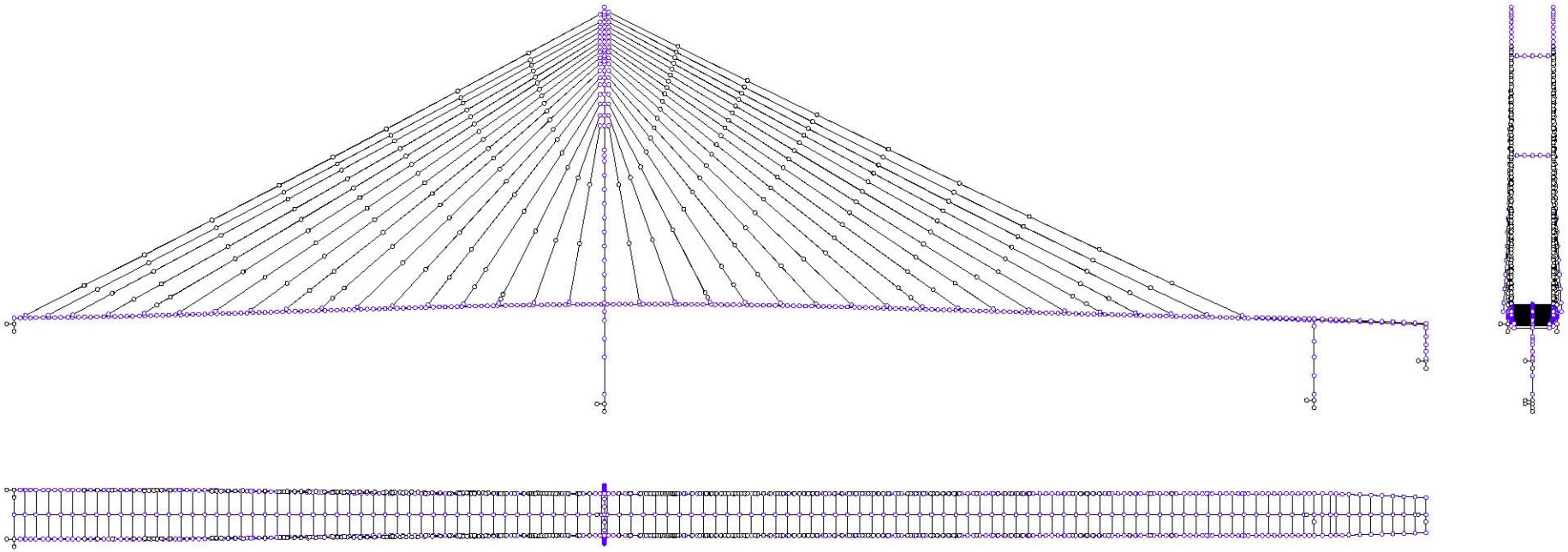
or

$$P_i = L/(i*140\text{m/s})$$

Dynamic Characteristics of Stay Cables

- **More accurate formulations for stay frequencies can account for stay inclination and sag.**
- **These formulations still assume:**
  - **No bending stiffness of stays**
  - **FIXED anchors**
- **Keep in mind that:**
  - **Anchors are attached to towers and decks which transmit vibrations and make actual behavior more complex!**

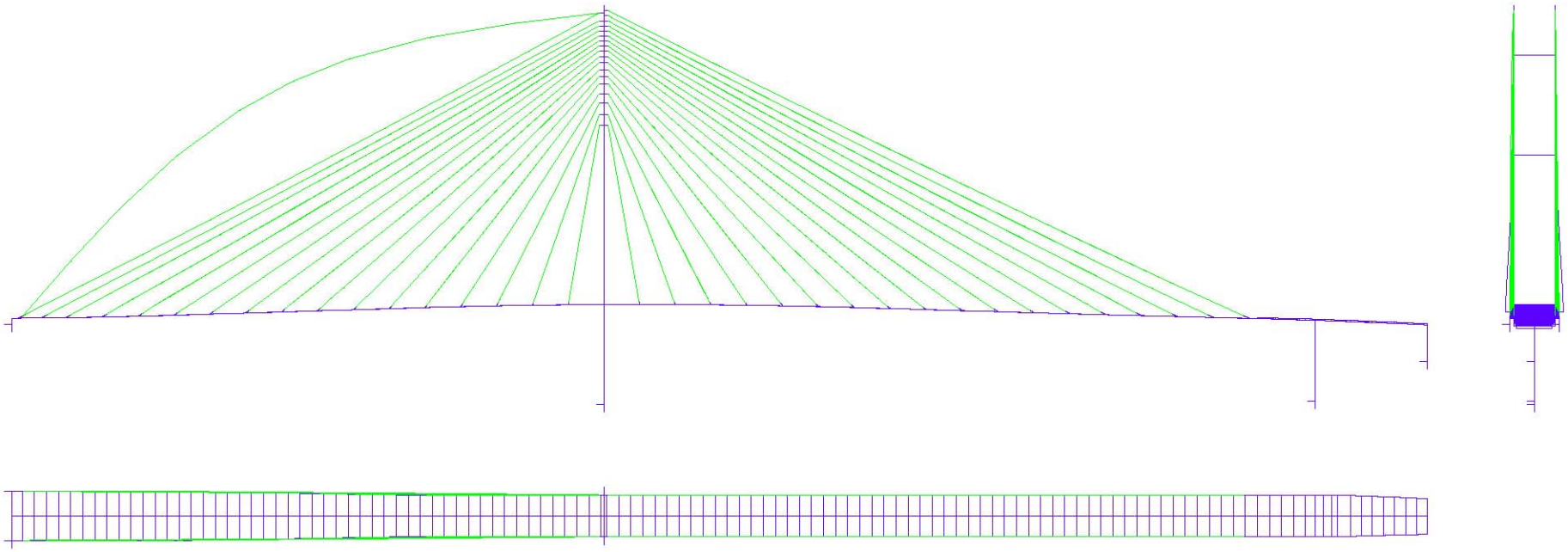
Model with Decks and Towers



Model with Deck & Tower Fixed

Mode 14, Period: 2.175 sec, Frequency: 0.460 HZ,

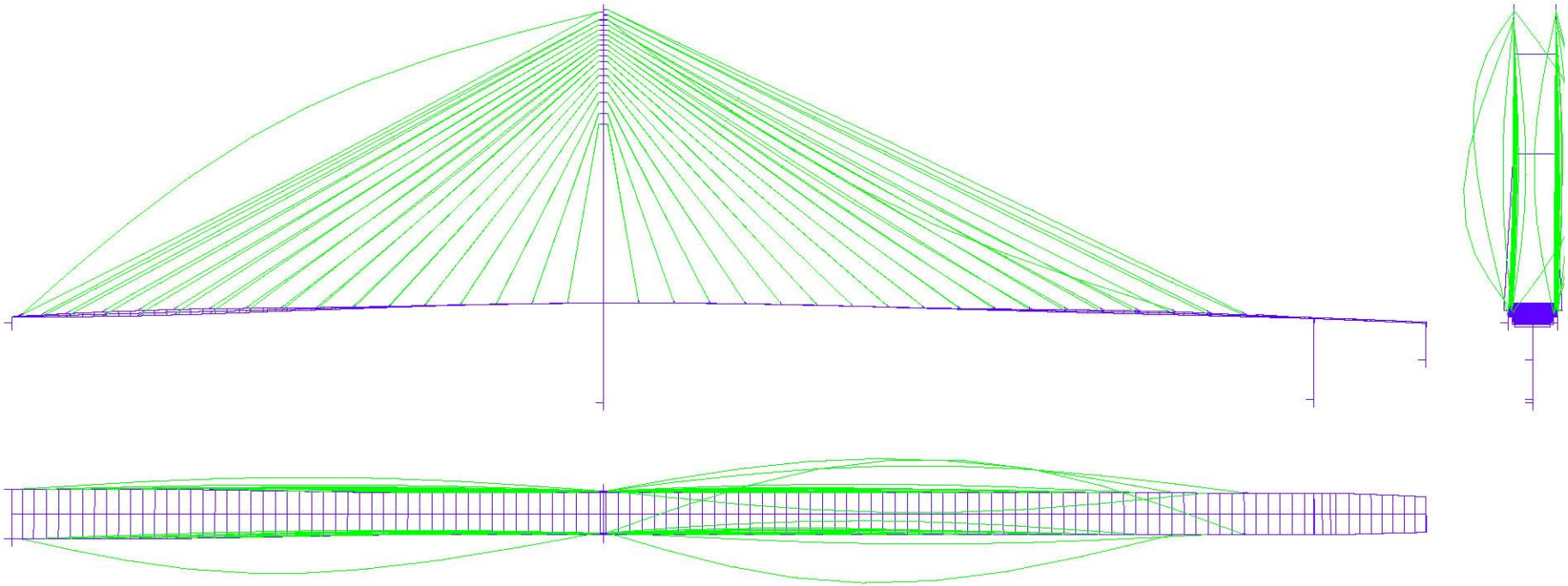
One cable at a time vibrating in isolation



Model with Deck & Tower Free

Mode 10, Period: 2.110 sec, Frequency: 0.474 HZ,

Multiple cables vibrate at same frequency with tower and deck participation



Scruton Number for Stays

$$Sc = m\zeta / \rho_{Air} D^2 \quad \text{OR} \quad \zeta = \rho_{Air} Sc D^2 / m$$

$$m = \rho_{AVG} * \text{Area} = \rho_{AVG} * \pi * D^2/4$$

$$\zeta = \rho_{Air} Sc D^2 / (\rho_{AVG} * \pi * D^2/4)$$

$$\zeta = Sc\ (4/\pi) \rho_{Air} / \rho_{AVG}$$

Scruton Number for Stays

$$\zeta = \mathbf{Sc}\ (4/\pi)\rho_{Air}/\rho_{AVG}$$

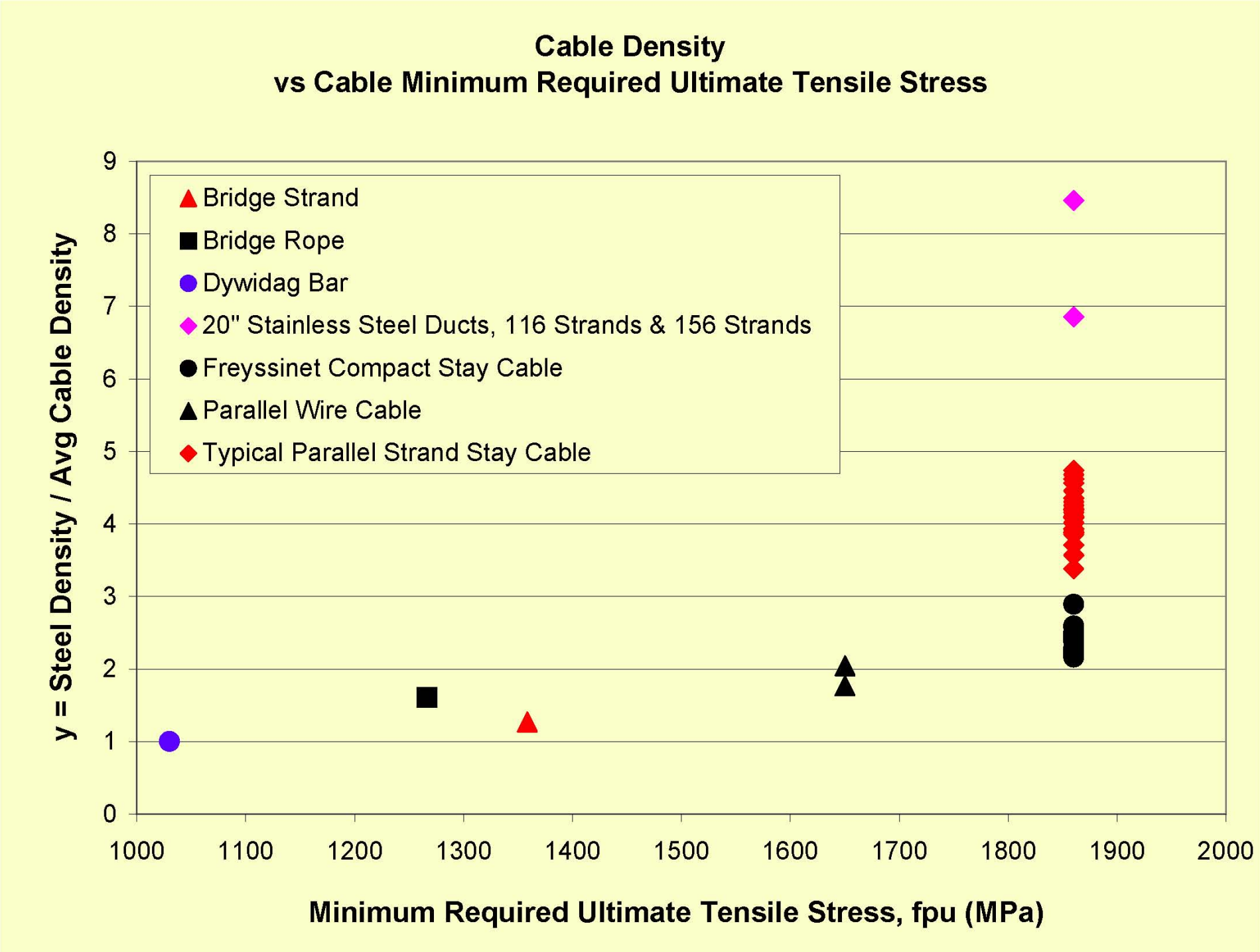
$\rho_{AVG} = \rho_S / Y$ **where** **Y="inefficiency factor"**

ρ_S= density of steel

$$\zeta = (4/\pi)\rho_{Air}/\rho_S\ \mathbf{Sc*Y}$$

$$(4/\pi)\rho_{Air}/\rho_S = 0.020\% = \text{constant}$$

$$\zeta = 0.02\%\ \mathbf{Sc*Y}$$


Cable Density
vs Cable Minimum Required Ultimate Tensile Stress
Bridge Strand
Bridge Rope
Dywidag Bar
20" Stainless Steel Ducts, 116 Strands & 156 Strands
Freyssinet Compact Stay Cable
Parallel Wire Cable
Typical Parallel Strand Stay Cable
y = Steel Density / Avg Cable Density
0
1
2
3
4
5
6
7
8
9
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Minimum Required Ultimate Tensile Stress, fpu (MPa)

Overview

- Current Design Guidelines
- Dynamic Characteristics of Stay Cables
- Cable Vibration Mechanisms
- Mitigation Measures
- Case Studies
- Further Research Needs

Cable Vibration Mechanisms

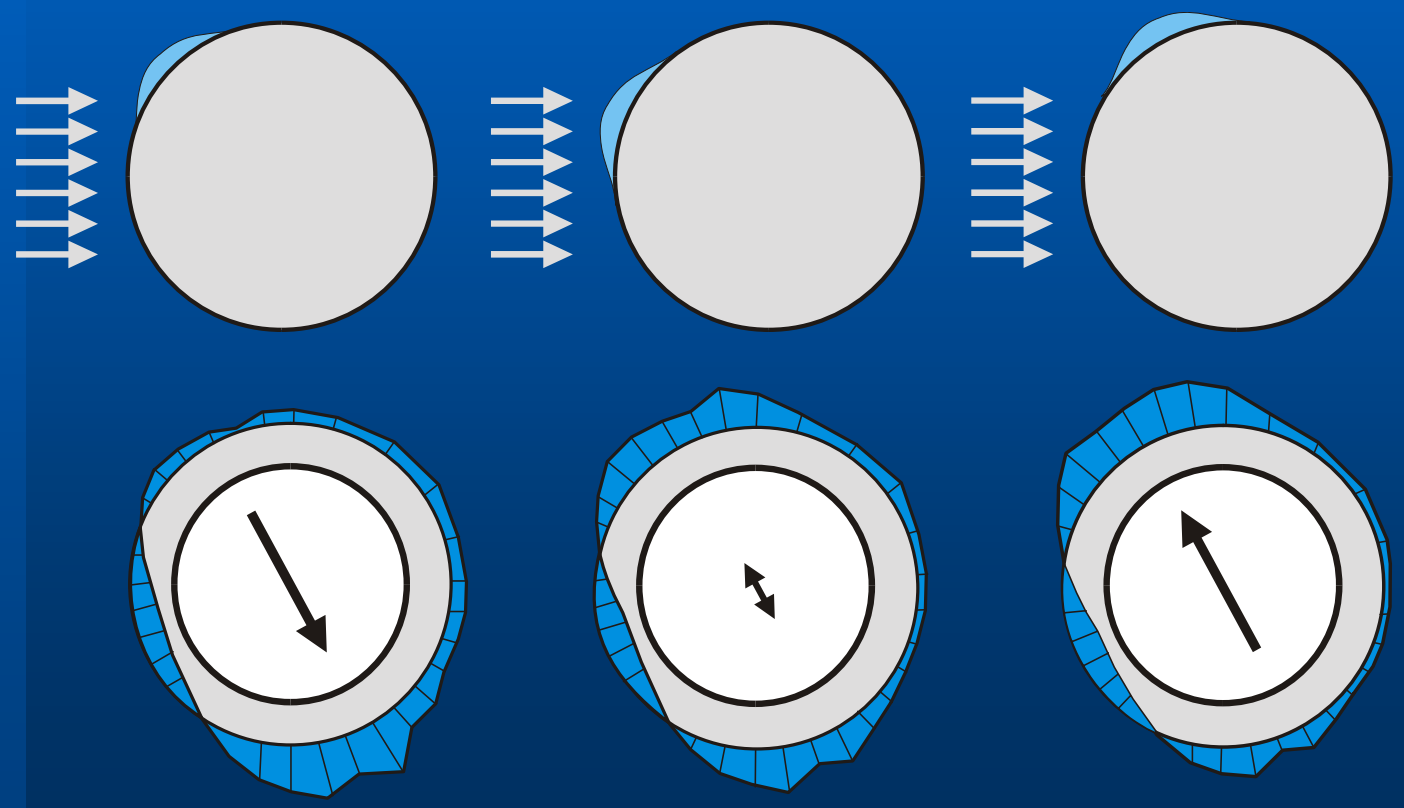
- **Direct Wind Induced**
  - **Vortex Shedding**
  - **Buffeting**
  - **Rain Wind Vibration**
  - **Wake Galloping**
  - **Galloping dry**
  - **Galloping sleet/frost (Allan Larsen 2005)**

- **Indirect Wind Induced**
  - **Parametric Excitation**

    Wind induces motions of the structure which causes excitation at the ends of the cable

Rain-Wind Excitation

Olivier Flamand of CSTB France, Presented in Montreal 2001



Rain-Wind Criteria

- **To suppress wind rain we need the stay cable's Scruton Number > 10 (Irwin, PTI)**

  $Sc = m\zeta/\rho D^2 > 10$ (for smooth cables)

- **For cables with helix a Scruton Number > 5 may be sufficient (Larose et all)**

  $Sc = m\zeta/\rho D^2 > 5$ (for cables with helix)

Wind Rain Criteria

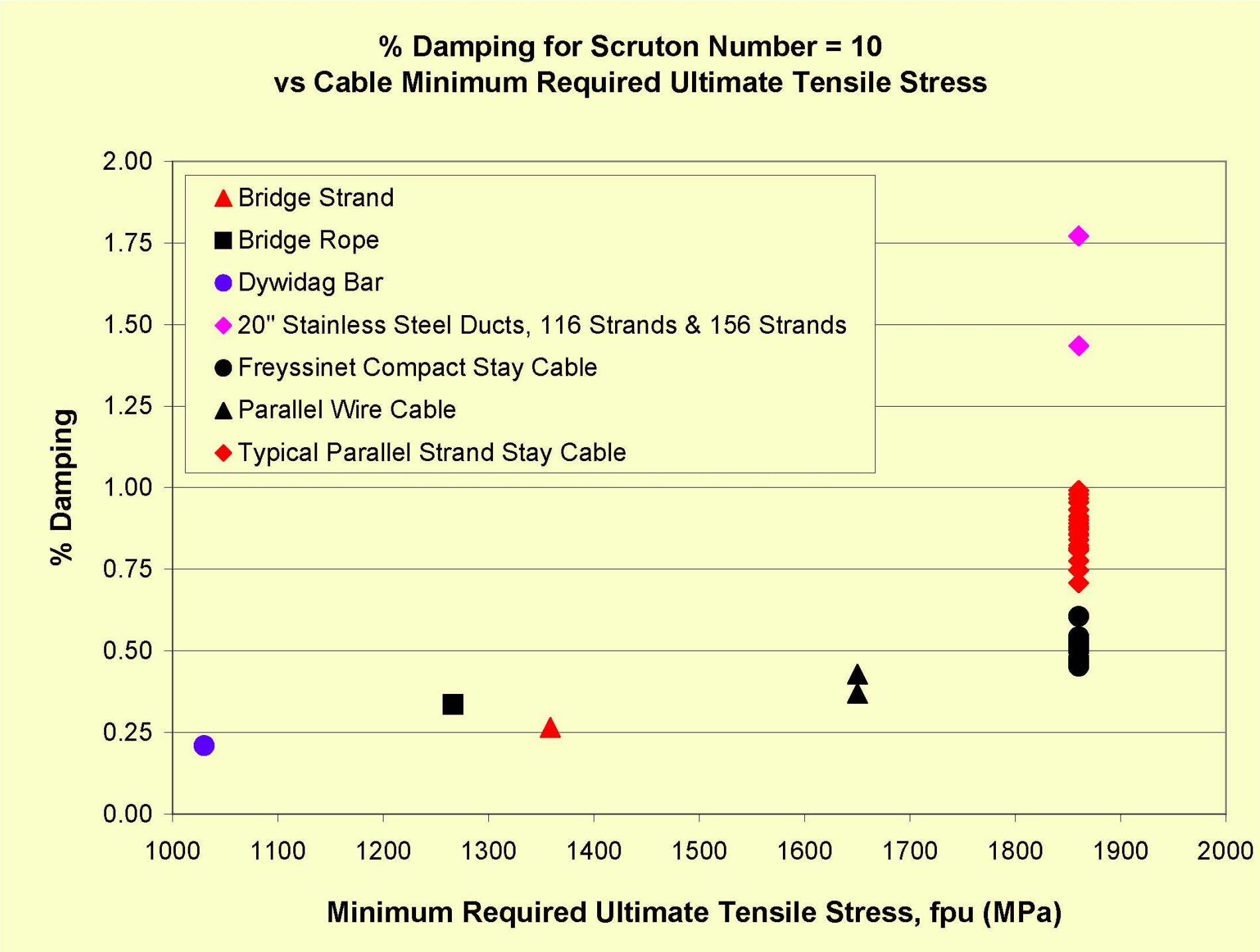
$$\zeta = 0.020\% \quad \mathbf{Sc} * \mathbf{Y}$$

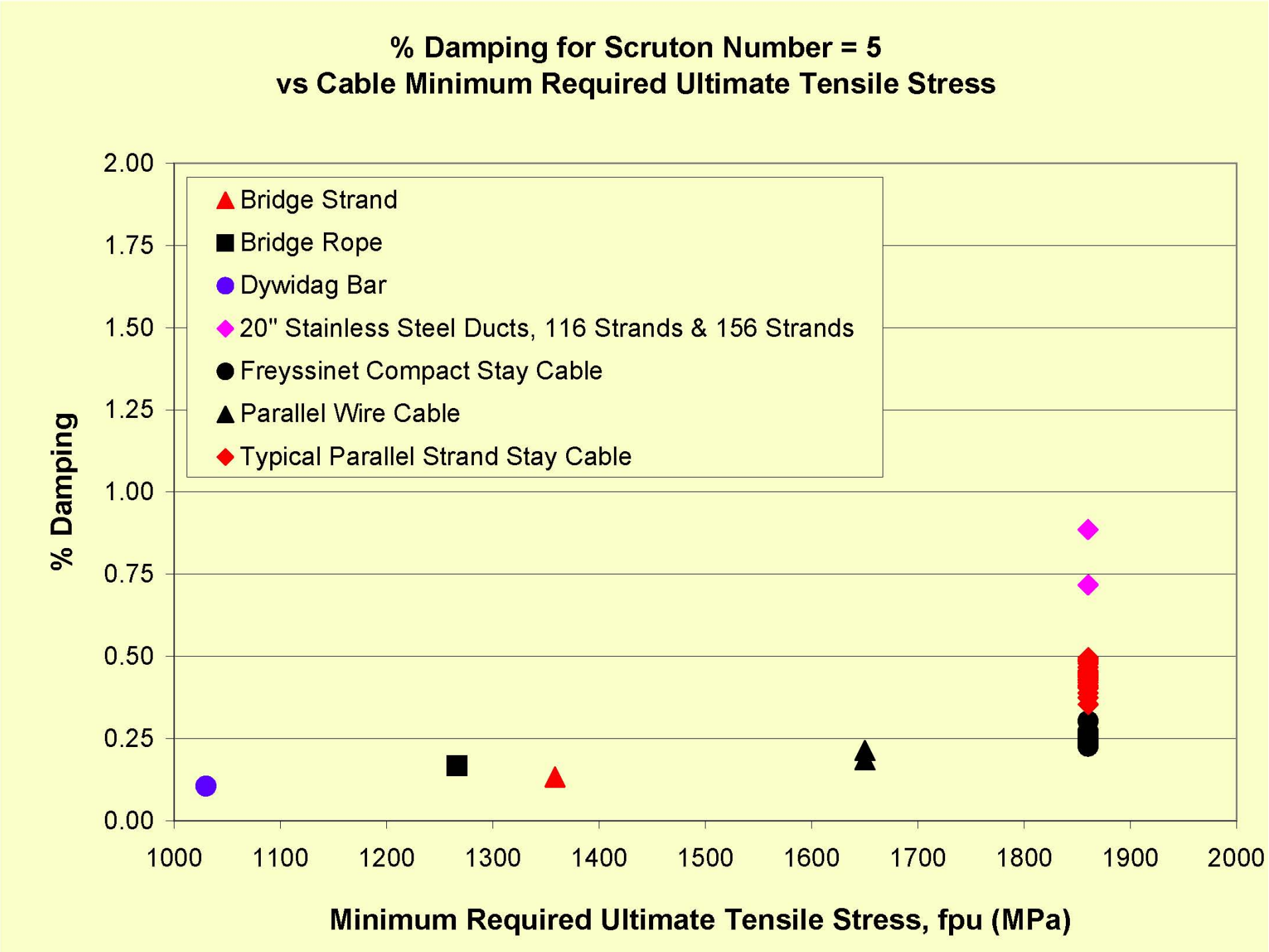
- **Without helix Sc>10**

$$\zeta > 0.20\% \quad \mathbf{Y}$$

- **With helix Sc>5**

$$\zeta > 0.10\% \quad \mathbf{Y}$$


% Damping for Scruton Number = 10
vs Cable Minimum Required Ultimate Tensile Stress
Bridge Strand
Bridge Rope
Dywidag Bar
20" Stainless Steel Ducts, 116 Strands & 156 Strands
Freyssinet Compact Stay Cable
Parallel Wire Cable
Typical Parallel Strand Stay Cable
% Damping
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Minimum Required Ultimate Tensile Stress, fpu (MPa)


% Damping for Scruton Number = 5
vs Cable Minimum Required Ultimate Tensile Stress
Bridge Strand
Bridge Rope
Dywidag Bar
20" Stainless Steel Ducts, 116 Strands & 156 Strands
Freyssinet Compact Stay Cable
Parallel Wire Cable
Typical Parallel Strand Stay Cable
% Damping
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
Minimum Required Ultimate Tensile Stress, fpu (MPa)

Recent work on Galloping

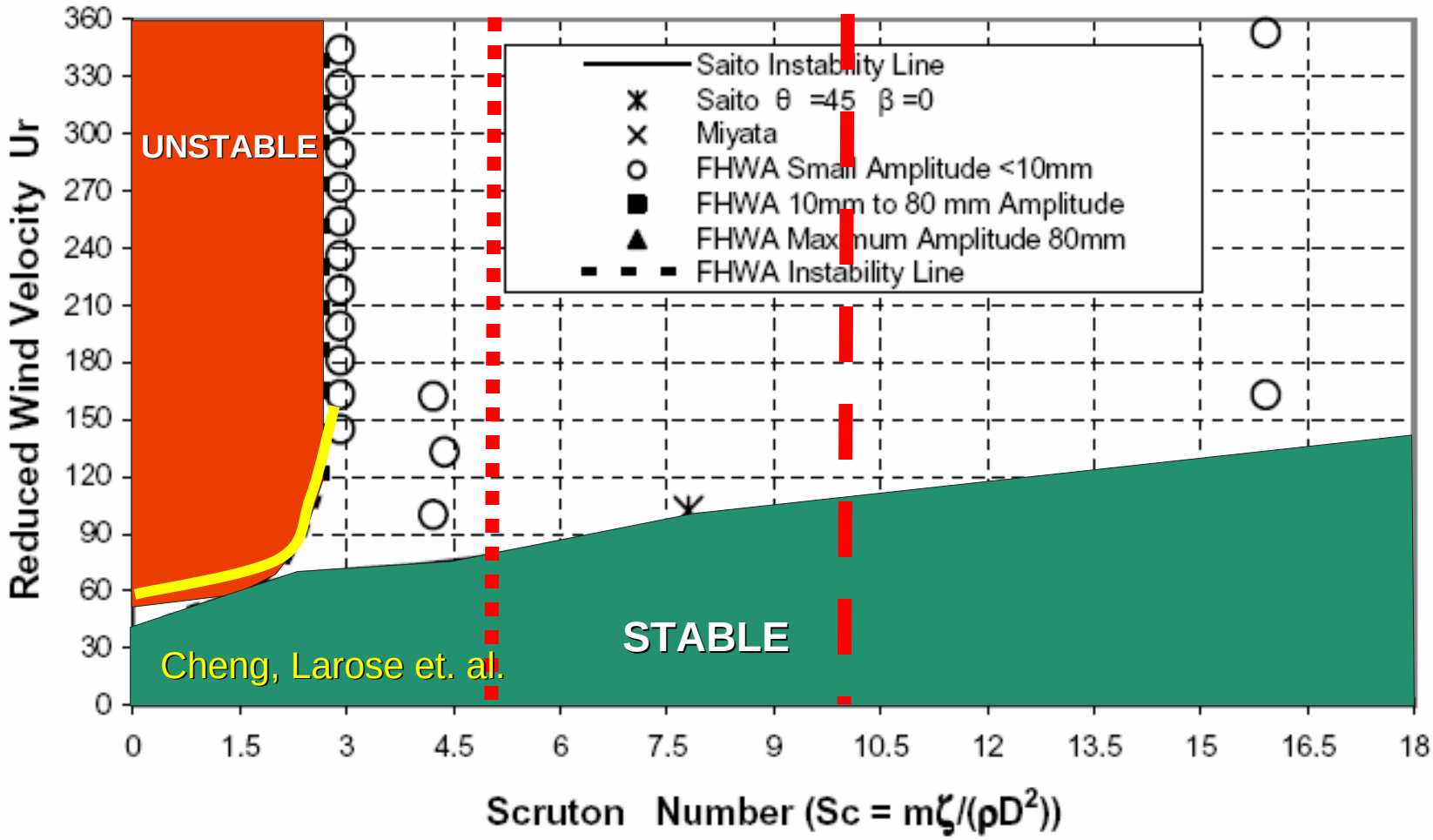
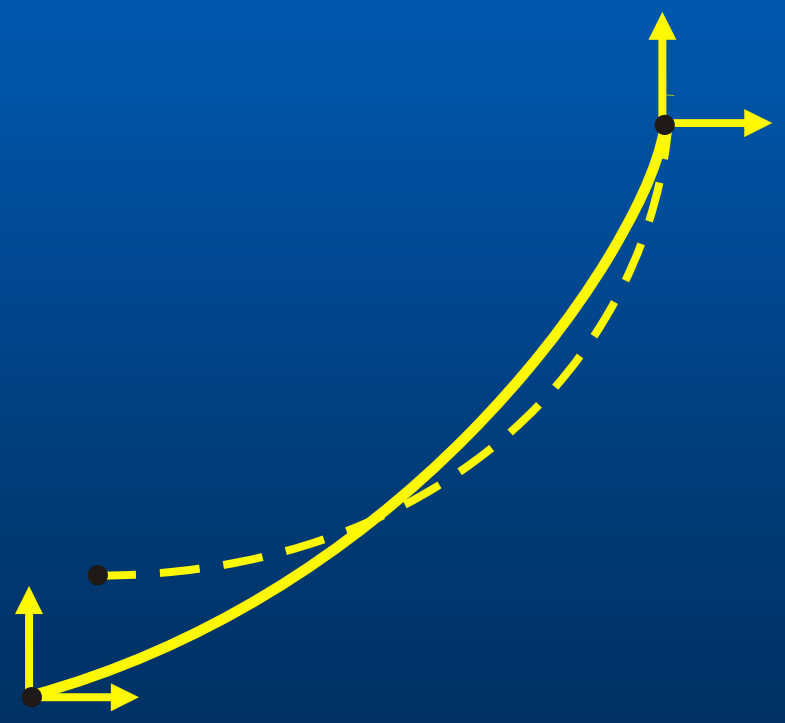


Figure 1: Comparison of wind velocity-damping relation of inclined dry cable.

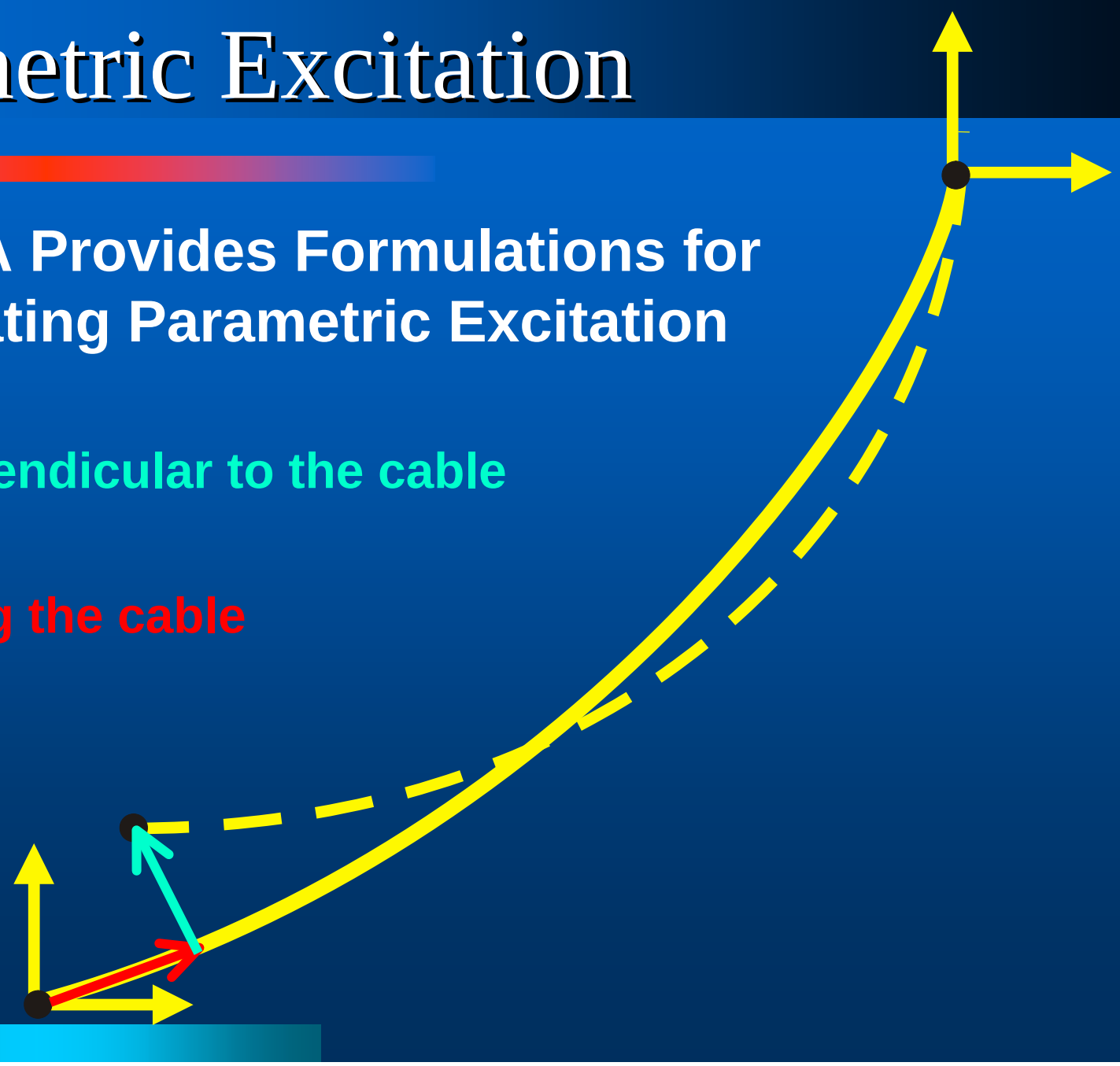
Parametric Excitations

- **Fluctuating cable tensions**
- **Deck and/or tower vibration due to**
  - **wind**
  - **vehicles**
  - **pedestrians**
  - **earthquakes**
  - **other live loads**



Parametric Excitation

- **SETRA Provides Formulations for Evaluating Parametric Excitation**
  - **perpendicular to the cable**
  - **along the cable**



Criteria for Limiting Stay Motions

- **Should it be based on:**
  - **Strength**
  - **Fatigue Life**
  - **NOT Public Response to Visual Observation**

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Bridge Engineering

Dynamic Bridge and Train Interaction Analysis

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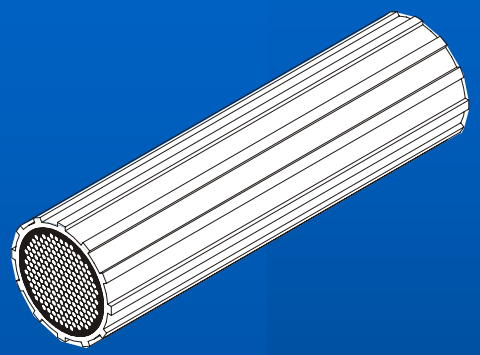
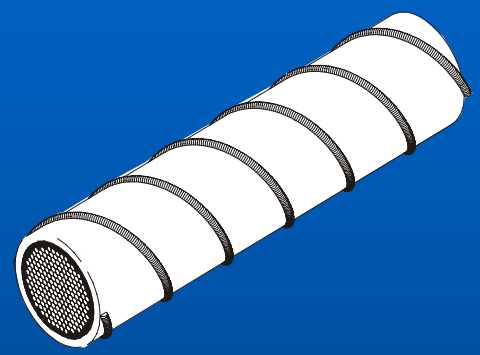
Mitigation Measures

- **Surface Treatment**
- **Discrete Dampers**
- **Cable Ties**

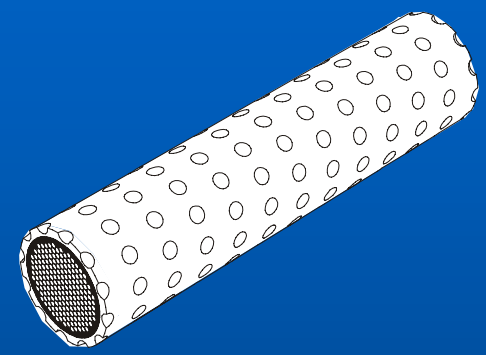
Stay Cable Surface Treatments



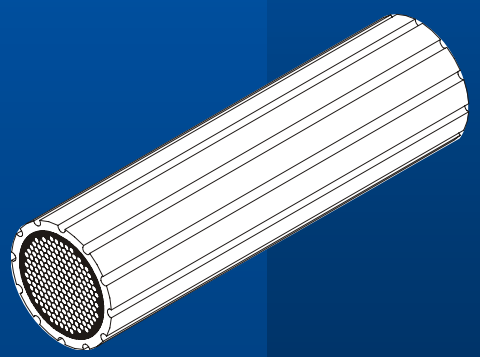
Axial Protuberance



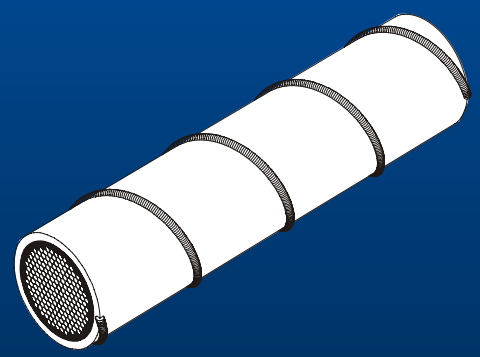
Double Helical Fillets



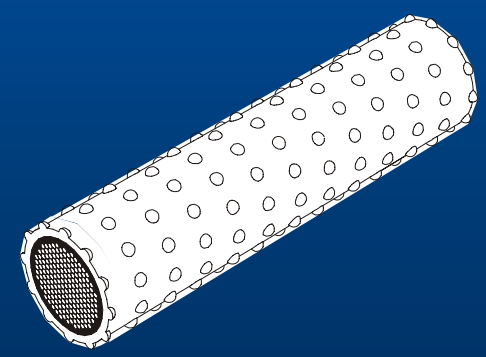
Recessed Dimples



U-Shaped Grooving



Single Helical Fillet

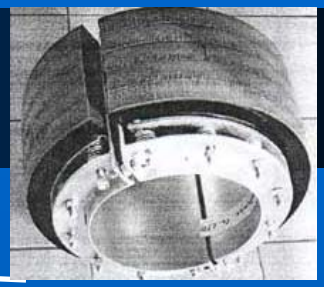


External Dimples

Stay Cable Surface Treatments

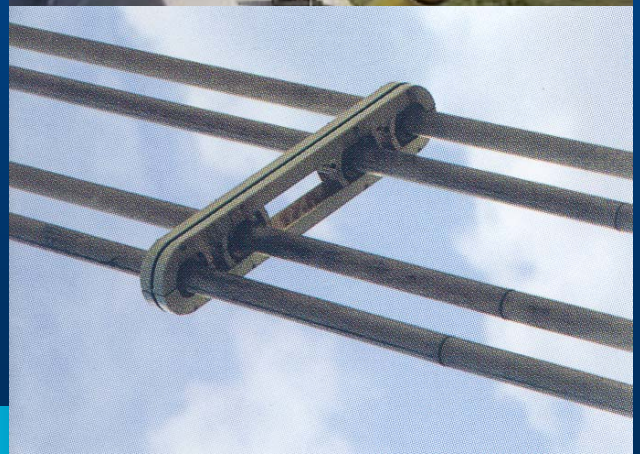
Dampers

- **Internal**



- **External**

- **Inter Cable**

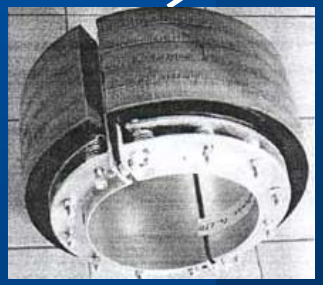


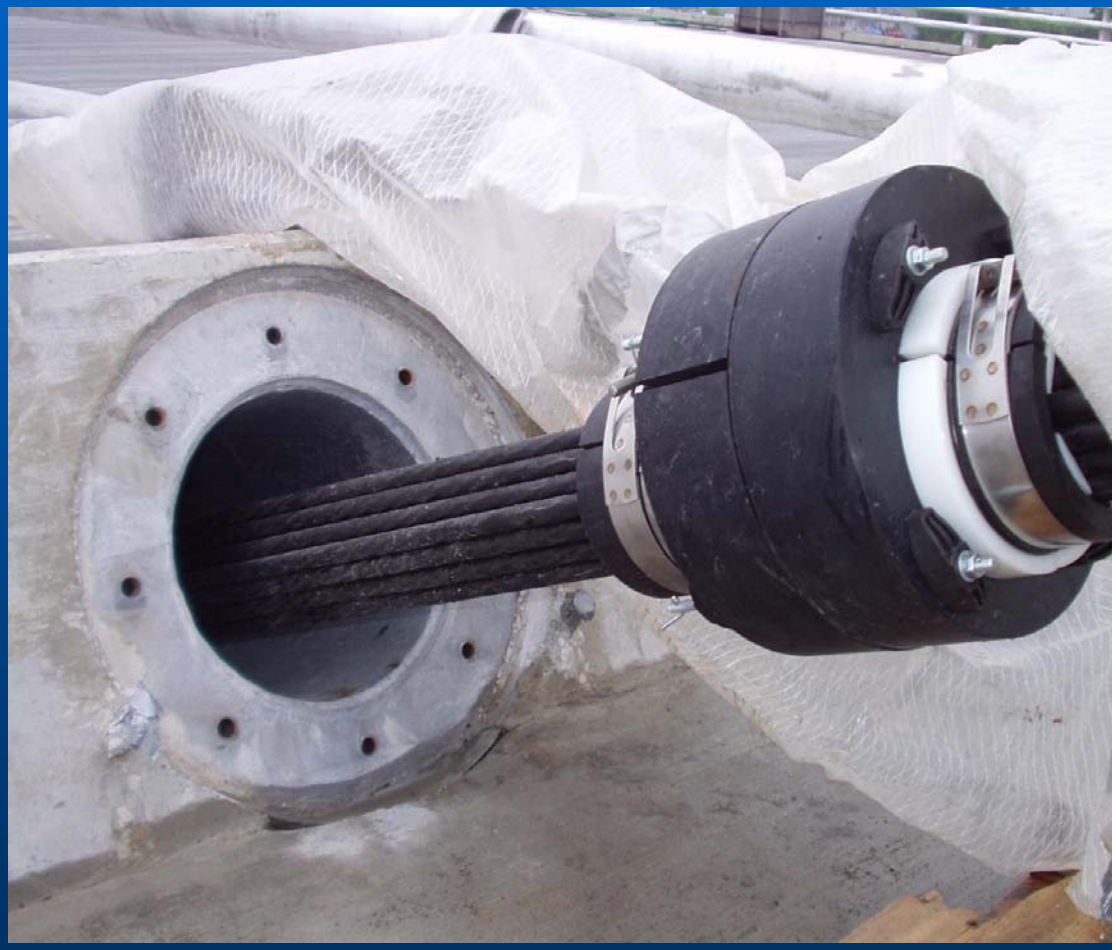
Damper Types

- **Credit for Photos/Figures of Dampers**

  (in alphabetic order)
  - **DSI (Khaled Shawwaf)**
  - **Freyssinet (Drew Micklus)**
  - **VSL (Hans Ganz)**

Elastomeric Dampers



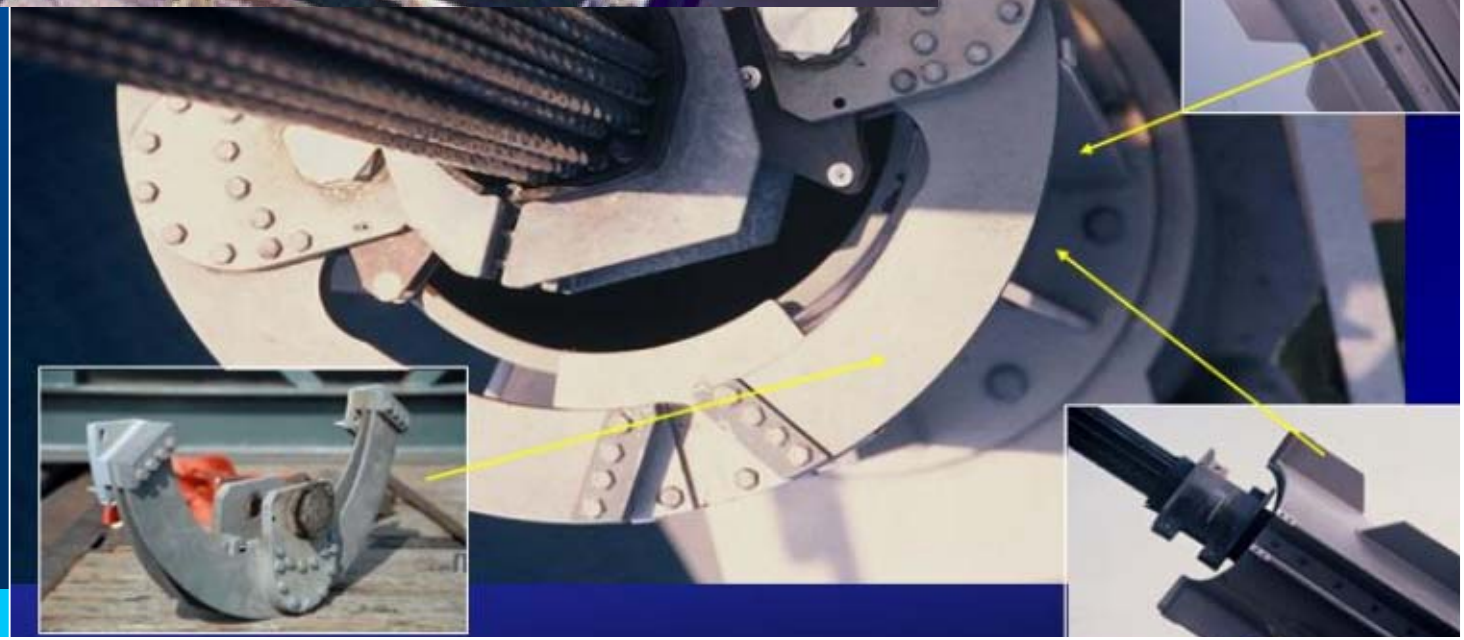


Elastomeric Dampers

Internal Radial Damper

- Three radial piston dampers
- Articulated on cable and tube

Internal Friction Dampers

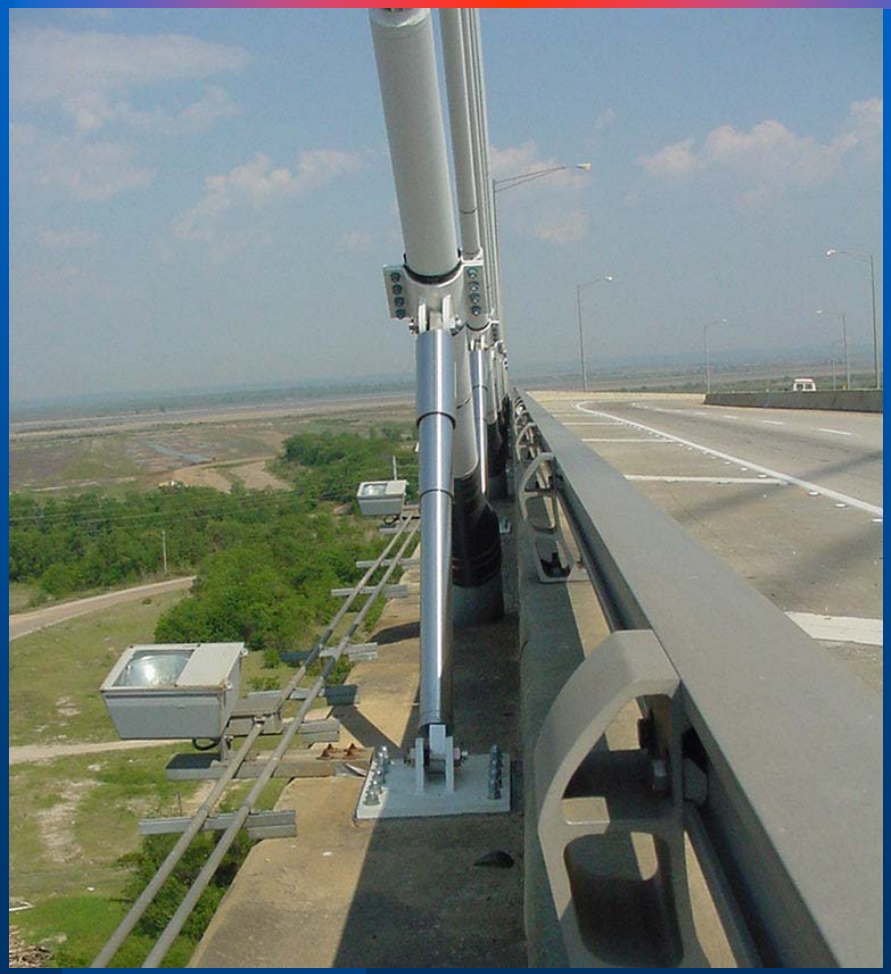


External Dampers 1977

External

Internal or External

Hydraulic Dampers



Cochrane, AL

Veteran's Memorial TX

High Damping Rubber Dampers

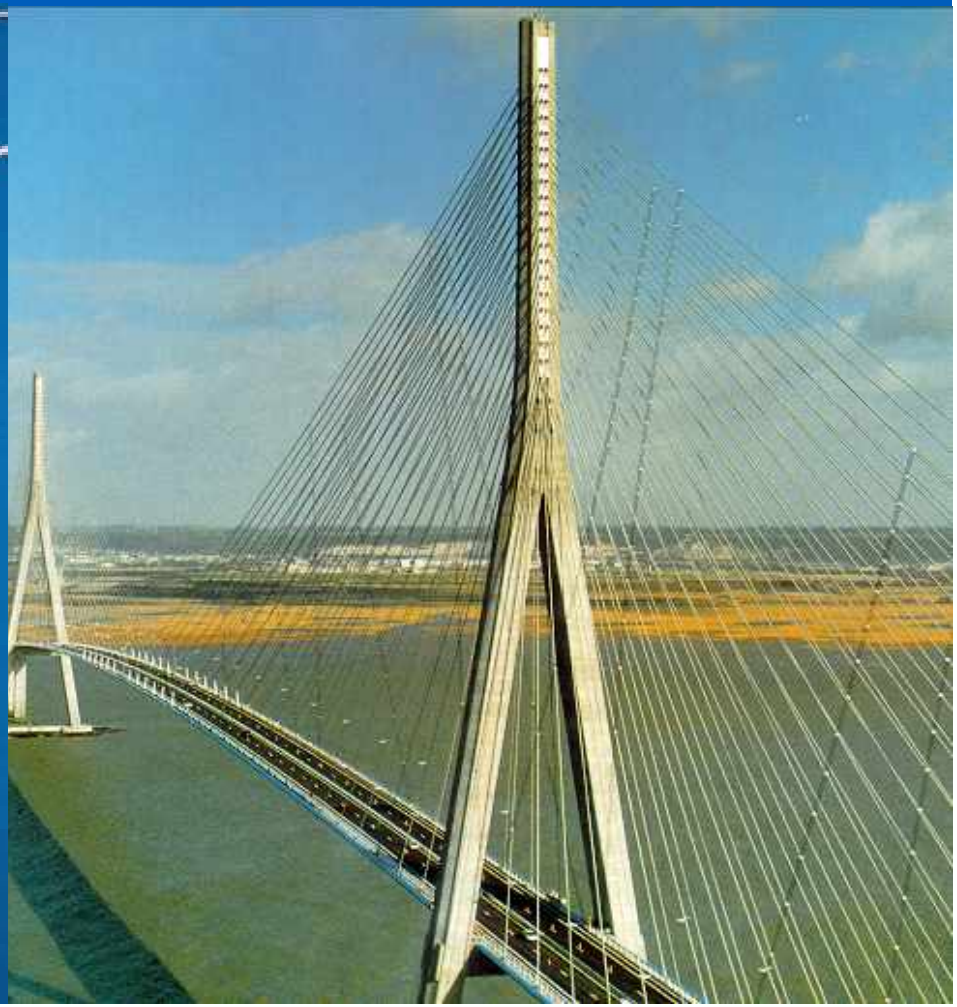
- **20+ bridges in Japan**
- **Modular Assemblies**

Stay Cable Cross Ties

- **Installed on the Faroe Bridge in 1986 to mitigate rain wind excitation.**

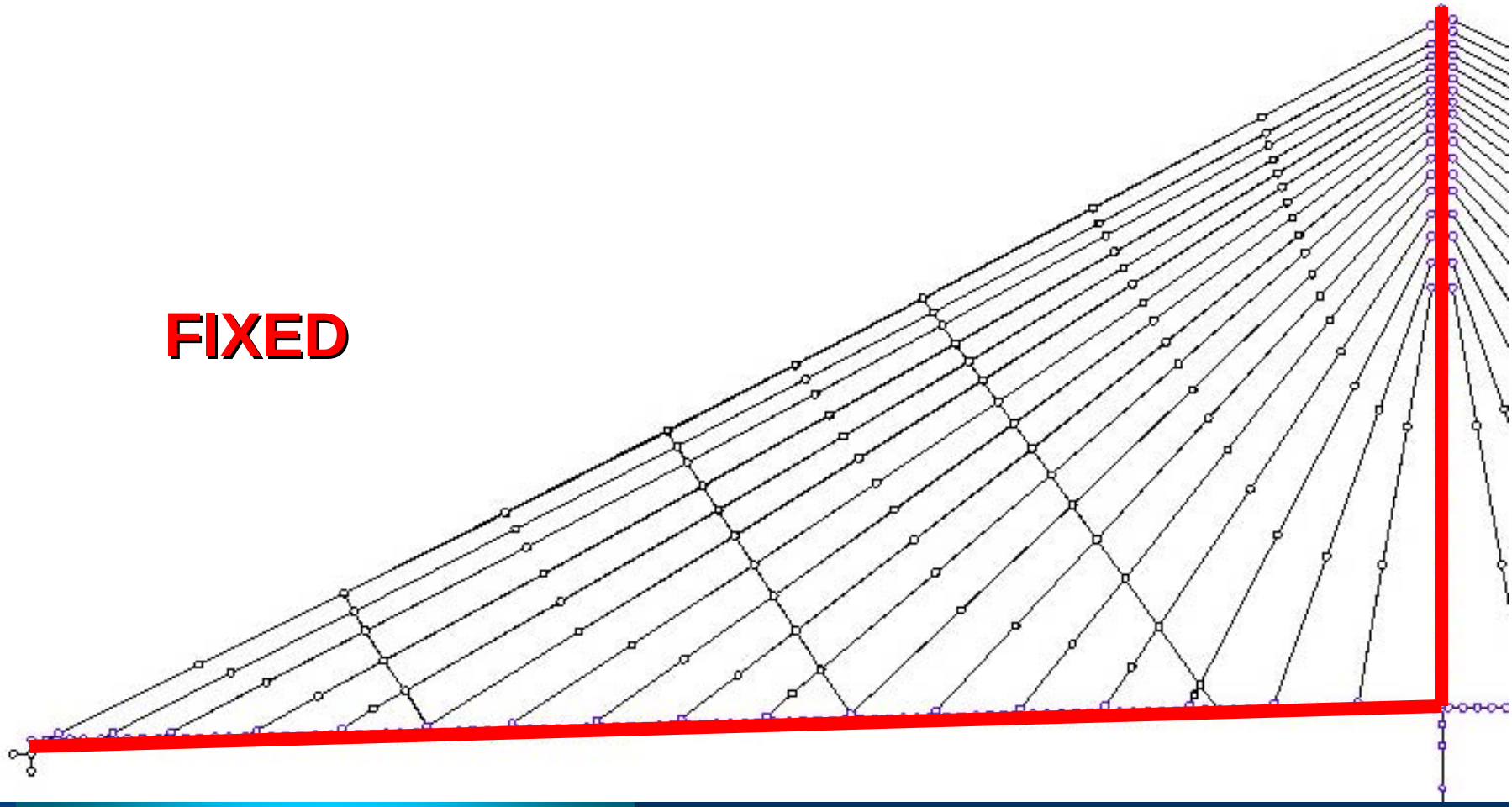
Ponte de Normandie

Cross ties were part of the record breaking design

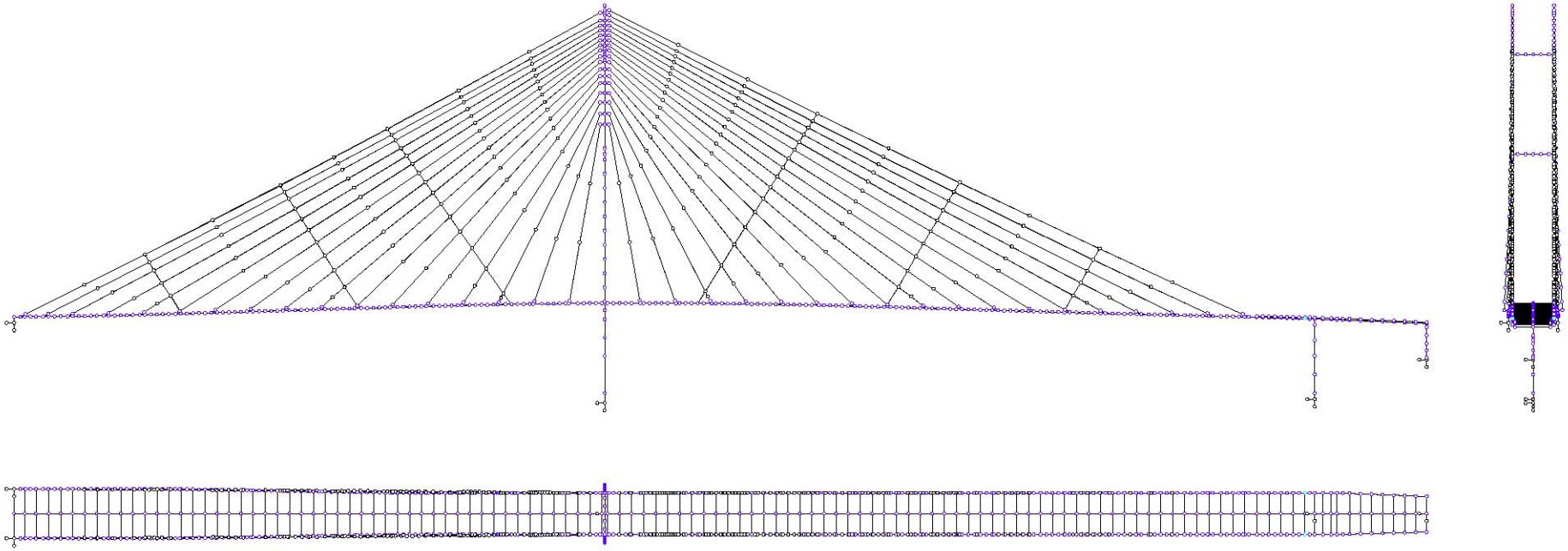


Quickly adopted in USA

Modeling of Cross Ties in Cable Fans

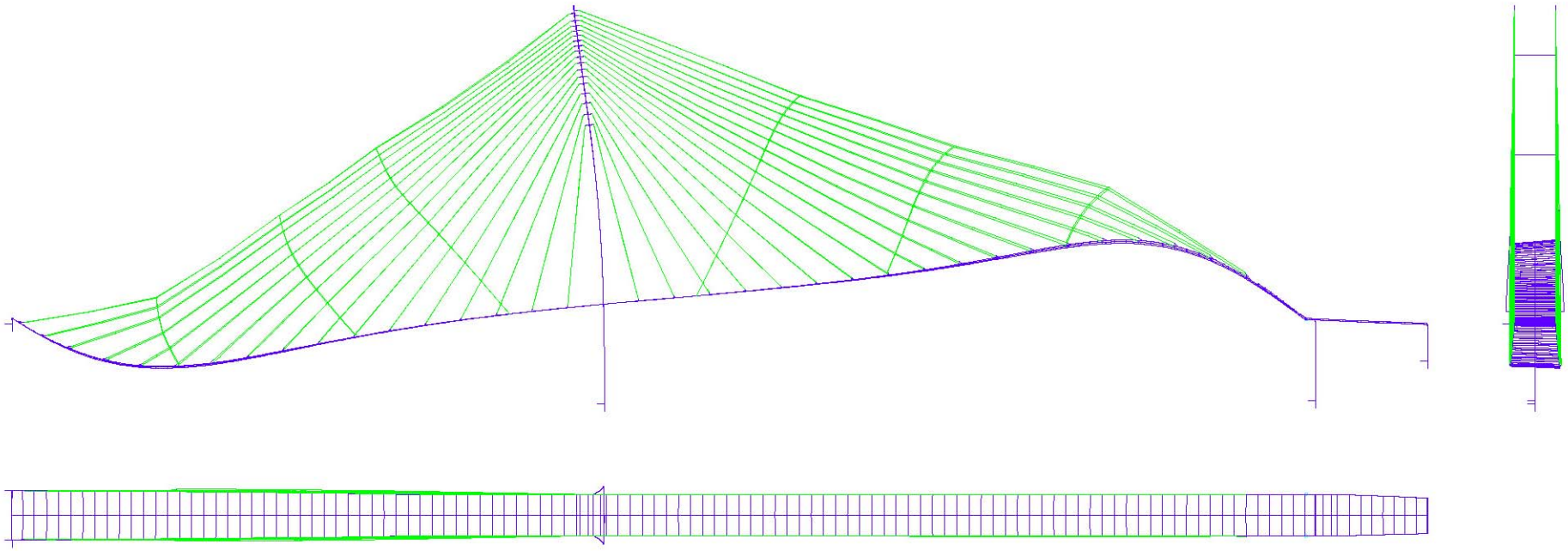


Cross Ties in Full 3D Model



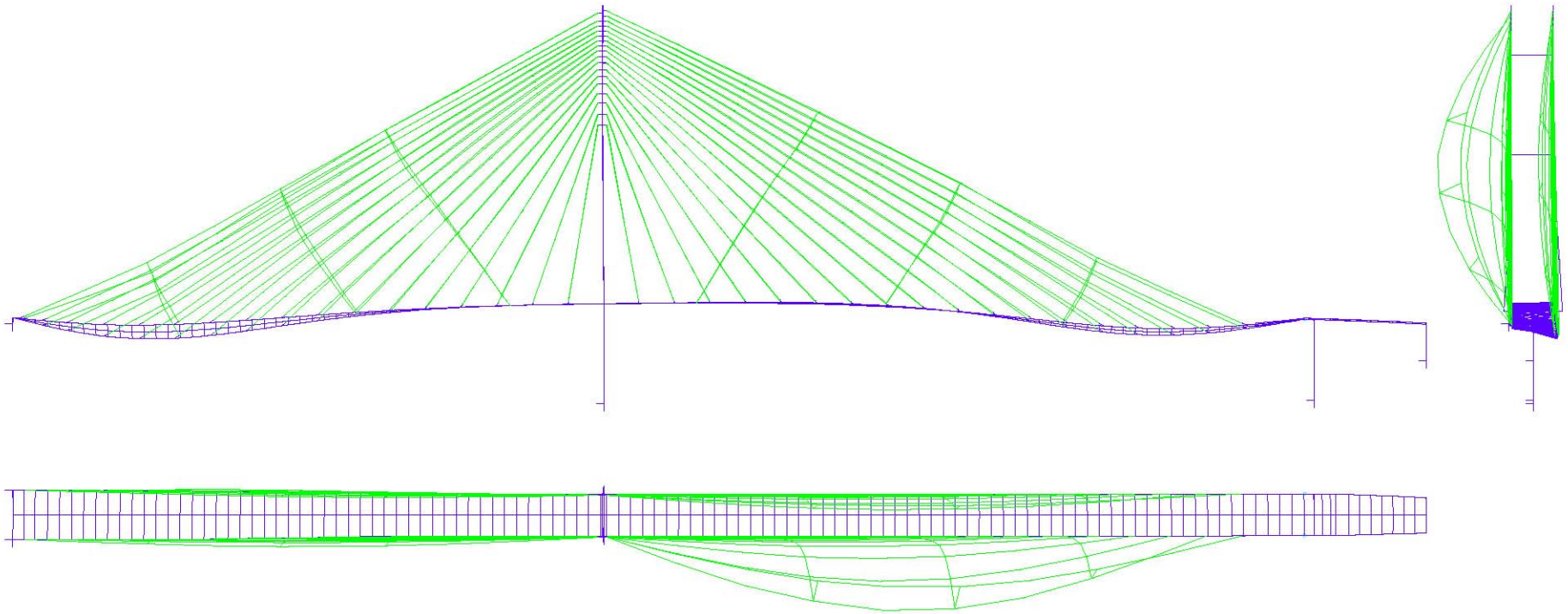
Mode 1

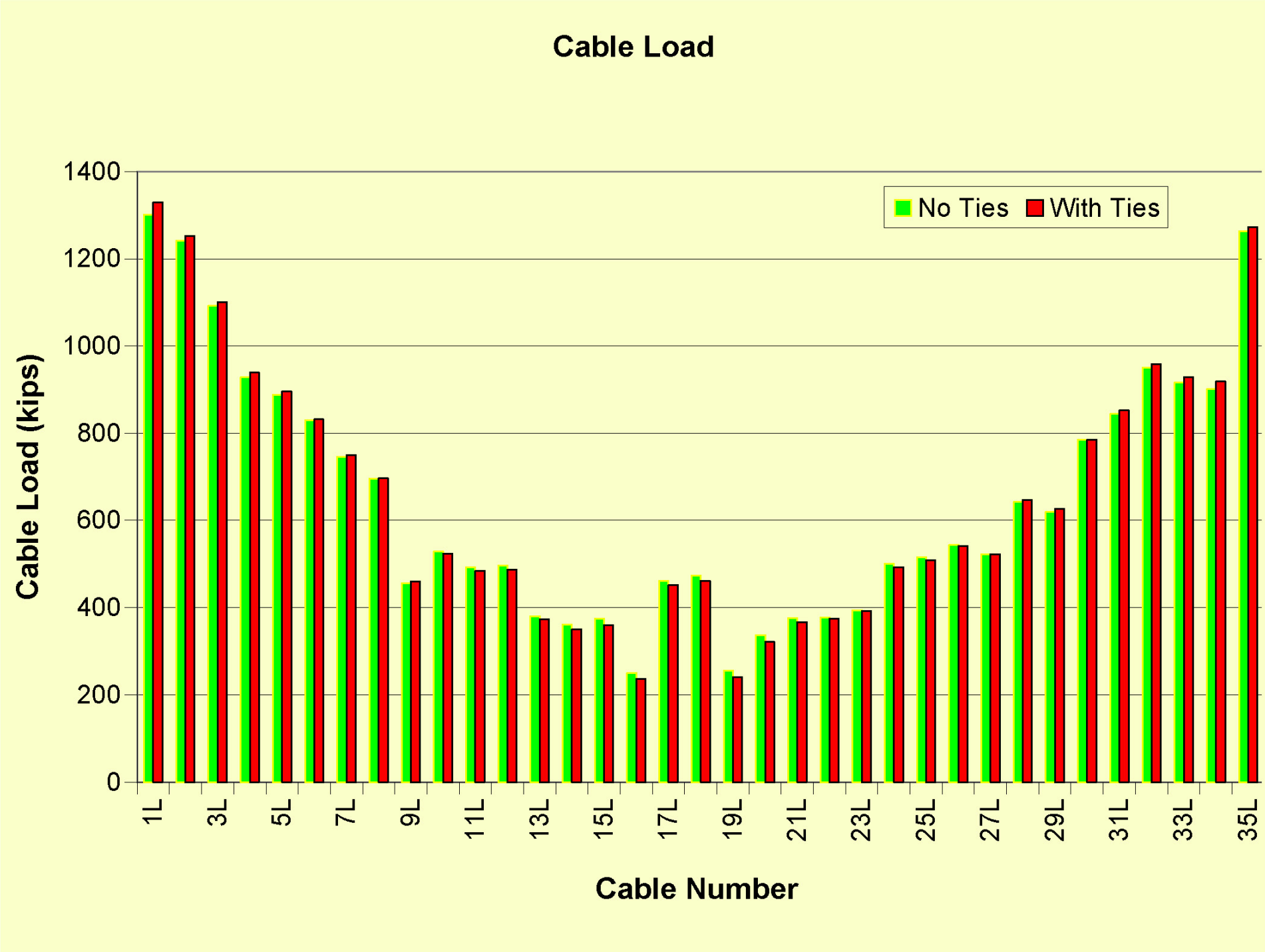
Mode 1,Period: 4.215 sec, Frequency: 0.237 HZ,

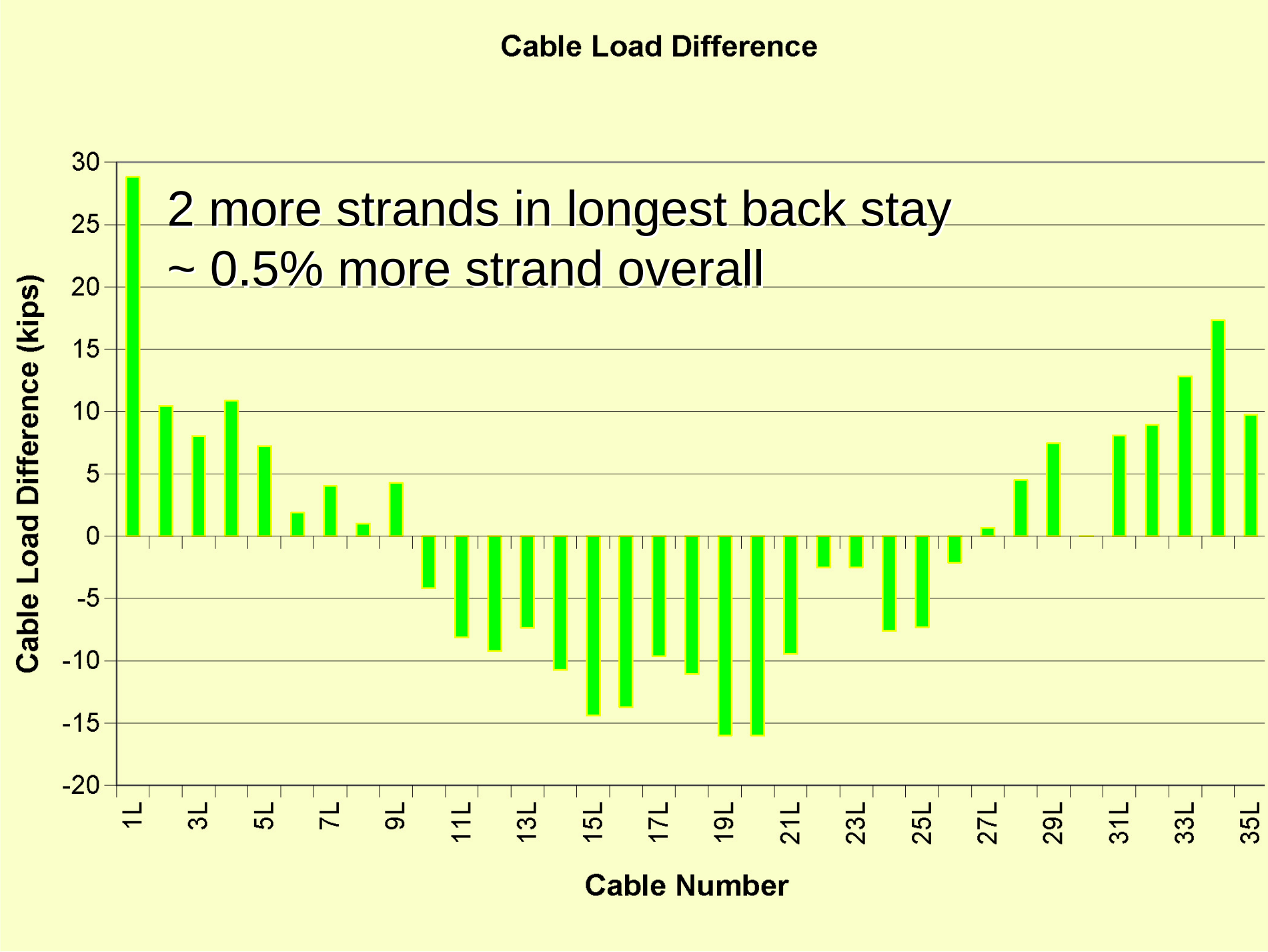


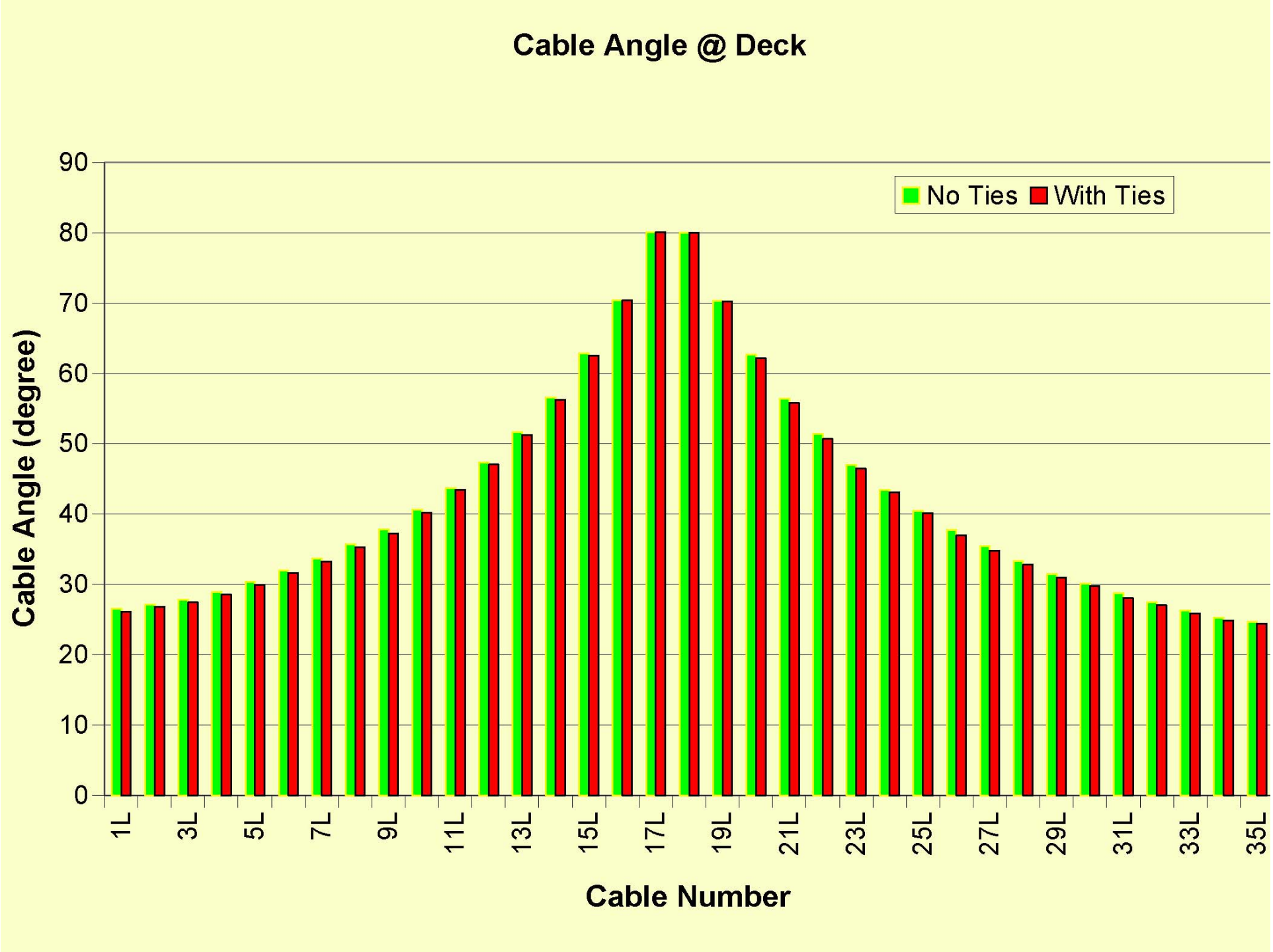
Interaction of tied Cable Fan and Deck

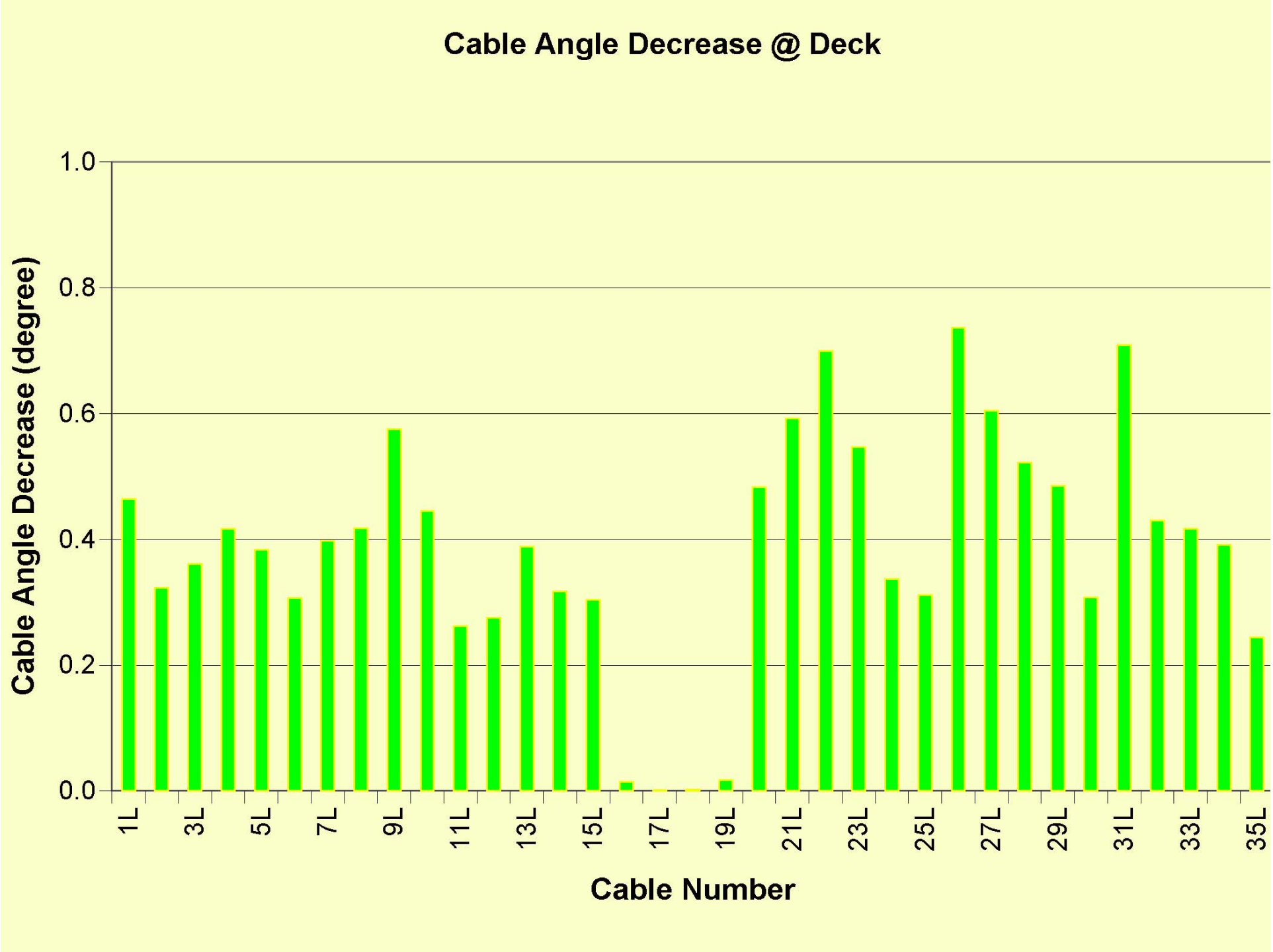
Mode 4,Period: 2.141 sec, Frequency: 0.467 HZ,



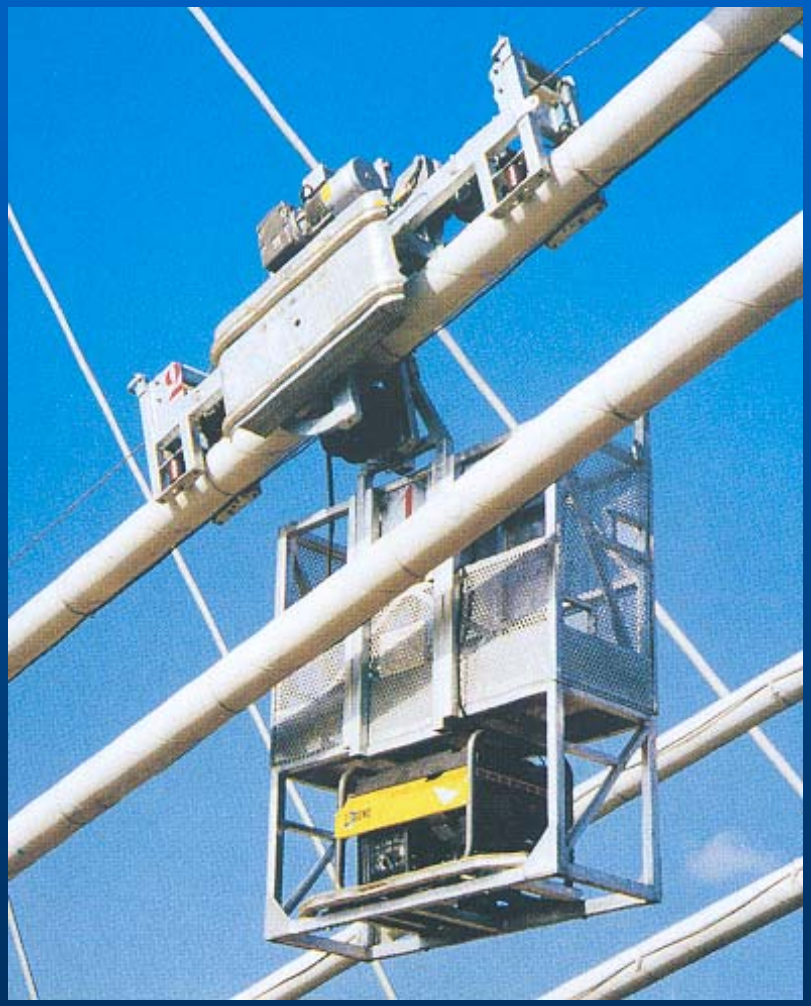

Cable Load
No Ties
With Ties
Cable Load (kips)
1400
1200
1000
800
600
400
200
0
1L
3L
5L
7L
9L
11L
13L
15L
17L
19L
21L
23L
25L
27L
29L
31L
33L
35L
Cable Number


Cable Load Difference
2 more strands in longest back stay
~ 0.5% more strand overall
Cable Load Difference (kips)
30
25
20
15
10
5
0
-5
-10
-15
-20
1L
3L
5L
7L
9L
11L
13L
15L
17L
19L
21L
23L
25L
27L
29L
31L
33L
35L
Cable Number


Cable Angle @ Deck
No Ties
With Ties
Cable Angle (degree)
0
10
20
30
40
50
60
70
80
90
1L
3L
5L
7L
9L
11L
13L
15L
17L
19L
21L
23L
25L
27L
29L
31L
33L
35L
Cable Number


Cable Angle Decrease @ Deck
Cable Angle Decrease (degree)
1.0
0.8
0.6
0.4
0.2
0.0
1L
3L
5L
7L
9L
11L
13L
15L
17L
19L
21L
23L
25L
27L
29L
31L
33L
35L
Cable Number

Cable Access for Inspection



Cross Tie Installation & Maintenance

Do you always need:

- **Helical Surface Treatment?**
  - **Low Cost**
- **Internal Dampers?**
  - **Not too Expensive?**
- **Internal and External Dampers?**
  - **Expensive and Aesthetic (local)?**
- **Cable Cross Ties?**
  - **Expensive and Aesthetic (global)?**
- **Belts, Suspenders and your shirt stapled to your pants?**

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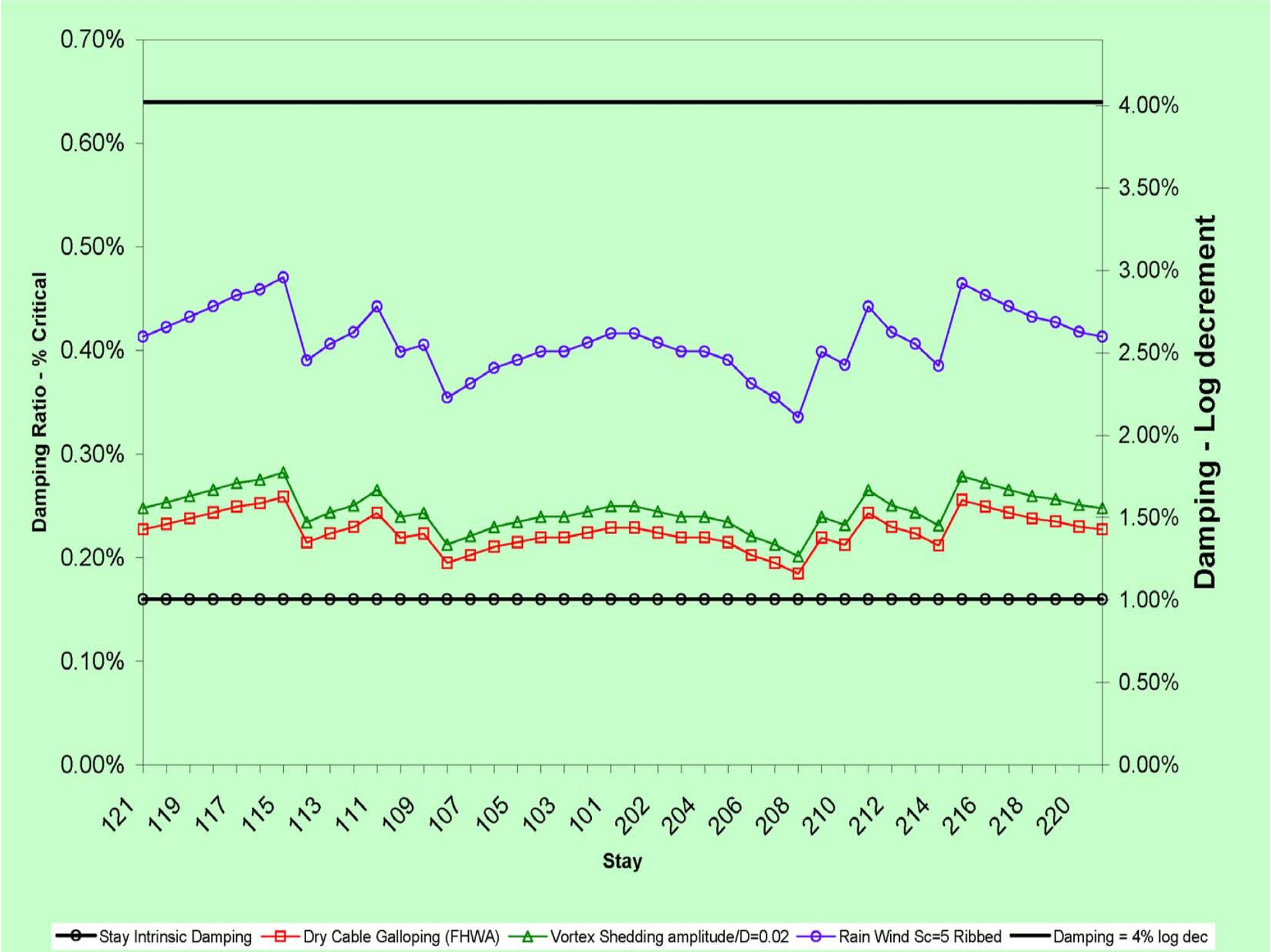
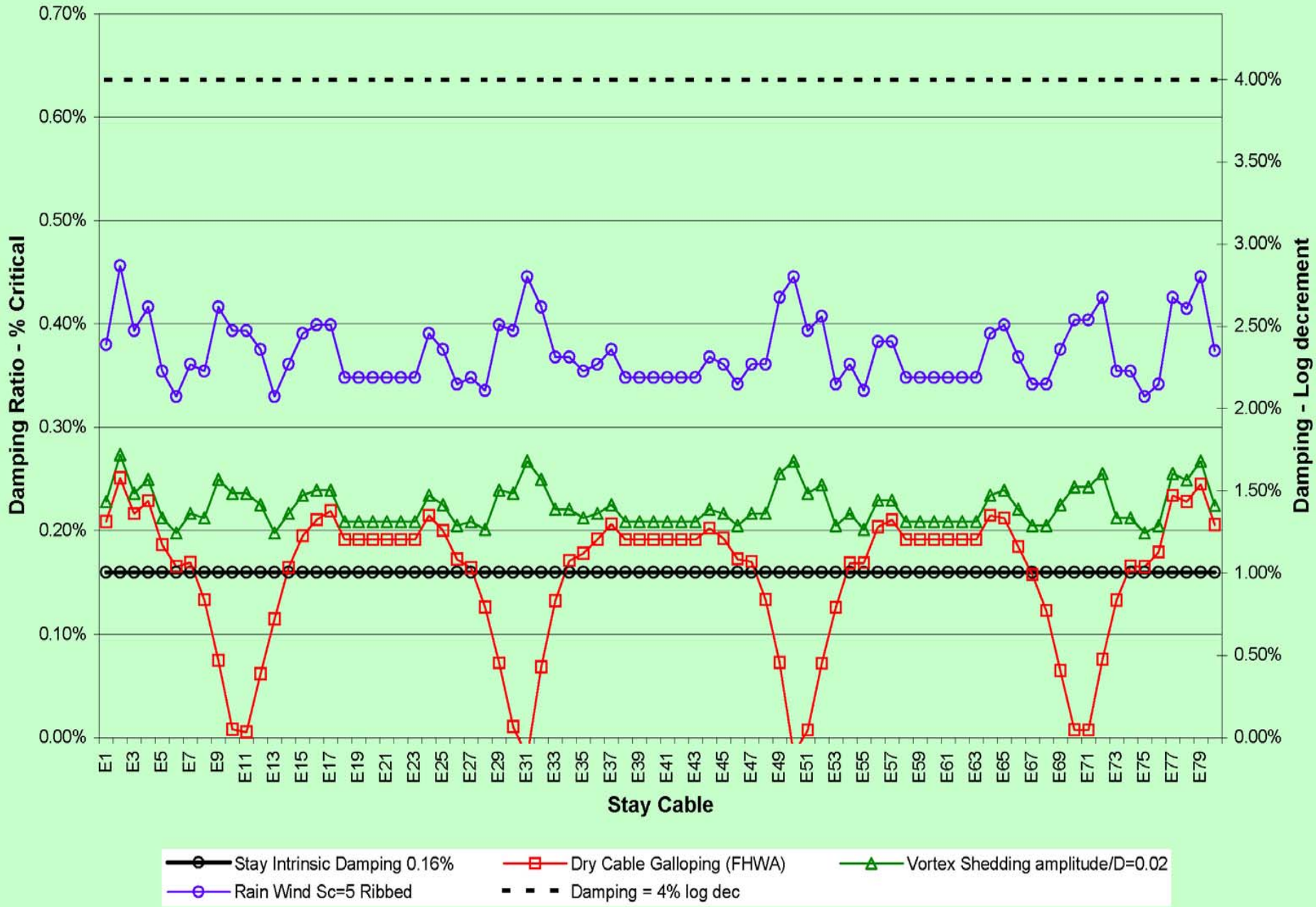
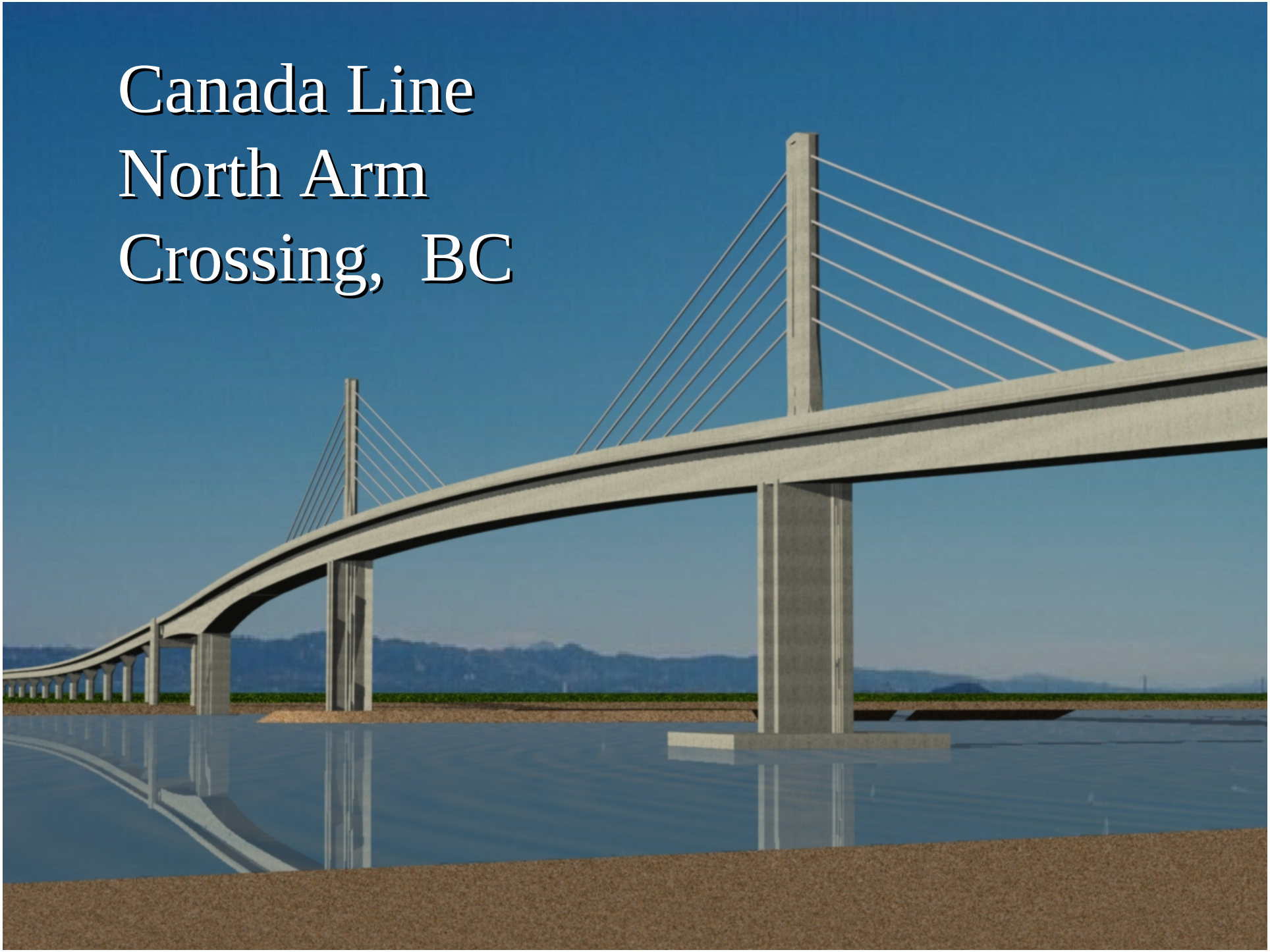
Sungai Johor Bridge,
Malaysia

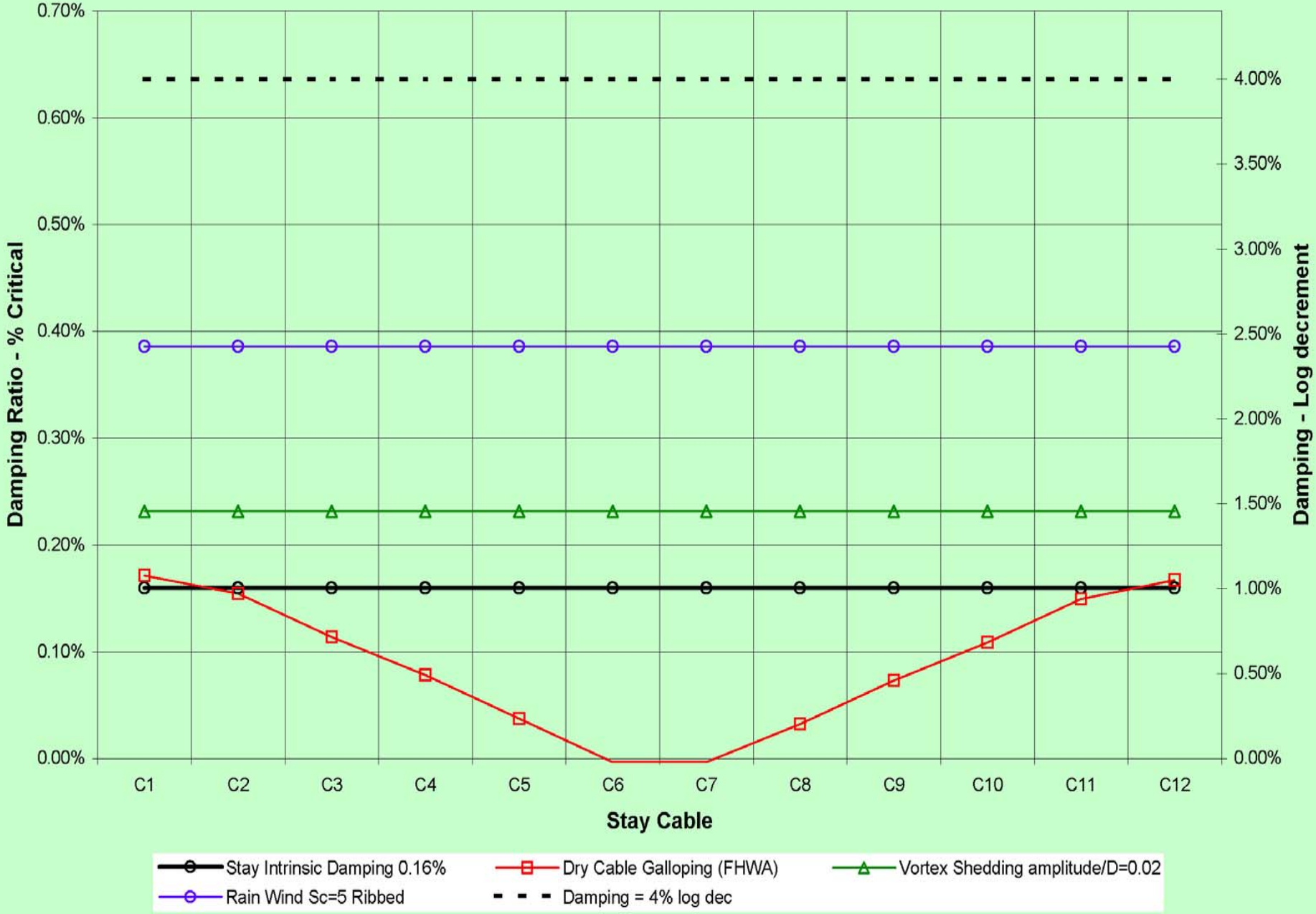

0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
Damping Ratio - % Critical
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Damping - Log decrement
121
119
117
115
113
111
109
107
105
103
101
202
204
206
208
210
212
214
216
218
220
Stay
Stay Intrinsic Damping
Dry Cable Galloping (FHWA)
Vortex Shedding amplitude/D=0.02
Rain Wind Sc=5 Ribbed
Damping = 4% log dec

Golden Ears Bridge,
Maple Ridge BC


0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
Damping Ratio - % Critical
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Damping - Log decrement
E1 E3 E5 E7 E9 E11 E13 E15 E17 E19 E21 E23 E25 E27 E29 E31 E33 E35 E37 E39 E41 E43 E45 E47 E49 E51 E53 E55 E57 E59 E61 E63 E65 E67 E69 E71 E73 E75 E77 E79
Stay Cable
Stay Intrinsic Damping 0.16%
Dry Cable Galloping (FHWA)
Vortex Shedding amplitude/D=0.02
Rain Wind Sc=5 Ribbed
Damping = 4% log dec

Canada Line North Arm Crossing, BC




0.70%
0.60%
0.50%
0.40%
0.30%
0.20%
0.10%
0.00%
Damping Ratio - % Critical
4.00%
3.50%
3.00%
2.50%
2.00%
1.50%
1.00%
0.50%
0.00%
Damping - Log decrement
C1
C2
C3
C4
C5
C6
C7
C8
C9
C10
C11
C12
Stay Cable
Stay Intrinsic Damping 0.16%
Dry Cable Galloping (FHWA)
Vortex Shedding amplitude/D=0.02
Rain Wind Sc=5 Ribbed
Damping = 4% log dec

Full Scale Aerodynamic Test

- **Hong Kong, China**
- **Millau, France**
- **Rion Antirion, Greece**
- **SkyBridge, Canada**

Ting Kau, Hong Kong

- In service since 1998

- 384 Cables
- Longest Stay Cables in the world at time of installation.

Ting Kau, Hong Kong

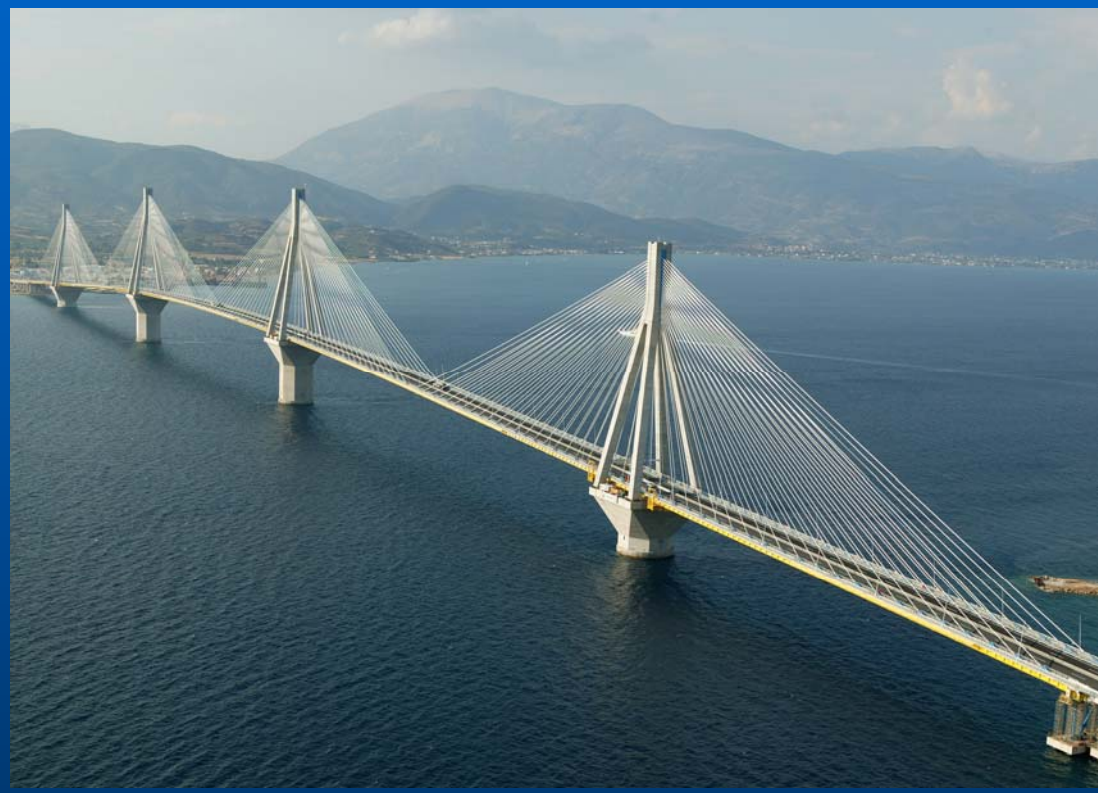
- **Helical Surface Treatment**
- **Dampers on longest Cables**

Viaduct de Millau, France

- In service since Dec 2004
- 154 Cables
- Height above ground varies from 70m to 240m

Rion Antirion, Greece

- In service since Aug 2004
- 368 cables
- Helical surface treatment
- Internal dampers



SkyTrain Bridge, Vancouver, BC

- In service since 1988
- No Helix
- No Dampers
- Y<=2

Overview

- Current Design Guidelines
- Dynamic Characteristics of Stay Cables
- Cable Vibration Mechanisms
- Mitigation Measures
- Case Studies
- Further Research Needs

Future Research Needs

- **Rain Wind Vibration**
  - **Design guidelines exist to determine the amount of damping required to avoid the problem for smooth cables (Sc>10)**
  - **However all new cables now have helical surface treatments. Savings could be realized if guidelines were drawn up to identify how much damping is required for cables with surface treatment**

Further Research Needs

- **Galloping Phenomena**
  - **Current codes need to incorporate findings from recent FHWA sponsored large scale tests carried out on smooth cables.**
  - **Further tests should be carried out on cables with helical surface treatments to determine if these findings can be extended.**

Further Research Needs

- **Cross Tie Arrangements & Parametric Excitation**
  - **The influence of including the real mass and stiffness properties of decks and towers in modeling of stay vibrations needs to be understood.**
  - **The performance of major international cable stayed bridges without cross ties should be examined to answer the question:**
    Is the helical surface treatment combined with internal/external dampers sufficient?

Thank You