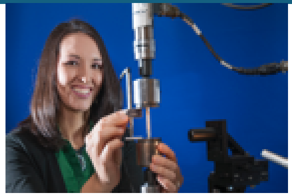
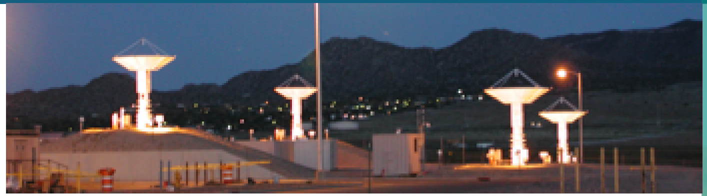
SAND2022-5982C

Sandia National Laboratories

Substructuring on Combinations of Steel and Aluminum Components of the Benchmark Structure of the Technical Division on Dynamic Substructures





Authors:

Daniel Roettgen

Andreas Linderholt

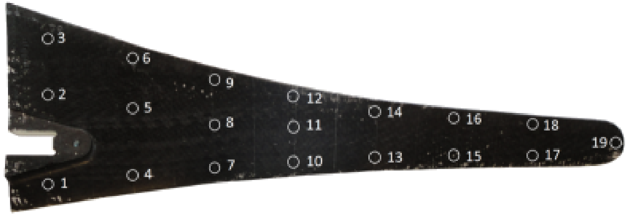
Linnæus University

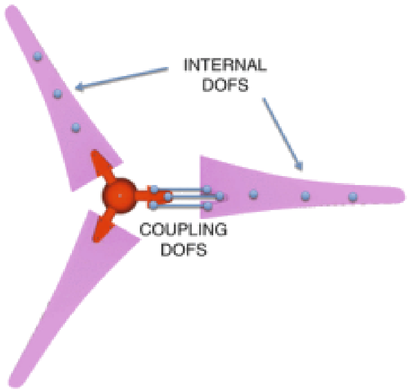
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

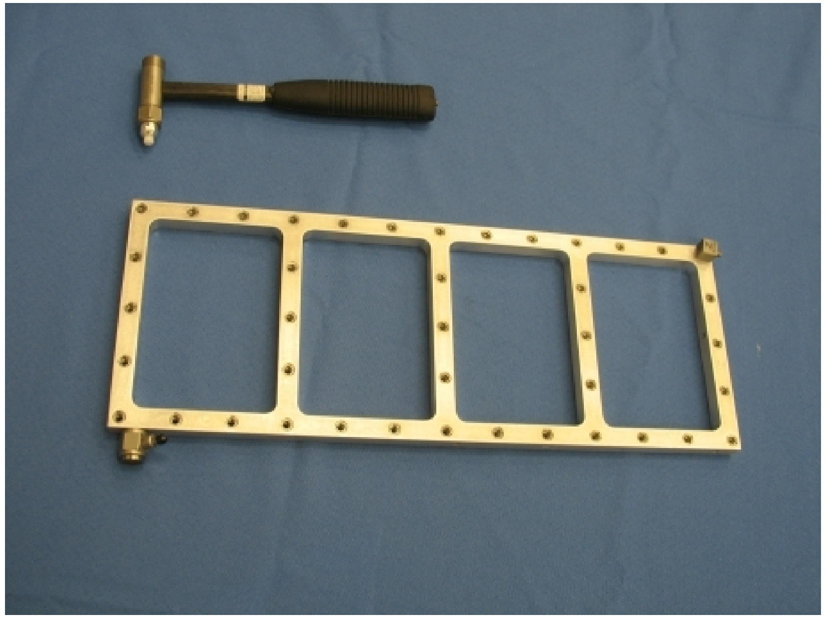
Background

- The substructuring community has a rich history which shares its roots with model reduction and structural modification
- Each year we see 4-5 sessions on substructuring at IMAC with various topics including:
  - Component Mode Synthesis
  - Frequency Based Substructuring
  - Transfer Path Analysis
  - Model Reduction
  - Applications of Substructuring
  - Real-time Hybrid Substructuring and many more
- In 2012 the AmpAir 600 Wind Turbine was selected as a round-robin substructuring example that many universities and research groups have studied
- The Dynamic Substructuring focus group continued organizing IMAC sessions and in 2018 it officially became a technical division.





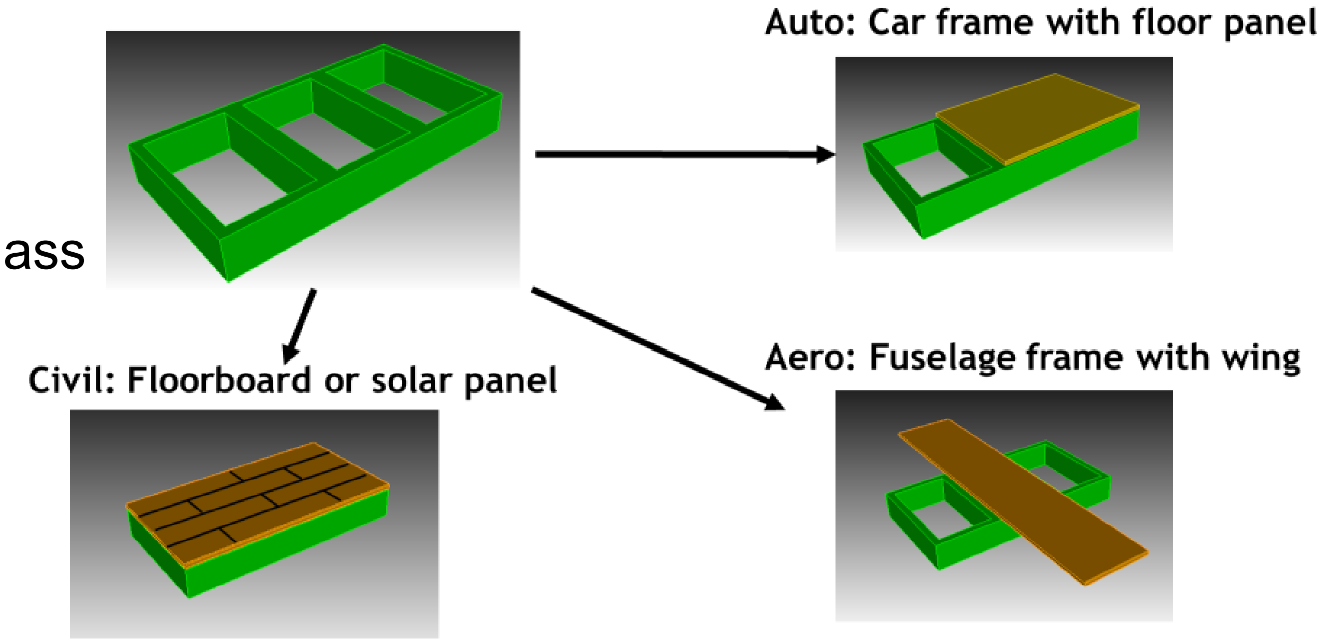
Experimental Substructure (Four-unit frame



- Team developed design for a “four-unit” frame

Key features

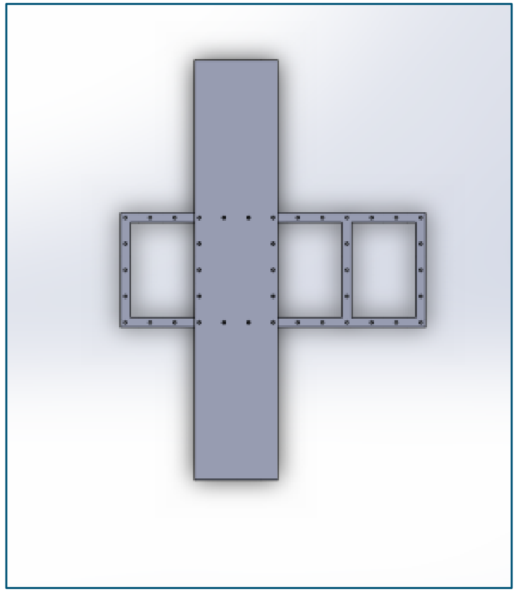
- Manufactured from one piece of metal of stock
- Subcomponent and shaker attachment points machined into frame
- Adaptable to many types of studies
- Possible circular/recursive transfer path
- Large enough to minimize error due to mass loading



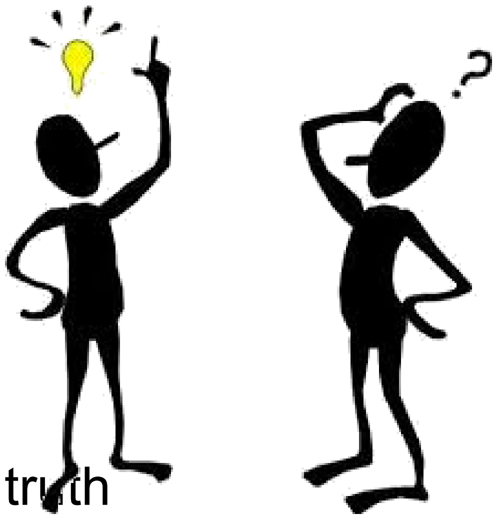
Shown is a 3-unit frame (final design has 4 units)

Substructuring Round-Robin Procedure

- Participants will be provided:
  - Hardware of the frame, rectangular thin wing, rectangular thick wings, and necessary fasteners
  - Assembly Procedure
  - Solid Models of the Rectangular Wing and Swept Wing
- Researchers can demonstrate their substructuring techniques using the rectangular wing hardware then predict the change from a thin to thick wing
- System can be tested with connection at just corner holes, or all 14 holes



What is the “truth” answer?

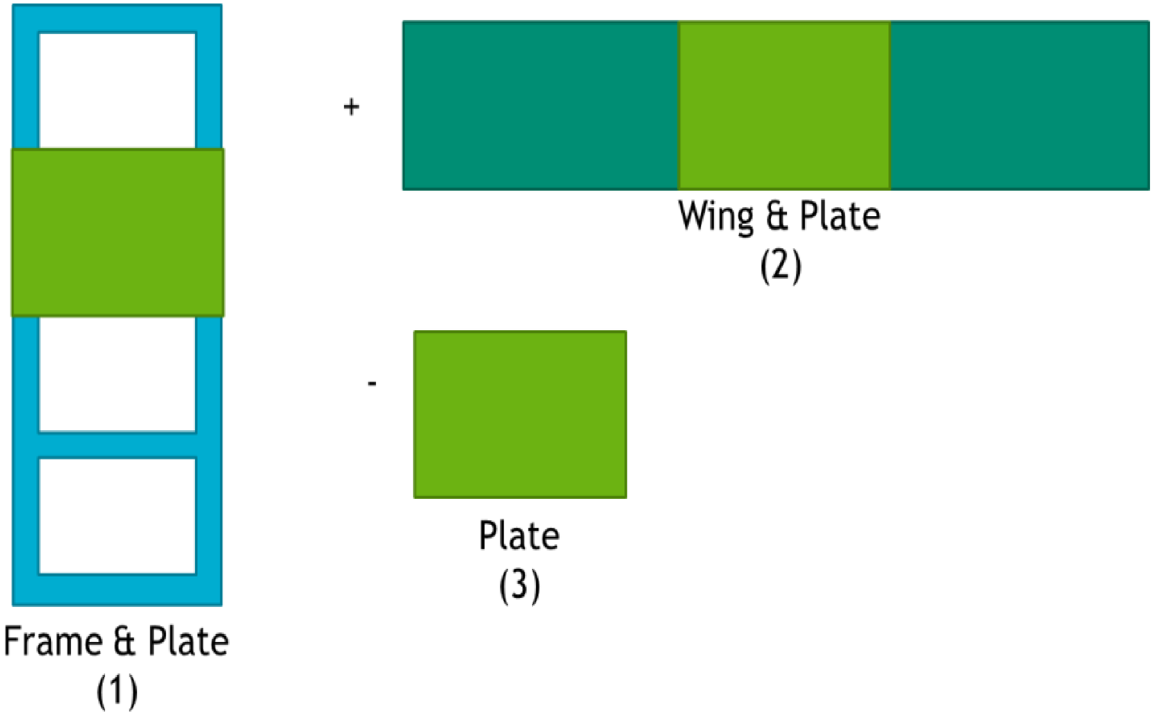


- Truth depends on a lot of factors:
  - Assembly procedure
  - Frequency range of interest
  - Linearity of joints
  - And other factors…
- The goal of this round-robin isn’t to see which method is the closest to truth
- Instead… Round-Robin goals include:
  - Fostering collaboration between universities and industrial researchers
  - Helping researchers focus on how to best approach a substructuring problem when truth is unknown
  - Discuss different approaches taken and why some methods are more suited for specific connection interfaces
  - See range of blind predictions to understand the range of answer found using substructuring practices

It depends… but we can learn a lot by comparing and collaborating on methods

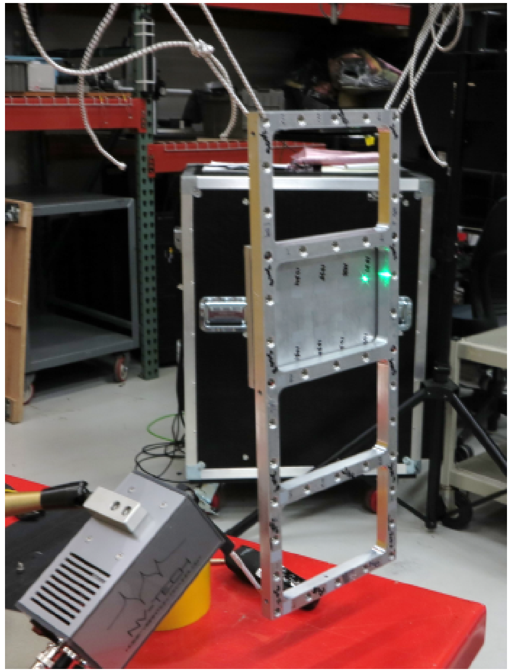
Trial Run

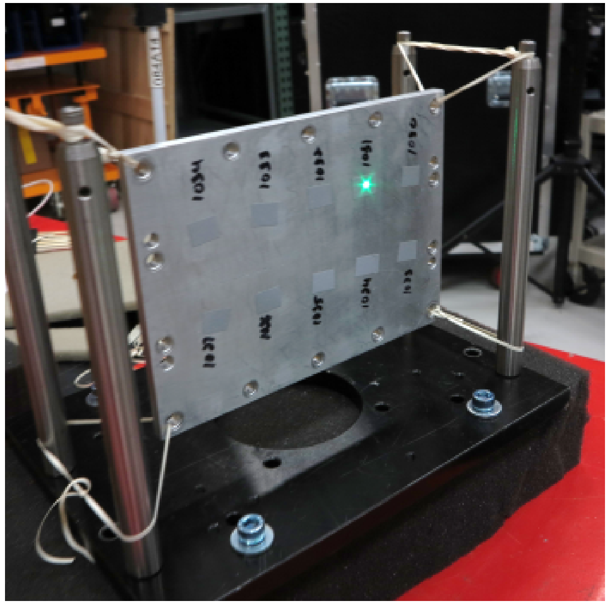
- In the last year SNL performed an updated trial run on the system connecting a frame and wing through a transmission simulator – the goal was to predict system level response

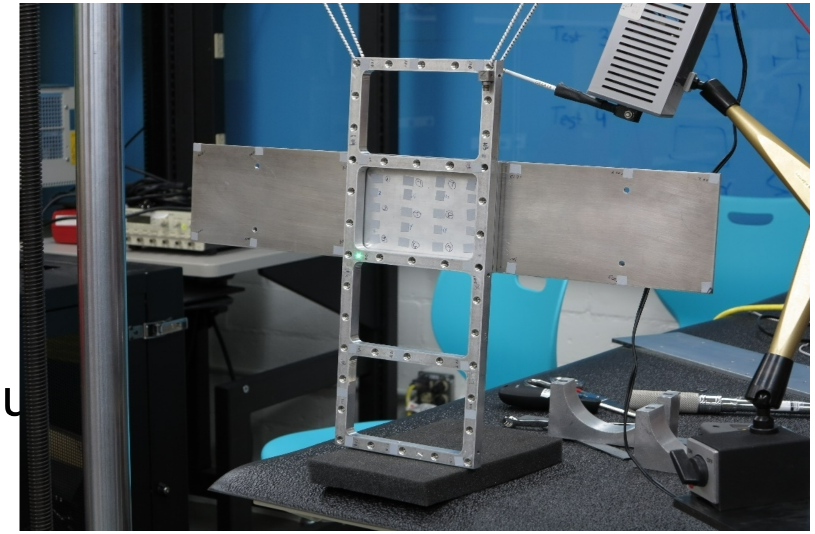


Experiments

- Testing was performed on all three substructures using an LDV (data from these tests will be available on the dynamic substructuring wiki!)







- A truth test was also completed to compare prediction resu

Substructuring Mathamatics

- To complete substructuring three experimental sets of data were used to fit modal modes for each substructure[1,2]

$$\begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & -I_3 \end{bmatrix} \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{Bmatrix} + \begin{bmatrix} [\ddots \omega_1^2 \ddots] & 0 & 0 \\ 0 & [\ddots \omega_2^2 \ddots] & 0 \\ 0 & 0 & -[\ddots \omega_3^2 \ddots] \end{bmatrix} \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = \begin{Bmatrix} \phi_1^T F_1 \\ \phi_2^T F_2 \\ \phi_3^T F_3 \end{Bmatrix}$$

- Constraints were defined connecting the wing/plate substructure to a lone plate and the frame/plate substructure the same.

$$\begin{bmatrix} \phi_3^+ & 0 \\ 0 & \phi_3^+ \end{bmatrix} \begin{bmatrix} \phi_1 & 0 & -\phi_3 \\ 0 & \phi_2 & -\phi_3 \end{bmatrix} \begin{Bmatrix} q_A \\ q_B \\ q_{TS} \end{Bmatrix} = \tilde{B} \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = 0$$

- The null space function was used to determine our synthetization matrix L

$$L = \text{null}(\tilde{B})$$

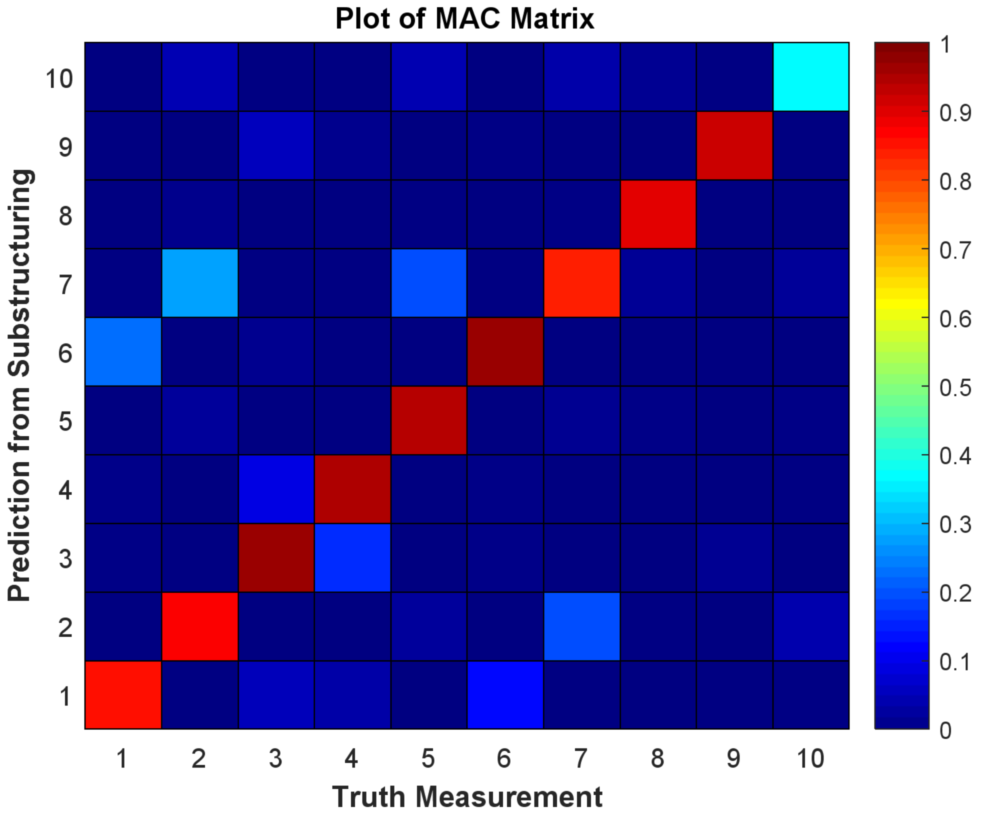
- L-matrix used to enforce constraints on equations of motion and predict system assembly response

$$L^T \begin{bmatrix} I_1 & 0 & 0 \\ 0 & I_2 & 0 \\ 0 & 0 & -I_3 \end{bmatrix} L \begin{Bmatrix} \ddot{q}_1 \\ \ddot{q}_2 \\ \ddot{q}_3 \end{Bmatrix} + L^T \begin{bmatrix} [\ddots \omega_1^2 \ddots] & 0 & 0 \\ 0 & [\ddots \omega_2^2 \ddots] & 0 \\ 0 & 0 & -[\ddots \omega_3^2 \ddots] \end{bmatrix} L \begin{Bmatrix} q_1 \\ q_2 \\ q_3 \end{Bmatrix} = L^T \begin{Bmatrix} \phi_1^T F_1 \\ \phi_2^T F_2 \\ \phi_3^T F_3 \end{Bmatrix}$$

Trial Results

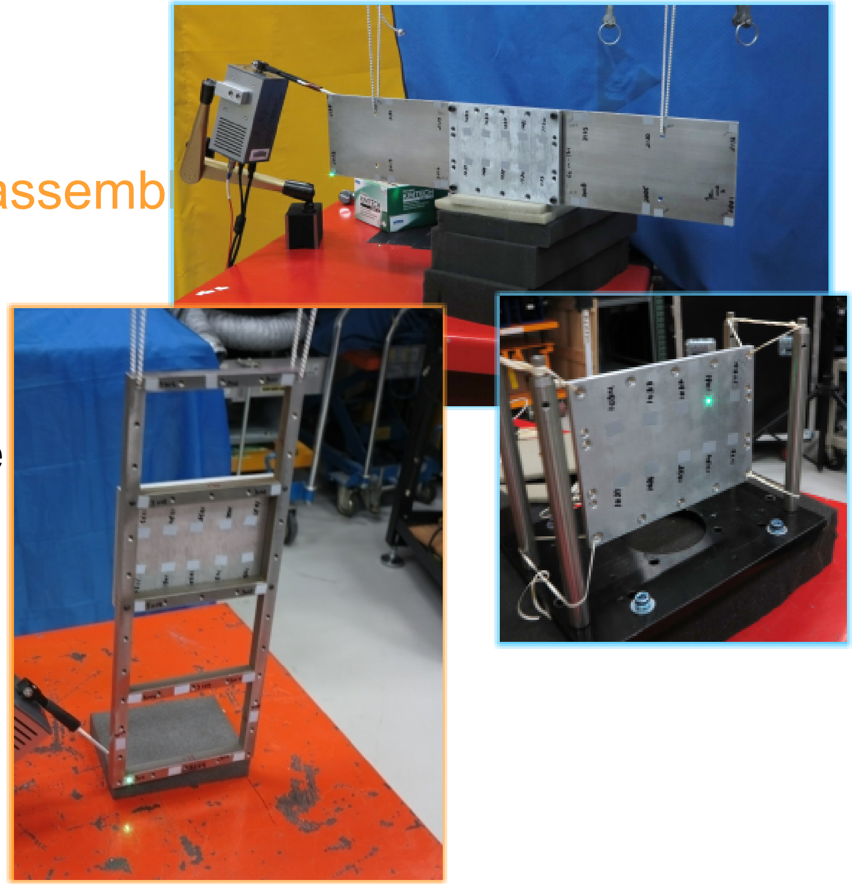
- Predictions led to low frequency and damping error outside of a few modes

Truth		Prediction		Error	
fn	zt	fn	zt	fn	zt
61.91	0.231%	55.76	0.033%	-9.93%	-85.83%
107.19	0.185%	96.16	0.123%	-10.29%	-33.70%
230.00	0.073%	225.92	0.069%	-1.77%	-5.42%
277.66	0.143%	272.85	0.045%	-1.73%	-68.61%
341.56	0.246%	330.92	0.104%	-3.12%	-57.59%
369.06	0.131%	352.90	0.072%	-4.38%	-45.50%
418.91	0.145%	396.28	0.067%	-5.40%	-53.61%
499.06	0.251%	598.74	0.100%	19.97%	-59.96%
656.09	0.103%	611.07	0.116%	-6.86%	12.57%
696.41	0.095%	688.10	0.164%	-1.19%	72.45%
798.75	0.029%	726.60	0.093%	-9.03%	215.58%
807.50	0.084%	733.88	0.069%	-9.12%	-17.92%
857.19	0.197%	784.65	0.119%	-8.46%	-39.35%
976.25	0.182%	784.65	0.119%	-19.63%	-34.25%



Hardware Exchange

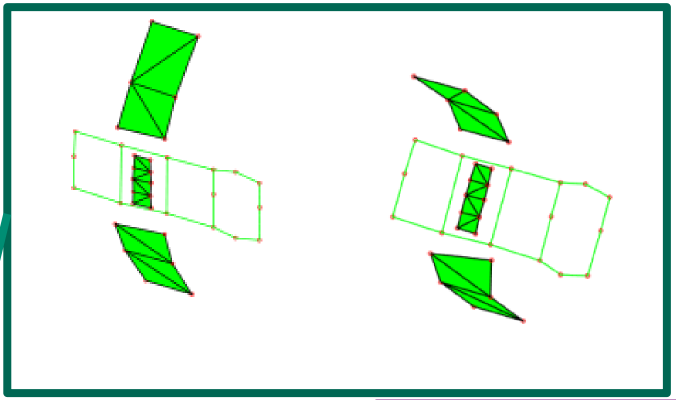
- Hardware was exchanged so both researchers have a steel frame and aluminum wing pair.
- Without testing the solution structure the teams set out to predict the response of an aluminum wing substructured to the now steel frame.
- Data from the plate and wing-plate subassembly were resued from previous testing
- New test data was obtained on the steel frame and plate subassembl
- The same methodology from Slide 8 was used to predict the response of the steel frame, aluminum plate, aluminum wing assembly.
- Connecting through the same modes we obtained reasonable

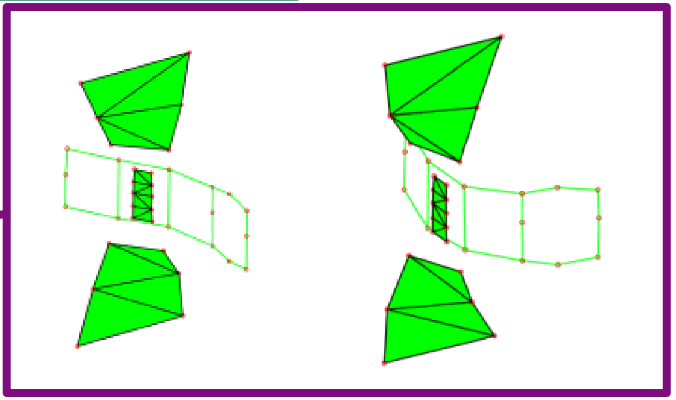


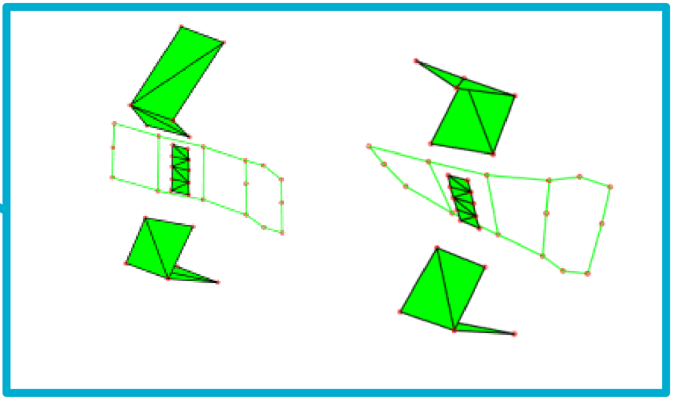
Modal Parameter Changes

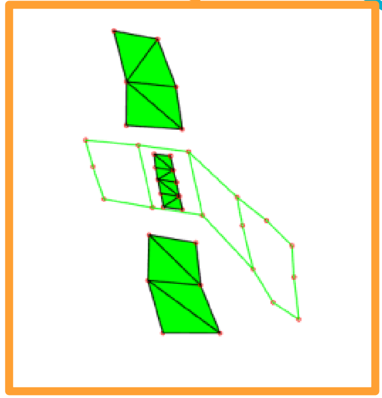
- Parameter Changes

Aluminum System		Steel System Prediction		Change %	
fn	zt	fn	zt	fn	zt
61.91	0.23%	49.73	0.11%	-19.67%	-52.38%
107.19	0.19%	60.02	0.04%	-44.01%	-78.92%
230	0.07%	229.9	0.07%	-0.04%	-4.11%
277.66	0.14%	276.87	0.15%	-0.28%	2.80%
369.06	0.13%	349.28	0.10%	-5.36%	-20.61%
418.91	0.15%	379.26	0.07%	-9.47%	-53.10%
499.06	0.25%	522.3	0.04%	4.66%	-84.06%





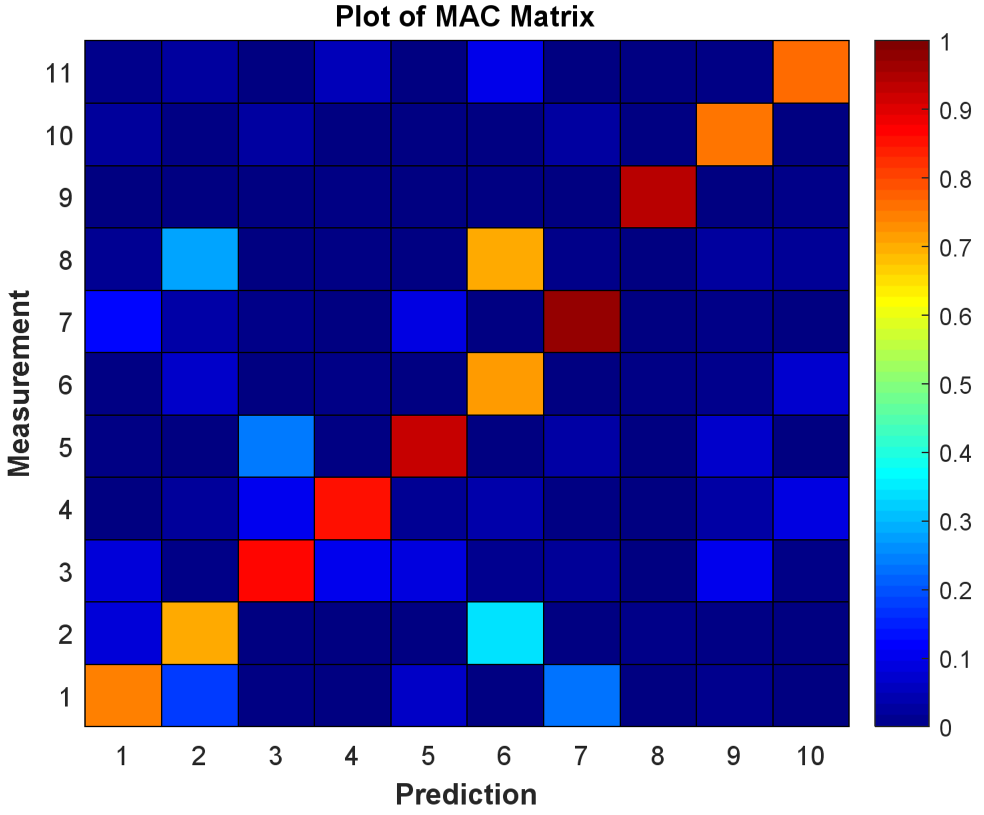




We did eventually measure truth to see how this worked out!

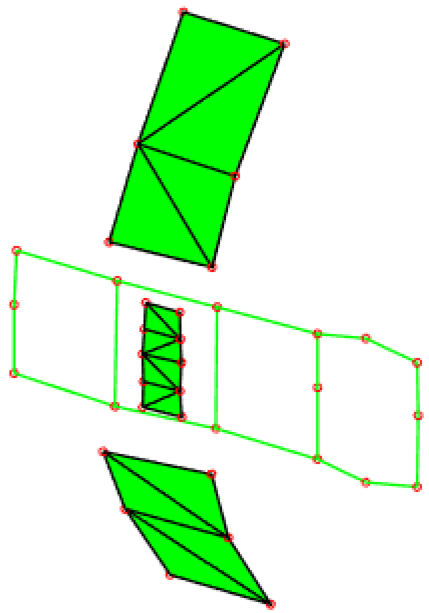
- Predictions led to low frequency error except for the lowest few modes, damping errors were much higher possibly joint driven?

Truth		Prediction		Error	
fn	zt	fn	zt	fn	zt
58.2962	0.07%	49.73	0.11%	-14.69%	67%
87.2175	0.01%	60.02	0.04%	-31.18%	175%
237.556	0.04%	234.02	0.13%	-1.49%	219%
238.768	0.01%	229.9	0.07%	-3.71%	470%
280.79	0.06%	276.87	0.15%	-1.40%	137%
336.551	0.01%	349.28	0.10%	3.78%	670%
357.724	0.06%	379.26	0.07%	6.02%	13%
391.7	0.07%	NA	NA	#VALUE!	-
558.26	0.03%	522.3	0.04%	-6.44%	22%
675.978	0.10%	636.6	0.13%	-5.83%	37%
716.994	0.04%	713.52	0.03%	-0.48%	-23%

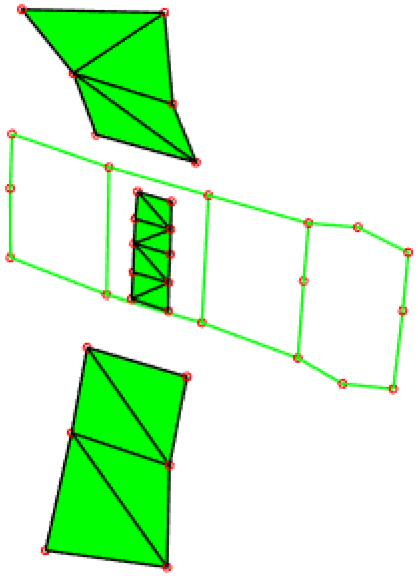


Ongoing Challenges

- Current measurement set needs refinement to fine tune modal predictions using CMS and is a piece of further study



Truth



Measurement

Conclusions & Future Work

- Dynamic Substructuring of the Aluminum Benchmark structure completed
- An exchange of benchmark hardware was conducted with Linneaus University and the substructuring techniques appear to be versatile
- Linnaeus / Sandia partnership will continue to work on this problem and exchange new components and model-based substructures
- Future studies include:
  - 14 vs 4 bolt-pattern
  - Additional components on the wings
  - Swept Wing study