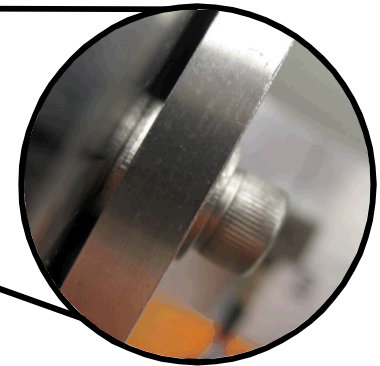
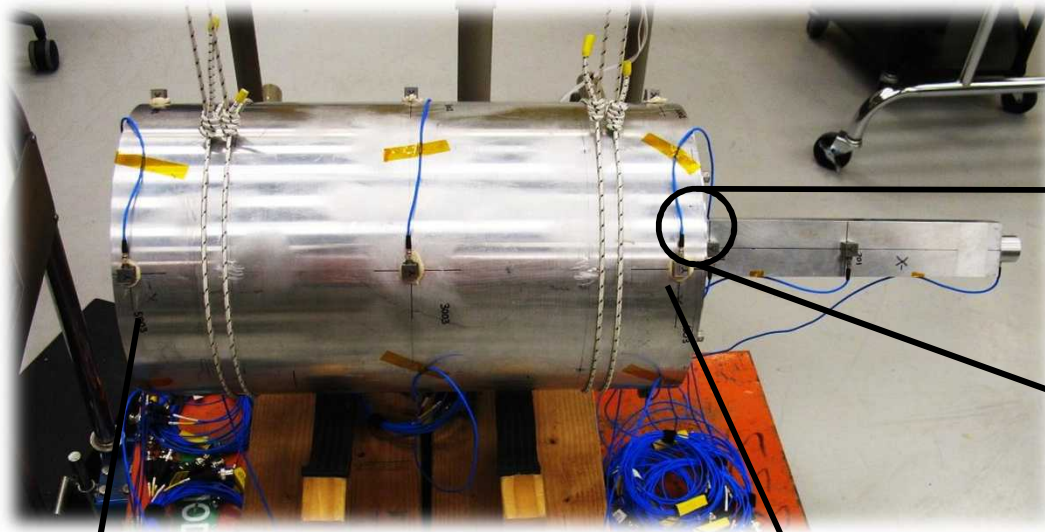


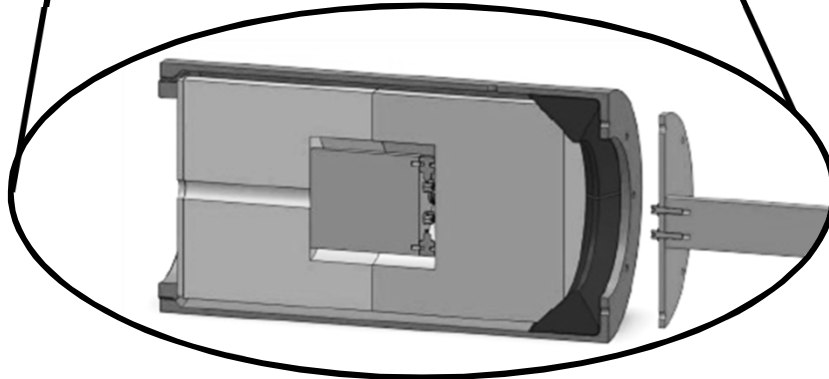
Reduced Order Modeling Techniques in Experimental Dynamic Substructuring

RJK1

SAND2015-6113D



8 bolted
connections



Internal foam package (material
nonlinearity, contacts)

Slide 1

RJK1

Kuether, Robert J., 7/17/2015

Team Members:

Wei Che Tai – University of Washington

Tilàn Dossogne – University of Liège

Seunghun Baek – University of Michigan

Benjamin Seegar – Universität Stuttgart

Dan Roettgen - University of Wisconsin – Madison

Mentors:

Robert Kuether – Sandia National Labs

Matthew Allen – University of Wisconsin – Madison

Matthew R. W. Brake – Sandia National Labs

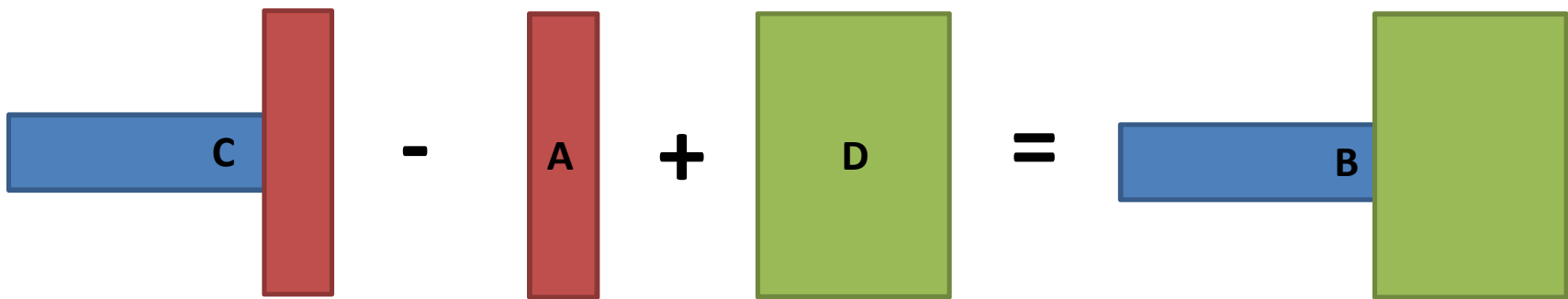
Randall Mayes – Sandia National Labs

Objective

- Compare different experimental substructuring techniques using two different systems
- Discover the best practices for experimental-numerical substructuring

Substructuring Theory

- Component Mode Synthesis (CMS) is used to combine two substructures to predict the dynamic response of the assembly
- This is useful when testing a full assembly is impractical or trying to analyze the effects of changing out different sub-assemblies
- These predictions can be very sensitive to interface errors where two substructures are joined
- In order to exercise the joints as they see in the assembly the experiment can be connected to known fixture or transmission simulator (TS)
- The Craig-Mayes method uses the transmission simulator theory to create an experimental Craig-Bampton like form of the experimental results



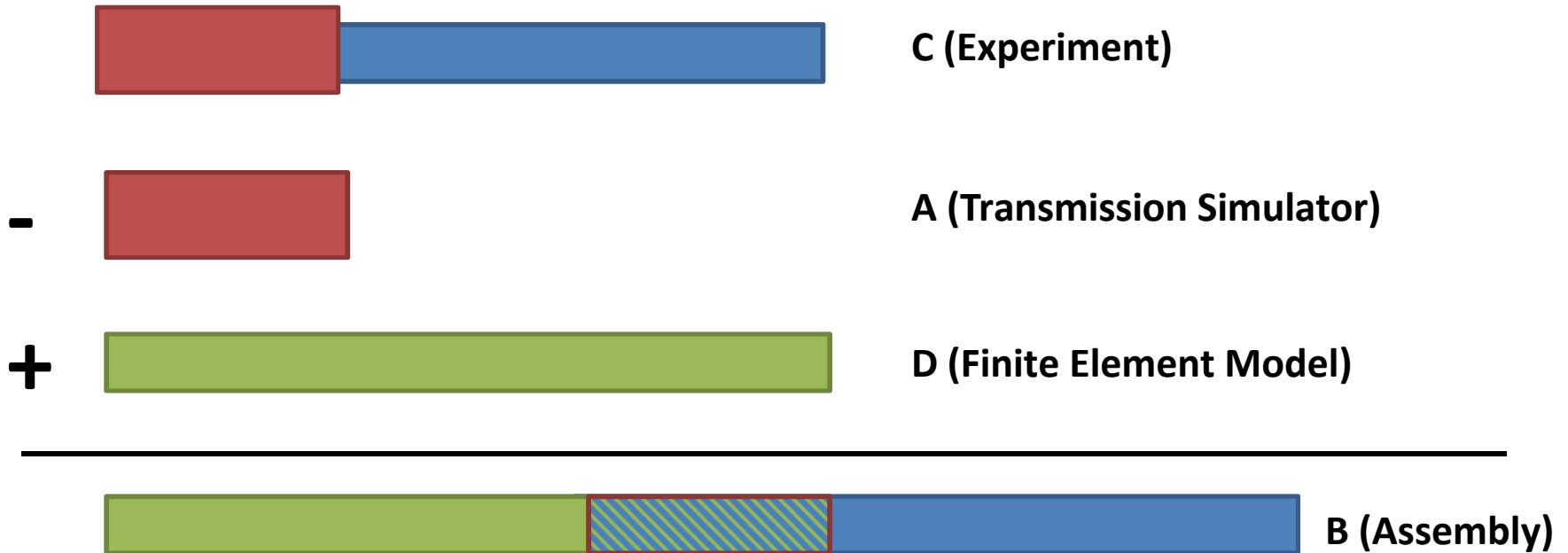
$$\mathbf{C} - \mathbf{A} + \mathbf{D} = \mathbf{B}$$

- In the transmission simulator method a known transmission simulator (A) is subtracted from the experimental subsystem (C)
- Next a new subsystem (D) is added to the result creating the target assembly (B)

$$\begin{bmatrix} I_C & 0 & 0 \\ 0 & I_D & 0 \\ 0 & 0 & -I_A \end{bmatrix} \begin{Bmatrix} \ddot{q}_C \\ \ddot{q}_D \\ \ddot{q}_A \end{Bmatrix} + \begin{bmatrix} 2\zeta_C\omega_C & 0 & 0 \\ 0 & 2\zeta_D\omega_D & 0 \\ 0 & 0 & -2\zeta_A\omega_A \end{bmatrix} \begin{Bmatrix} \dot{q}_C \\ \dot{q}_D \\ \dot{q}_A \end{Bmatrix} + \begin{bmatrix} \omega_C^2 & 0 & 0 \\ 0 & \omega_D^2 & 0 \\ 0 & 0 & -\omega_A^2 \end{bmatrix} \begin{Bmatrix} q_C \\ q_D \\ q_A \end{Bmatrix} = \begin{Bmatrix} \phi_C^T F_C \\ \phi_D^T F_D \\ \phi_A^T F_A \end{Bmatrix}$$

$$\begin{bmatrix} \phi_A^+ & 0 \\ 0 & \phi_A^+ \end{bmatrix} \begin{bmatrix} \phi_C & 0 & -\phi_A \\ 0 & \phi_D & -\phi_A \end{bmatrix} \begin{Bmatrix} q_C \\ q_D \\ q_A \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \\ 0 \end{Bmatrix}$$

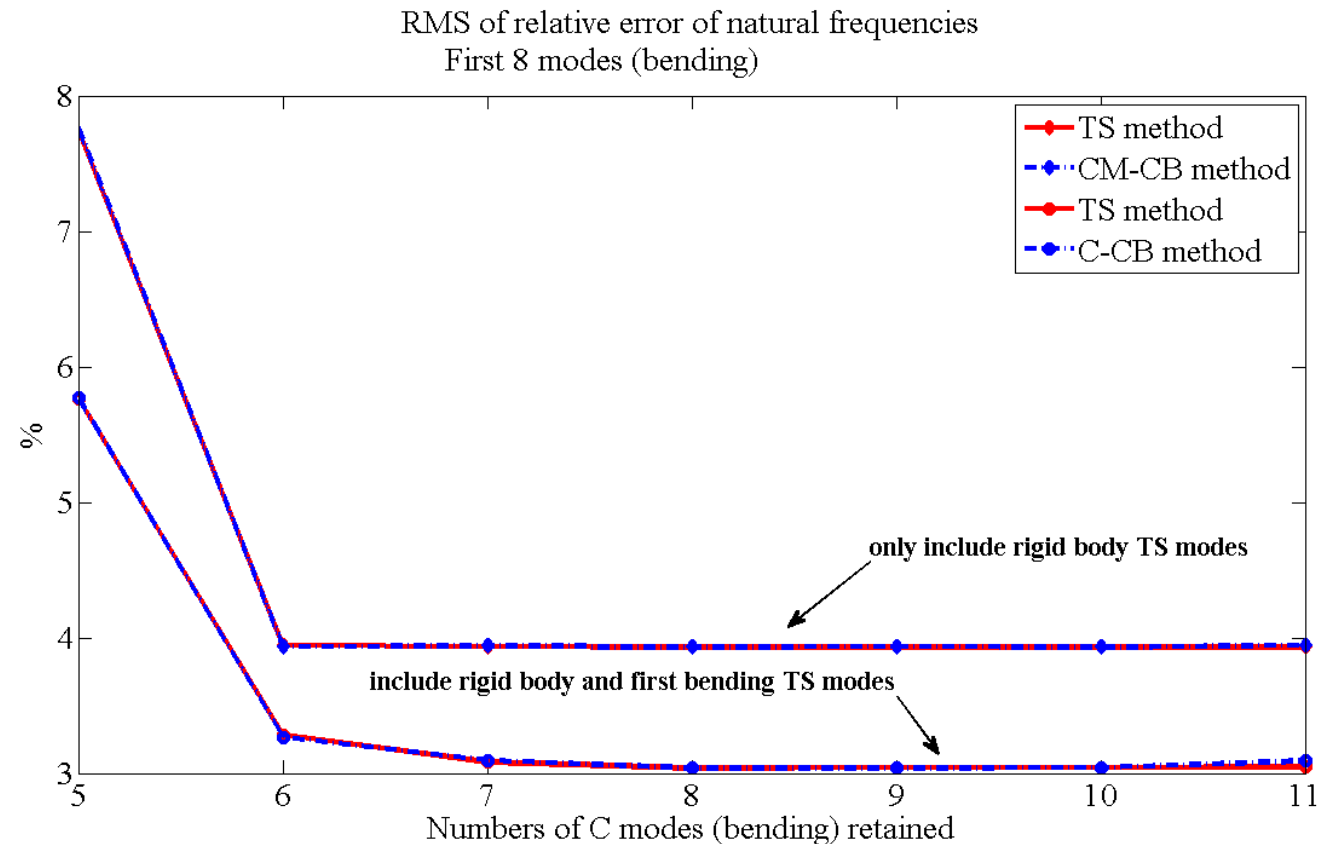
Beam Example



- Substructuring $B = D + C - A$ by
 - Craig-Mayes model of C-A attached to Craig-Bampton model of D (CM-CB) and traditional transmission simulator (TS)
 - 2 degrees of freedom used at 3 node locations as connection

Convergence Test

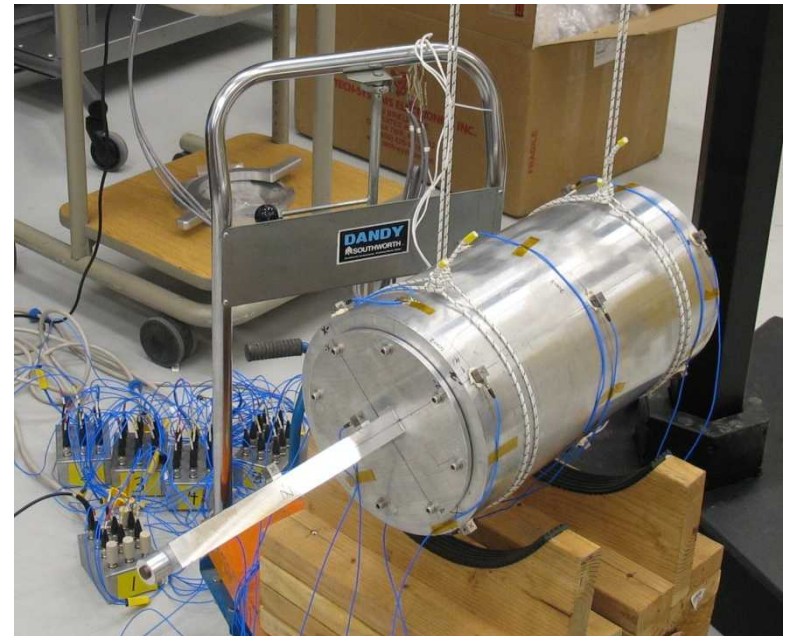
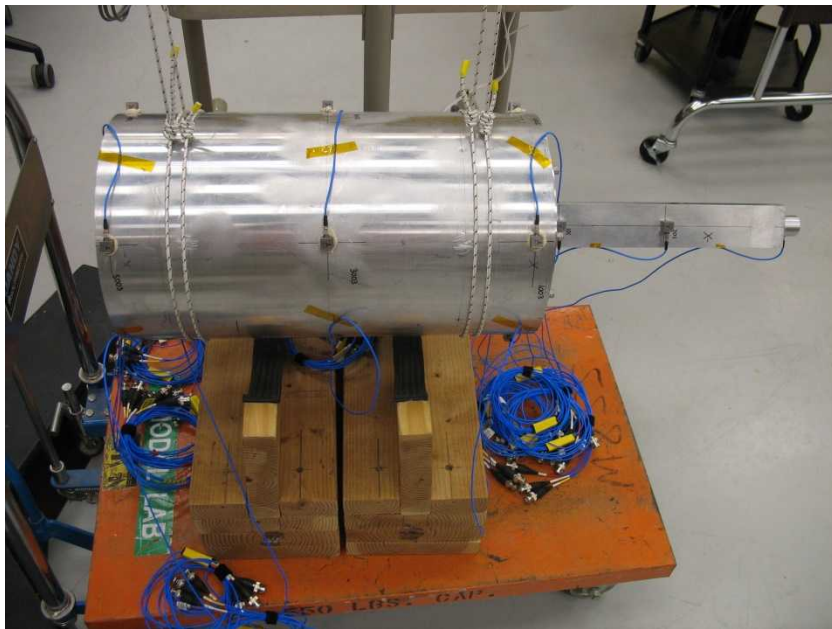
- In this simulation, the TS and CM-CB method show similar convergence rates given the same TS and experimental modes
- The convergence improves when TS modes estimate the connection points motion more accurately



- After including sufficient (e.g., >6) experimental modes convergence rates show no significant improvement
- Further improvement is observed when the first bending mode of TS is included

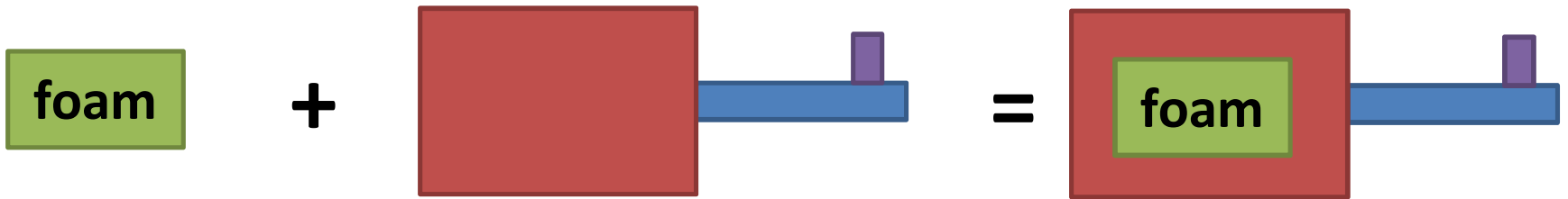
Experimental System

- Experimental system consists of the can-plate-beam system packed with foam and some internal instrumentation pieces
- Testing complete with low-level excitations to avoid non-linearities in the system
- 14 Elastic modes extracted from experimental data





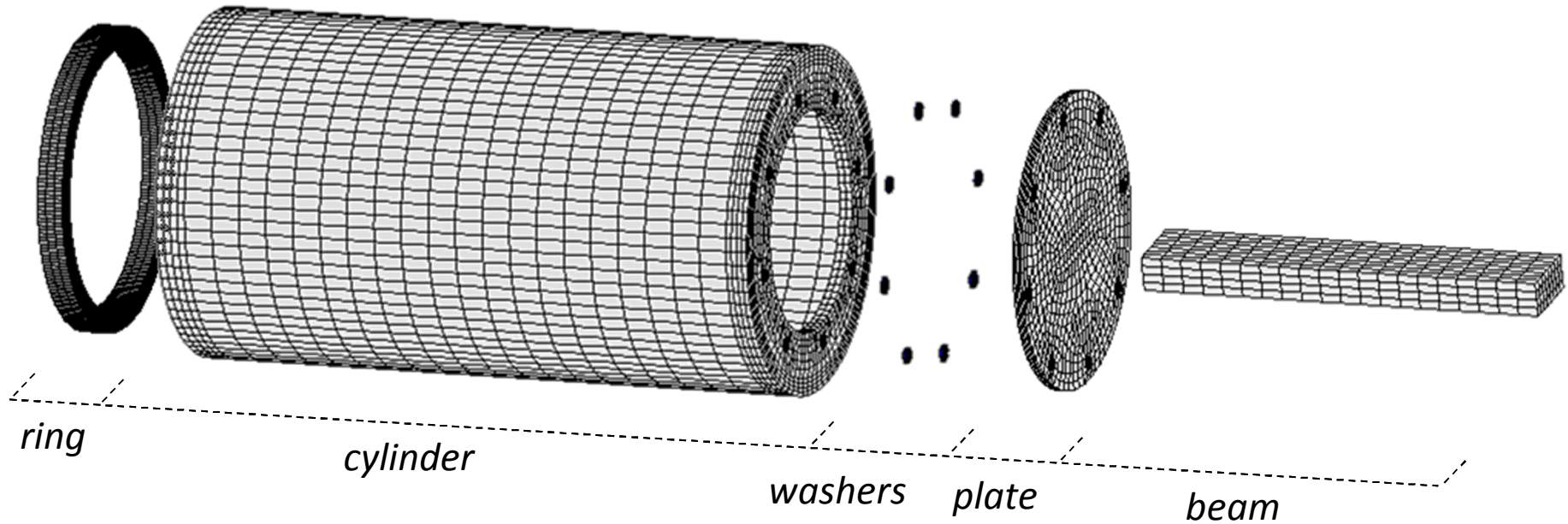
C (Experiment) - A (Transmission Simulator FEM) = (Foam Model)



(Foam Model) + D (New Sub-System FEM) = B (New Assembly)

Finite Element Model

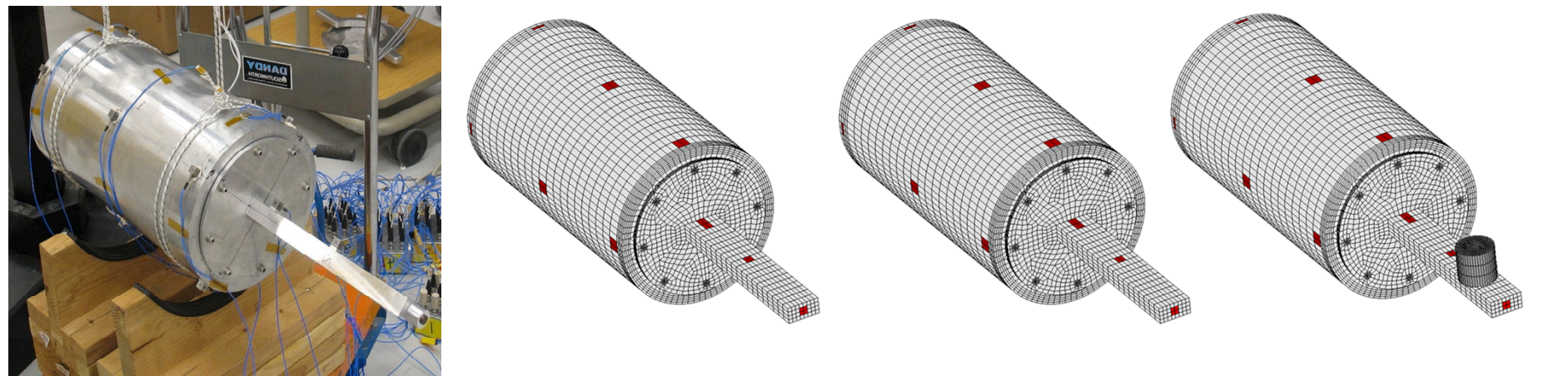
- Transmission components and properties



Components	Element type	Material
Beam, plate, cylinder, ring	Higher order 3-D 20 node solid	6061-T6 Aluminum
Washer	Higher order 3-D 20 node solid	Steel

• System frequencies

■ Measurement point



Experiment [Hz]	Can-Plate-Beam Only	% Difference	System A Can-Plate-Beam with Ring	% Change Due to Ring	System D Validation Structure
134.2	136.8	1.90	137.2	2.23	101.9
171.2	175.8	2.60	177.5	3.68	133.9
430.0	422.8	1.70	848.5	97.32	848.5
511.2	525.9	2.80	540.8	5.78	407.6
975.7	960.6	1.50	993.8	1.85	993.8
1027	1025	0.19	1026	0.019	861.5
1312	1312	0.00	1549	18.04	1548.7
1528	1535	0.45	1598.5	4.62	1598.6
1637	1610	1.68	1598.2	2.37	1707.8
1801	1835.15	1.86	1834.2	1.85	1924.6
1833	1835.35	0.12	1835.3	0.13	2108.5

Nonlinear Characterization

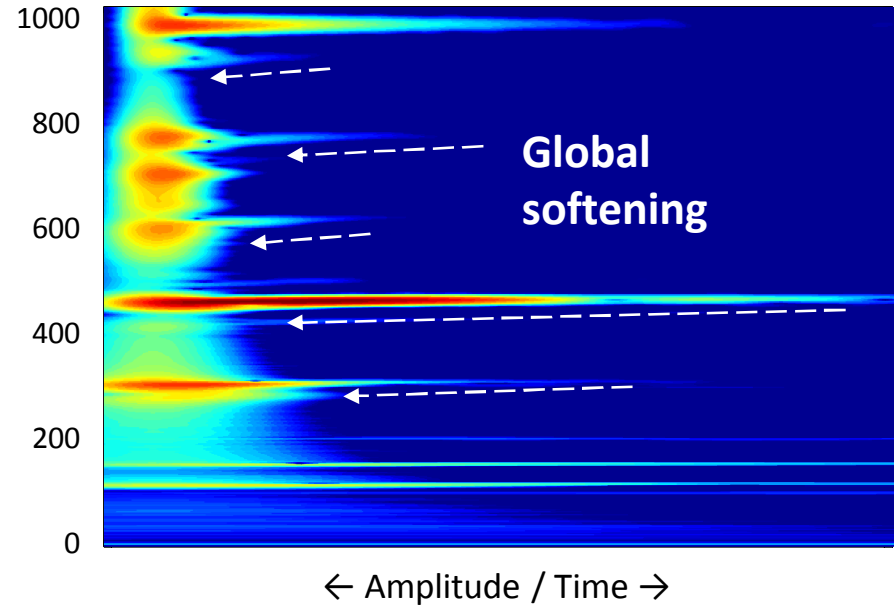
DETECTION

Wavelet Transform

Most nonlinear modes (exercising the joints)

- **Mode 1**: First bending mode of the beam in the horizontal plane
- **Mode 2**: First bending mode of the beam in the vertical plane
- **Mode 6**: Axial mode, beam and internals out-of-phase

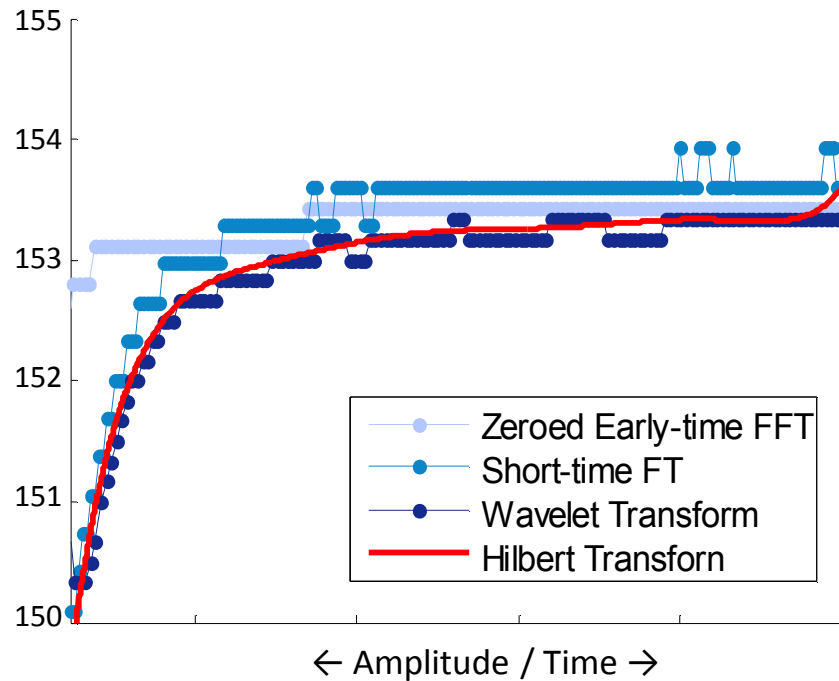
Instantaneous frequency [Hz]



CHARACTERIZATION & QUANTIFICATION

ZEFFT - STFT - WT - HT

Natural frequency [Hz]



Amplitude ↗ ⇒ Natural frequency ↘

Amplitude ↗ ⇒ Damping ratio ↗

Natural frequency variations

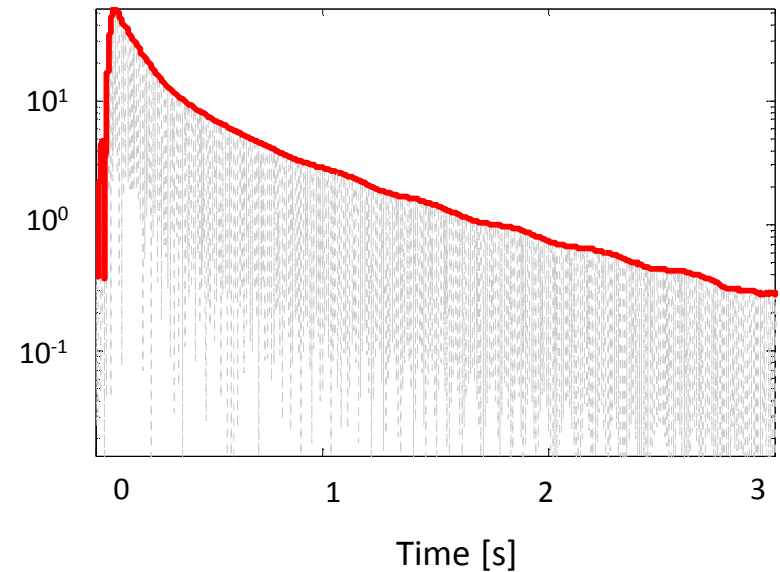
- Mode 1: - 4%
- Mode 2: - 3%
- Mode 6: - 2.5%

PARAMETER ESTIMATION

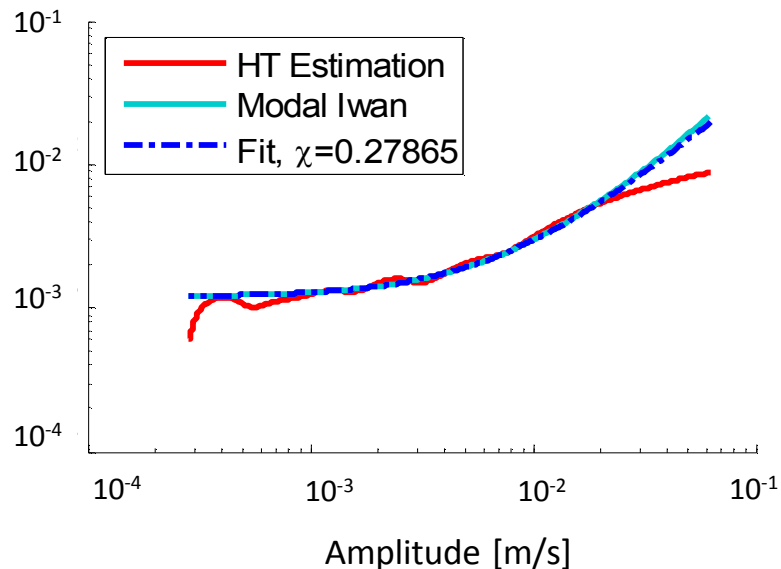
Iwan Model

Fitting a modal Iwan model on damping and natural frequency vs. amplitude curves using Hilbert transform

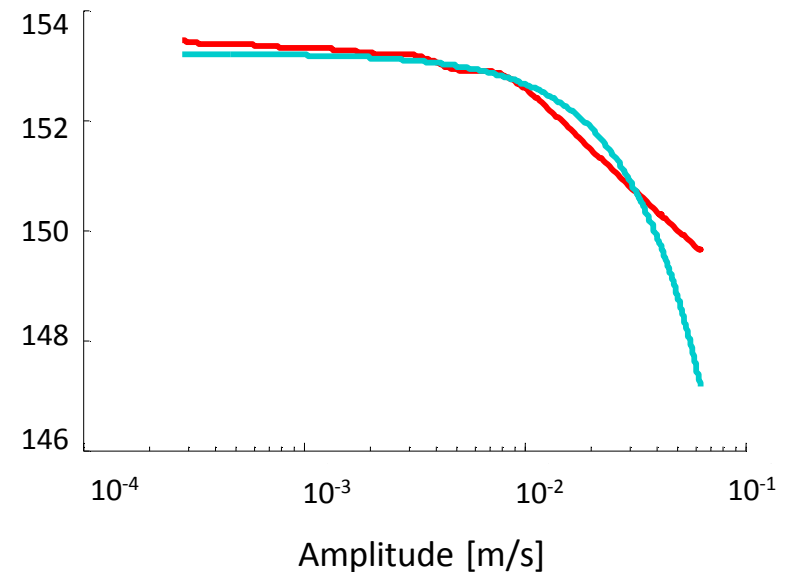
Hilbert amplitude of acceleration [m/s^2]



Damping ratio [-]



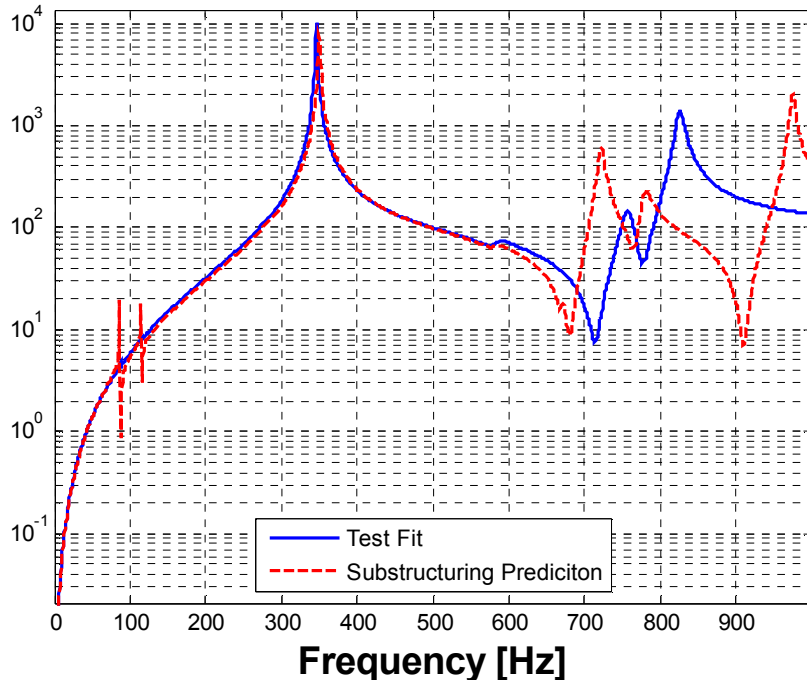
Natural frequency [Hz]



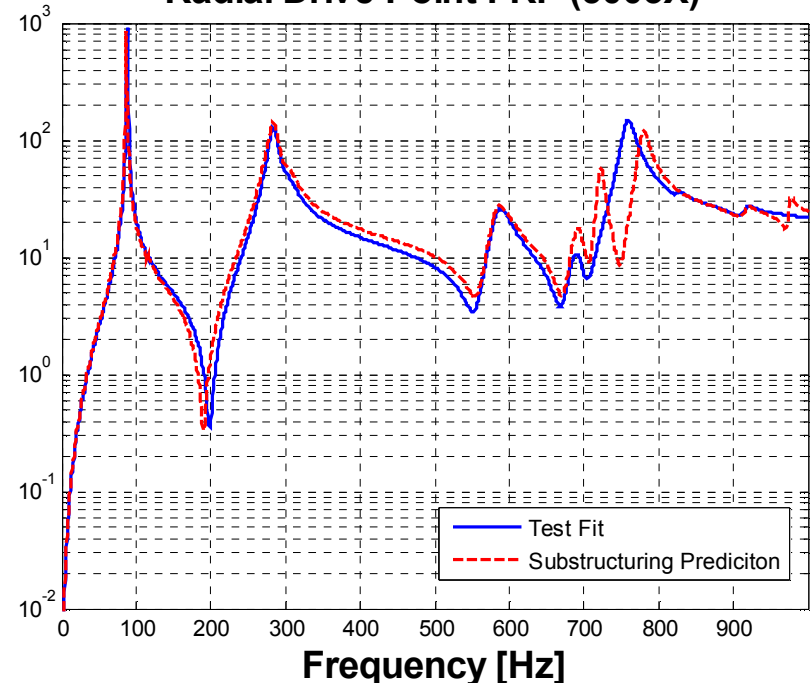
Substructuring Predictions

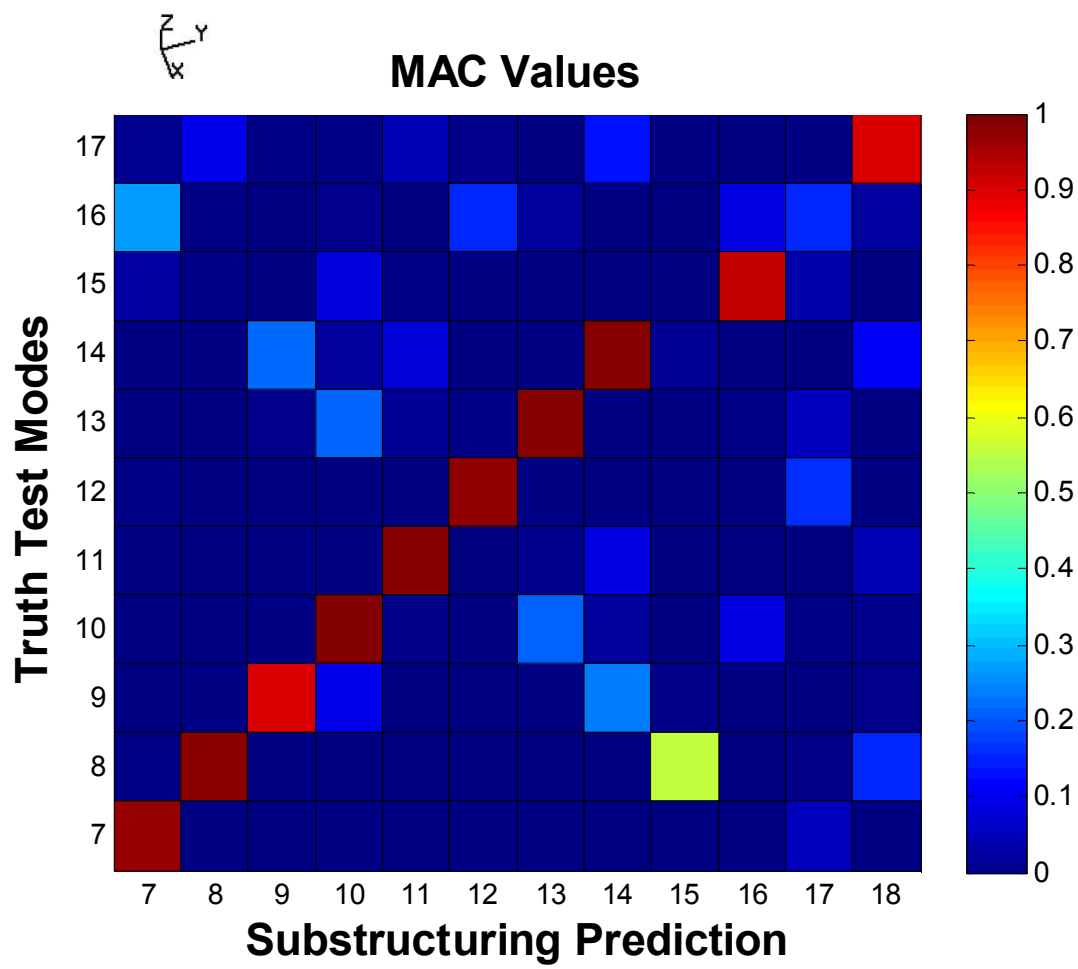
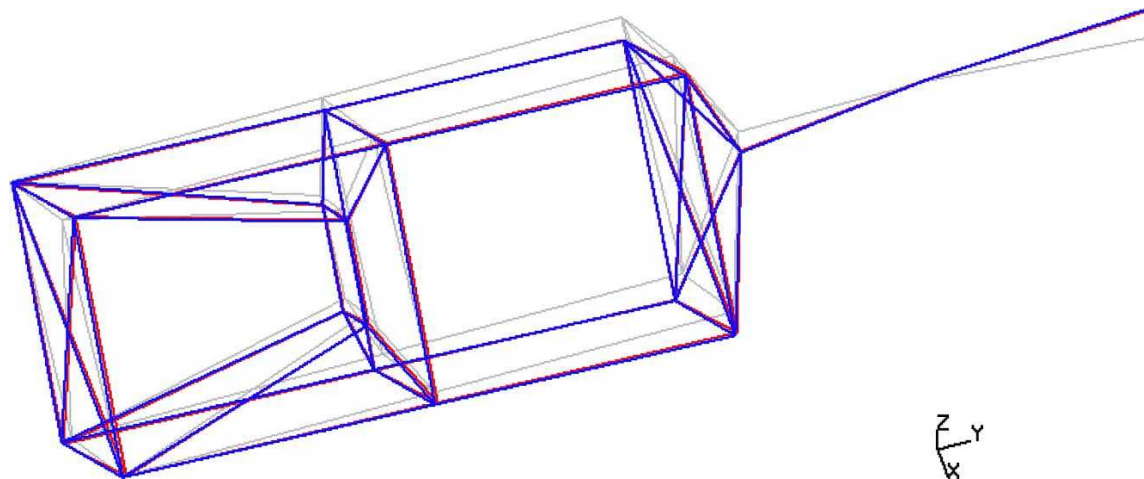
- Transmission Simulator approach completed using 13 modes from the transmission simulator (A) and 17 modes of the new subsystem (D)
- Modes of system A kept up to 989 Hz
- Modes of system D kept up to 1495 Hz

Axial Drive Point FRF (301Y)



Radial Drive Point FRF (5003X)





Mode #	f_{test} [Hz]	$f_{\text{prediction}}$ [Hz]	f_n Error [%]	ζ_{test}	$\zeta_{\text{prediction}}$	ζ Error [%]	MAC
7	88.33	87.09	-1.41%	0.00196	0.00214	8.83%	.9798
8	115.80	115.13	-0.58%	0.00163	0.00207	26.75%	.9925
9	275.97	276.21	0.09%	0.02468	0.02465	-0.14%	.9116
10	283.32	283.45	0.05%	0.02151	0.02166	0.72%	.9957
11	301.40	301.76	0.12%	0.02327	0.02290	-1.60%	.9869
12	346.25	349.95	1.07%	0.00291	0.00358	23.33%	.9683
13	584.71	583.33	-0.24%	0.02119	0.02138	0.92%	.9963
14	635.16	634.96	-0.03%	0.02037	0.01897	-6.85%	.9955
-	NA	671.02	NA	NA	0.00505	NA	NA
15	688.92	690.42	0.22%	0.01515	0.01367	-9.73%	.9372
-	NA	721.79	NA	NA	0.00579	NA	NA
16	758.36	NA	NA	0.01131	NA	NA	NA
17	769.71	771.16	0.19%	0.01191	0.01203	1.09%	.9121

References

1. Mayes R.L. and Rohe, D.P. *Coupling Experimental and Analytical Substructures with a Continuous Connection Using the Transmission Simulator Method*. in *31st International Modal Analysis Conference*. 2013.
2. Allen, M.S., Mayes, R. L., and Bergman, E.J., *Experimental Modal Substructuring to Couple and Uncouple Substructures with Flexible Fixtures and Multi-point Connections*. *Journal of Sound and Vibration*, 2010. **329**: p. 4891-4906.
3. Mayes, R.L., *A Modal Craig-Bampton Substructure for Experiments, Analysis, Control and Specifications*, in *33rd International Modal Analysis Conference* 2015: Orlando, FL.
4. Mayes, R.L., *A Craig-Bampton Experimental Dynamic Substructure using the Transmission Simulator Method*, in *33rd International Modal Analysis Conference* 2015.
5. Allen, M.S., Kammer, D.C., and Mayes, R.L., *Experimental Based Substructuring Using a Craig-Bampton Transmission Simulator Model*, in *32nd International Modal Analysis Conference* 2014.
6. Kammer, D.C., Allen, M.S., Mayes, R.L., *Formulation of a Craig-Bampton Experimental Substructure Using a Transmission Simulator*, in *31st International Modal Analysis Conference* 2013.
7. Rixen, D.J., *A dual Craig-Bampton method for dynamic substructuring*. *Journal of Computational and Applied Mathematics*, 2004. **168**(1-2): p. 383-391.
8. Allen, M.S., Kammer, D.C., and Mayes, R.L., *Metrics for Diagnosing Negative Mass and Stiffness when Uncoupling Experimental and Analytical Substructures*. *Journal of Sound and Vibration*. **331**(5435-5448).
9. Mayes R.L., A., M.S., and Kammer D.C., *Correcting indefinite mass matrices due to substructure uncoupling*. *Journal of Sound and Vibration*, 2013. **332**: p. 5856-5866.

Suggested Layout of slides:

Title (slide 1)		Authors (Slide 2)
Objective (slide 3)		
Substructure Theory (slide 4-5)	Experiment (slide 8-9)	Non-linearity Char. (slide 12-14)
Beam Example (slide 6-7)	Model (slide 10-11)	Substructuring Results (slide 15-17)

Please fit references (Slide 18) into on of the bottom corners may need to shrink them to fit. We are unsure.