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IMAC-XL: Next Frontier in Structural Dynamics
Submission # 12359

Using Reduced Order Models to Predict Modal Coupling in Jointed Structures

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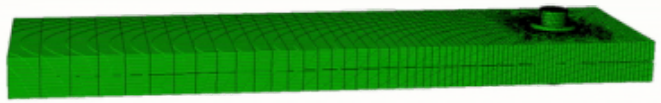
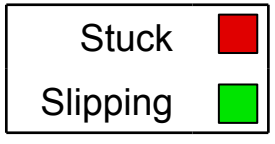
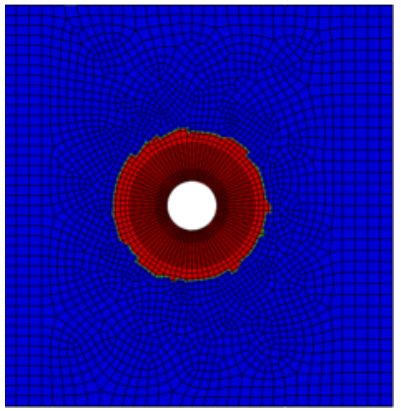
Consider a Structure with a Joint

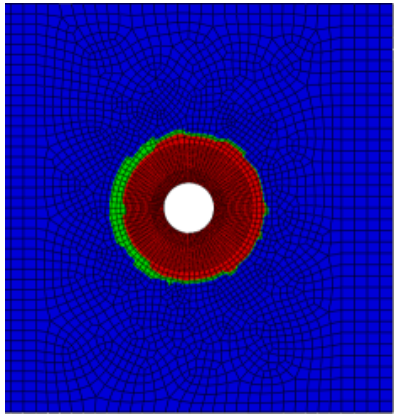
- Throughout loading, we see the interface begins to exhibit slip
  - Microslip (slipping on the extremities of contact)
  - Macroslip (global slipping)

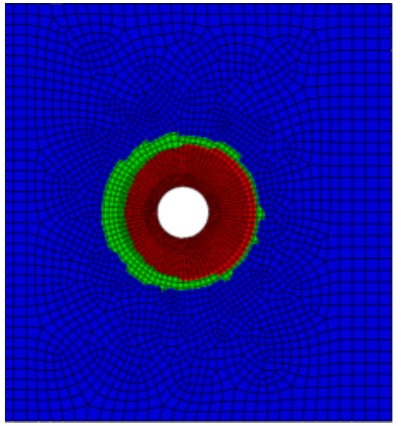


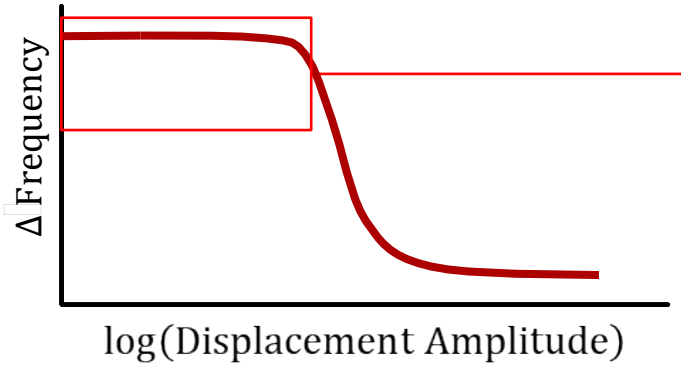


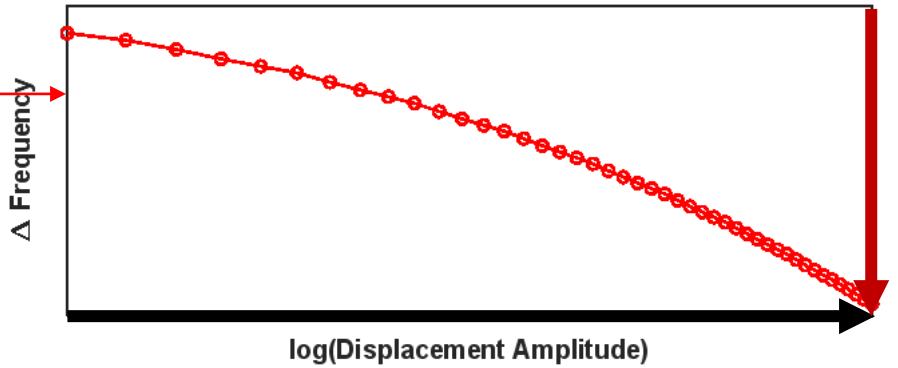
Increasing Load

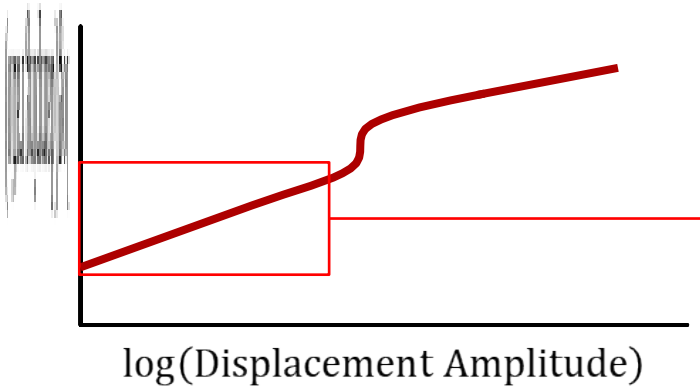


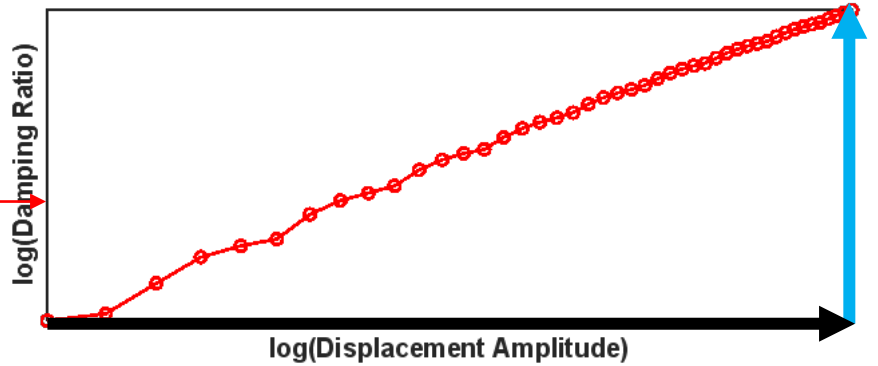






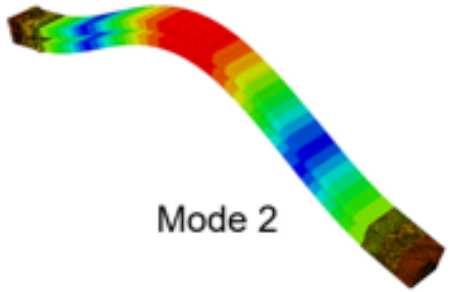


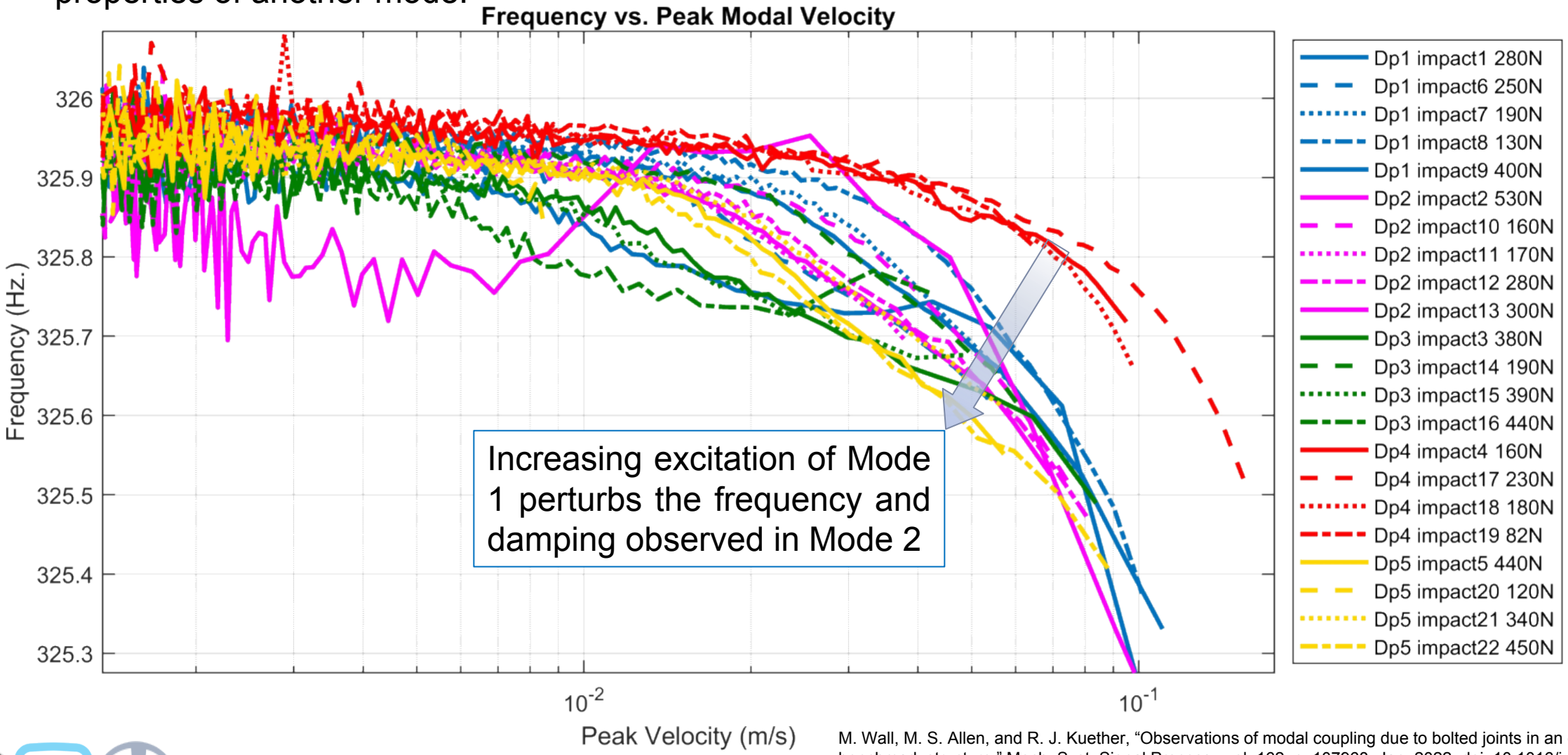




Variation in experimental response

- Recent experiments show a case where excitation of one mode changes the apparent properties of another mode.

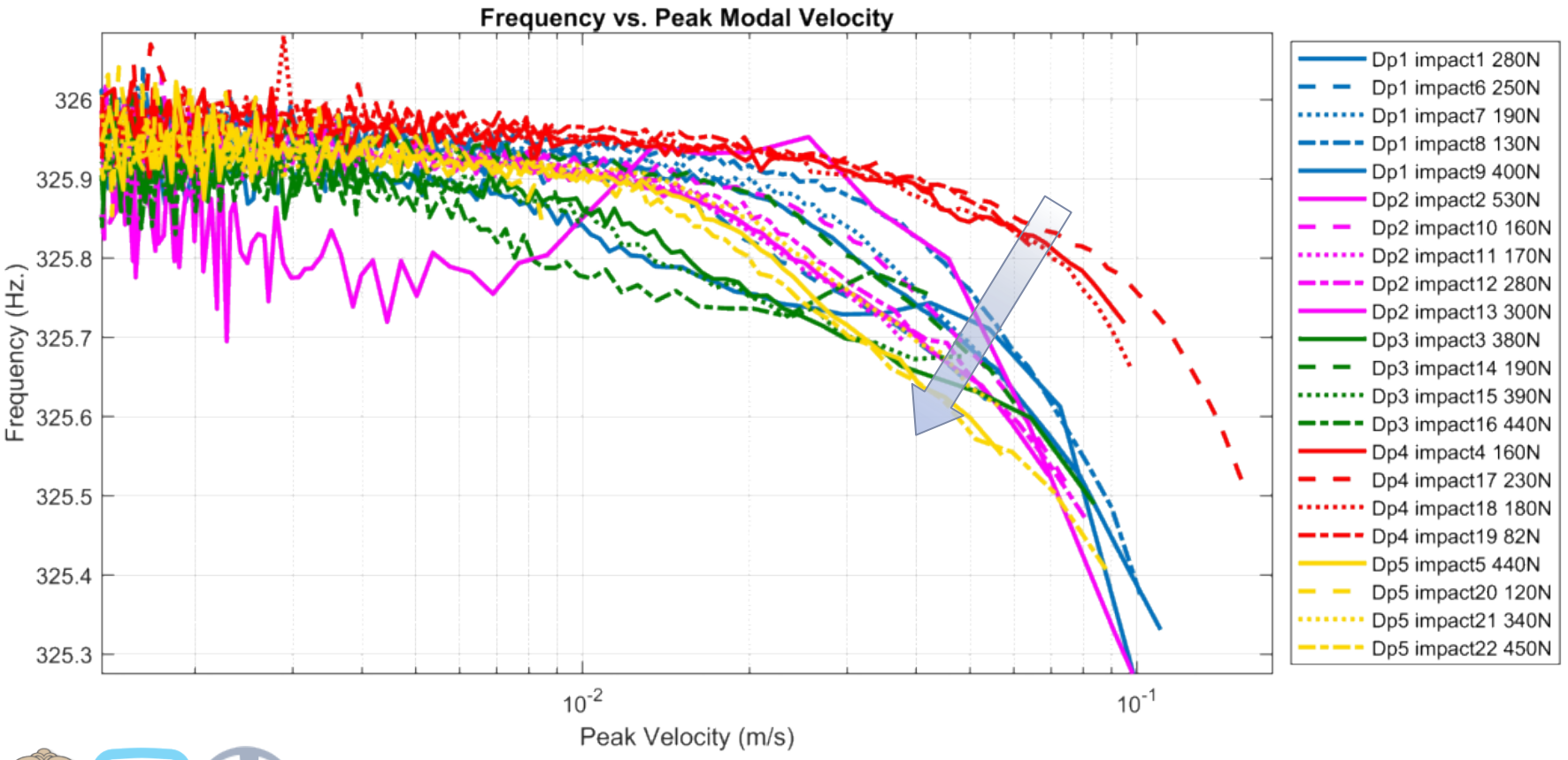


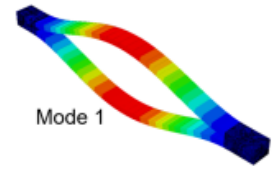


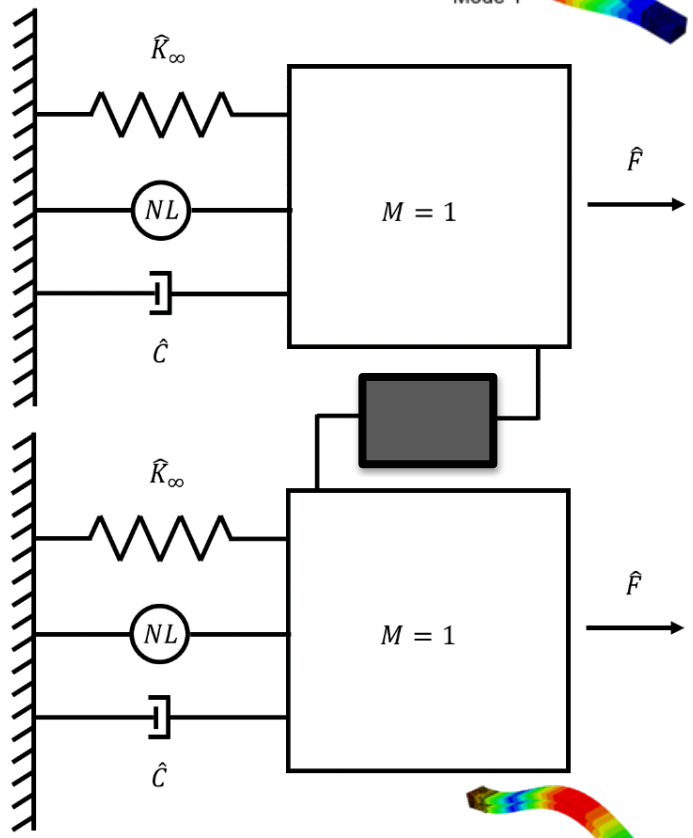
M. Wall, M. S. Allen, and R. J. Kuether, "Observations of modal coupling due to bolted joints in an experimental benchmark structure," Mech. Syst. Signal Process., vol. 162, p. 107968, Jan. 2022, doi: 10.1016/j.ymssp.2021.107968.

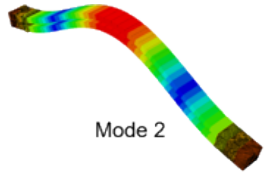
How do we predict modal coupling?

- Nonlinear forces at the joints couple the SDOF oscillators in the modal domain.
  - Few models exist that capture this for hysteretic systems.
- Could we predict this using a finite element model that includes friction at the interfaces?





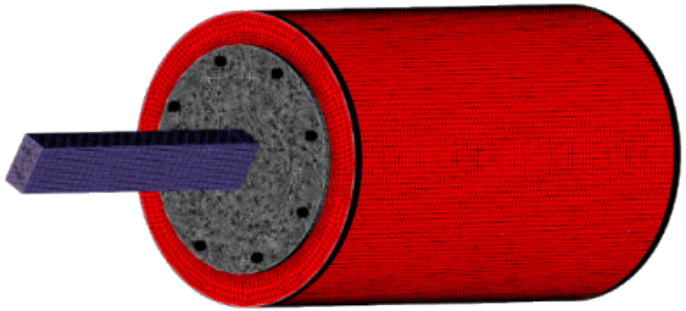




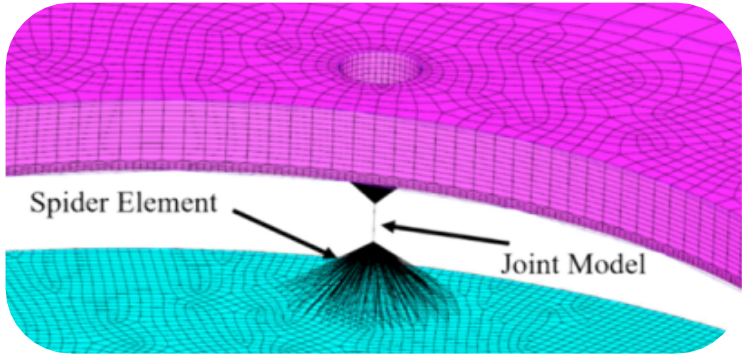
Alternative to Full Order Modeling

Transient/ Quasi-Static Analysis of a Full FEM

Computationally Expensive



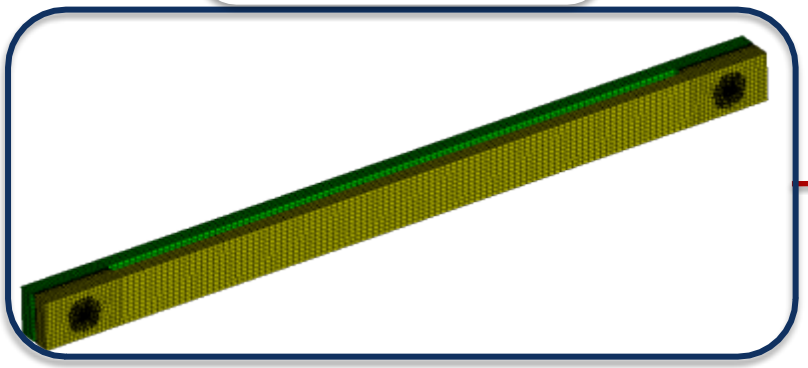
Analysis of a Reduced Order Model



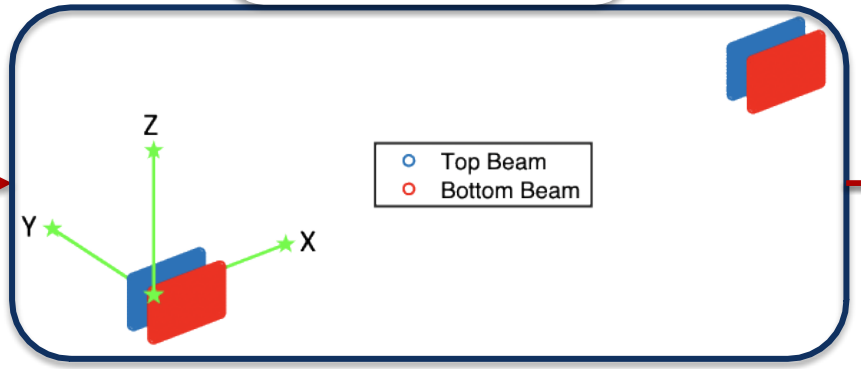
Objective: Construct a Reduced Order Model (ROM) that can capture the dynamics of the full system in a fraction of the time AND capture coupling

ROMs Used in this Study

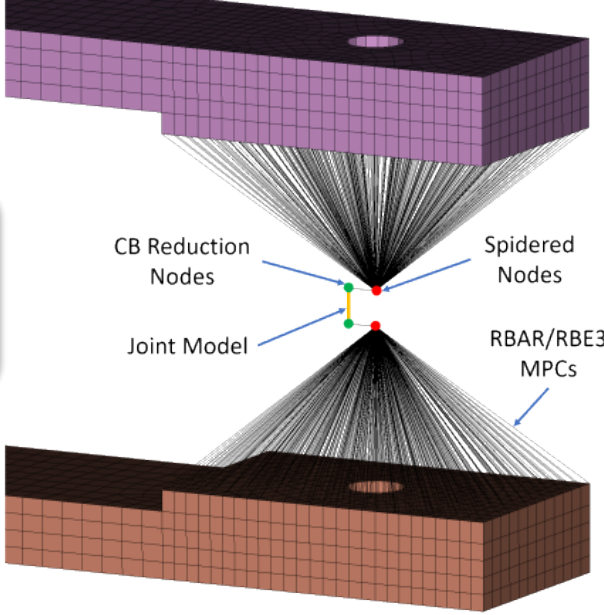
Full Model



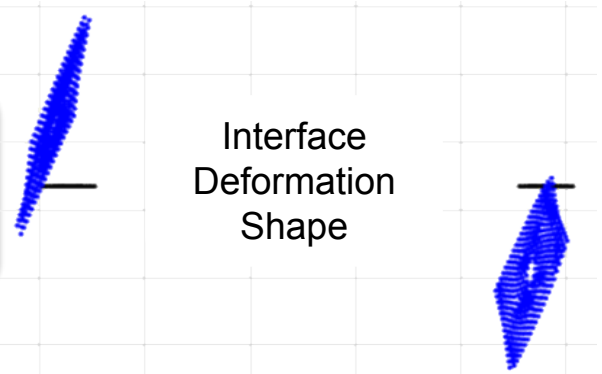
HCB ROM



Spidered ROM[1]



S-CC ROM[2]



***Note:** Refer to each paper for more information and steps for the reduction process

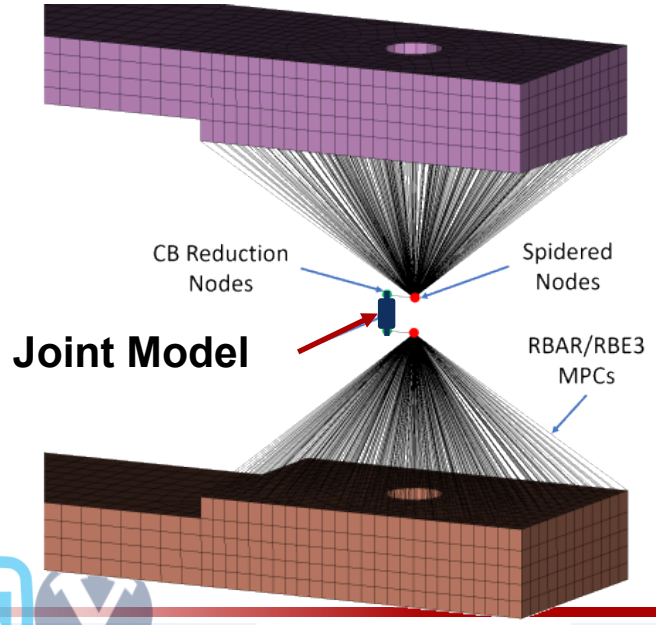
[1]A. Singh, M. Wall, M. S. Allen, and R. J. Kuether, "Spider Configurations for Models with Discrete Iwan Elements," in *Nonlinear Structures and Systems, Volume 1*, Orlando, FL, Jan. 2019, pp. 25–38. doi: 10.1007/978-3-030-12391-8_4.

[2]A. Singh, M. S. Allen, and R. J. Kuether, "Substructure Interface Reduction Techniques to Capture Nonlinearities in Bolted Structures," presented at the ASME 2020 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Nov. 2020. doi: 10.1115/DETC2020-22417.

Differences between Spidering and S-CC ROMs

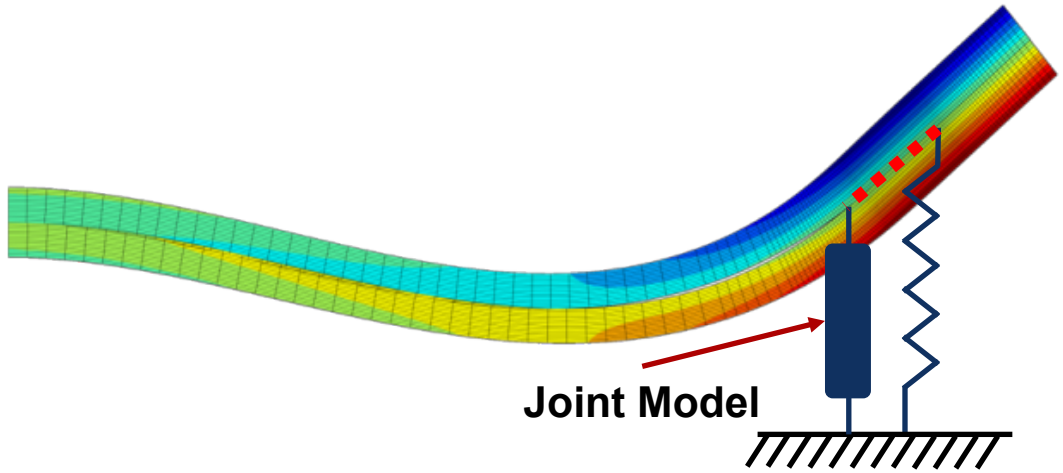
MPC Approach

- **Basis**
  - Physical coordinates
- **Usage**
  - Linear springs/nonlinear elements in between <u>two physical nodes that are spidered</u>

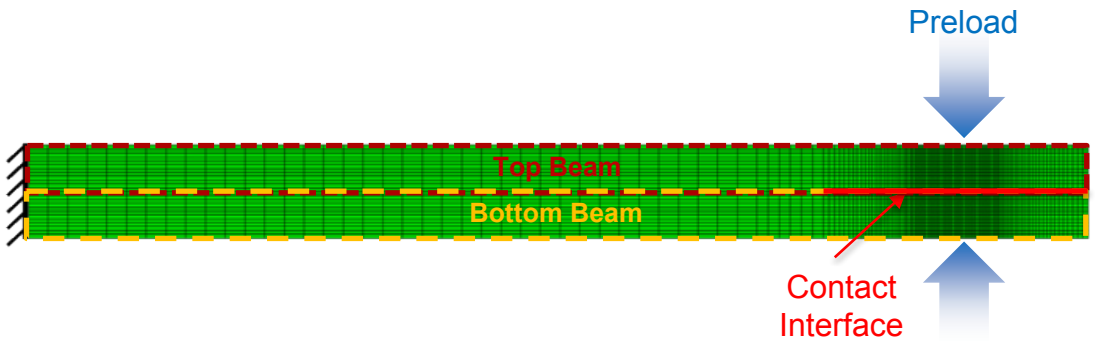


S-CC Approach

- **Basis**
  - S-CC Deformation Shapes (Φ_{CC})
- **Usage**
  - Linear springs/nonlinear elements attached to <u>S-CC deformation shapes</u>



Numerical Structure of Interest – 2D Beam



Full Model

DOF	8684

HCB Model

FIM	20
DOF	260
Total	**280**

Spidered ROM

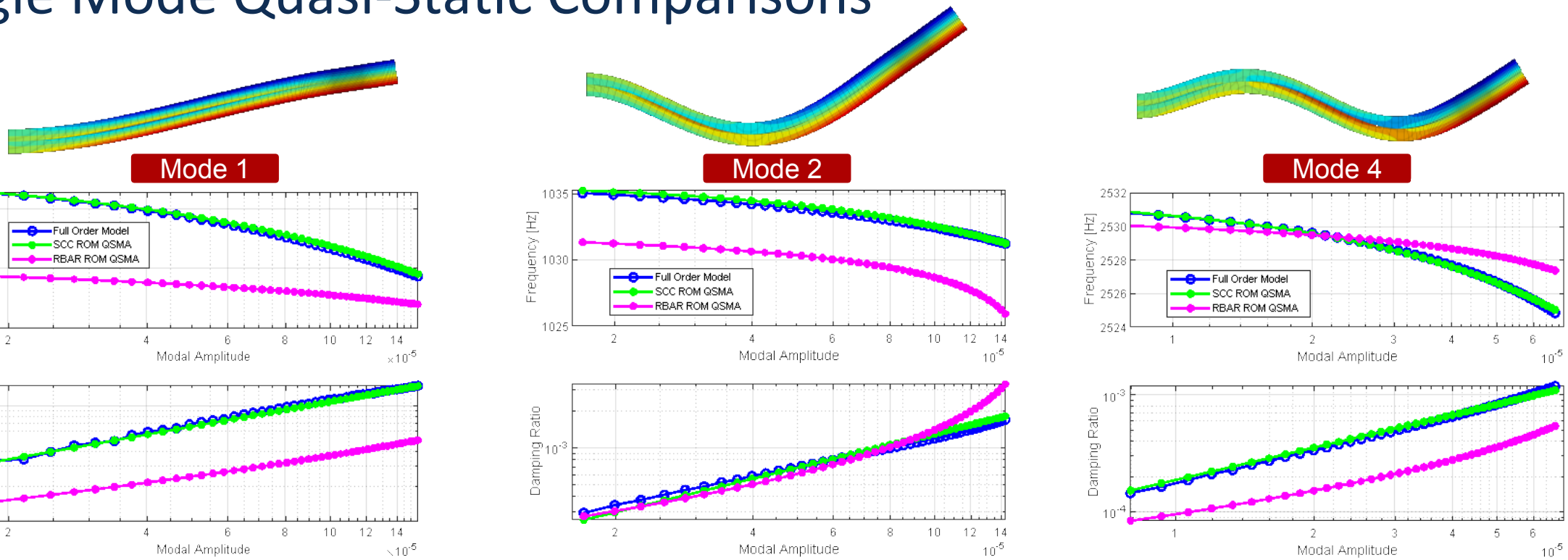
FIM	20
DOF	24
Total	**44**

S-CC ROM

FIM	20
DOF	6
Total	**26**

- Use a 2D cantilever beam built in Abaqus
  - Compare quasi-static sims of single mode response for the full model and the ROMs
  - Compare full/ROM transient responses with coupled loading

Single Mode Quasi-Static Comparisons

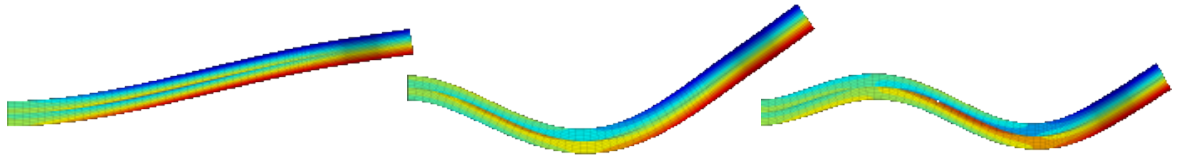


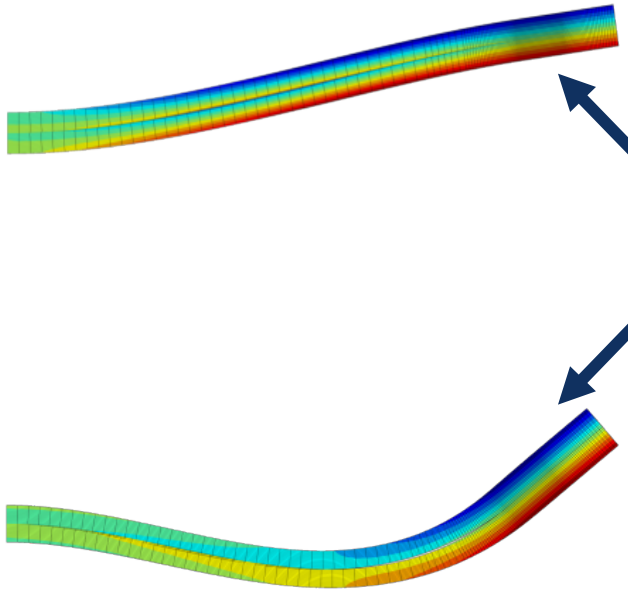
- Apply an Iwan element to each ROM and tune the four parameters iteratively (F_s, K_T, χ, β)
- **One** set of Iwan parameters for spidered ROM for all three modes
- **Two** sets of Iwan parameters for S-CC ROM for all three modes
- RBAR (rigid bar) spidered ROM produces higher frequency and damping errors

Single mode analysis provides a baseline to compare to the multi-mode excited ROMs

Degree of Coupling

- S-CC reduction matrix gives an estimate of the extent of coupling that the S-CC ROM can model
- Examine the coupling between Modes 2 and 4 in two cases:
  - **Case 1:** Mode 2 has 10x the peak amplitude of Mode 4
  - **Case 2:** Mode 4 has 10x the peak amplitude of Mode 2

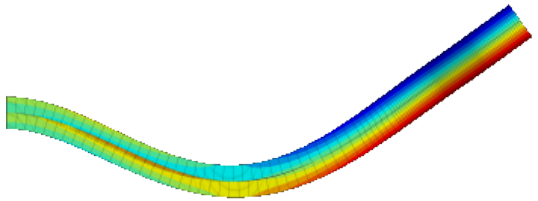


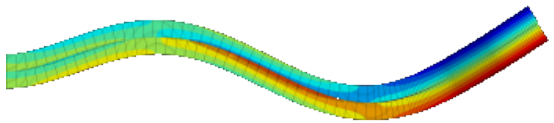


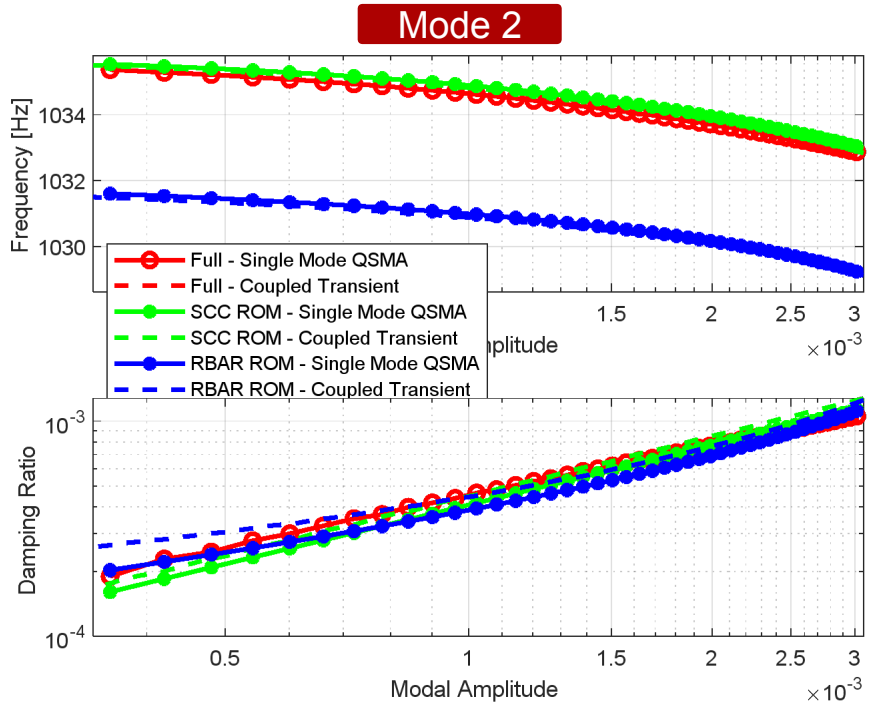
	Mode 1	Mode 2	Mode 4
Fixed Interface Modes	2.05	46.26	62.73
S-CC DOF 1	97.93	17.86	10.63
S-CC DOF 2	0.02	30.84	26.39
S-CC DOF 3	0.00	0.00	0.00
S-CC DOF 4	0.00	0.00	0.00
S-CC DOF 5	0.00	0.00	0.00
S-CC DOF 6	0.00	0.09	0.25

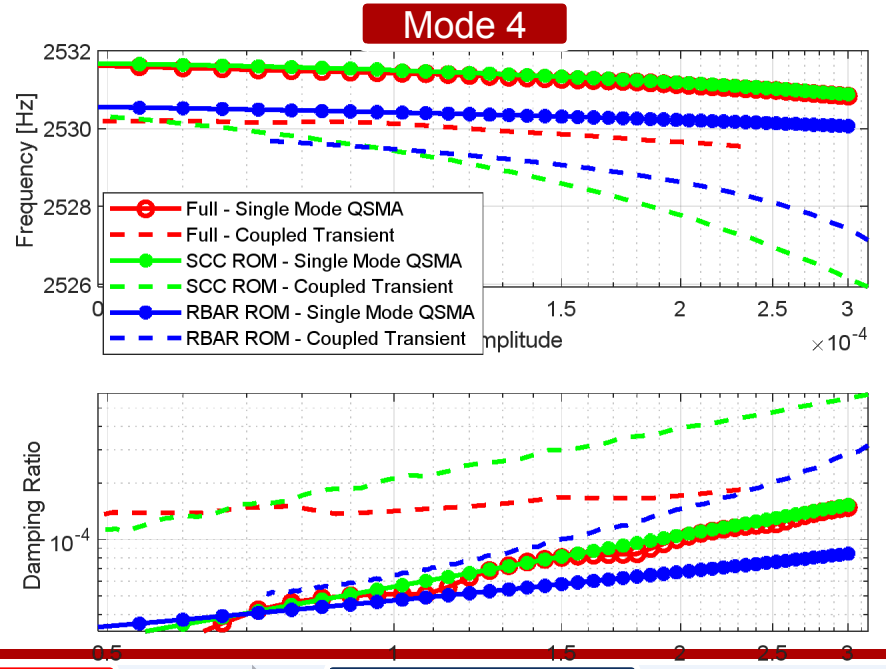
Case 1: Mode 2 has 10x Peak Amplitude of Mode 4

- Mode 2 influences the response of Mode 4
- Both ROMs correctly predict that the effect of Mode 4 on Mode 2 will be negligible
- **S-CC ROM** can predict the coupled effect on the damping of Mode 4 closer to the full model
- **RBAR ROM** underpredicts the coupling
- Both ROMs overpredict the frequency response of Mode 4

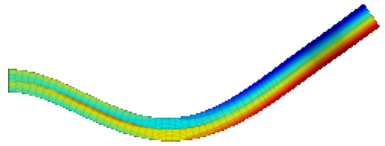




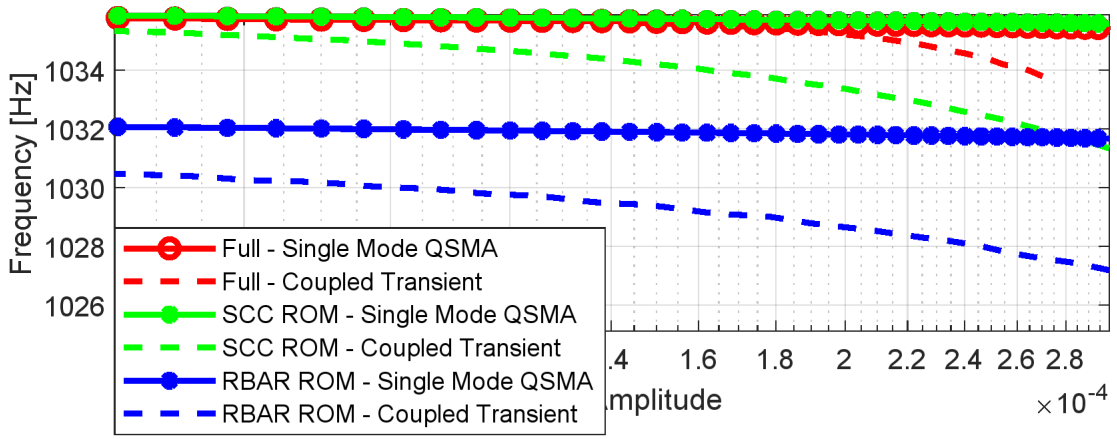


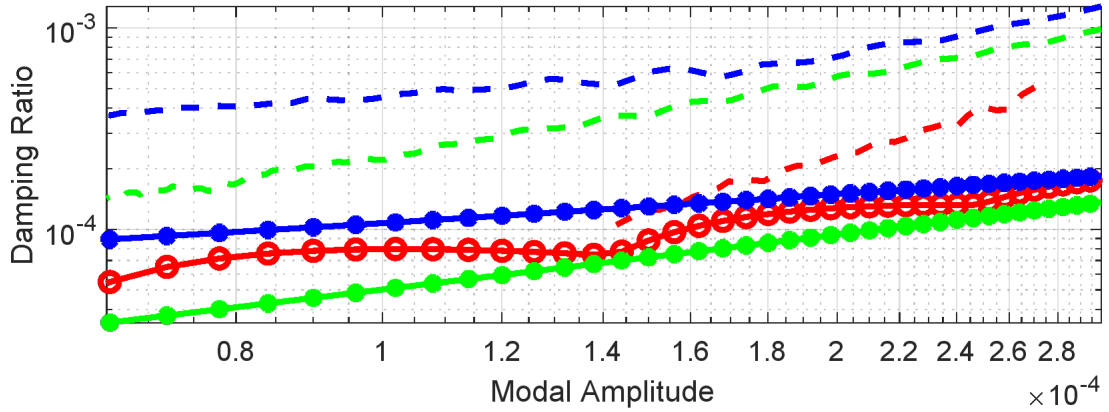


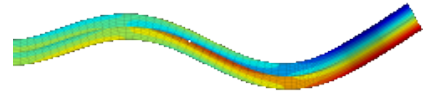
Case 2: Mode 4 has 10x Peak Amplitude of Mode 2



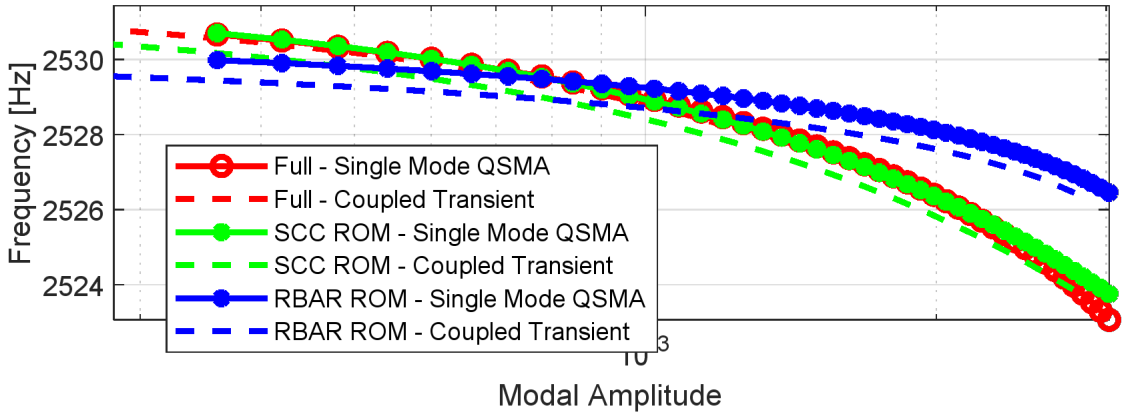
Mode 2

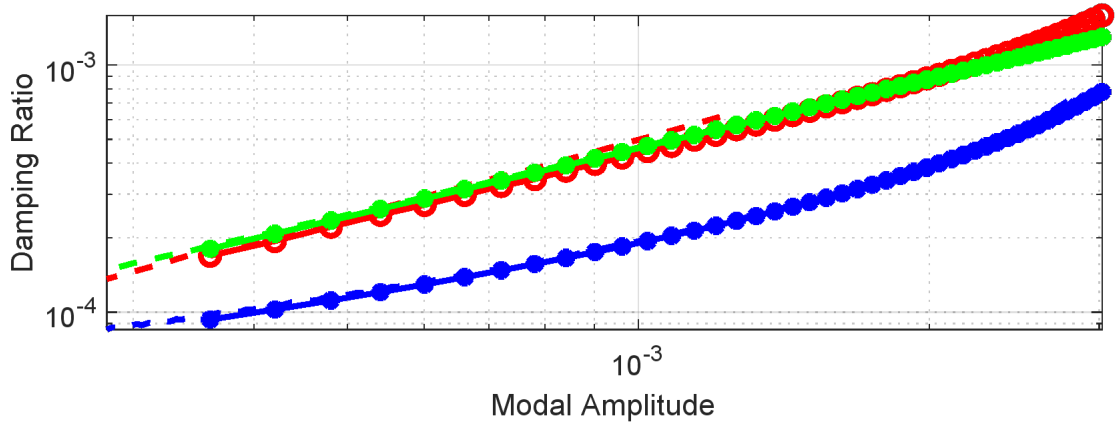






Mode 4

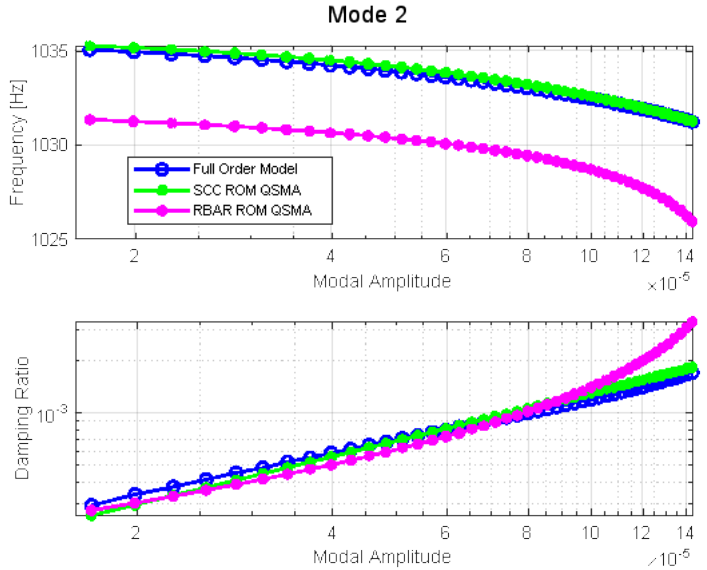




Concluding Remarks

- Preliminary study to evaluate coupling on reduced order models
- Significant run-time reduction to compute ROMs for the 2D Cantilever Beam
  - **Full Model Transient:** *26 – 30 hours* on a single core
  - **ROM Transient:** *0.5 – 2 minutes* on a single core
- **RBAR ROM** produces higher errors for calibration (3 modes) than the **S-CC ROM** using an Iwan element
- Multi-Mode excitation perturbs the response for both the **full model** and the ROMs
- Study opens the idea of tuning and using ROMs in an effort to evaluate modal coupling
- Future work seeks to extend this to other ROMs and to complicated structures with different DOFs that couple

Single Mode Calibration



Multi Mode Excitation