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Damping Models for Shear Beams with Applications to Spacecraft Wiring Harnesses

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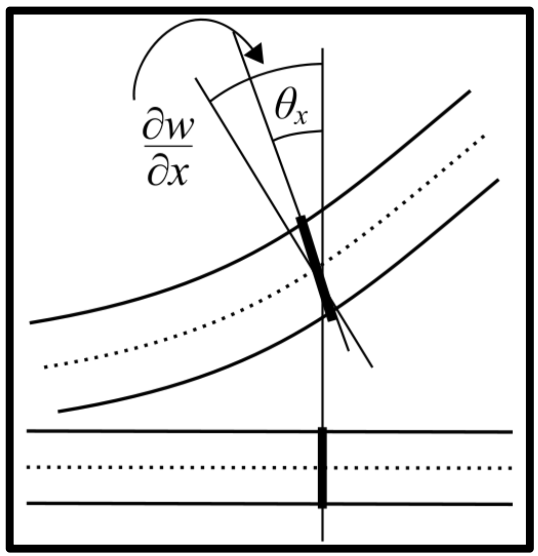
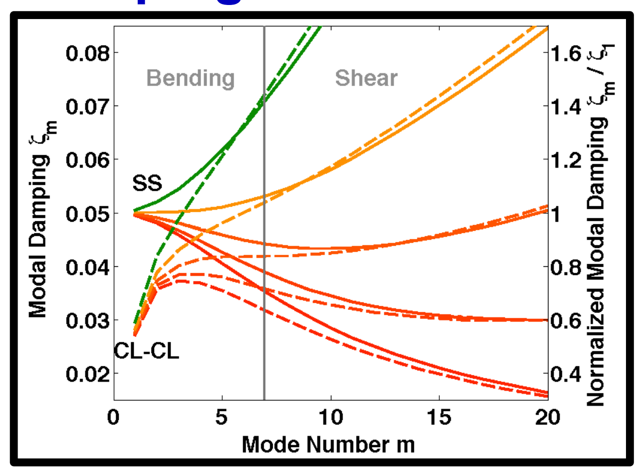
Presenting a new viscous damping model for shear beams that yields approximately constant modal damping

Spacecraft Cable Applications

Shear Beam & Model Development



Damping Model Results



Ardelean et al. (2010)
http://upload.wikimedia.org/wikipedia/commons/thumb/e/e4/Plate_theory.svg/500px-Plate_theory.svg.png

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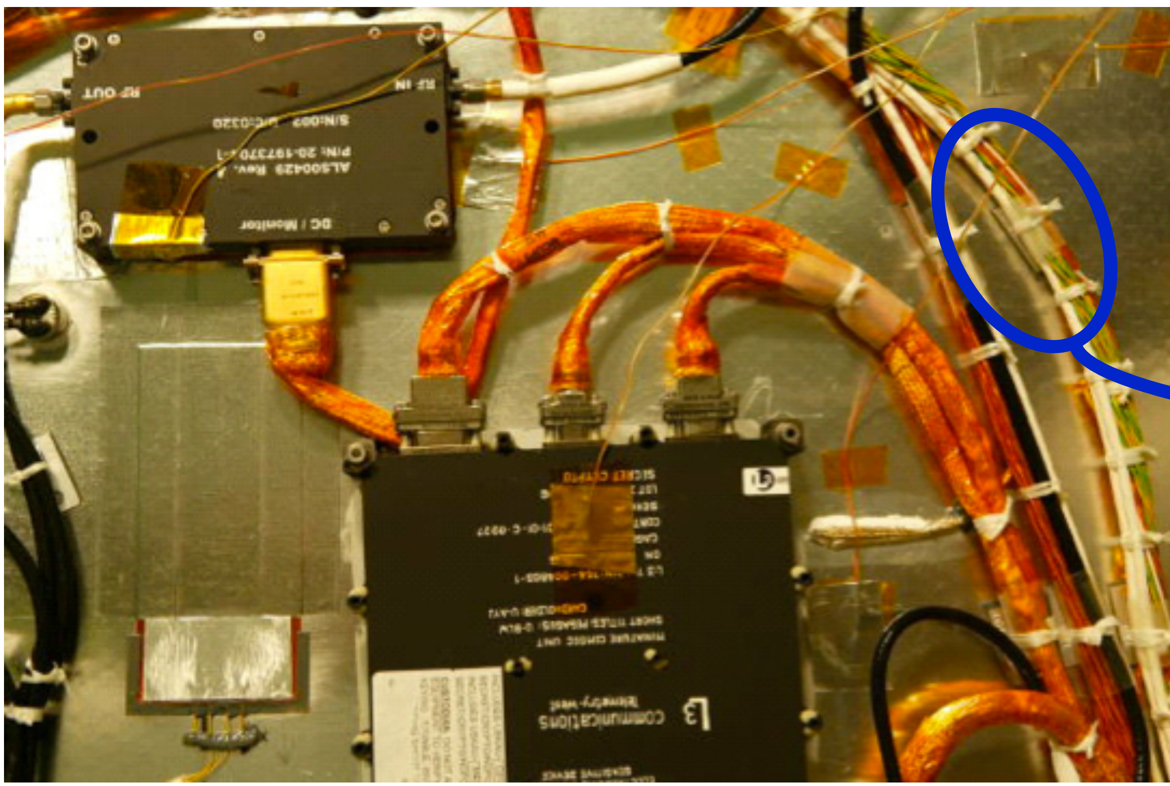
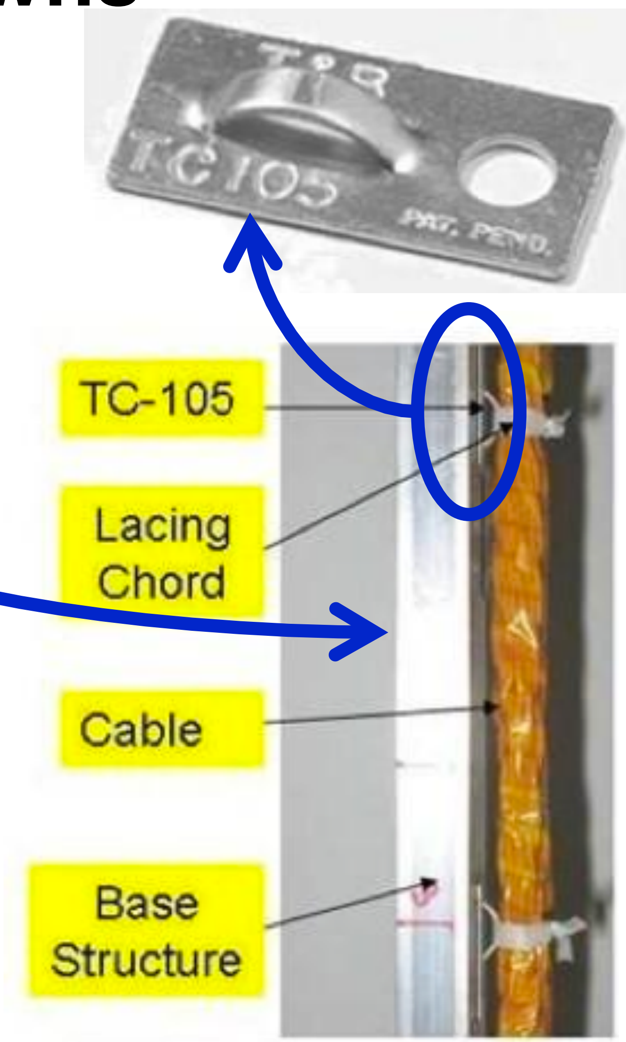
Power & data cables modify spacecraft dynamics, especially at high frequency

- Cabling can account for 30% of spacecraft dry mass!
  - Increasing power / data reqts
  - Decreasing density of structure
- Accurate dynamics model is essential for spacecraft design
  - Launch loads
  - Precision control
- Current models (structure only) over-predict response levels
  - Cables add damping
- Ground testing can augment models, but is incomplete

Ardelean et al. (2010)

Spacecraft & cable dynamics are coupled through cable tiedowns



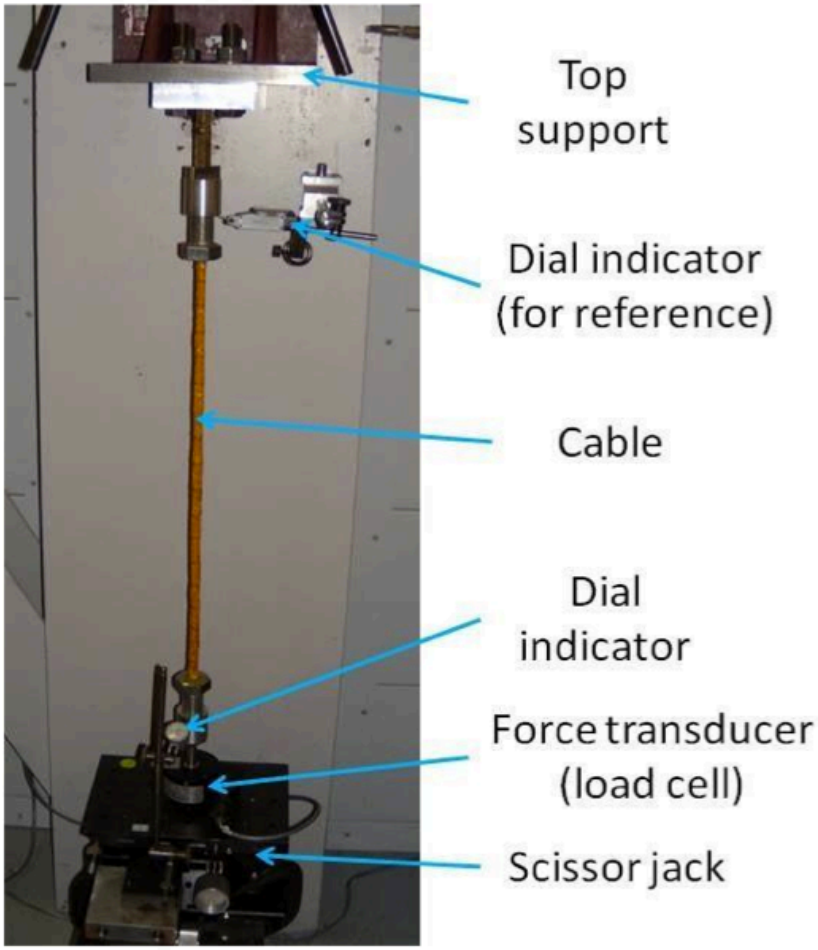


Goodding (2008)
Ardelean et al. (2010)

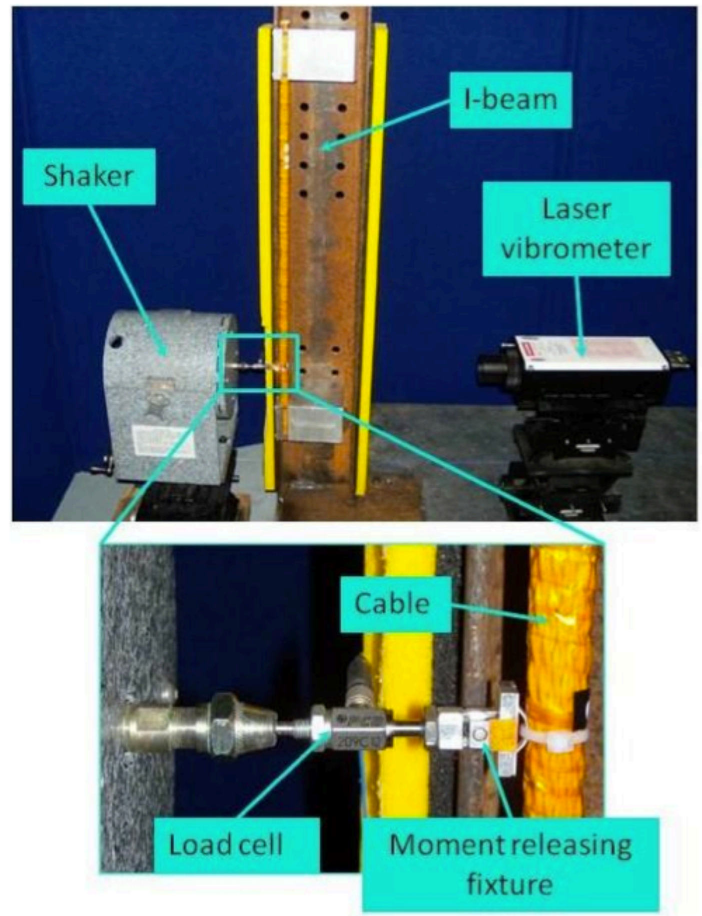
Cables are modeled using effective stiffnesses determined experimentally

- **Extension testing: *EA***

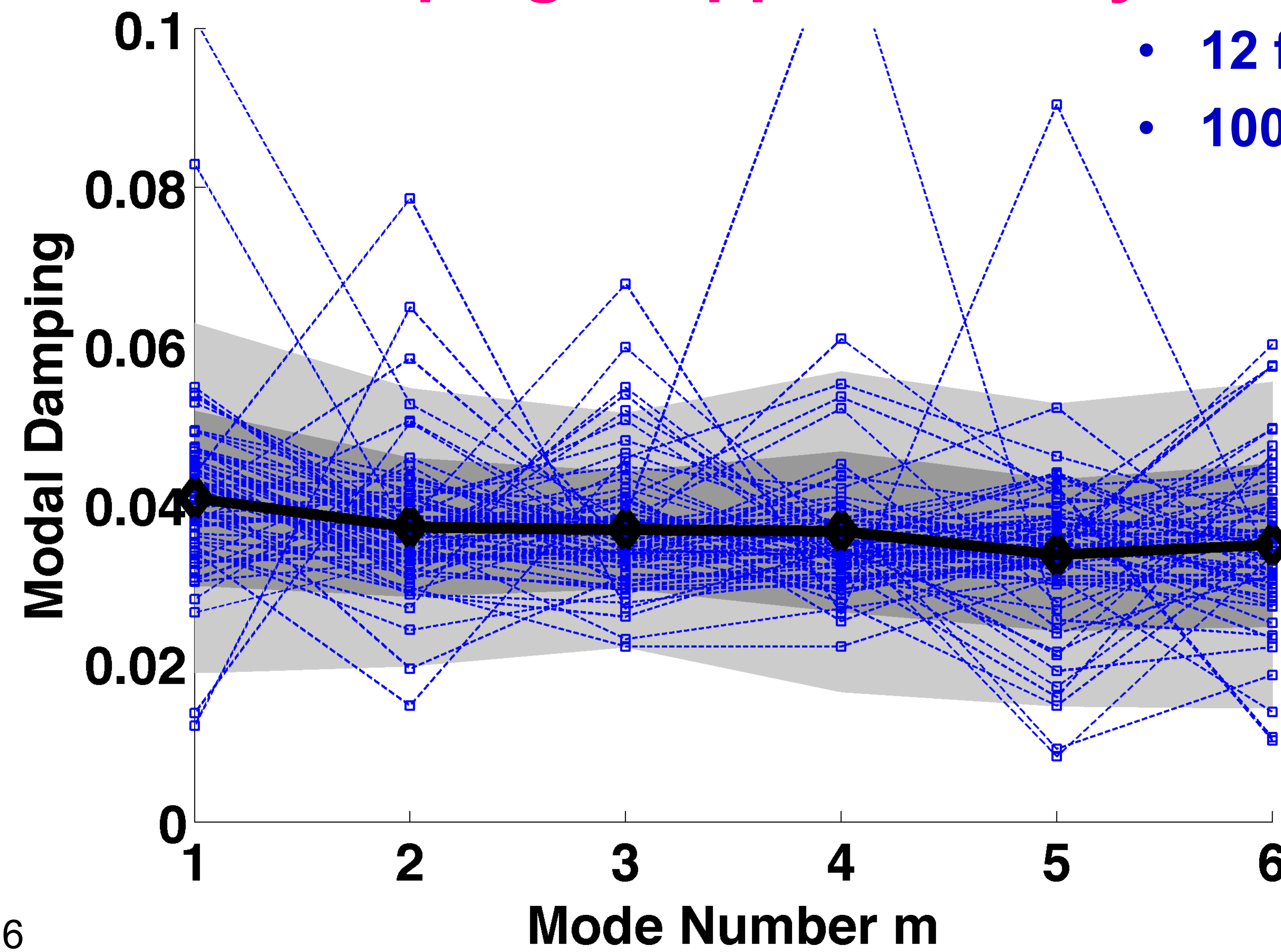
Lateral testing: *EI* & *κG*



Sandia NL — Ardelean et al. (2010)



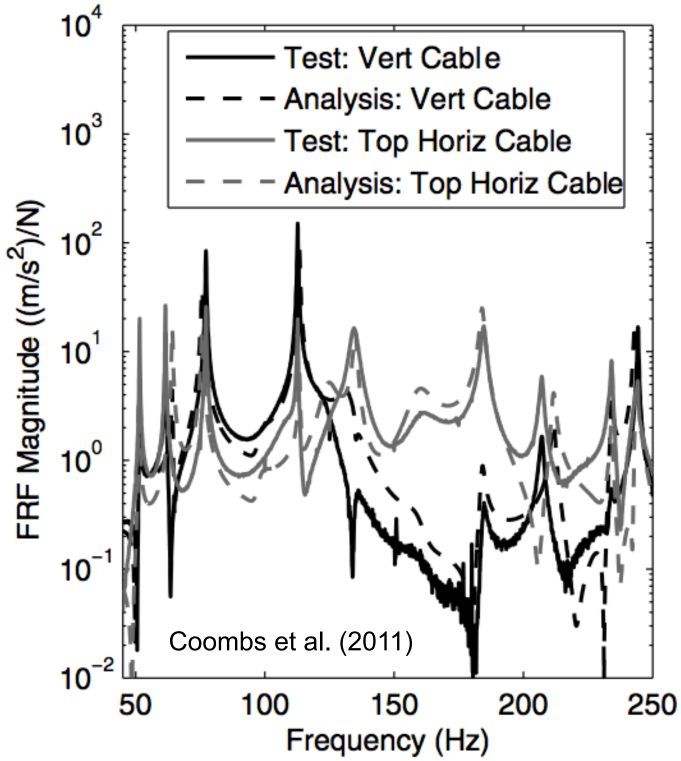
Experimental results show that modal damping is approximately constant



- 12 families
- 100 cables

Cables modeled as shear beams initially with "structural" damping

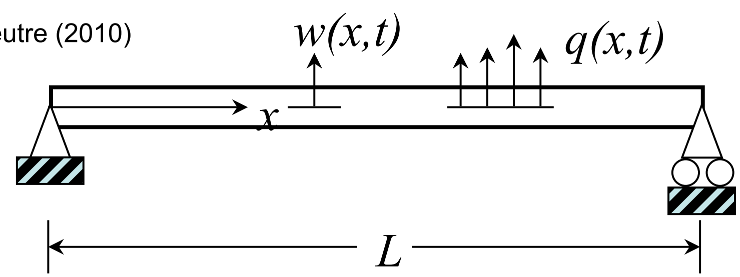
- **By researchers at Sandia / AFRL / CSA Engineering / Schafer Corp.**
  - **Goodding, Ardelean, Babuška, Coombs, et al. (2008-2011)**
- **Predicts natural frequencies, but damping model is inadequate**
- **Time-domain model essential**
  - **Transients & impact response**
  - **Nonlinearities**
- **Ideal: ~constant damping**
  - **Higher damping in higher modes to reduce response**
- **Need better understanding of physical mechanisms**



Frequency-independent modal damping is possible for Euler-Bernoulli beams

- **Especially for SS BCs**

Lesieutre (2010)



$$\rho A\ddot{w} - \alpha_G \dot{w}'' + EIw'''' = q$$

BCs: $w(0,t) = w(L,t) = w''(0,t) = w''(L,t) = 0$

$$w_m = a_m \sin\frac{m\pi x}{L}$$

- **Modal EOM**

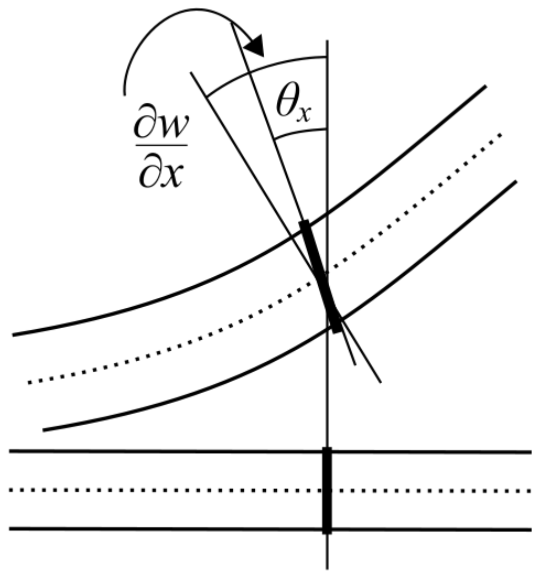
$$\ddot{a}_m \rho A + \dot{a}_m \alpha_G \left(\frac{\pi}{L}\right)^2 m^2 + a_m \left(\frac{\pi}{L}\right)^4 m^4 = 0$$

$$\omega_m = \sqrt{\frac{EI}{\rho A}}\left(\frac{m\pi}{L}\right)^2$$

$$\zeta_m = \frac{\alpha_G}{2\sqrt{\rho AEI}} = \text{constant!}$$

Can this be extended to a shear beam?

Including first-order transverse shear requires two variables from three choices



$w =$ transverse displacement

$\varphi =$ rotation due to bending

$\beta =$ shear angle

$$\beta = w' - \varphi$$

- **Shear strain contains correction factor *κ***
  - **Actual shear strain is not constant through the thicknes**

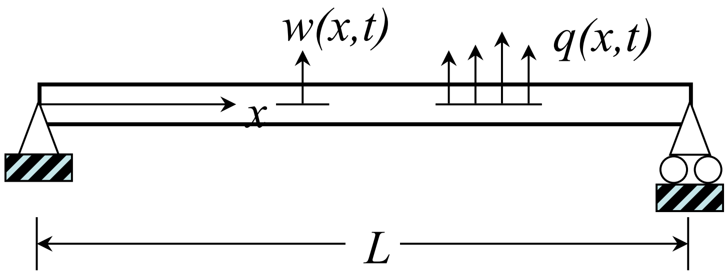
$$\varepsilon_{xz} = \kappa \beta = \kappa \left(w' - \varphi \right)$$

  - **Shear force related to nominal shear strain**

$$\int_A \tau \, \mathrm{d}A = \kappa AG \left(w' - \varphi \right) = -EI\varphi''$$

http://upload.wikimedia.org/wikipedia/commons/thumb/e/e4/Plate_theory.svg/500px-Plate_theory.svg.png

Simply-supported BCs provide valuable insight into behavior



$$\rho A\ddot{w} - \frac{\rho A E I}{\kappa A G}\ddot{w}'' + EIw'''' = q - \frac{EI}{\kappa A G}q''$$

$$w(0,t) = w(L,t) = w''(0,t) = w''(L,t) = 0$$

- **Mode shape is integer number of half-sine waves**

$$w_m = a_m \sin\frac{m\pi x}{L}$$

- **Modal EOM and natural frequencies**

$$\ddot{a}_m \rho A\left(1+\varepsilon m^2\right) + a_m\left(\frac{\pi}{L}\right)^4 m^4 = 0 \Rightarrow \omega_m = \underbrace{\sqrt{\frac{EI}{\rho A}}\left(\frac{m\pi}{L}\right)^2}_{\omega_{m,BE}}\frac{1}{\sqrt{1+\varepsilon m^2}}$$

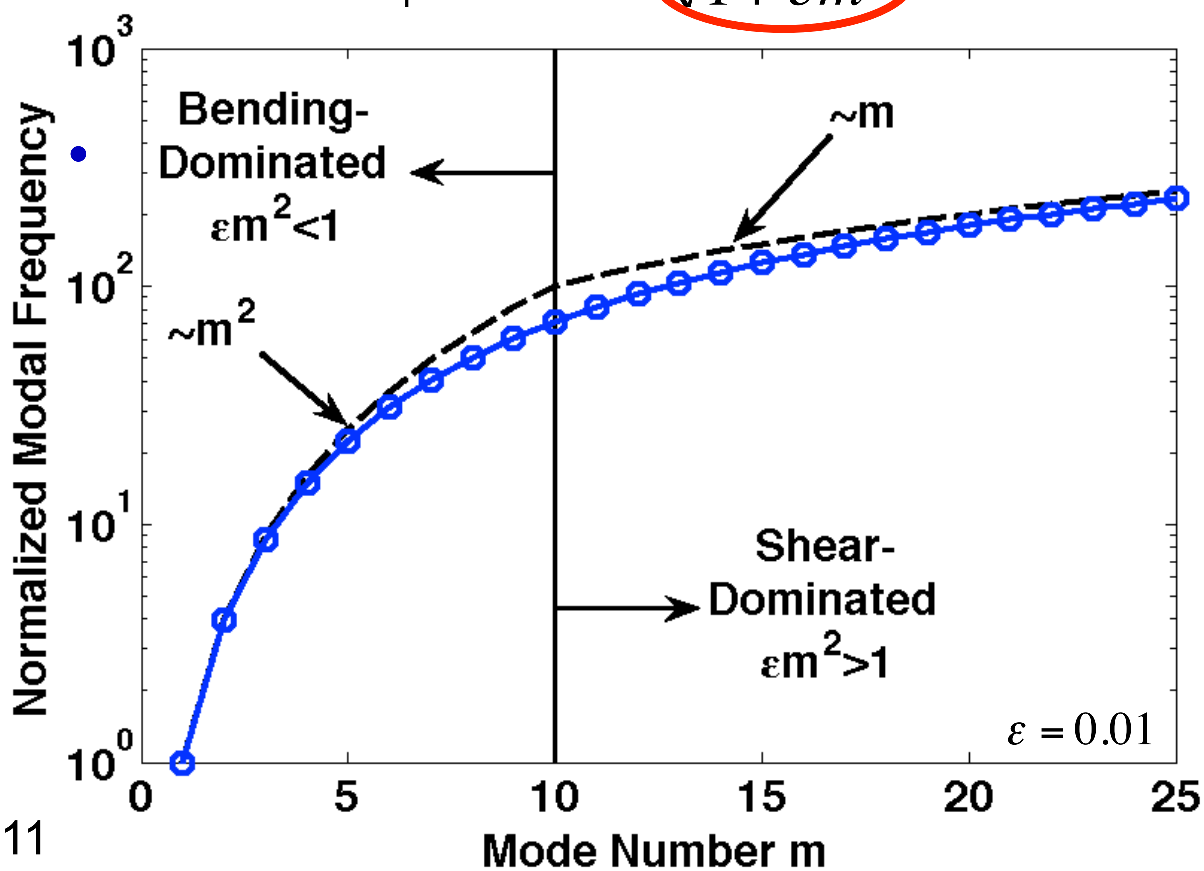
- **Shear parameter relates bending & shear stiffness**

$$\varepsilon \equiv \frac{EI\pi^2}{\kappa A G L^2}$$

Vibration modes can be separated into bending- and shear-dominated regimes

- **Transition described by shear parameter**

$$\frac{\omega_m}{\omega_1} = \sqrt{1+\varepsilon}\,\frac{m^2}{\sqrt{1+\varepsilon m^2}} \quad\rightarrow\quad \varepsilon m^2 = 1 \quad \Rightarrow \quad m = \frac{1}{\sqrt{\varepsilon}}$$



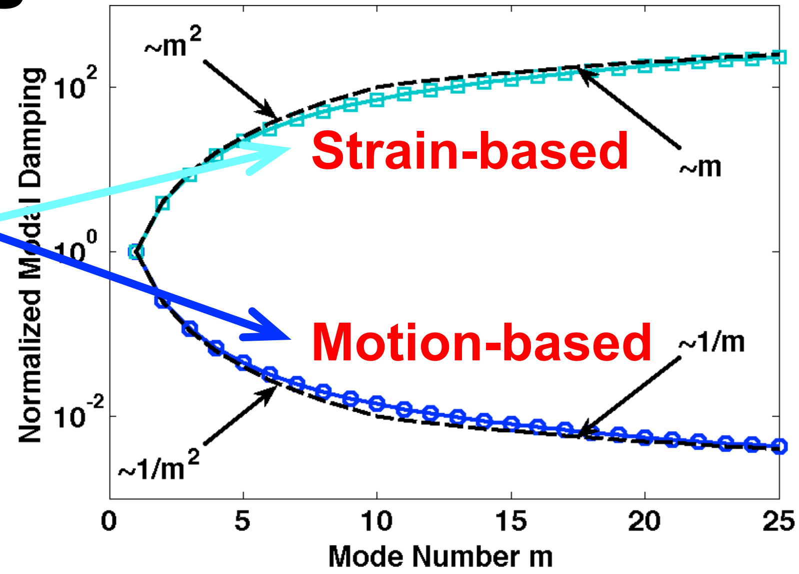
- **Limiting behavior**

$$\frac{\omega_m}{\omega_1} \sim \begin{cases} m^2 & \varepsilon m^2 << 1 \\ m & \varepsilon m^2 >> 1 \end{cases}$$

Two common viscous damping models yield unrealistic damping behavior

- **Coupled EOM:**

$$-\rho A\ddot{w}+\kappa AG\left(-\varphi'+w''\right)=-q+\alpha_M\dot{w}$$
$$EI\varphi''+\kappa AG\left(-\varphi+w'\right)=-\alpha_{EI}\dot{w}'''$$



- **Combined in single EOM:**

$$\rho A\ddot{w}-\frac{\rho AEI}{\kappa AG}\ddot{w}''+EIw''''+$$
$$+\alpha_M\dot{w}-\alpha_M\frac{EI}{\kappa AG}\dot{w}''+\alpha_{EI}\dot{w}''''=q-\frac{EI}{\kappa AG}q''$$

- **Resulting damping:**

$$\zeta_m=\frac{1}{2\sqrt{\rho AEI}}\left[\alpha_m\frac{\sqrt{1+\varepsilon m^2}}{\left(\frac{\pi}{L}\right)^2 m^2}+\alpha_{EI}\frac{\left(\frac{\pi}{L}\right)^2 m^2}{\sqrt{1+\varepsilon m^2}}\right]$$

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Shear- and bending-related damping terms yield good results

- **Introduce two internal shear forces for damping**
  - **Associated with time rate of change of shear & bending angles**

$$V = -\alpha_\beta \dot{\beta} - \alpha_\varphi \dot{\varphi}$$

- **EOM with damping**

$$-\rho A\ddot{w} + \kappa AG\left(-\varphi' + w''\right) = -q - \alpha_\beta \dot{\beta}' - \alpha_\varphi \dot{\varphi}'$$

$$EI\varphi'' + \kappa AG\left(-\varphi + w'\right) = 0$$

$$\rho A\ddot{\varphi} - \frac{\rho AEI}{\kappa AG}\ddot{\varphi}'' - \alpha_\varphi \dot{\varphi}'' + \alpha_\beta \frac{EI}{\kappa AG}\dot{\varphi}'''' + EI\varphi'''' = q' \quad \Rightarrow \quad \zeta_m = \frac{\alpha_\varphi}{2\sqrt{\rho AEI}} \frac{1 + \frac{\alpha_\beta}{\alpha_\varphi}\varepsilon m^2}{\sqrt{1+\varepsilon m^2}}$$

- **Shear- and bending-related damping contributions are explicitly separated**

$$\zeta_m \sim \begin{cases} \alpha_\varphi & \varepsilon m^2 << 1 \\ \alpha_\beta m & \varepsilon m^2 >> 1 \end{cases}$$

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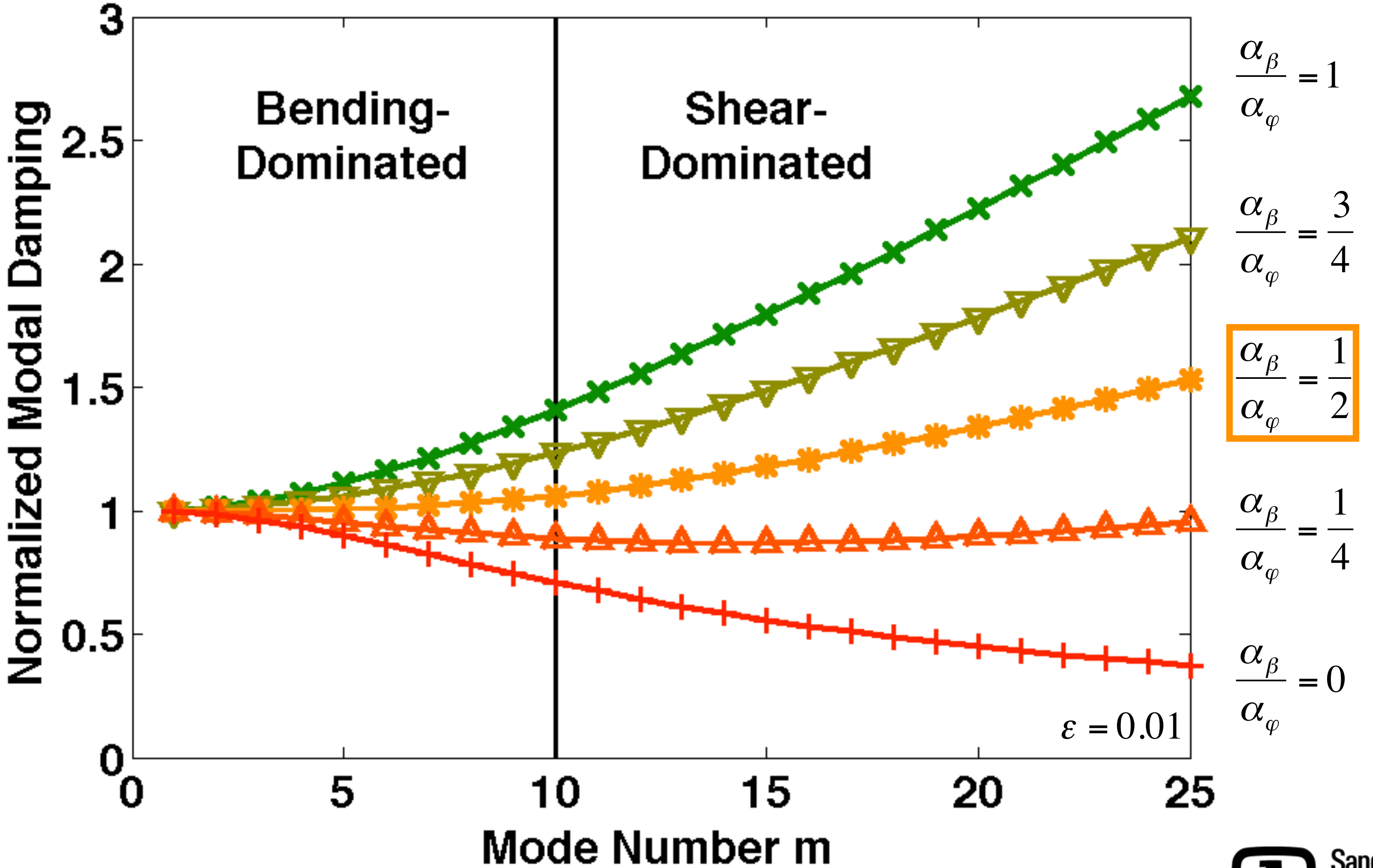
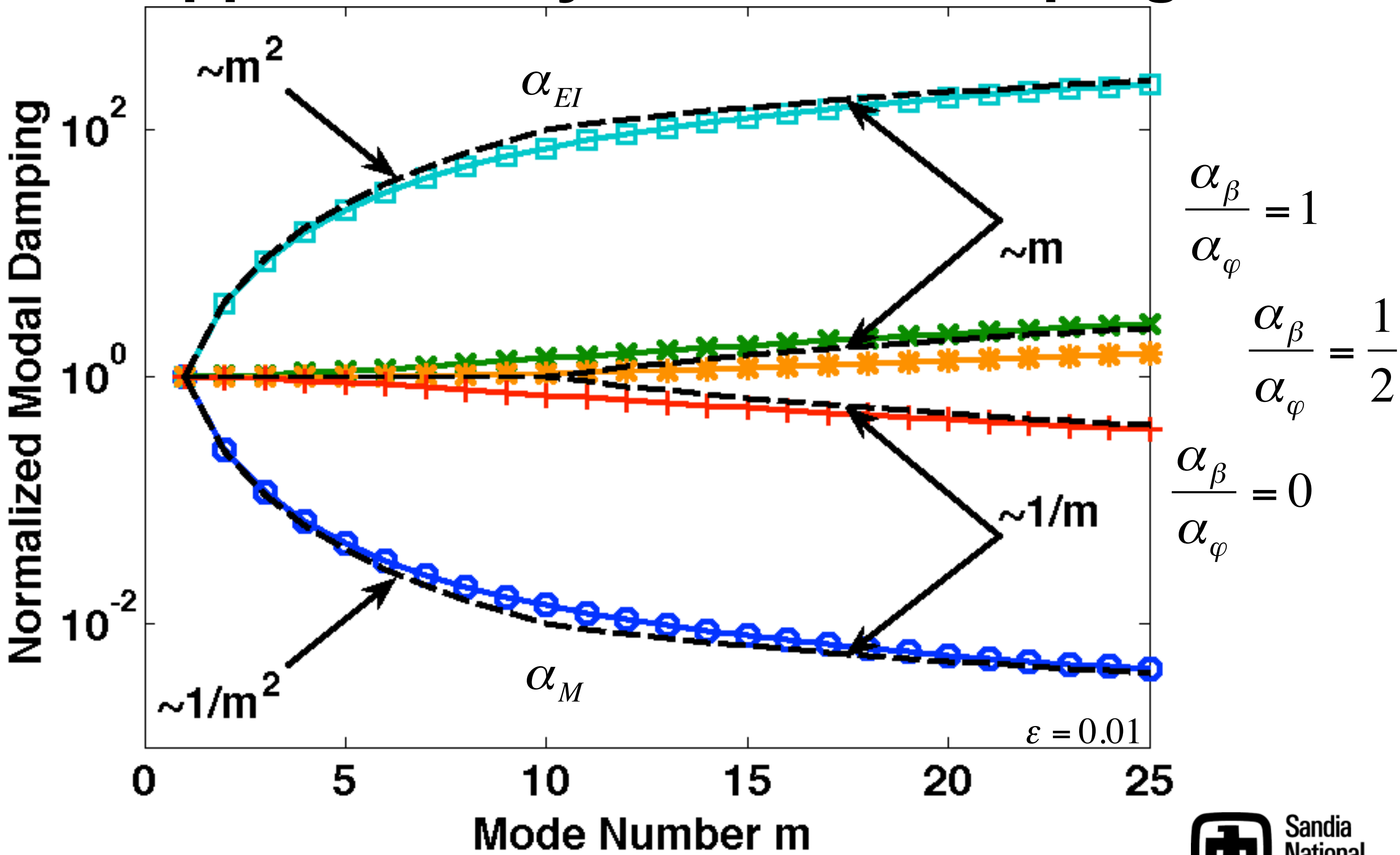
A range of damping trends available from choice of shear & bending terms



Proposed model provides realistic and approximately constant damping



A numerical (FE) approach can use conventional K, K_G, & M matrices

- **Coupled EOM**

$$-\rho A\ddot{w} + \kappa AG\left(-\varphi' + w''\right) = -q - \alpha_\beta \dot{\beta}' - \alpha_\varphi \dot{\varphi}'$$

$$EI\varphi'' + \kappa AG\left(-\varphi + w'\right) = 0$$

- **Combined in single EOM in *φ***

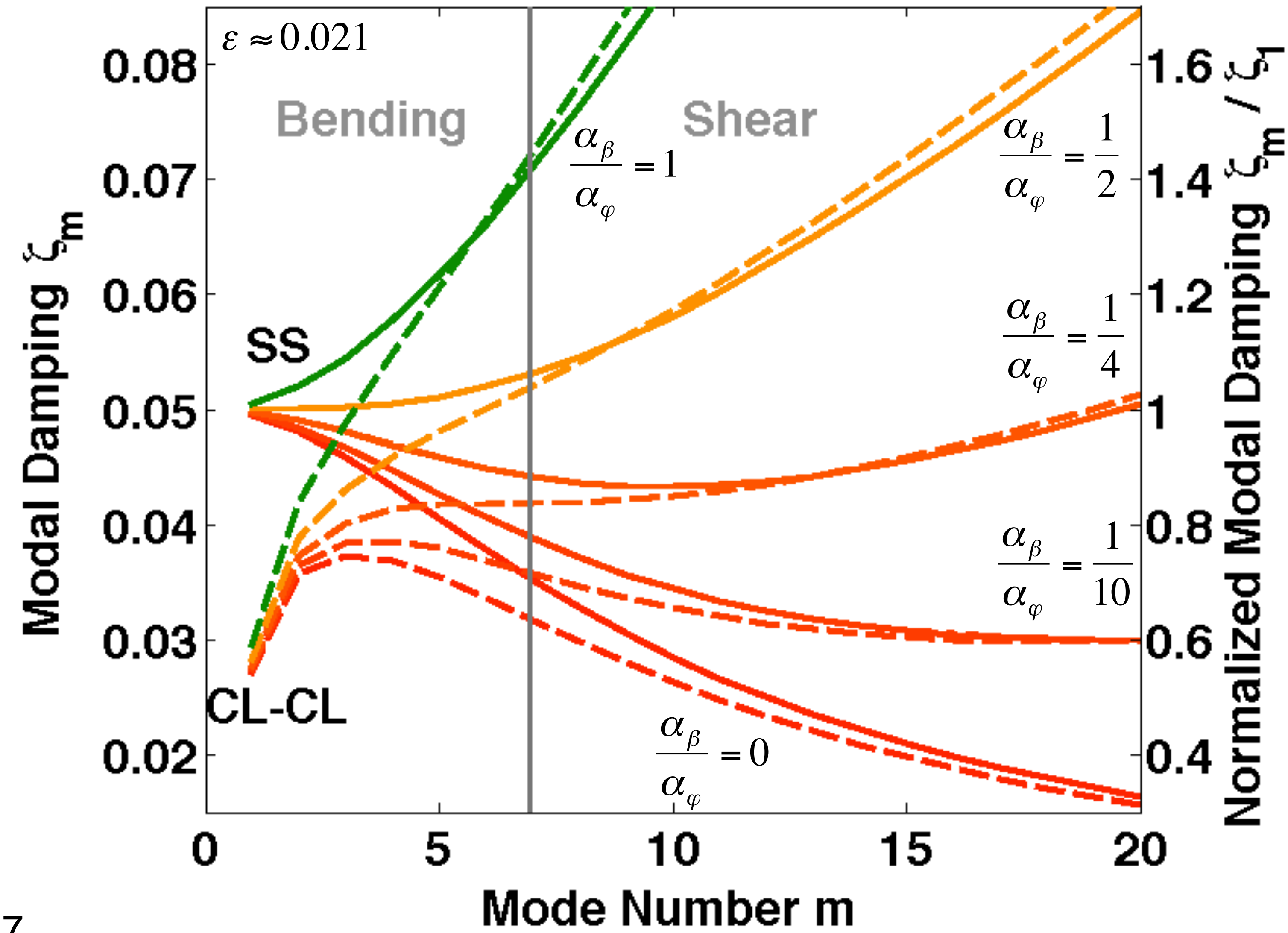
$$\rho A\ddot{\varphi} + \frac{\rho AEI}{\kappa AG}\ddot{\varphi}'' - \alpha_\varphi \dot{\varphi}'' + \alpha_\beta \frac{EI}{\kappa AG}\dot{\varphi}'''' + EI\varphi'''' = q'$$

$$\left[\left[M\right] + \frac{\rho AEI}{\kappa AG}\left[K_G\right]\right]\left\{\ddot{\varphi}\right\} + \left[\alpha_\varphi\left[K_G\right] + \alpha_\beta \frac{1}{\kappa AG}\left[K\right]\right]\left\{\dot{\varphi}\right\} + \left[K\right]\left\{\varphi\right\} = \left\{q'\right\}$$

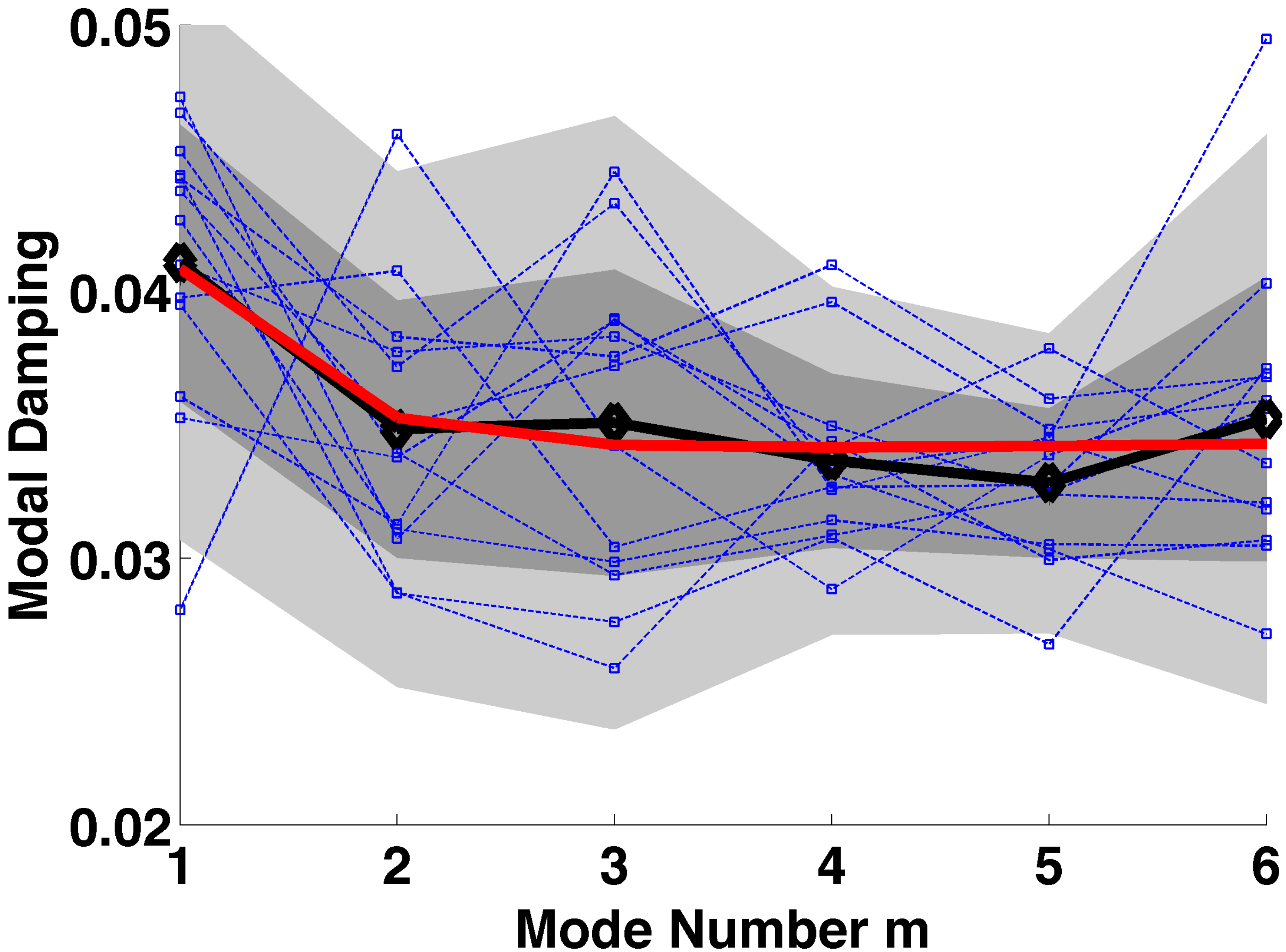
- **Forcing might be known; it could be finite-differenced**

$${}^{n}\left\{q'\right\} \approx \frac{{}^{n+1}\left\{q\right\} - {}^{n-1}\left\{q\right\}}{2L_{el}}$$

FE analysis confirms damping variation with mode number for various BCs



Proposed model with motion-, shear-, and bending-based terms fits data well



$$\alpha_M = 0.043$$
$$\alpha_\varphi = 0.038$$
$$\frac{\alpha_\beta}{\alpha_\varphi} = 0.3$$

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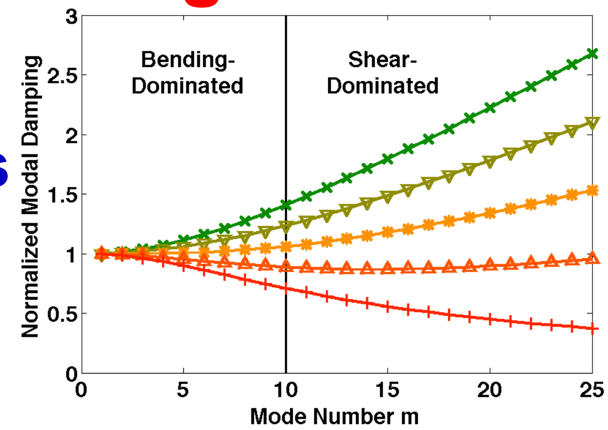
Time-domain damping model for shear beams captures dynamics of spacecraft cabling

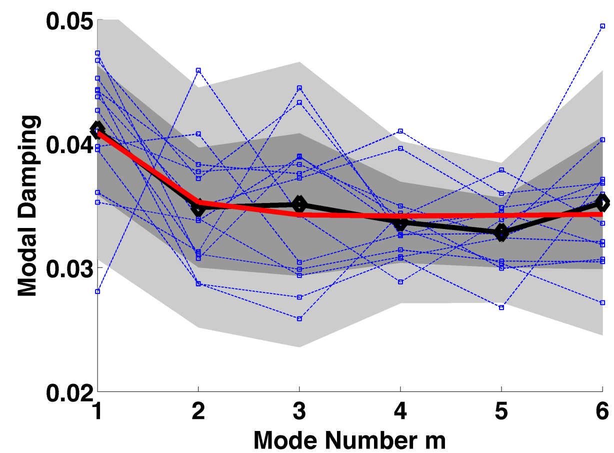
- **Behavior can be separated into bending- and shear-dominated regimes**
  - Corresponding physical understanding

$$-\rho A\ddot{w} + \kappa AG\left(-\varphi' + w''\right) = -q - \alpha_\beta \dot{\beta}' - \alpha_\varphi \dot{\varphi}'$$

- **Freq-independent modal damping achievable in bending region**
  - Can control damping in shear regime
  - Can achieve best possible freq-indep
- **Damping model can be readily implemented using FEM**
  - Uses conventional K, K_G, & M matrices
- **Model predictions agree well with experimental data**

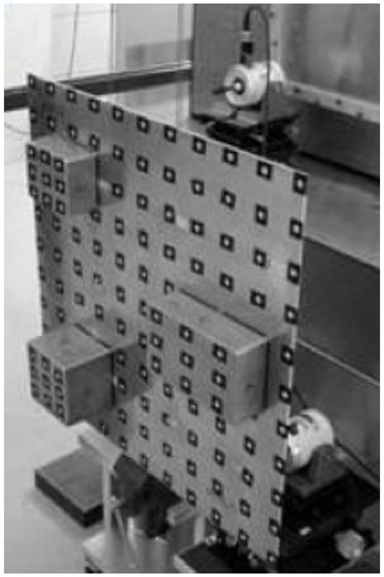


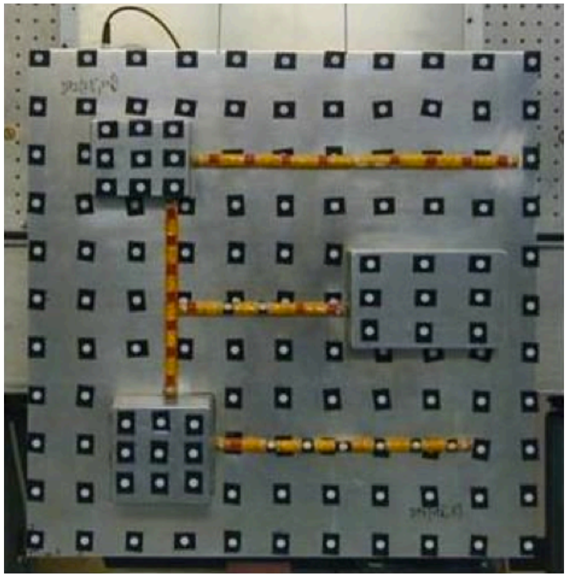
$$\zeta = \frac{\alpha_\varphi}{2\sqrt{\rho AEI}} \frac{1 + \frac{\alpha_\beta}{\alpha_\varphi}\varepsilon m^2}{\sqrt{1+\varepsilon m^2}}$$



Future work will examine realistic BCs and consider Timoshenko beam model

- **Typical spacecraft cabling configuration**
  - **Not really SS or CC BCs**
  - **Model as adjustable rotational stiffness**





Ardelean et al. (2010)

- **Timoshenko model adds rotatory inertia**

$$-\rho A\ddot{w} + \kappa AG\left(-\varphi' + w''\right) = -q - \alpha_\beta \dot{\beta}' - \alpha_\varphi \dot{\varphi}'$$

$$-\rho I\ddot{\varphi} + EI\varphi'' + \kappa AG\left(-\varphi + w'\right) = 0$$

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