Characterisation of the Force and Integrity of Tensioned Members

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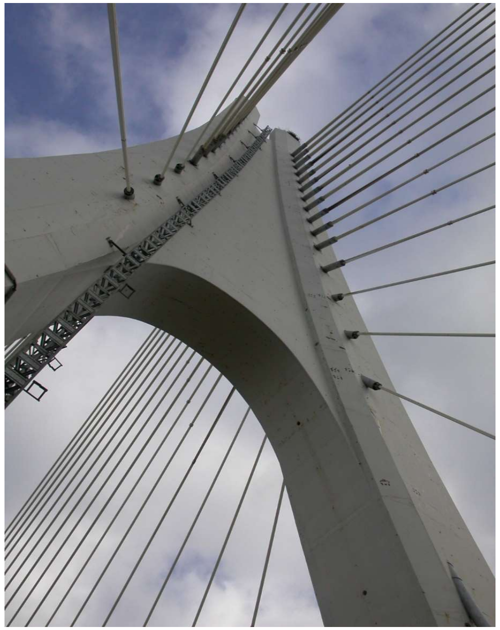
POLITECNICO MILANO 1863

Introduction

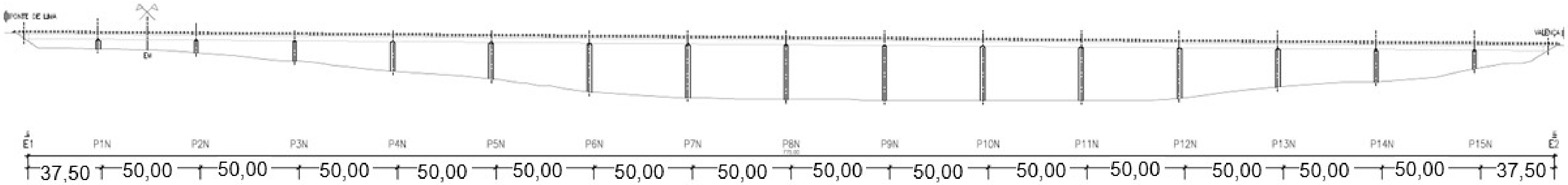


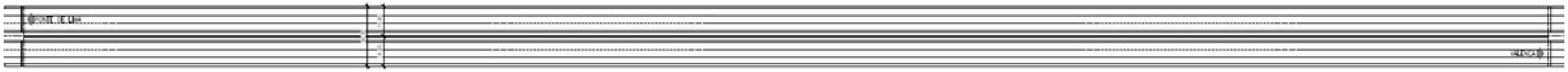




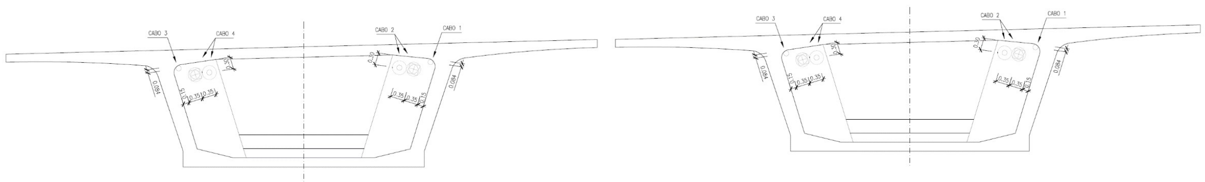



Assessing damage in a cable structure

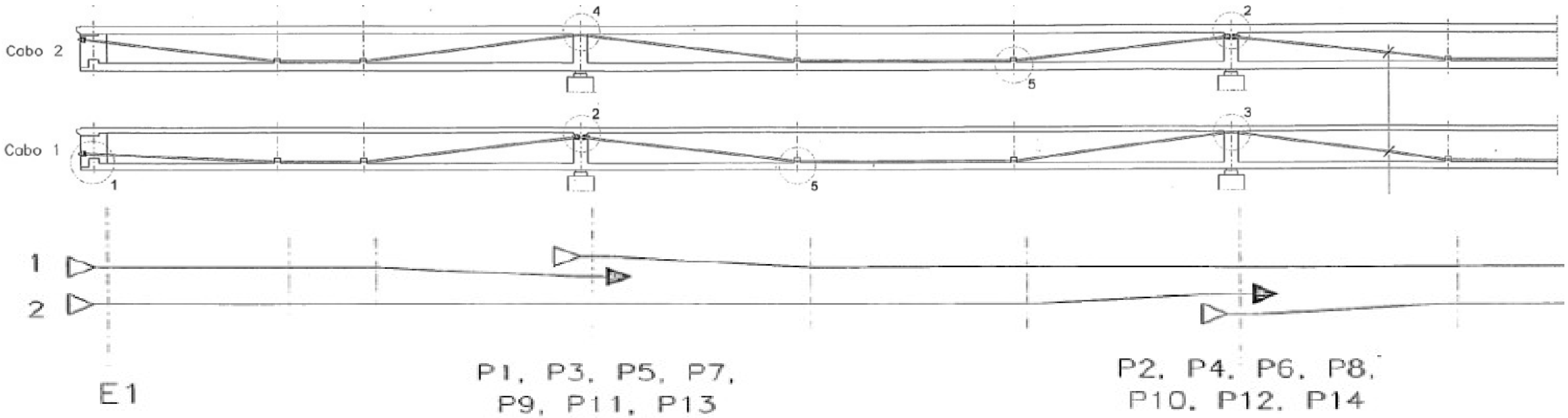





Câncio Martins, 1997



Assessing damage in a cable structure



Can we use global bridge monitoring to detect cable damage?

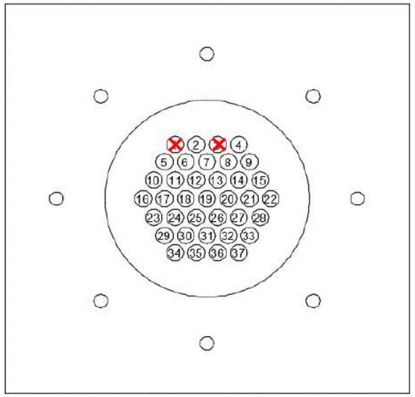
Rongrong Hou, Yong Xia, “Review on the new development of vibration-based damage identification for civil engineering structures: 2010–2019 “, Journal of Sound and Vibration491 (2021): … Although vibration-based damage identification methods have been successfully applied to mechanical and aerospace structures, the applications of these methods to practical civil structures are far from maturity…

The International Guadiana Bridge

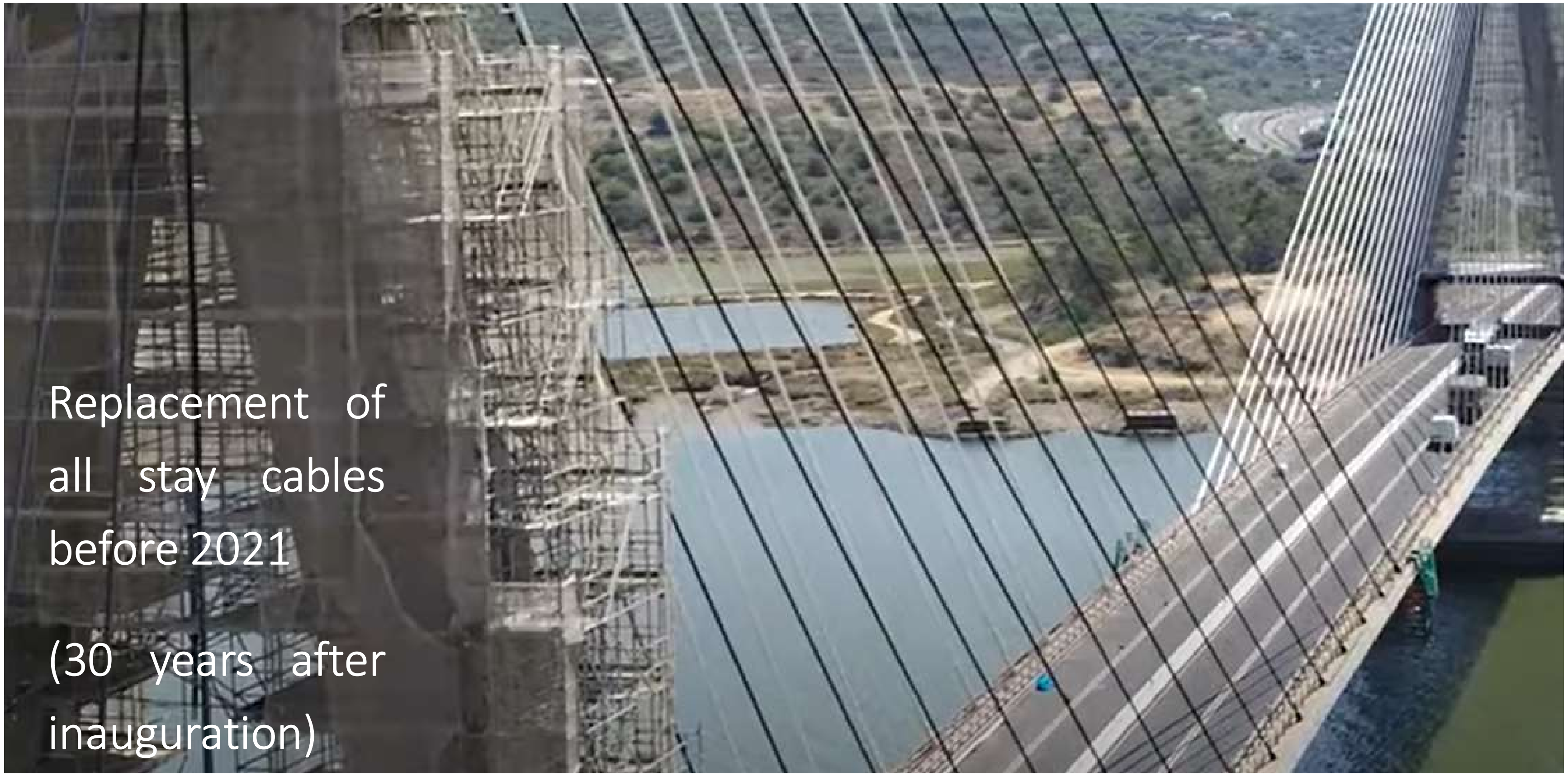
(TSF Notícias, 2017)

In 2015, 1 strand of cable 3-29S broke from the lower anchorage.

In 2017, a second strand broke from the tower anchorage (In Martins et al, JPEE 2022)



The International Guadiana Bridge

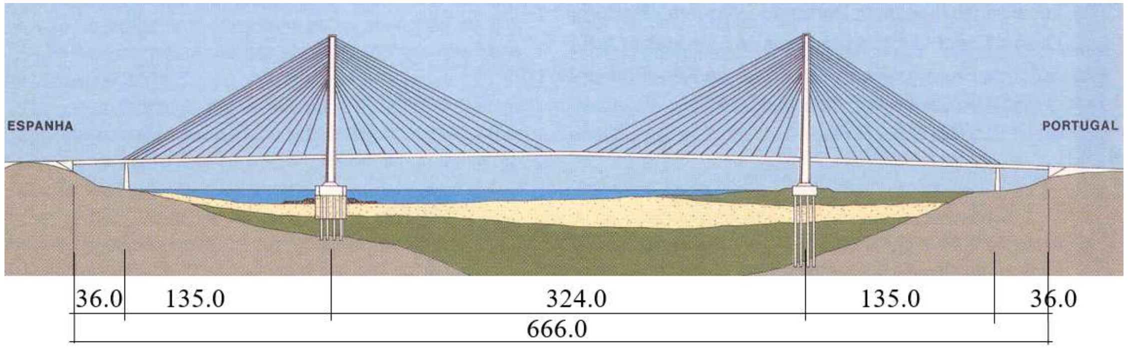


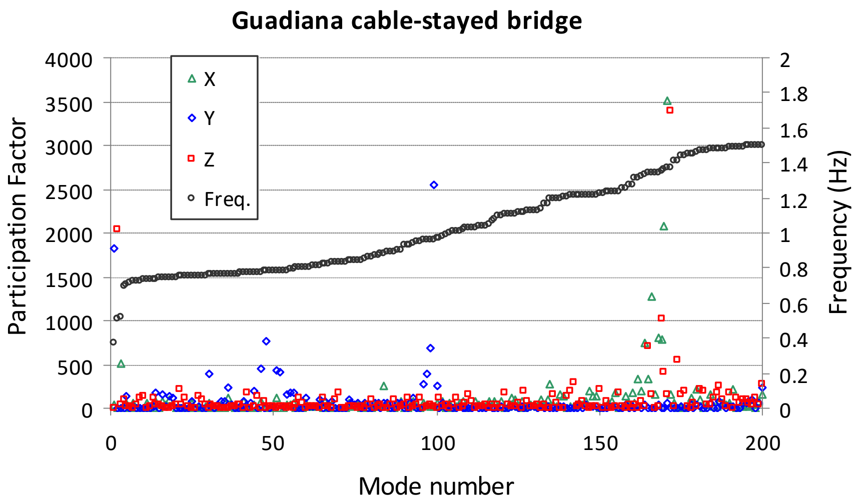
More than 500 km of strands were needed

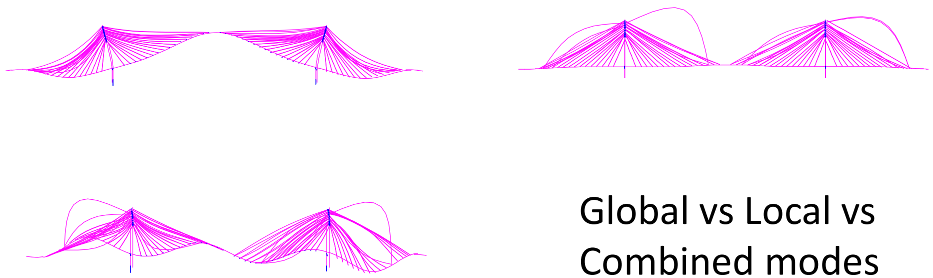
The Guadiana Bridge: detecting broken strands from global monitoring?

First global frequency: 0.39 Hz;

First cable frequencies: 0.78 Hz to 2.96 Hz







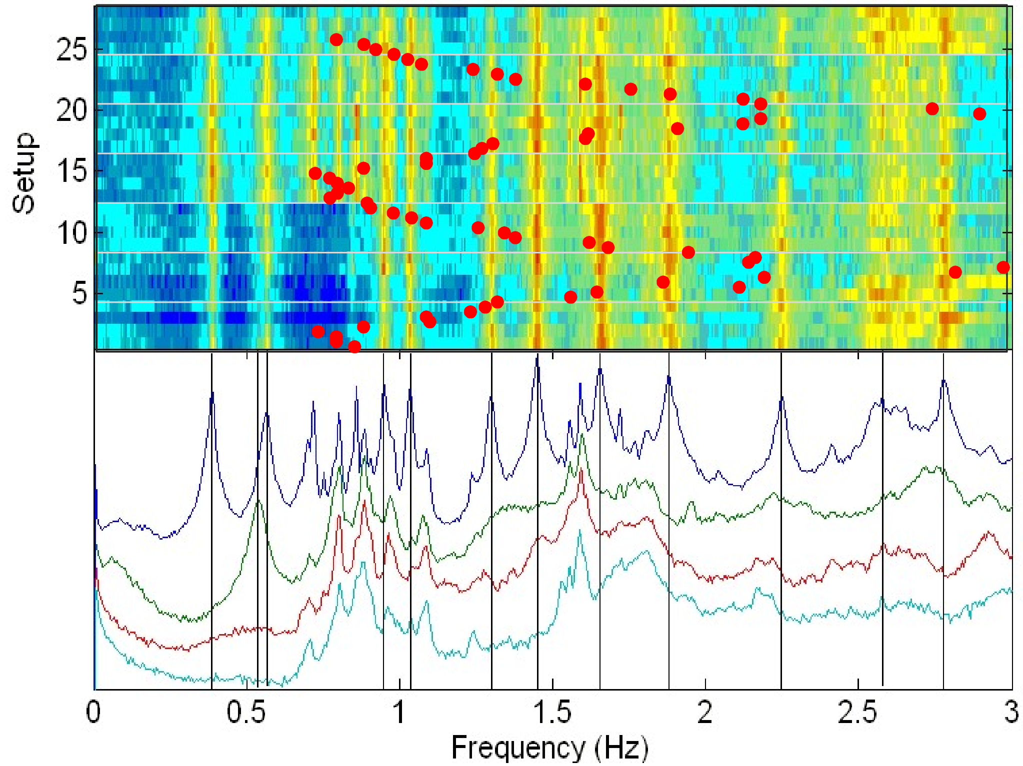
Global vs Local vs Combined modes

The Guadiana Bridge: detecting broken strands from global monitoring?

First global frequency: 0.39 Hz;

First cable frequencies: 0.78 Hz to 2.96 Hz

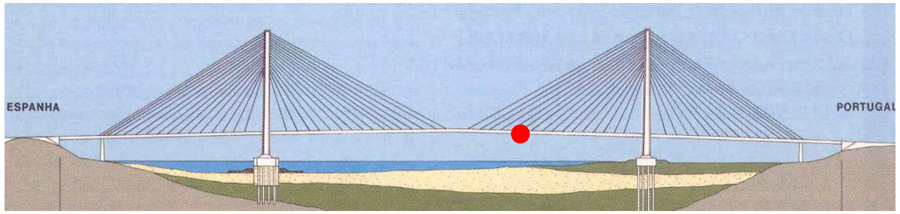
Guadiana International Bridge, Portugal

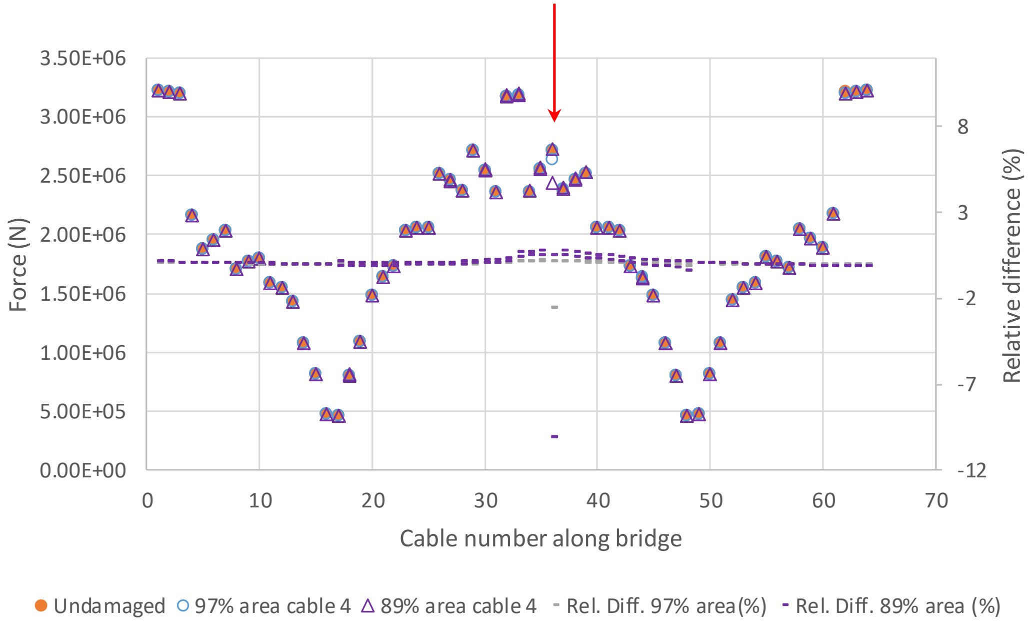


The Guadiana Bridge: detecting broken strands from global monitoring?

- Reduction of section of 4th longest cable to 97% (1/37 strand broken): 3% loss of force in that cable

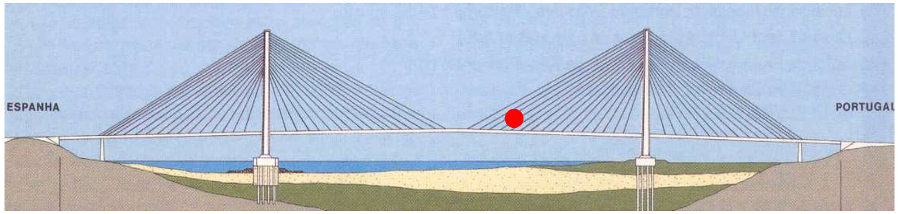
- Reduction of section of 4th longest cable to 89% (4/37 strands broken): 10% loss of force in that cable





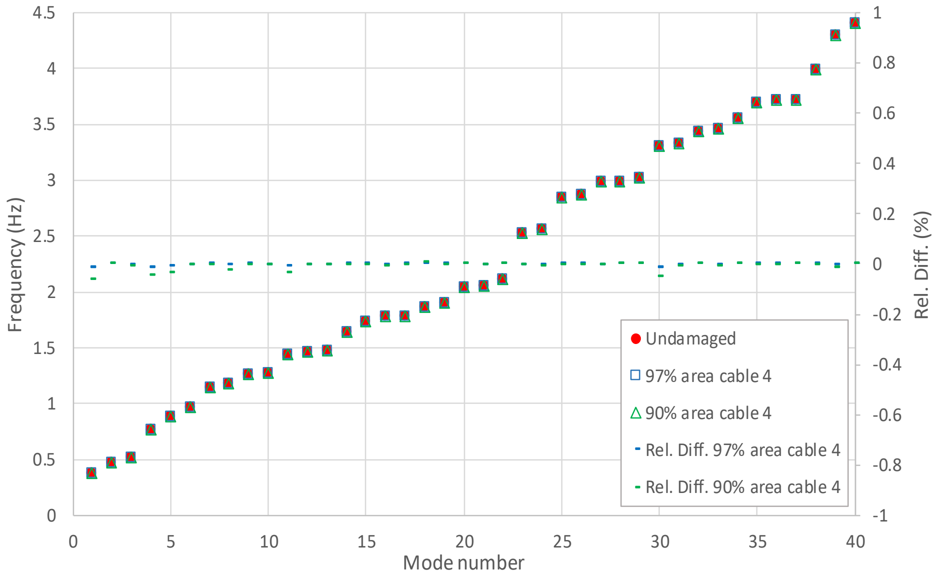
The Guadiana Bridge: detecting broken strands from global monitoring?

- Reduction of section of 4th longest cable to 89% (4/37 strands broken): 0.2% reduction of frequency

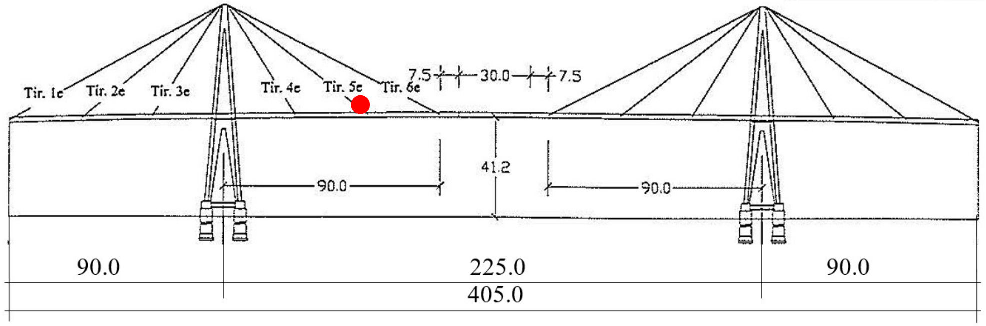


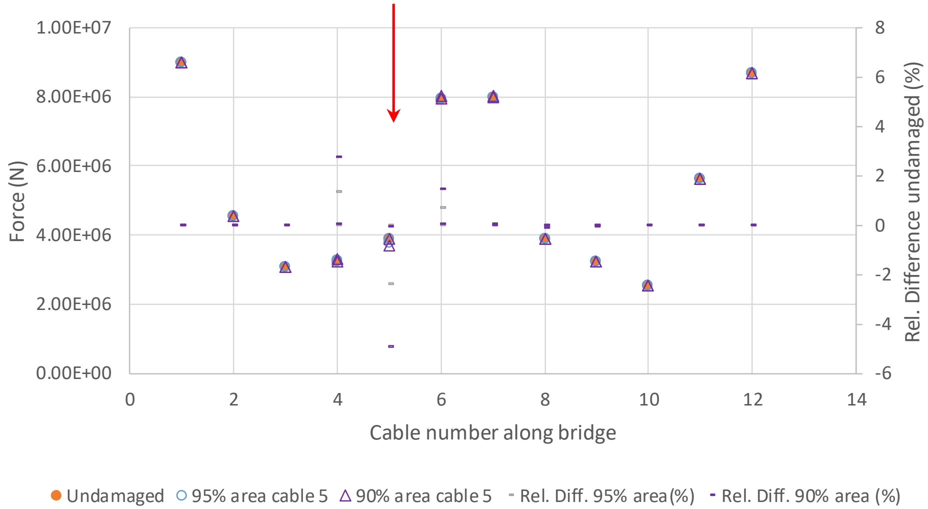
Global measurements as natural frequencies cannot be used to detect small amounts of damage in cables

Local measurements of installed force enable the identification of 10% reduction of section at this bridge



The Edgar Cardoso Bridge: detecting broken wires from global monitoring?





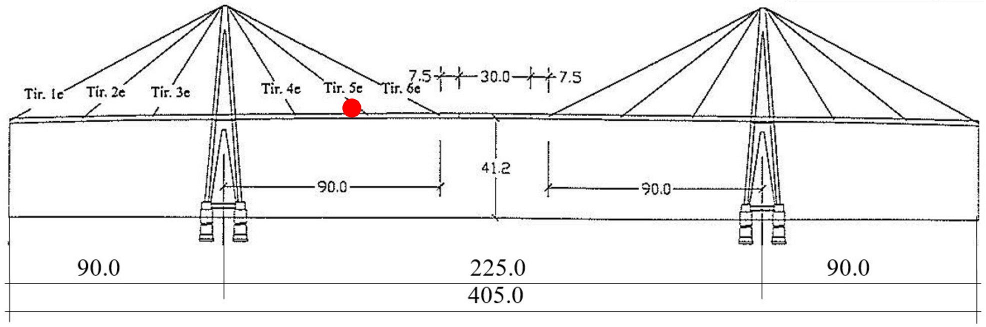
- Reduction of section of medium-length cable to 95% : 2% loss of force in that cable
- Reduction of section of medium length cable to 90% : 5% loss of force in that cable

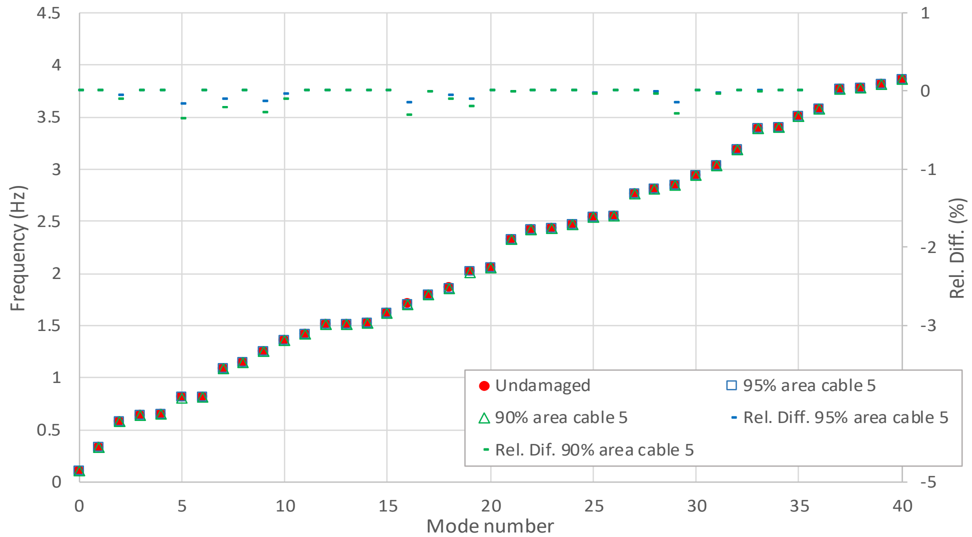
The Edgar Cardoso Bridge: detecting broken wires from global monitoring?

- First global frequency: 0.50 Hz;

- First cable frequencies: 1.2 Hz to 2.2 Hz

- Reduction of section of the medium length cable to 90%: 5% reduction of force





Global Measurements as natural frequencies could hardly be used to detect small amounts of damage in cables

Local measurements of installed force enable the identification of 10% reduction of section at this bridge

Direct assessment of cable force: vibration chord based methods

$$EI\frac{\partial^4 y}{\partial x^4} - T\frac{\partial^2 y}{\partial x^2} + m\frac{\partial^2 y}{\partial t^2} = 0$$

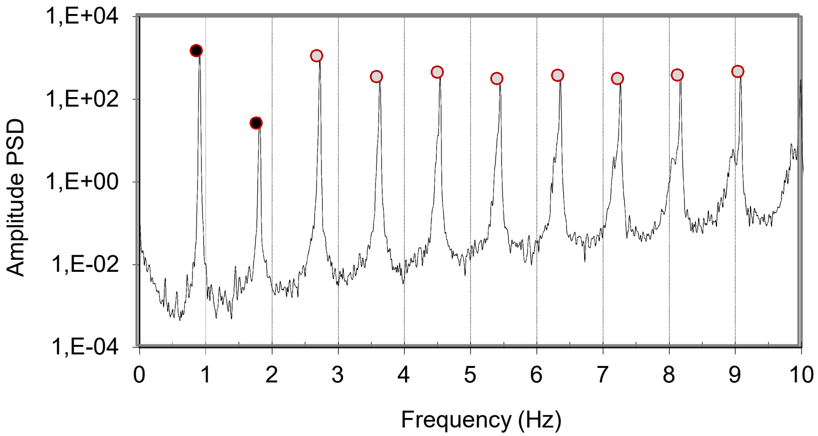
(Morse and Ingard, 1968)
(Mars and Hardy, 1985; Robert et al, 1991)

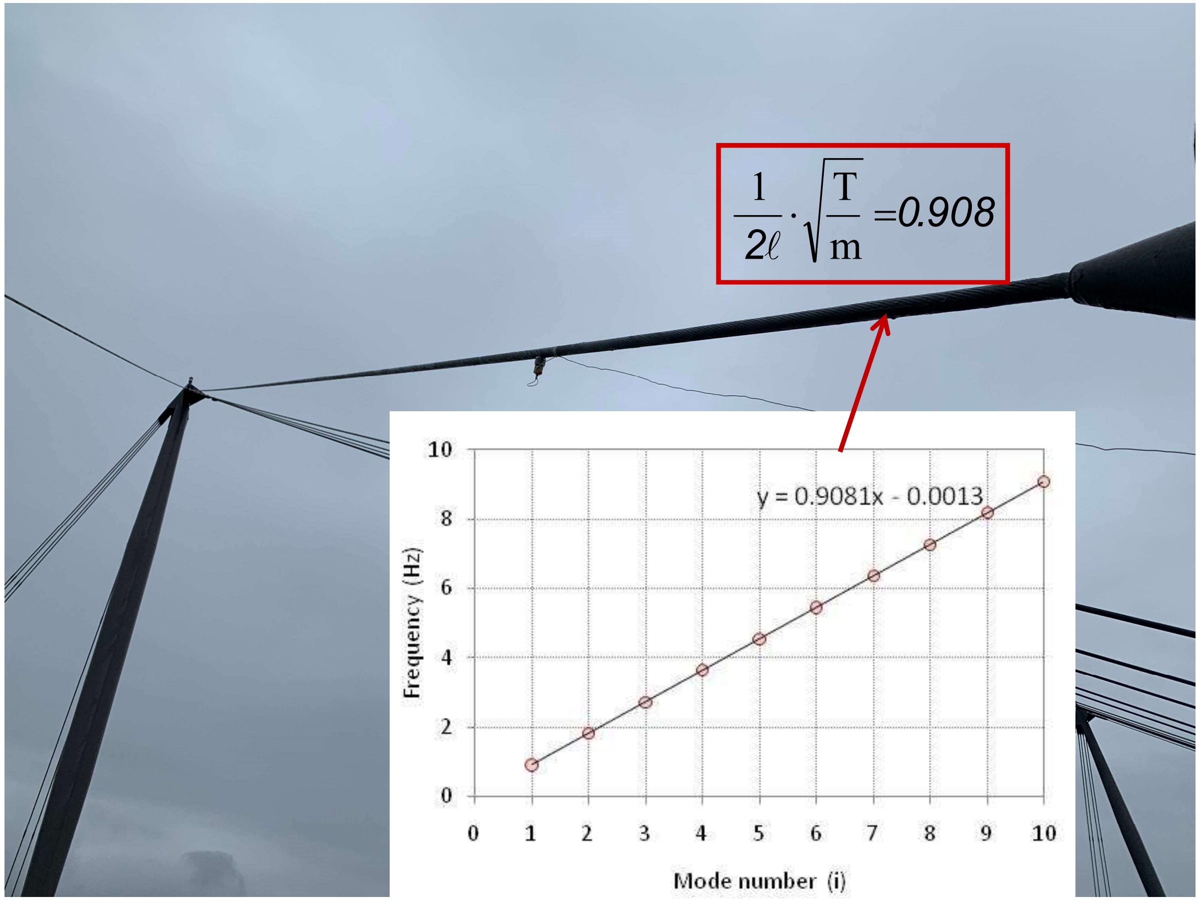
Model	Description	ω (rad/s)
1	Clamped, EI≠0	$\omega = \frac{T}{2\sqrt{mEI}} \cdot \frac{sh(a\ell) \cdot \sin(b\ell)}{ch(a\ell) \cdot \cos(b\ell) - 1}$, $a = \sqrt{\frac{T}{2EI} \cdot \left(1 + \sqrt{1 + \frac{4m\omega^2 \cdot EI}{T^2}}\right)}$, b=…
2	Simply supported, EI=0	$\omega_s = \frac{i\pi}{\ell} \cdot \sqrt{\frac{T}{m}}$
3	Simply supported, EI≠0	$\omega = \sqrt{\omega_s^2 + \omega_{EI}^2}$, $\omega_{EI} = \pi^2 \cdot i^2 \cdot \sqrt{\frac{EI}{m\ell^4}}$

Direct assessment of cable force: vibration chord based methods

Vibrating chord theory

$$f_s = \frac{i}{2\ell} \cdot \sqrt{\frac{T}{m}}$$





Direct assessment of cable force: vibration chord based methods

$$\omega_i = \frac{i\pi}{\ell} \cdot \sqrt{\frac{T}{m}} \cdot (1 + \varepsilon_{EI}^{i})$$

$$\varepsilon_{EI}^{i} = \frac{2}{\zeta} + \frac{4 + \frac{i\pi^2}{2}}{\zeta^2}$$ and $$\zeta = \sqrt{T\ell^2 / EI}$$

When $\zeta \geq 50$, it can be observed that, for the first modes, $\varepsilon_{EI}^{i} \leq 0{,}05$

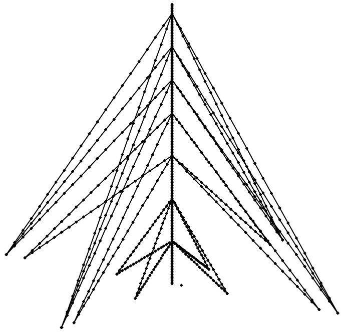
Vibration chord formula

$$\omega_i = \frac{i\pi}{\ell} \cdot \sqrt{\frac{T}{m}}$$

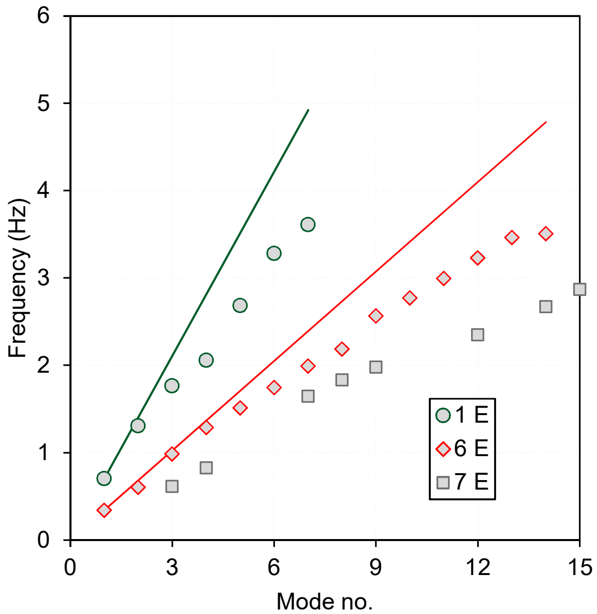
Direct assessment of cable force: vibration chord based methods

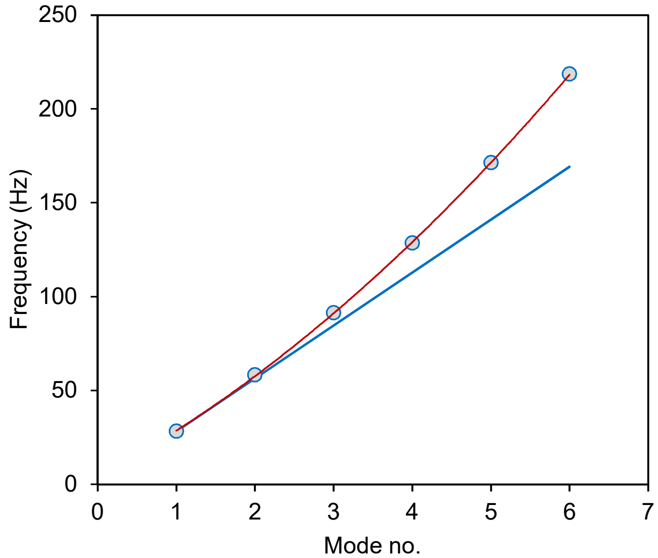
Guyed mast

(L=72.4; 288.22; 313.43 m)

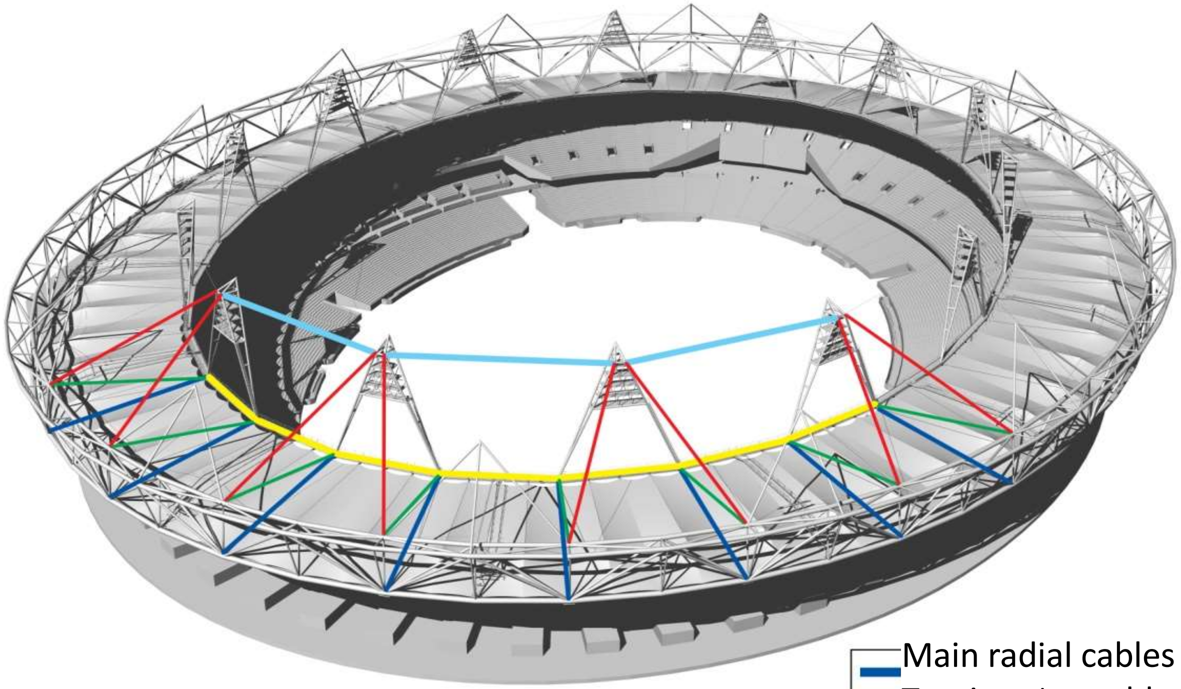


$$f_n = \frac{n}{2\ell}\sqrt{\frac{T}{m}}\cdot\left[1+2\sqrt{\frac{EI}{T\ell^2}}+\left(4+\frac{n\pi^2}{2}\right)\cdot\frac{EI}{T\ell^2}\right]$$





Applications of vibration chord based methods: London Olympic stadium 2012



- Main radial cables (SS70) **(28)**
- Tension ring cables (10 x SS60) **(10)**
- Main Suspension cables (SS80) **(28)**
- Lightning tower suspension cables (SS25)**(7)**
- Circumferential ring cables (2 x SS35) **(3)**

Applications of vibration chord based methods: London Olympic stadium 2012

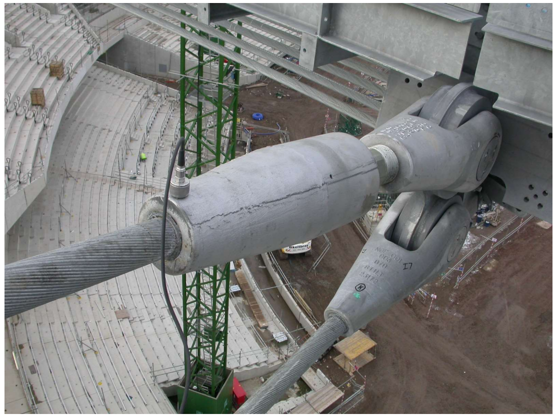
Difficulties in the application of vibration methods:

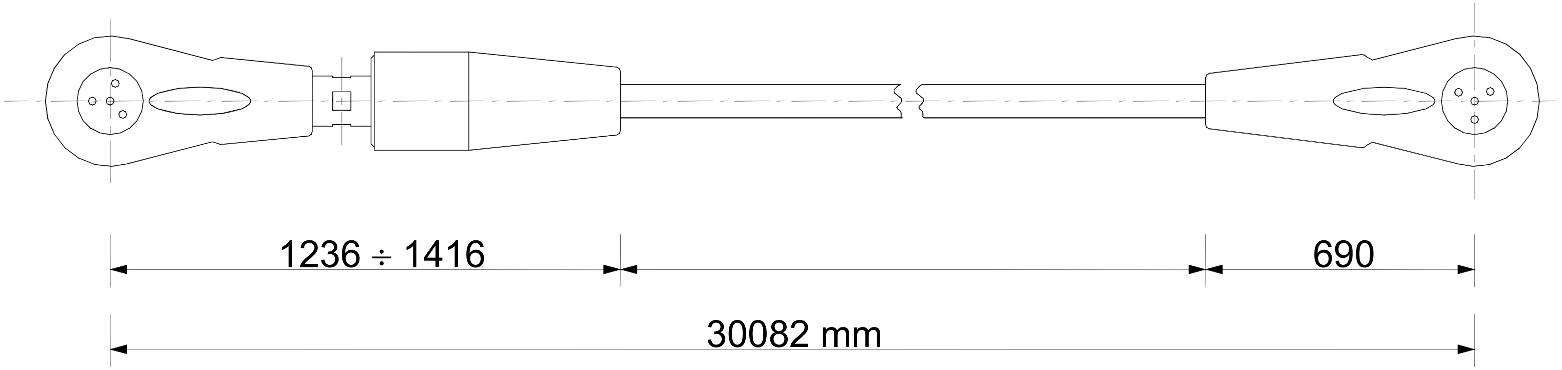
-Cables with short length

-Non-negligible bending stiffness

-Some low tensioned cables

-Relative large size of sockets to cable length



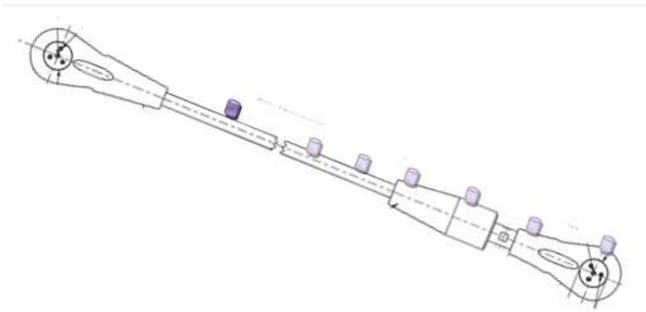


Applications of vibration chord based methods: London Olympic stadium 2012

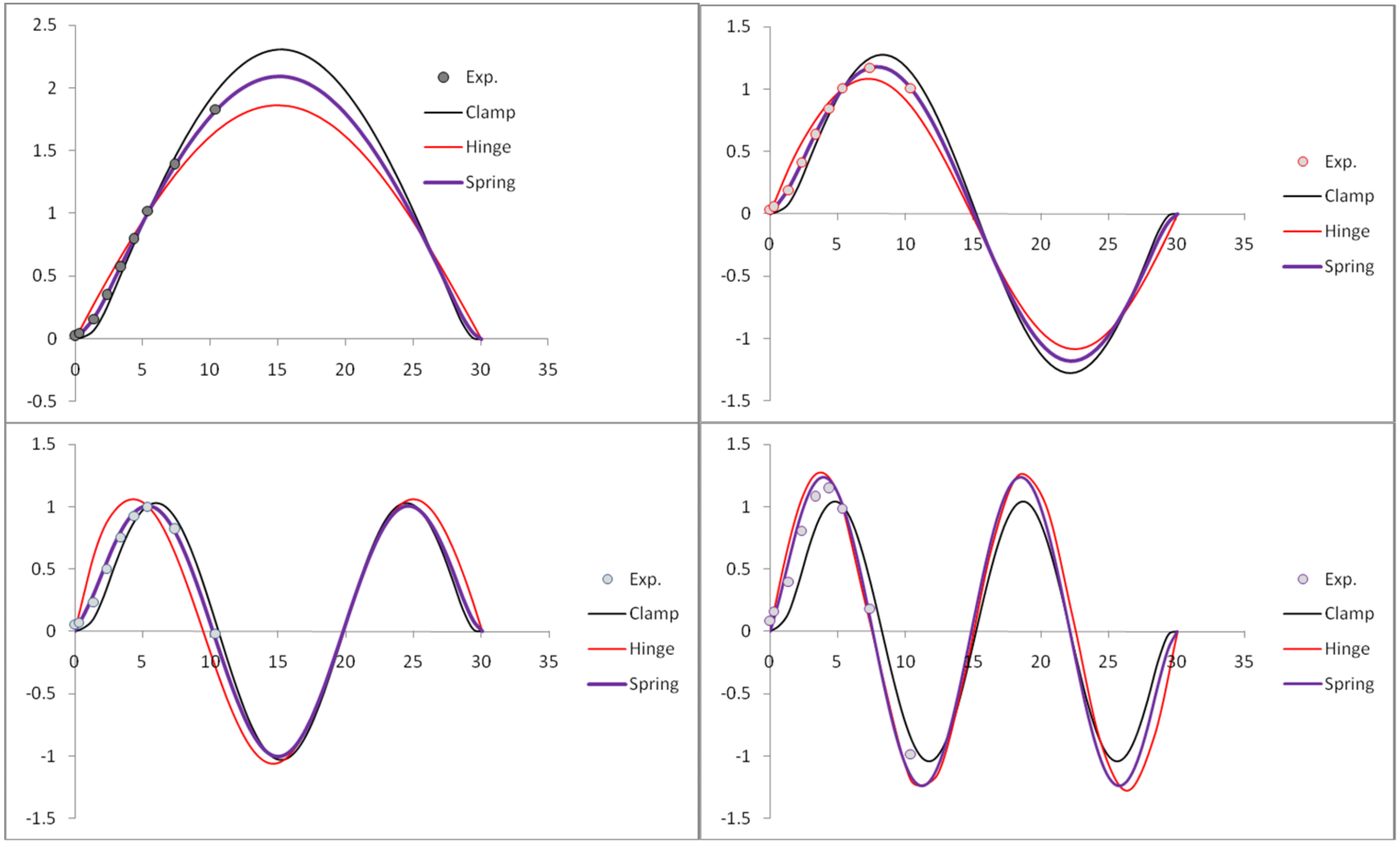
Combination of FE models with experimental assessment:

-Identification of great number of natural frequencies;

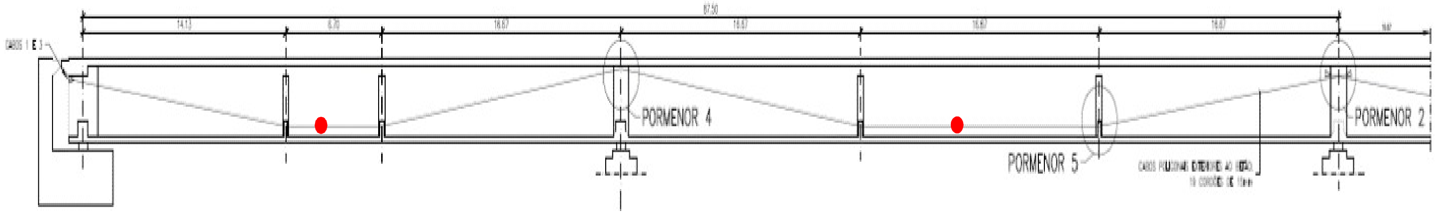
-Iterative FE modelling and updating with experimental data to extract T,K, L, I

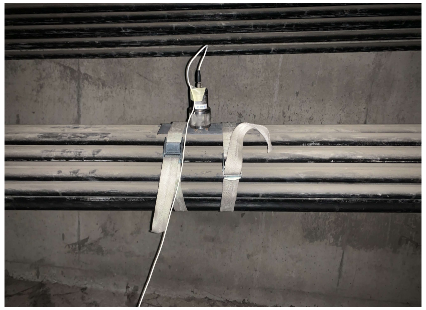


Applications of vibration chord based methods: London Olympic stadium 2012



Applications of vibration chord based methods

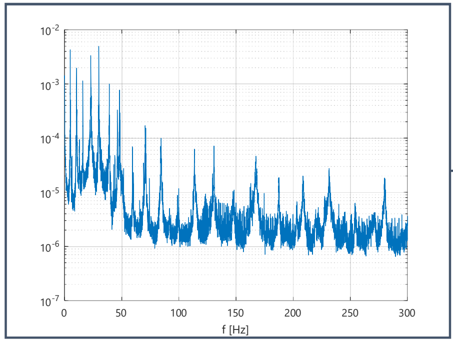




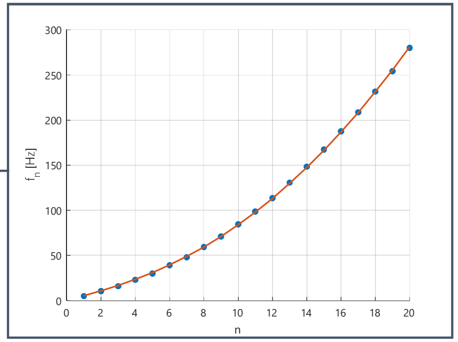
Removing end effects in tension and damage identification

Detection	Localisation	Quantification	Prognosis
Modal-Based Features			

Identification of Axial Force and Stiffness Properties

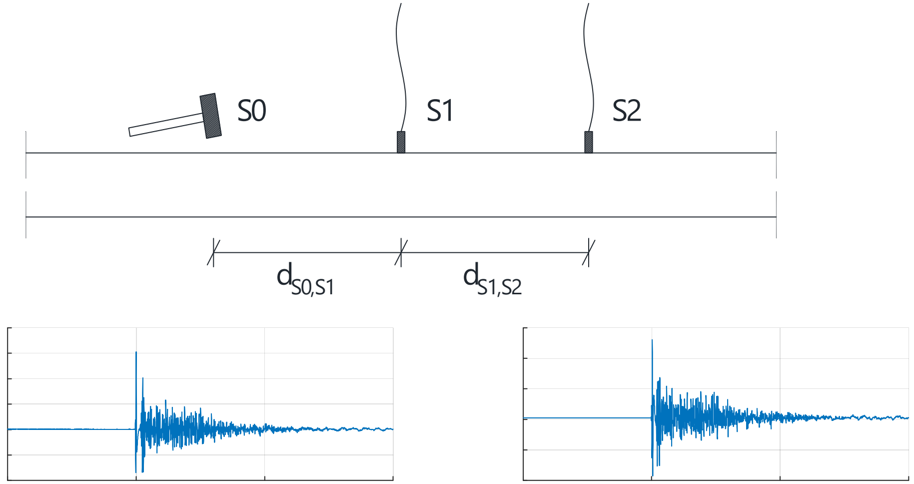


$$f_n = f(n, \mu, L, T, EI, GAK)$$



A new method for force and damage assessment in cables based on transverse wave propagation

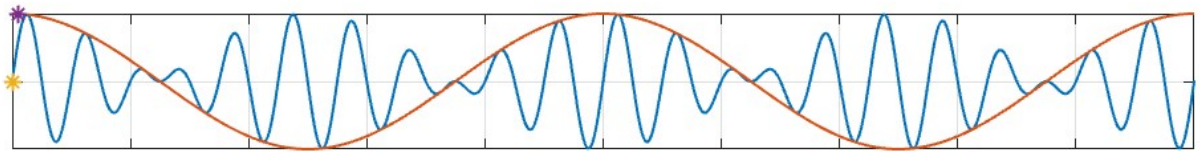
A new method has been developed focusing on the use of the characteristics of the cable as a wave propagation medium, enabling the relation between installed force and cable properties without the need to characterize the end conditions



(PhD research João Rodrigues)

A new method for force and damage assessment in cables based on transverse wave propagation

Vibration Mode (Standing Wave)	=	Wave Propagation	+	Reflection at Supports
		Stiffness Properties of the Cable Medium		Cable Boundary Conditions



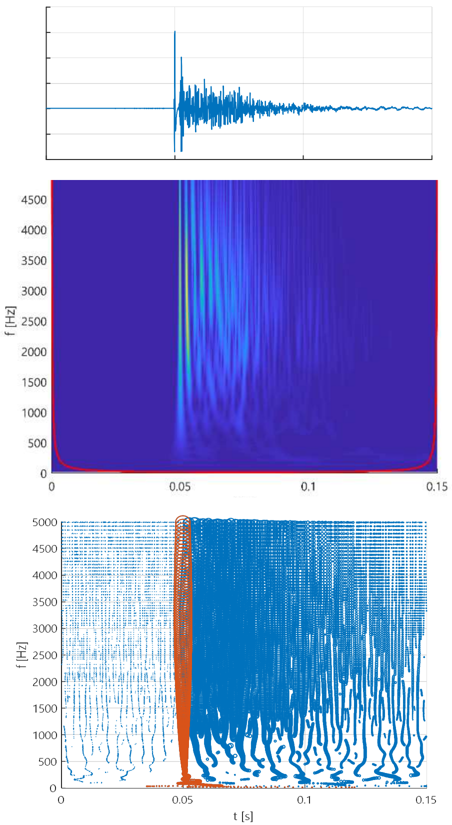
Phase Velocity *   Group Velocity *

Equilibrium Equation	Timoshenko Model
Dispersion Relation for Phase Velocities	$c_{pht}(\omega) = \sqrt{\dfrac{\tau_2\omega^2 - c_t^2 - \sqrt{(\tau_2\omega^2 - c_t^2)^2 - 4\tau_3\omega^2(\tau_1\omega^2 - 1)}}{2(\tau_1\omega^2 - 1)}}$

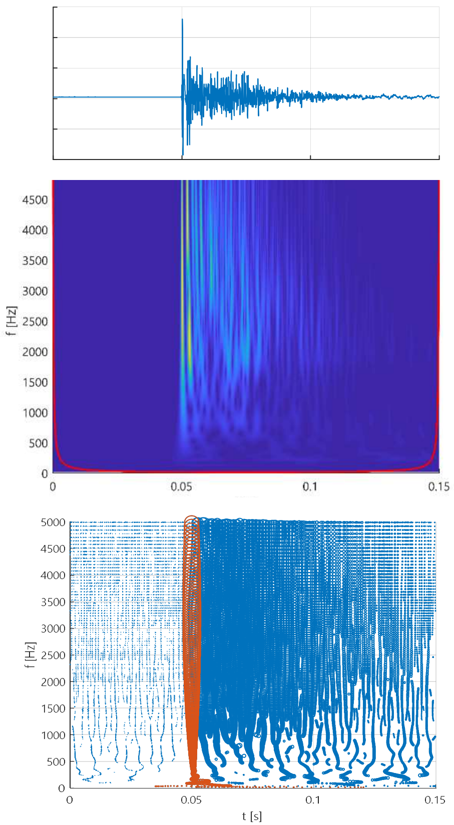
$$c_t = \sqrt{\frac{T}{\mu}} \quad c_f = \sqrt{\frac{EI}{\mu}} \quad c_s = \sqrt{\frac{GAK}{\mu}} \quad r = \sqrt{\frac{I}{A}} \quad \tau_1 = \frac{r^2}{c_s^2} \quad \tau_2 = \left(1 + \frac{c_t^2}{c_s^2}\right) r^2 + \frac{c_f^2}{c_s^2} \quad \tau_3 = \left(1 + \frac{c_t^2}{c_s^2}\right) c_f^2$$

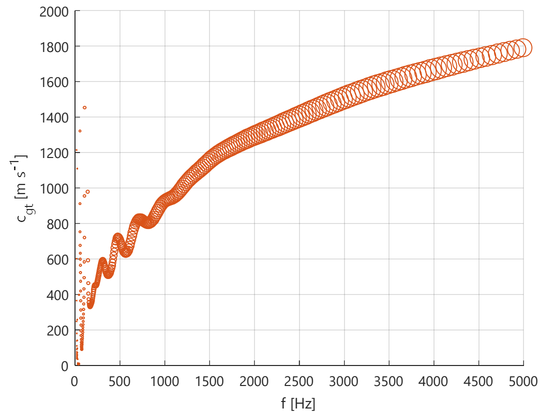
A new method for force and damage assessment in cables based on transverse wave propagation

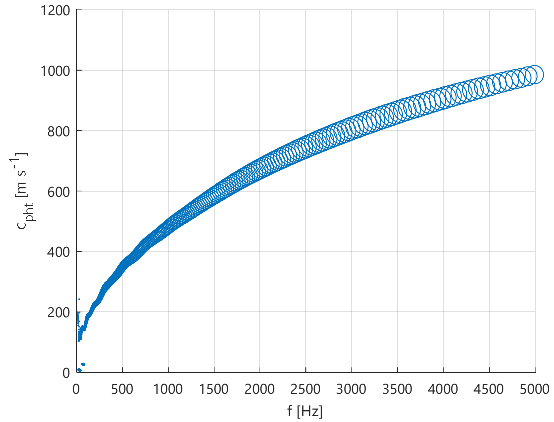
Time Series S1



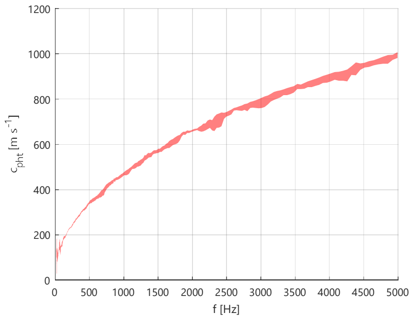
Time Series S2





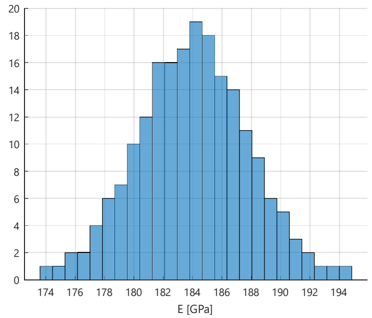


A new method for force and damage assessment in cables

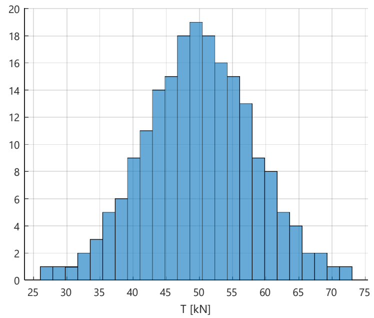


99% confidence interval

Phase Velocity

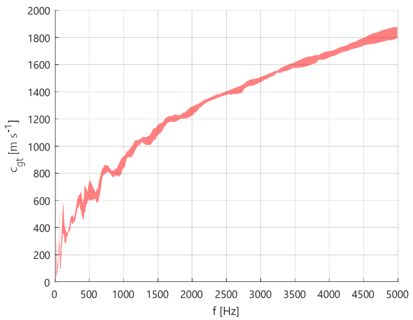


$E = [184.0 \pm 3.8]$ GPa



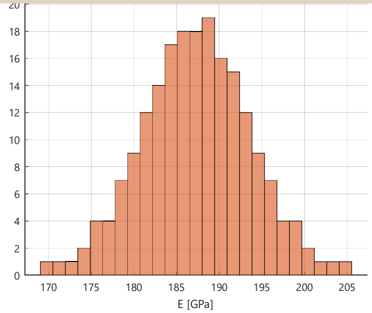
$T = [49.9 \pm 8.3]$ kN

$\boldsymbol{E}$ **= 188.9 GPa**	**Vibration Test**	$\boldsymbol{T}$ **= 48.1 kN**

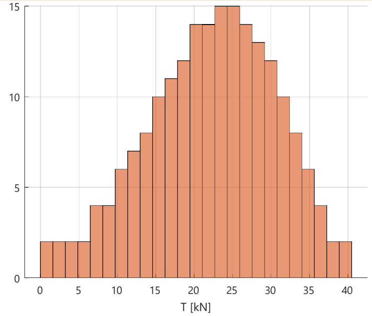


99% confidence interval

Group Velocity



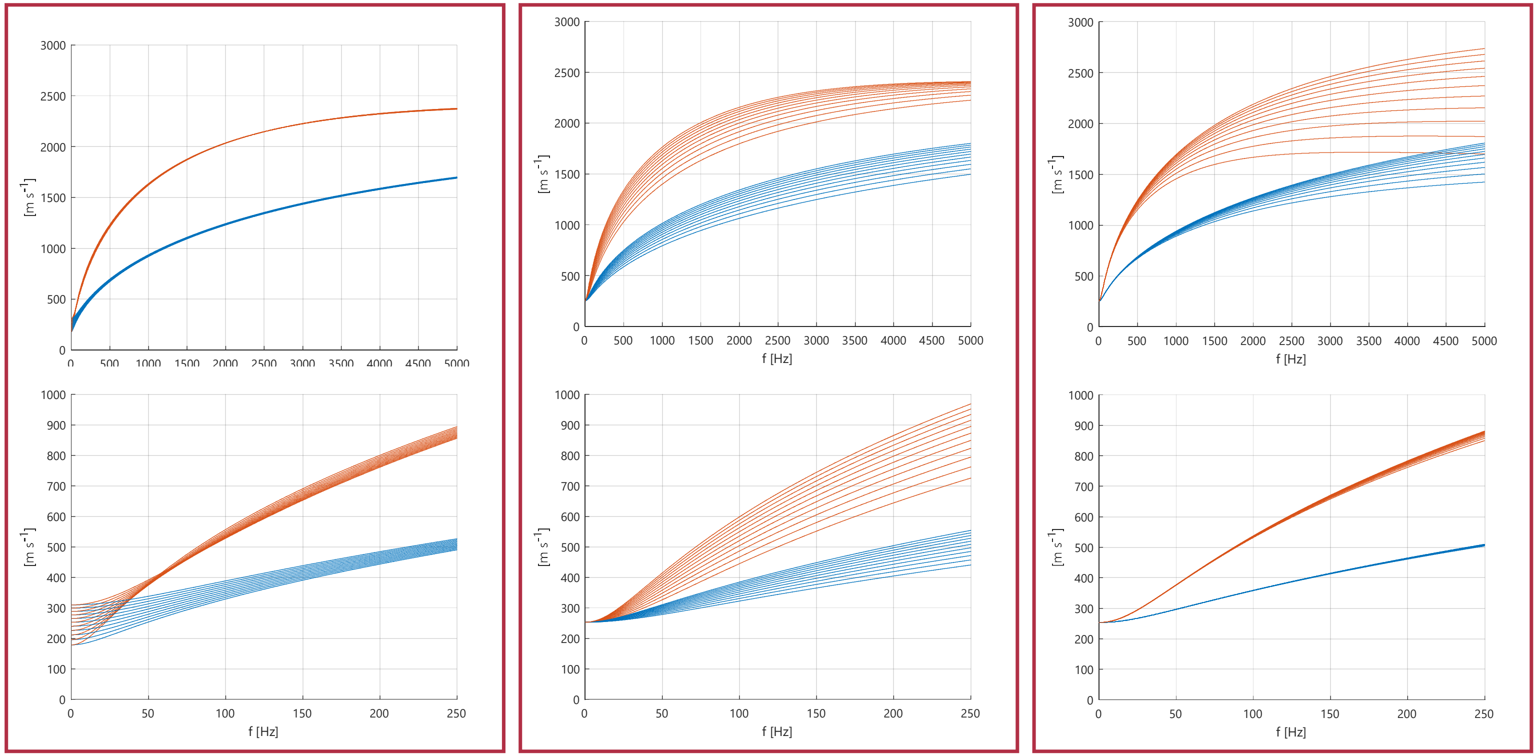
$E = [187.2 \pm 6.3]$ GPa



$T = [22.3 \pm 8.4]$ kN

A new method for force and damage assessment in cables

10% Variations in T	10% Variations in EI	10% Variations in GAK

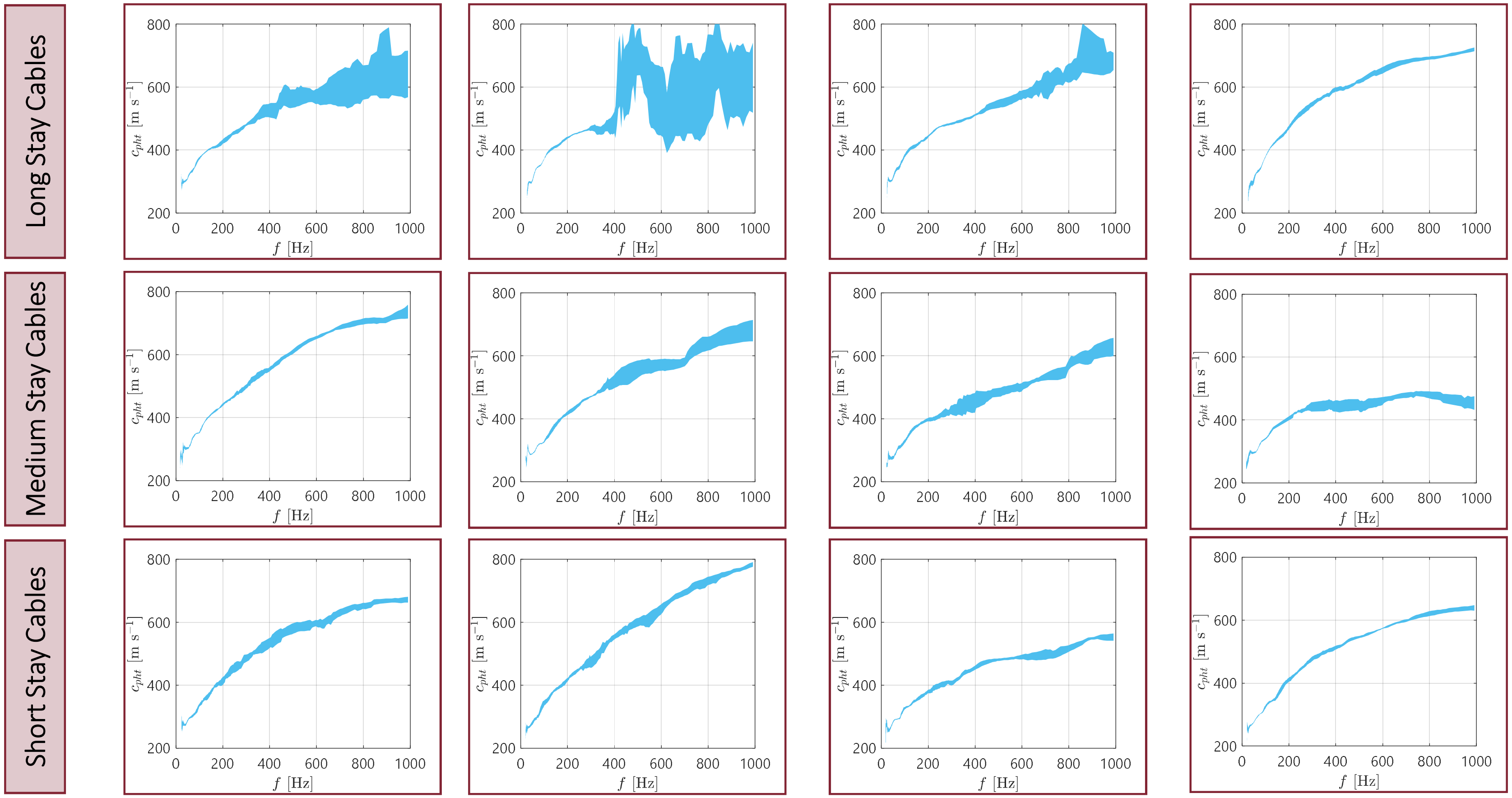


Phase Velocity **Group Velocity**

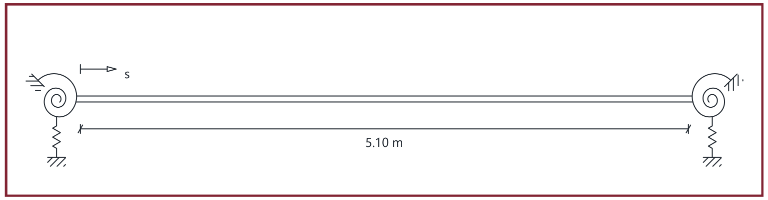
Application of transverse wave propagation method to the cables of the Edgar Cardoso Bridge

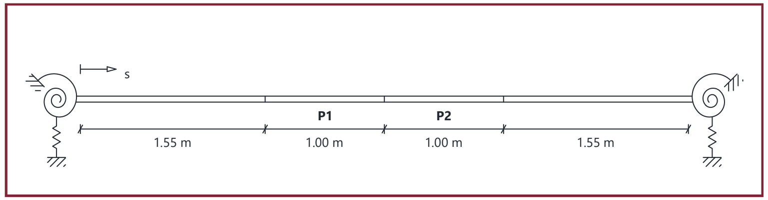
Long Stay Cables	900ϕ5 Parallel Wires $L = 100.62$ m $T_{ref} = 8740$ kN
Medium Stay Cables	540ϕ5 Parallel Wires $L = 75.00$ m $T_{ref} = 5320$ kN
Short Stay Cables	390ϕ5 Parallel Wires $L = 54.08$ m $T_{ref} = 3398$ kN

Application of transverse wave propagation method to the cables of the Edgar Cardoso Bridge



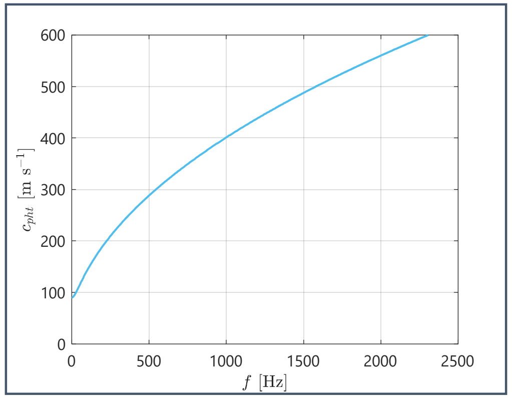
Laboratory validation of transverse wave propagation method





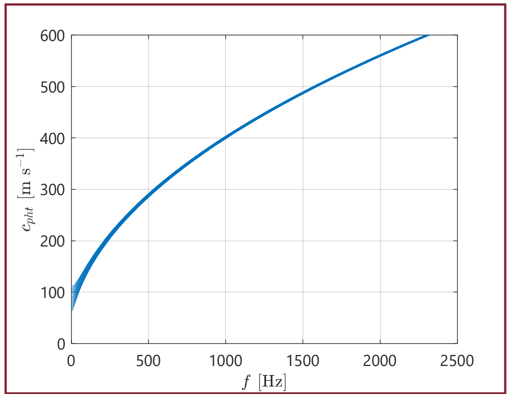
$\phi_{P1} = 20$ mm
$\phi_{P2} = \{20, 18, 19\}$ mm
$T_{ref} = 20$ kN

Laboratory validation of transverse wave propagation method: Sensitivity tests

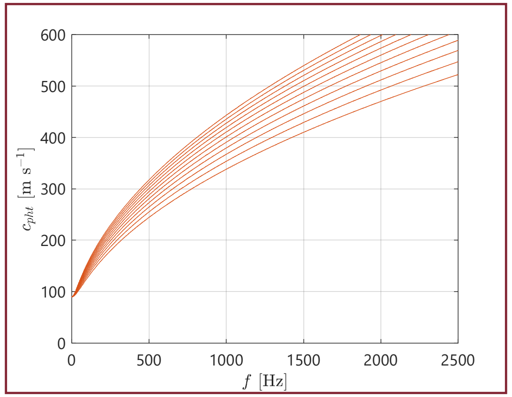


$T = 20$ kN
$E = 200$ GPa
$\phi = 20$ mm

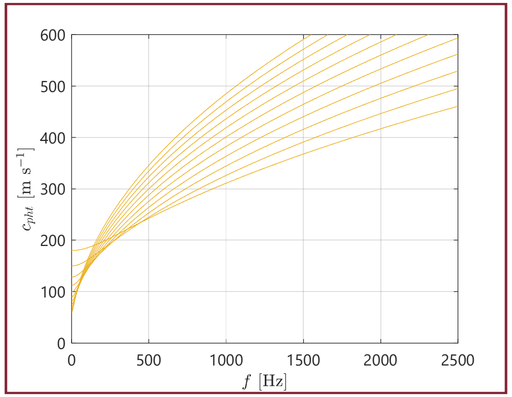
10% Variations in $\boldsymbol{T}$



10% Variations in $\boldsymbol{E}$

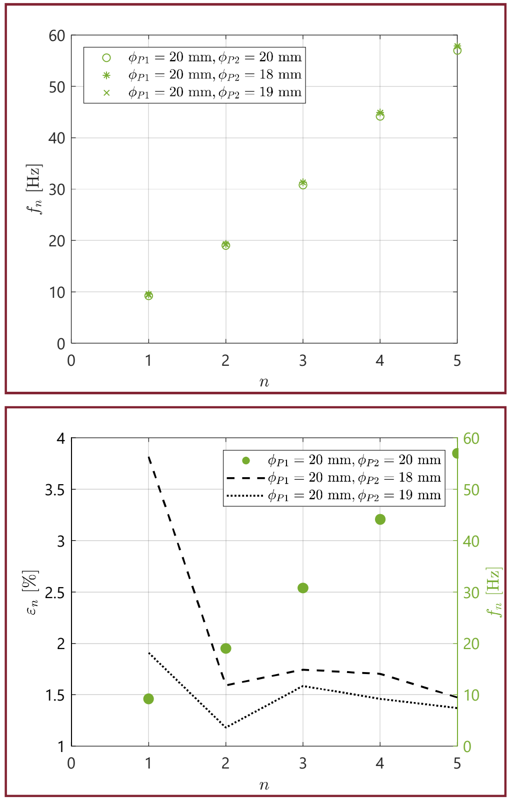


10% Variations in $\boldsymbol{\phi}$

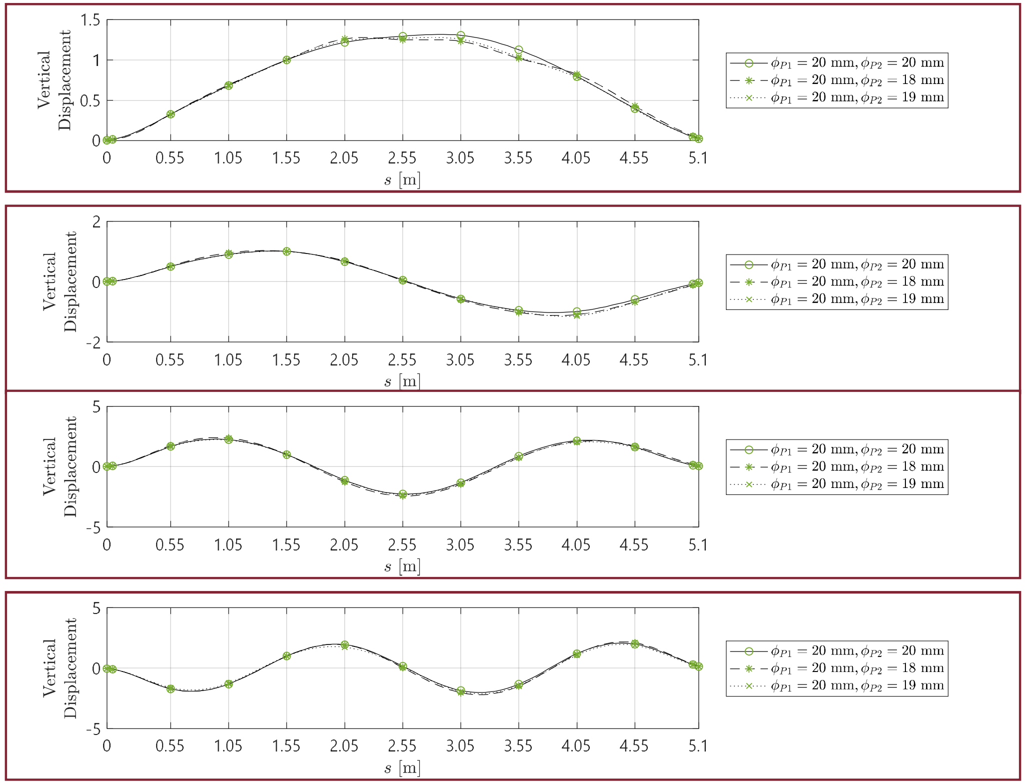


Laboratory validation of transverse wave propagation method: modal tests

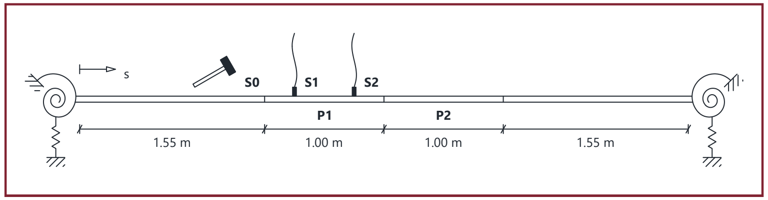
Natural Frequencies

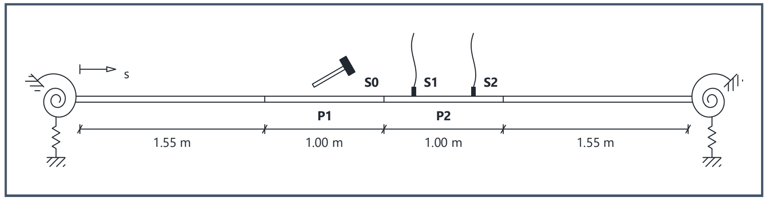


Mode Shapes



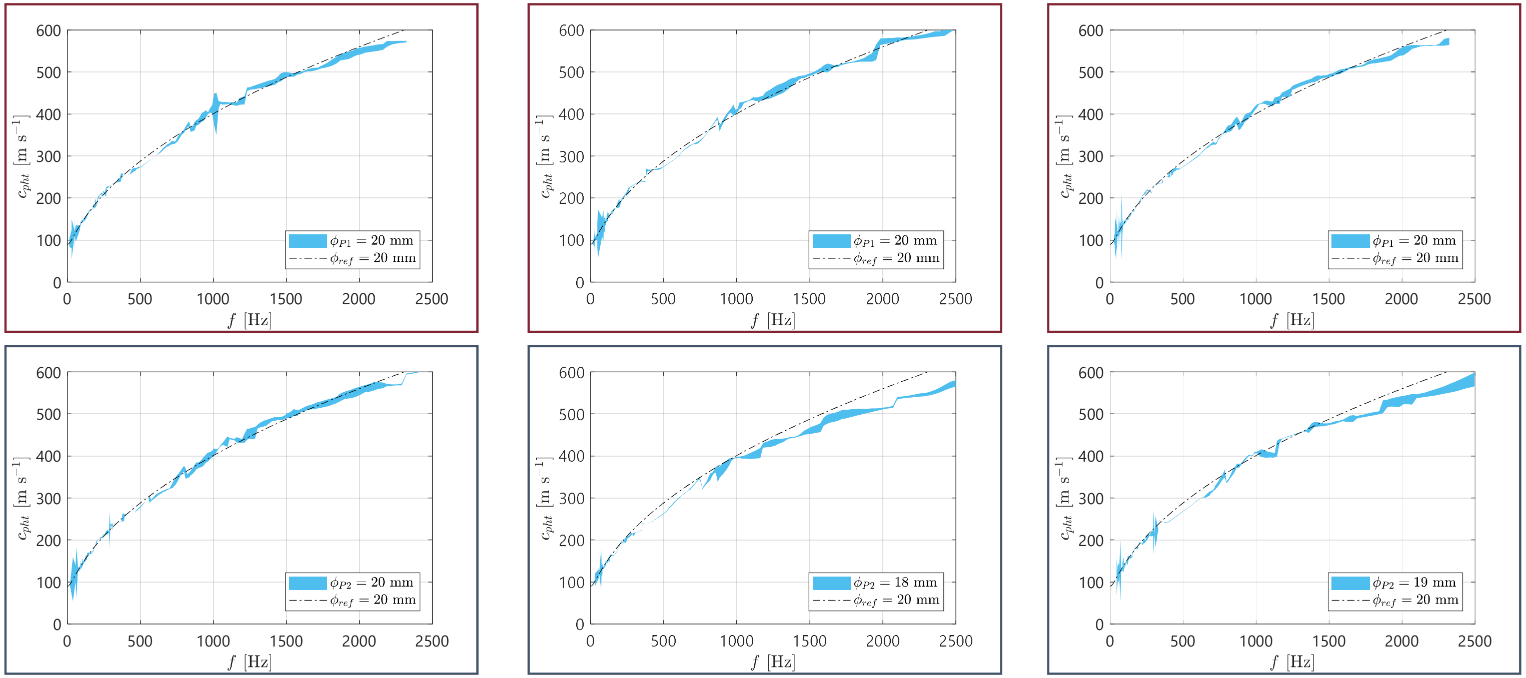
Laboratory validation of transverse wave propagation method: wave velocities





Segment P1

Segment P2

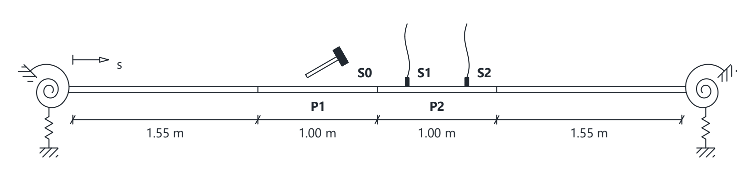


Undamaged

Damaged

Laboratory validation of transverse wave propagation method: wave velocities

$$\hat{E}_{P1} = \arg\min_{E} \sum_{i=1}^{n} \left(c_{pht\,i}^{exp} - c_{pht}(\omega_i, E) \right)^2$$



Segment P1

Point Estimate:
$\hat{E}_{P1}$ = 193.14 GPa (-3.4%)

95% Confidence Interval:
[189.75, 196.56] GPa

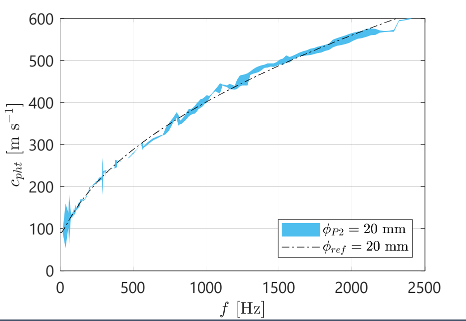
Point Estimate:
$\hat{E}_{P1}$ = 199.11 GPa (-0.4%)

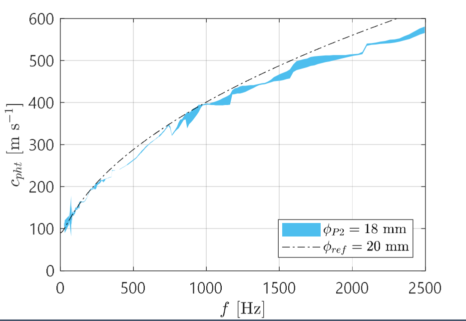
95% Confidence Interval:
[195.70, 202.56] GPa

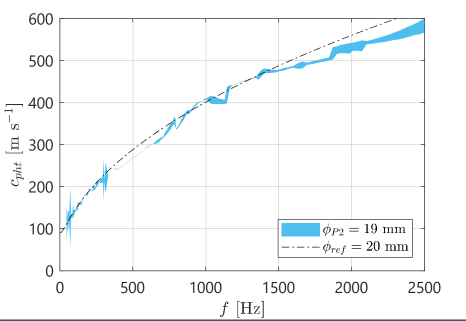
Point Estimate:
$\hat{E}_{P1}$ = 196.13 GPa (-1.9%)

95% Confidence Interval:
[192.53, 199.79] GPa

Segment P2







Laboratory validation of transverse wave propagation method: Estimates of E and ϕ

$$\hat{E}_{P1} = \arg\min_{E} \sum_{i=1}^{n} \left(c_{pht\,i}^{exp} - c_{pht}(\omega_i, E) \right)^2$$

$$\hat{\phi}_{P2} = \arg\min_{\phi} \sum_{i=1}^{n} \left(c_{pht\,i}^{exp} - c_{pht}(\omega_i, \phi) \right)^2$$

Segment P1

Point Estimate: $\hat{E}_{P1}$ = 193.14 GPa (-3.4%) 95% Confidence Interval: [189.75, 196.56] GPa	Point Estimate: $\hat{E}_{P1}$ = 199.11 GPa (-0.4%) 95% Confidence Interval: [195.70, 202.56] GPa	Point Estimate: $\hat{E}_{P1}$ = 196.13 GPa (-1.9%) 95% Confidence Interval: [192.53, 199.79] GPa

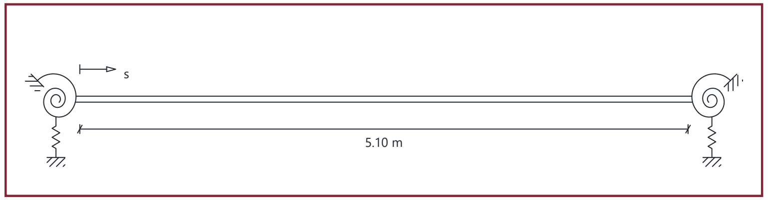
Segment P2

Point Estimate: $\hat{\phi}_{P2}$ = 20.01 mm (+0.1%) 95% Confidence Interval: [19.83, 20.19] mm	Point Estimate: $\hat{\phi}_{P2}$ = 17.79 mm (-1.2%) 95% Confidence Interval: [17.62, 17.97] mm	Point Estimate: $\hat{\phi}_{P2}$ = 18.66 mm (-1.8%) 95% Confidence Interval: [18.43, 18.90] mm

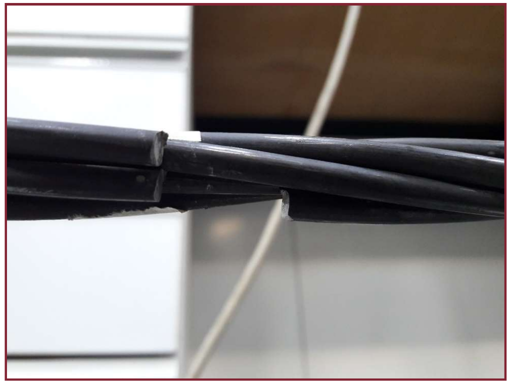
Laboratory validation of transverse wave propagation method: strand test

15.2 Helical Strand

$T_{ref} = 20$ kN



(Support by VSL)



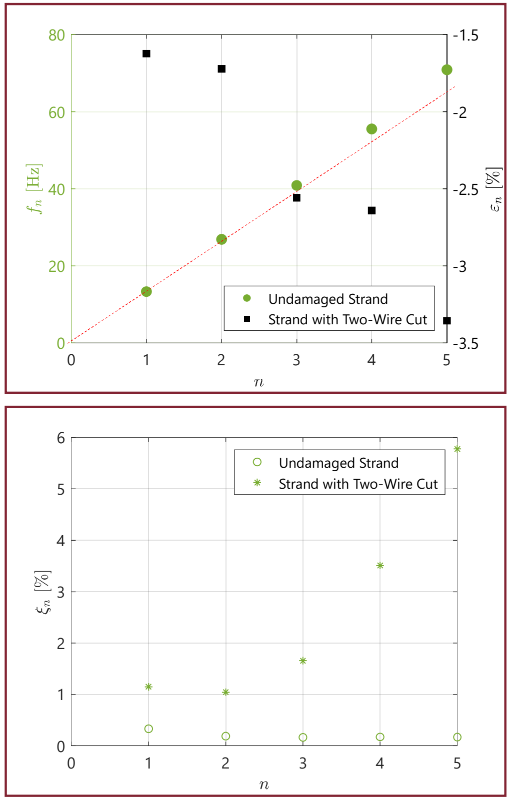
Undamaged Condition
&
Two-Wire Cut at $s = 2.05$ m

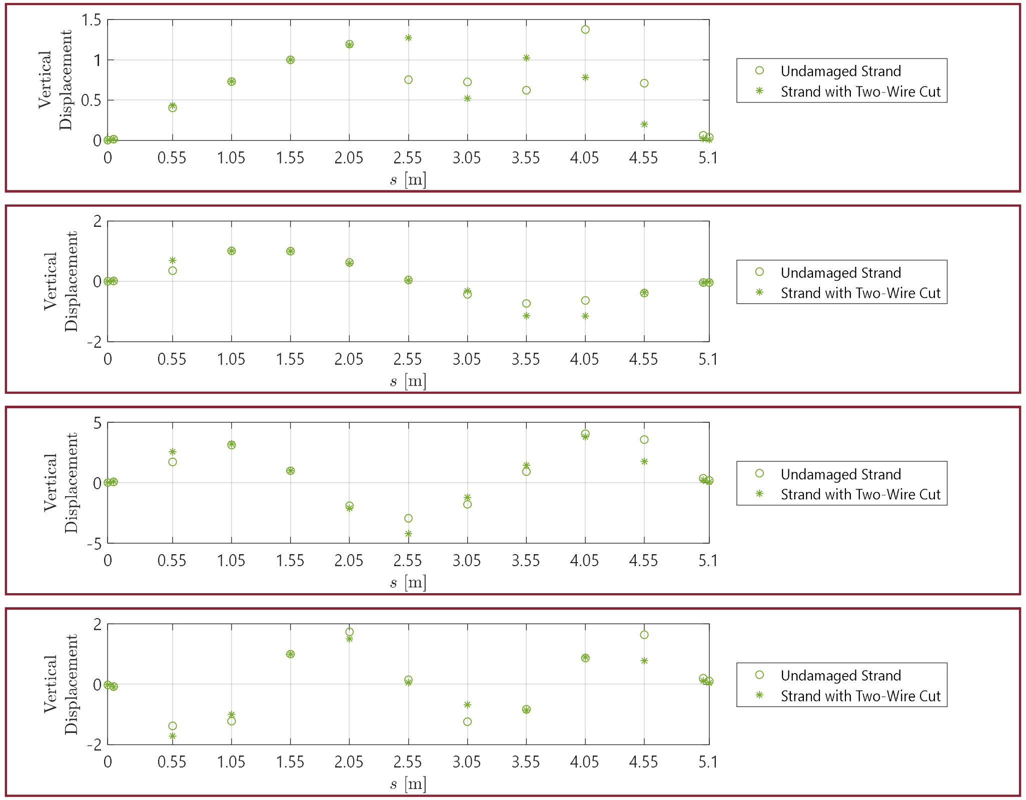
Modal Identification Tests

Wave Propagation Tests

Laboratory validation of transverse wave propagation method: Modal tests

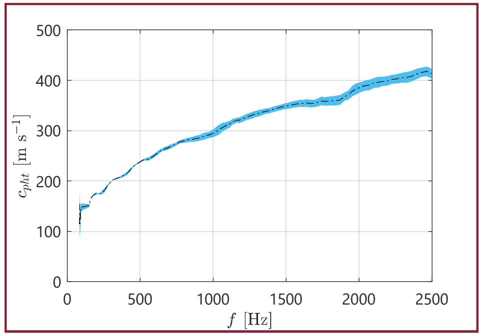
Natural Frequencies and Damping	Mode Shapes

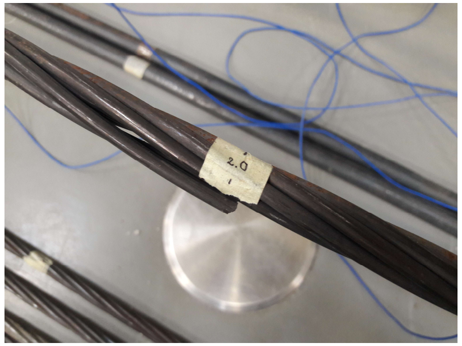


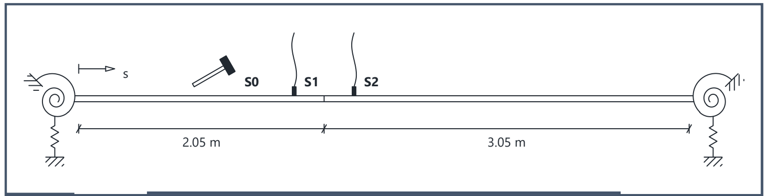


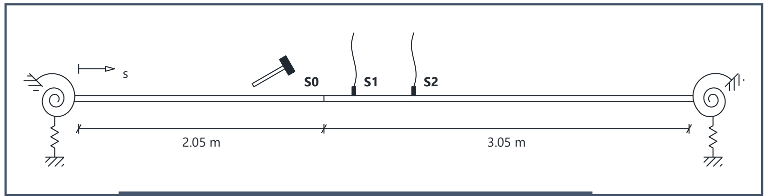
Laboratory validation of transverse wave propagation method: wave tests

Undamaged Strand

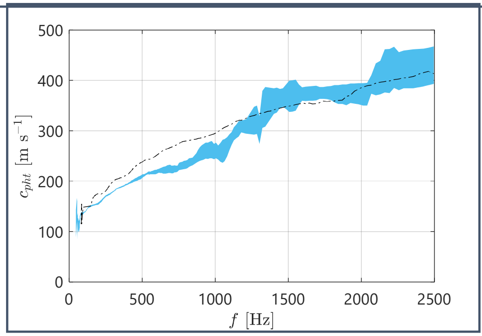


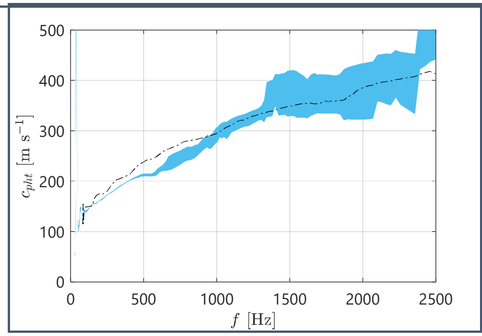






Two-Wire Cut





Conclusions

- Sensitivity studies enable to demonstrate that a small percentage of damage in cables can only be detected from local measurements of force and cable parameters.

- Cable force identification is an important approach to detecting damage and therefore, accurate identification techniques are needed.

- The application of vibration-based methods provides very accurate estimates of force but requires an accurate knowledge of cable mass and length.

- Combined with numerical models, vibration based methods can be extended outside the typical intervals of application to short cables, cables with unknown end conditions, and sagged cables.

- To overcome limitations associated with difficult end conditions, a new direction has been followed to identify force and damage in cables using wave propagation relating the characteristics of the measured velocity to cable properties, such as the bending and shear stiffness and the installed tension.

- Results from laboratory tests on a solid bar demonstrated that a cross-section loss is associated with variation of phase velocities and that they can be employed for damage quantification.

- Preliminary results from laboratory tests on a strand demonstrated that wire breakage produces variations in the wave velocities and leads to confidence intervals wih greater amplitudes.

Thanks for your kind attention

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