Wind Induced Vibration of Cable Stay Bridges Workshop
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Vibration Mitigation through Cross-ties between Cables. Analysis and Design Experiences (Part 1)

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Organization of the Presentation

- **Part 1: Luca Caracoglia**, Department of Civil and Environmental Engineering, Northeastern University, Boston, MA (**22 min**):
  - Cross-ties between stays. Mechanical system, proposed analytical method for the solution of the free-vibration problem.
  - Case study, Fred Hartman Bridge, Houston, TX. Analysis, identification of the network mechanics through experimental data; suggestions, potential limitations, alternative solutions.

- **Part 2: Steven T. Hague**, Chief Structural Engineer, HNTB Corporation, Kansas City Bridge Group, Kansas City, MO (**22 min**):
  - Cross-ties between stays. A case study for the Bill Emerson Memorial Bridge at Cape Girardeau, Missouri. Application of the design procedure prescribed in current recommendations for stay cable design, testing and installation.

- Questions, discussion

Motivation

- Susceptibility of inclined stays to wind and wind-rain induced vibration in long cable-stayed bridges.
- Large-amplitude oscillation due to very low mechanical damping in cables.

Countermeasures (more frequently used):

1) Installation of mechanical dampers on “sensitive” stays: linear, nonlinear, MR (semi-active);
2) **Transformation of the system into a cable network by means of transverse cross-ties;**
3) Combination of the above methods;
4) Others.

Objectives of Part 1

Three main objectives will be addressed:

- *Objective 1*: Cross-ties and cable networks: Analytical solutions and case study: Fred Harman Bridge, Houston Ship Channel, Texas.
- *Objective 2*: Suggestions for design: number of restrainers, configuration, frequency interval to be detuned.
- *Objective 3*: Introduction to alternative solutions: cable networks with the addition of localized dampers (internal locations or connected to the deck).

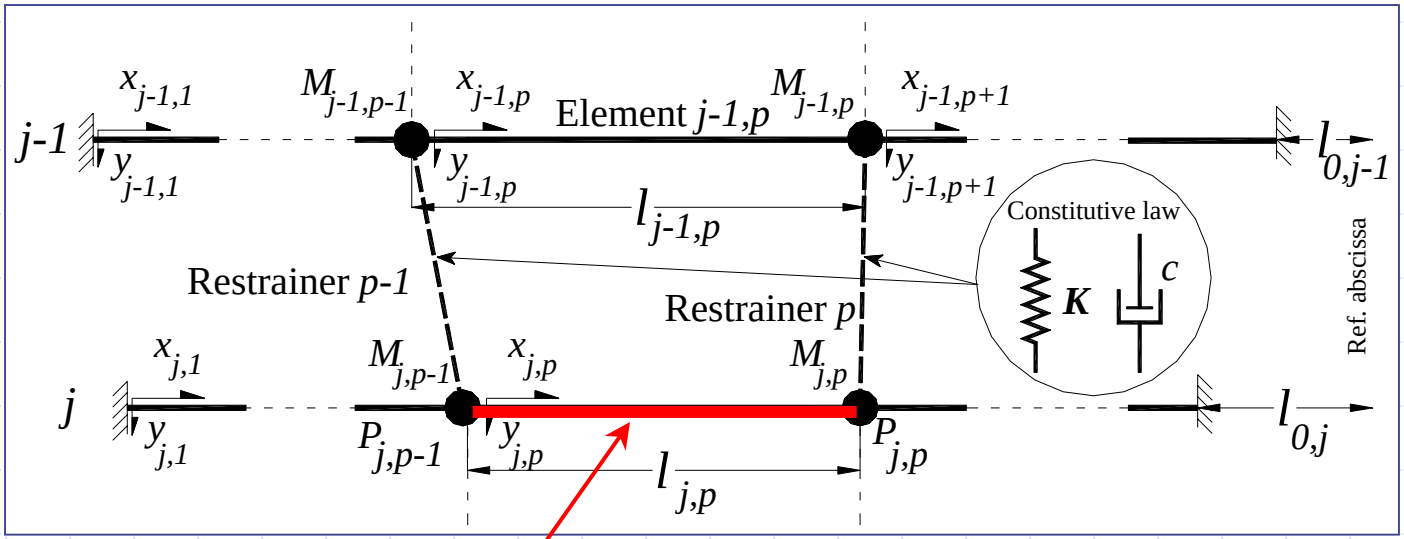
Objective 1:

Dynamic Modeling of Cable Networks (Stay Systems with Cross-Ties)

Generalized Cable Network Configuration (Taut-String Theory)

j-th cable:

- Length L_j
- Tension H_j
- Mass per unit length m_j
- Lumped mass M_{jp}



- Simulation of each ***j,p-th*** **cable element** by means of the wave equation (PDE).
- Free-vibration problem for transverse displacements, $y_{jp}(x_{jp},t)$:

$$H_j \frac{\partial^2 y_{jp}}{\partial x_{jp}^2} = \mu_j \frac{\partial^2 y_{jp}}{\partial t^2} \quad \text{with } j = 1,\ldots,n;\ p = 1,\ldots,m_j$$

Extension of the Taut-String Theory to Cable Networks (cont'd)

The transverse motion can be postulated as $y_{jp}(x_{jp},t) = \mathrm{Re}[Y_{jp}(x_{jp})e^{i\omega t}]$,

where ω is a **complex frequency** (from PDE's to ODE's) $\omega = \omega_{RE} + i\omega_{IM} = \gamma\omega_{01}$

(NB: complex frequency is introduced when dampers are also present; otherwise **real**)

Proposed solution for the spatial coordinate (trigonometric functions):

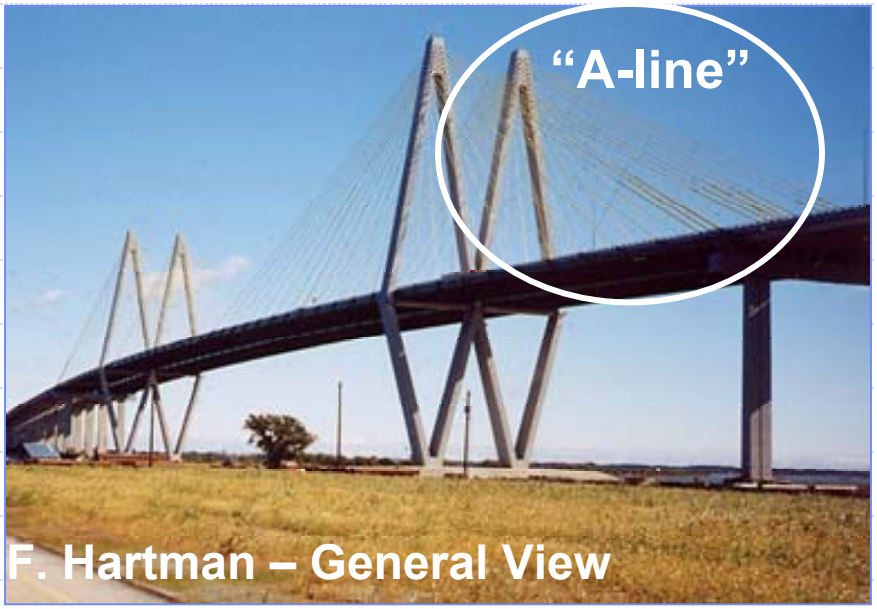
$$Y_{j,p}(x_{j,p}) = A_{j,p}\sin\left(\frac{\gamma\pi}{L_j}f_j x_{j,p}\right) + B_{j,p}\cos\left(\frac{\gamma\pi}{L_j}f_j x_{j,p}\right)$$

Reference Cable with circular frequency $\omega_{01} = \pi / L_1 \cdot (H_1/\mu_1)^{1/2}$

Unknown amplitudes $A_{j,p}$ and $B_{j,p}$ (real modes if only restrainers)

Algebraic system to be solved by a set of equilibrium, compatibility and continuity equations
$S\Phi=0$ (e-value problem)

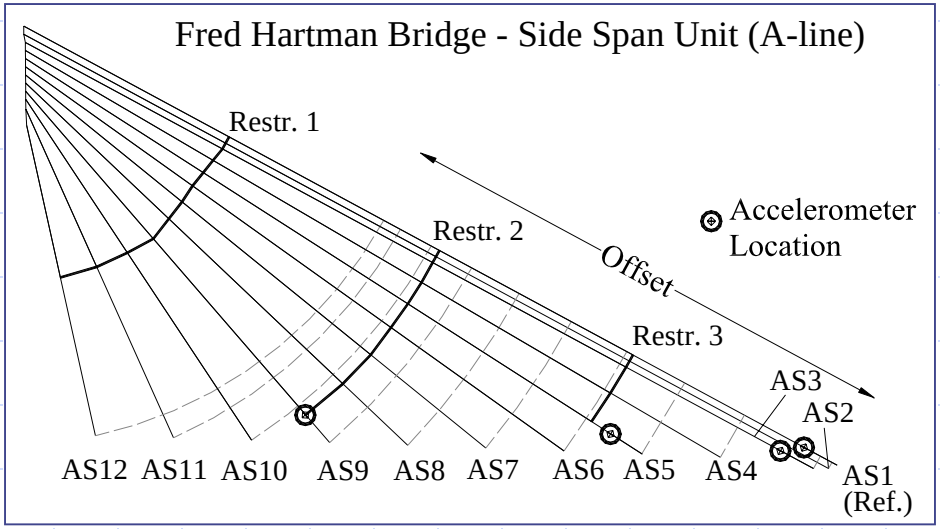
Long-term Monitoring on the Fred Hartman Bridge (Houston, TX)



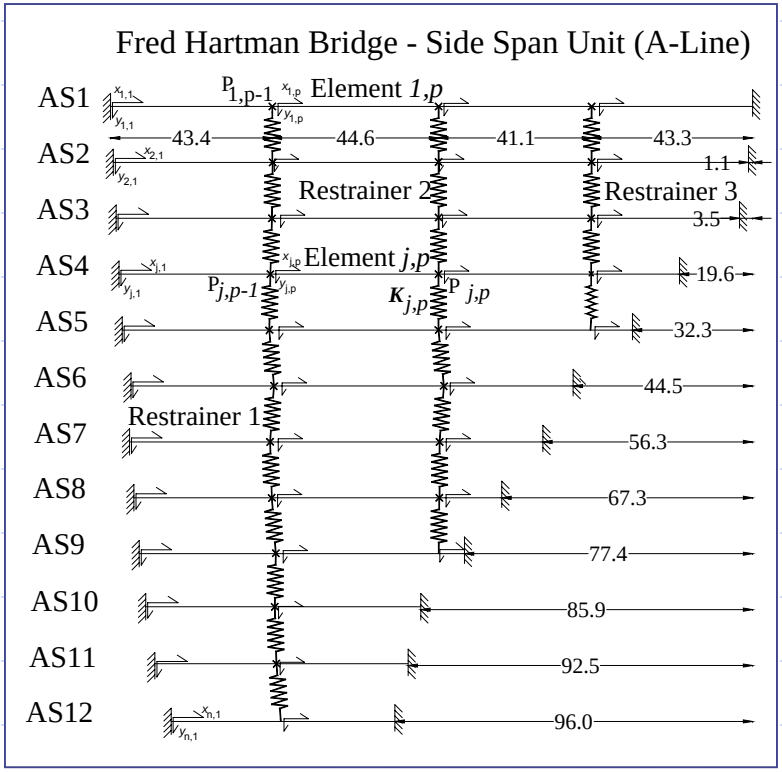
- Twin-deck cable stayed bridge, central span 380m, side spans of 147m
- Fred Hartman cross-ties: "A-line" side span network: 12 stays, 3 cross-ties (original configuration)

Cable Network Analysis

- Study of the current configuration of the "A-line" twelve-stay three-tie network, Fred Hartman Bridge, Houston, Texas

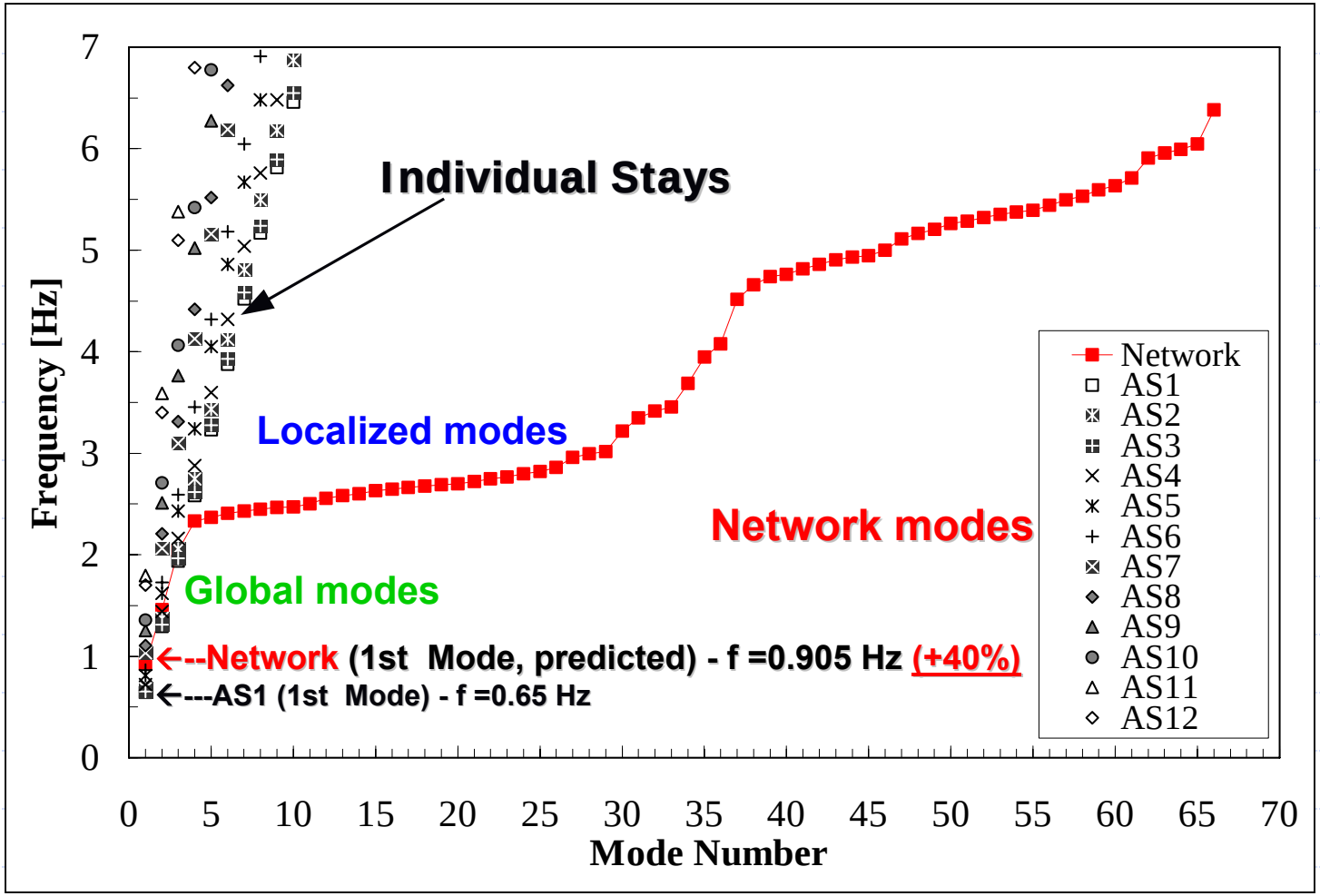


A-line Network

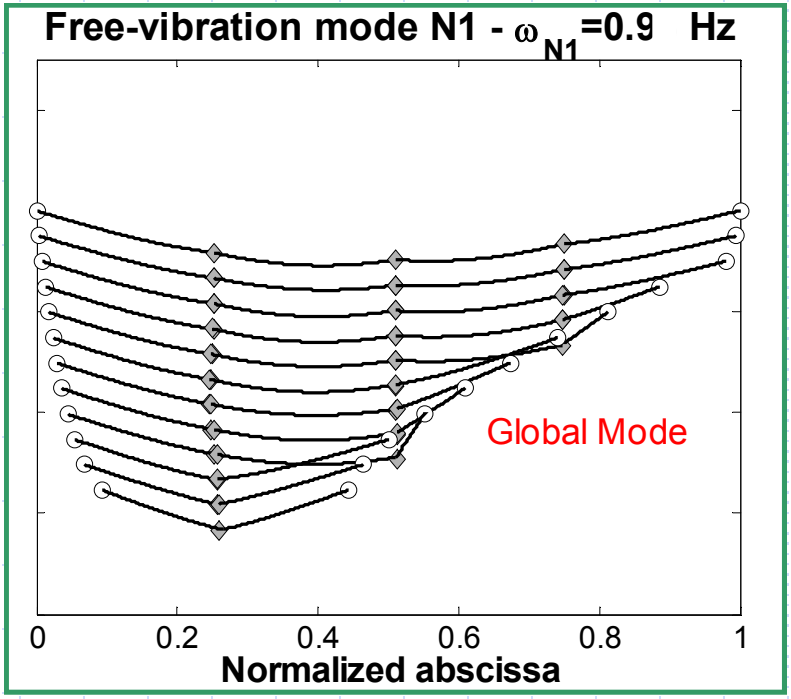


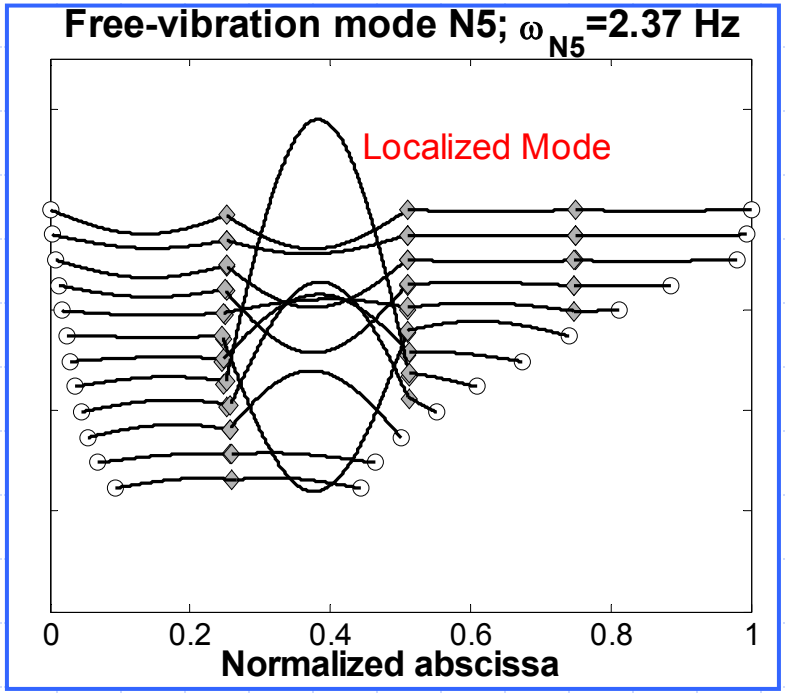
Analytical Model

Fred Hartman ("A-line" – Side Span) Mode-Frequency Evolution Chart



Example of Global and Localized Modes



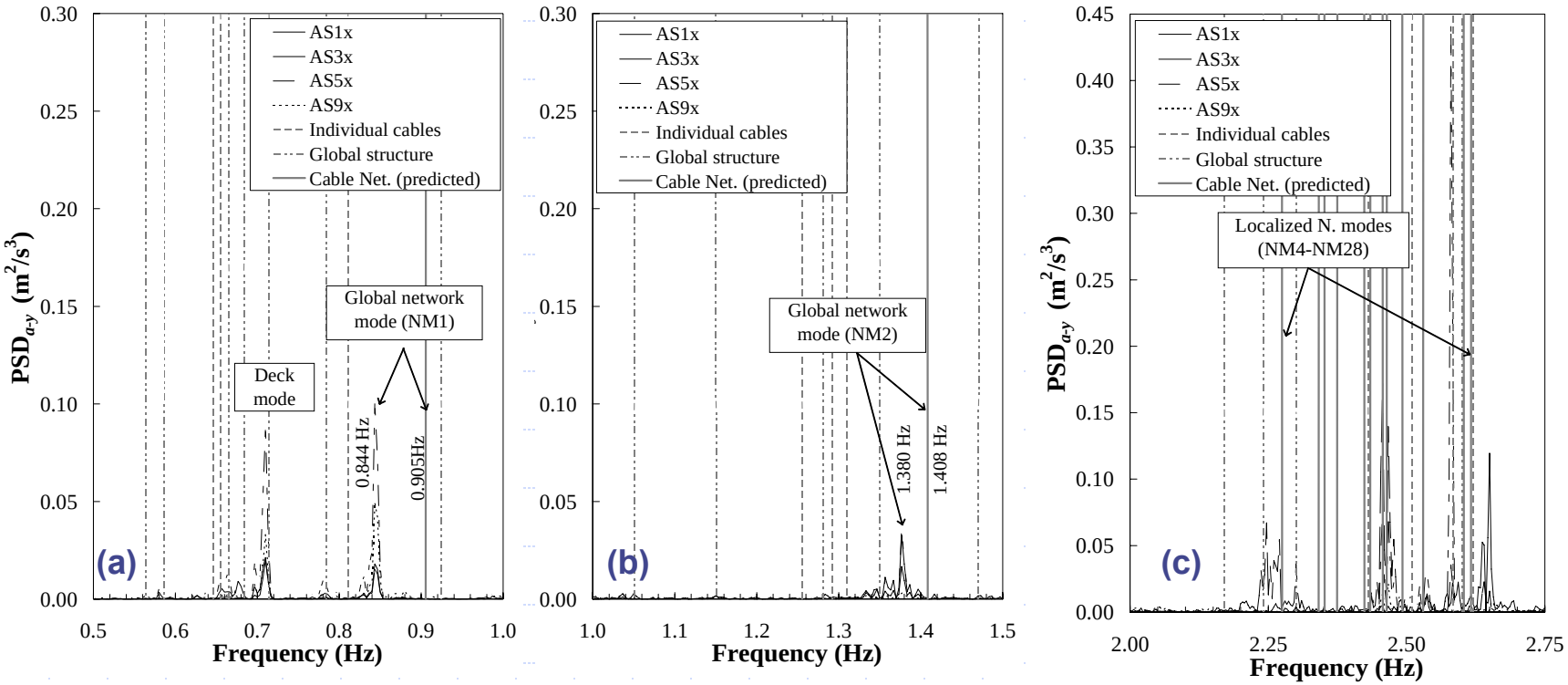


- Fred Hartman Bridge, current configuration, side span ("A-line") network: 12 stays, 3 cross-ties

Observations on the Network Performance

- **Global modes** (e.g., 1-4):
  - Contribution from all network elements;
  - Frequency increment with respect to individual stays;
  - Large modal mass (more input wind energy is required).
- **Localized modes** (e.g., 5-29):
  - Contribution from internal elements of the network only;
  - High number of solutions (plateau);
  - Low modal mass (susceptible to vibration, if the location of the plateau is unfavorable);
  - "No" frequency increment with respect to individual stays.
- Both cases apply to in-plane vibration only. Out-of-plane?

Comparison of the Proposed Model with Experimental Observations



Fred Hartman Bridge -"A-line" side span.

Acceleration Power Spectral Density (in-plane) recorded on stays AS1, AS3, AS5, AS9 (record H02236) and predicted network frequencies (solid, dashed and dotted lines).

(a) 0.5 to 1.0 Hz, **(b)** 1.0 to 1.5 Hz, **(c)** 2.0 to 2.75 Hz.

Objective 2:

Optimization of a Cable Network (In-plane Modes and Absence of Dampers)

Optimization of "In-Plane" Cable Networks

- Two aspects need to be considered:
  1. Characteristics of the external action to be suppressed (performance)
  2. Expected forces/stresses on the secondary system (cross-ties)

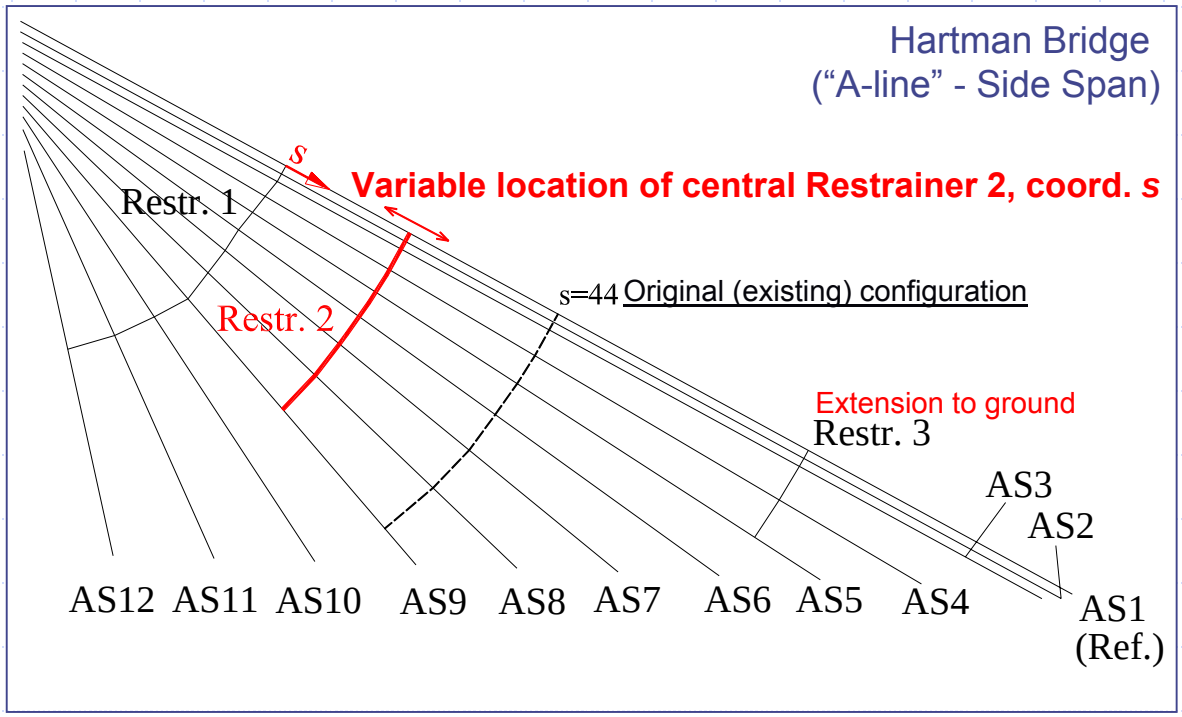
First Aspect:

- Number and location of restrainers (configuration)
- Fundamental frequency of a 150m inclined stay in the range of 0.5 to 0.7Hz
- Frequency interval of significance for wind and wind-rain vibration (from full-scale measurements on the Fred Hartman Bridge): 0 to 3 Hz

Second Aspect:

- Geometric and physical characteristics of the wire ropes and anchorages

In-Plane Networks - Parametric Study



7 Cases were analyzed (variable number of elements between AS7 and AS9)**:**

- *s*=0 (two restrainers), *s*=15,30,58,72 (m) *s*=44 (existing network)
- *s*=88 (2 restrainers with extension to ground of Restrainer 3)

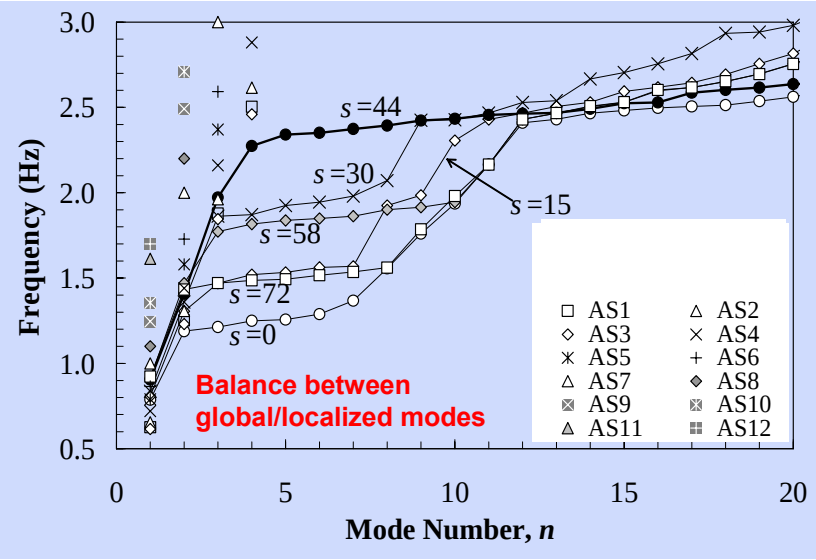
Optimization of Cable Networks (cont'd) :

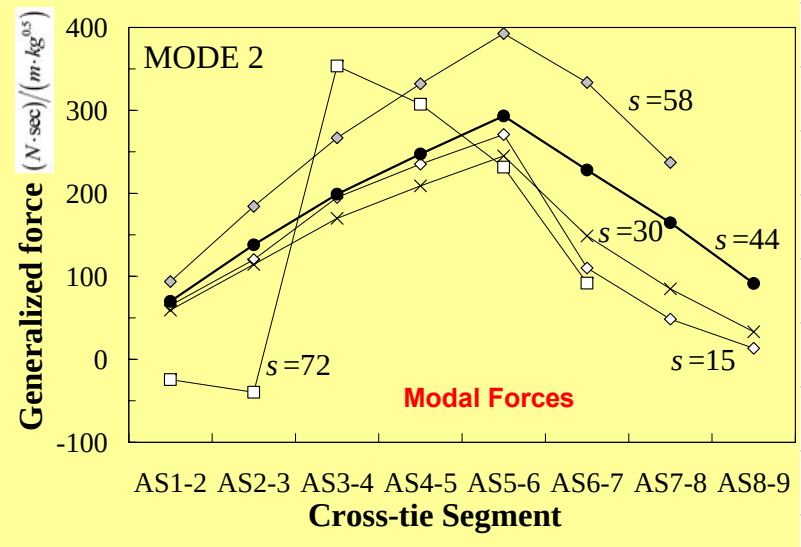
Guidelines for Network Performance

- Two restrainers are necessary on the Hartman Bridge (Caracoglia and Jones, 2005)

- Balance between global (frequency increment) and localized modes;
- Favorable location of the "first plateau" (first set of localized modes);
- Limit the extension of the "first plateau" to reduce the number of these solutions.

- Attention to generalized modal forces (e.g., non-symmetric tie configurations).





Objective 3:

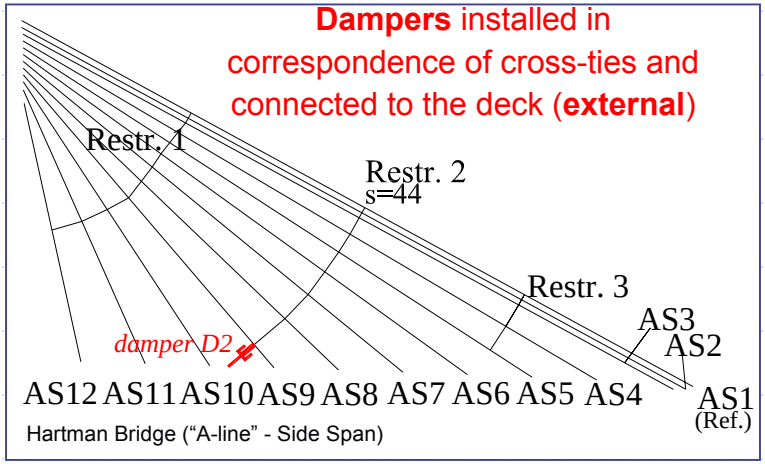
Introduction to Alternative Solutions (Cable Network with the Addition of Discrete Dampers)

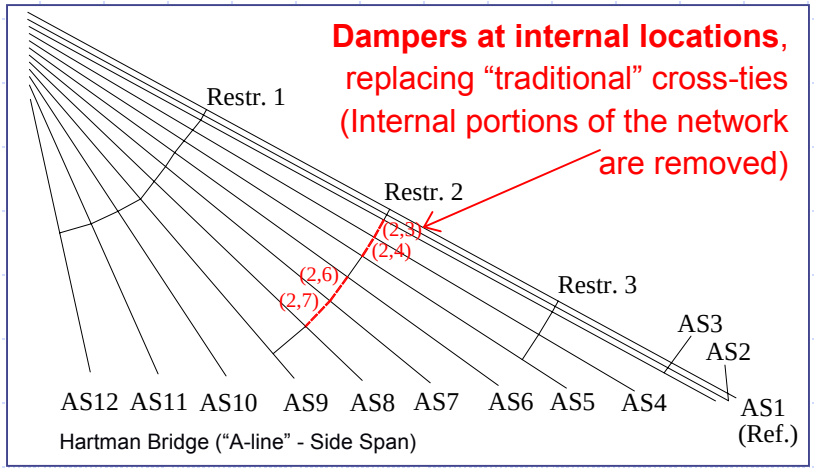
Optimization of "Damped" Cable Networks

Introduction:

- Adding damping may be desirable (cross-ties incapable of direct energy dissipation).
- Severe but rare events can induce significant vibration.
- Dampers can be <u>connected to the deck</u> (Caracoglia and Jones, 2003 and 2006) or <u>between two stays</u> (Caracoglia and Jones, 2004).

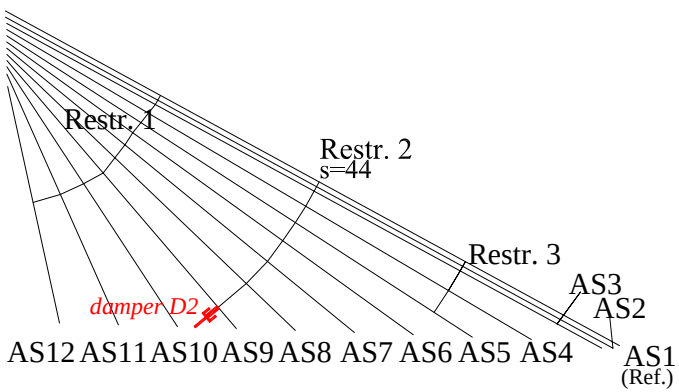
Idea (look at the problem from the point of view of the designer):

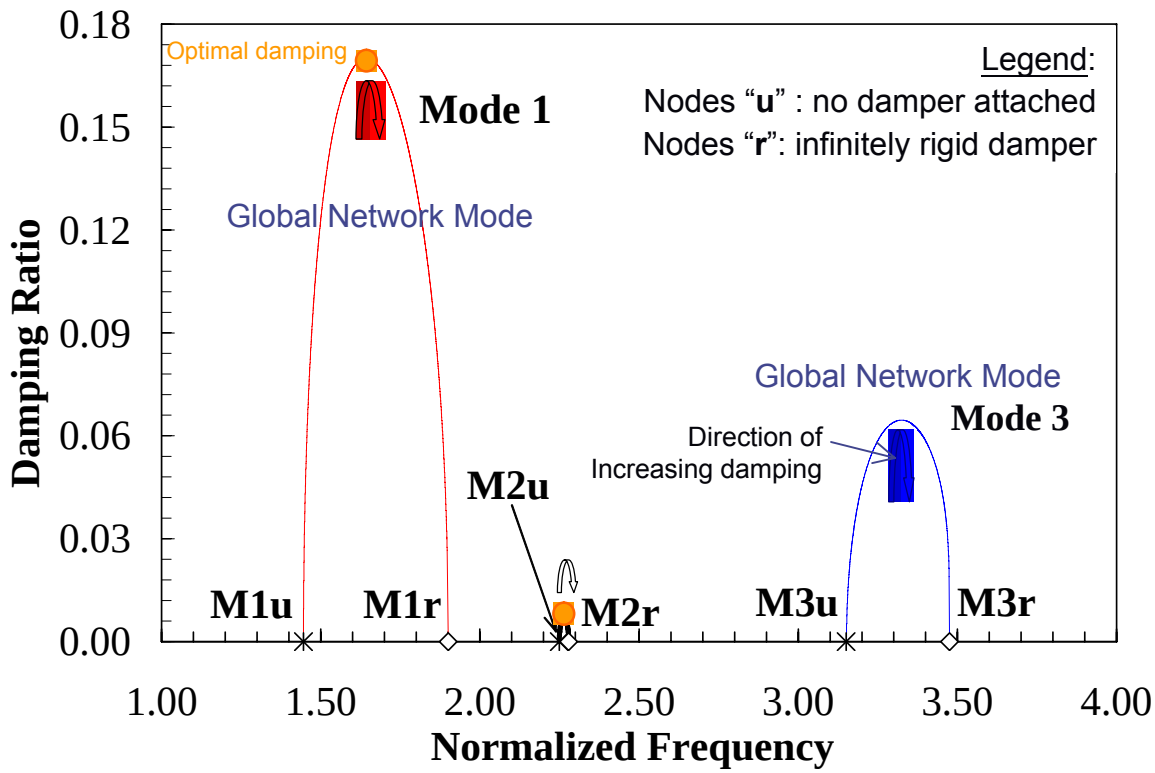




Example: Cable Network with One External Damper

Fred Hartman Bridge; (damper AS9 to deck, Restrainer 2), global network modes 1 to 3





$$\rho_{D2} = c_{D2}\left(H_1\mu_1\right)^{-0.5}$$ Normalized damper parameter

$$\eta = \sqrt{\frac{\left(\omega_{IM}/\omega_{RE}\right)^2}{\left(\omega_{IM}/\omega_{RE}\right)^2+1}}$$ Damping ratio (% to critical)

Note: The addition of a second damper connected to the deck (Restrainer 3) allows for the simultaneous optimization of more (global) modes at the same time (Caracoglia and Jones, 2006).

Concluding Remarks (Part 1)

- Modeling of cable networks (systems of stays and cross-ties) through linear wave-equation. Validation through the study of an existing system.
- Analyses confirm the efficacy of the cross-ties for suppression of in-plane stay vibration (frequency and modal mass increment; no direct dissipation).
- Design and optimization guidelines derived from the study of the existing system.
- Generalization to broad range of cases is difficult (complexity of the system, asymptotic design curves are seldom derivable).
- Alternative solutions (dampers and cross-ties). Introduction.

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Main References

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Cable Networks with the Addition of Dampers Connected to the Deck

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Cable Networks with the Addition of Dampers at Internal Locations

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