RAPID CONSTITUENT PAYLOAD ENVIRONMENTS FOR MULTICONFIGURATION ORBITAL VEHICLES

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ENGINEERING FORWARD

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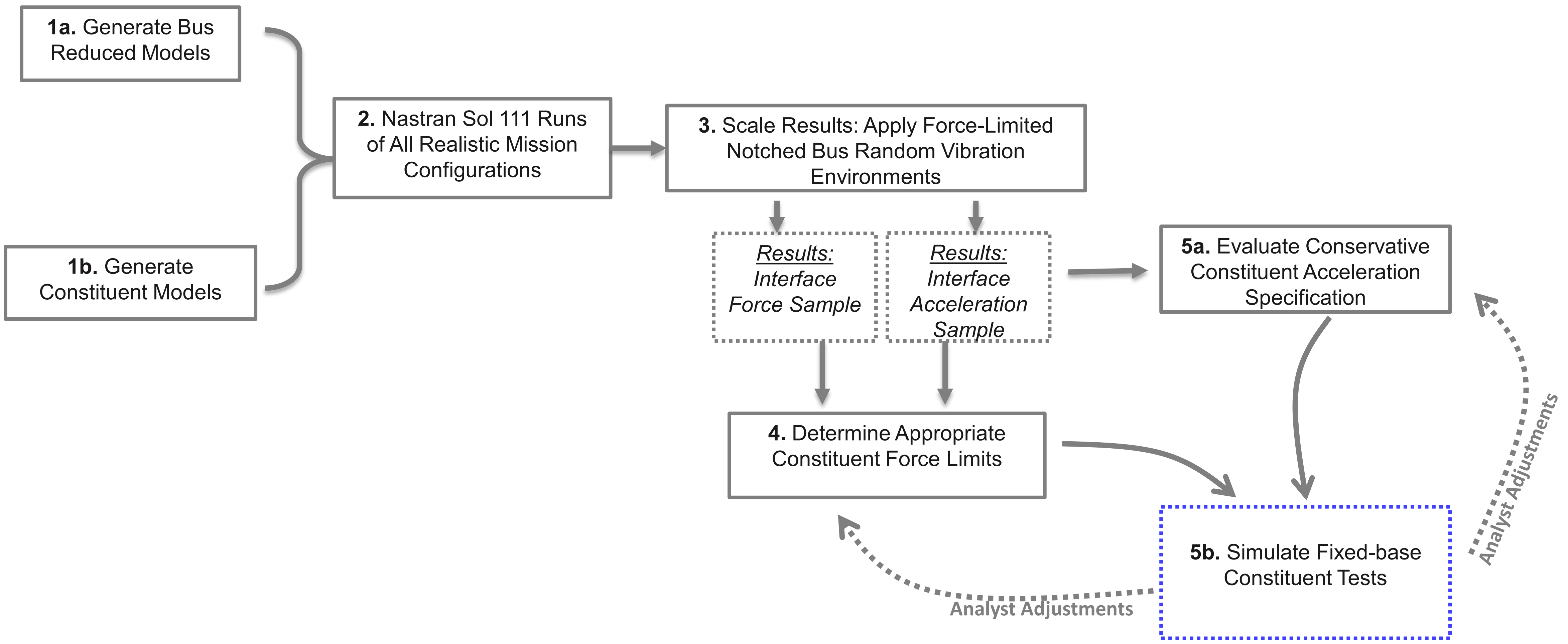
Overview

- Background:
  - Increasing demand for efficient dissemination of vibration load specifications
  - Vehicles with onboard payloads / critical subcomponents require additional testing & analysis on the *constituent* level
    - Interface environments typically recovered during pre-test analysis using explicit FEM simulation for all known bus-constituent configurations
  - For vehicles with a range of uncertain mission profiles and a high volume of flights, this explicit analysis can be extremely expensive and time consuming

- Quartus Engineering and Momentus Space have collaborated to develop a semi-automated Coupled Base Shake Analysis (CBSA) framework for efficient generation of constituent vibration environments
  - Specifically geared toward random vibration, but could be developed for sine environments as well
  - Uses simplified dynamic representation of constituents for rapid generation of database
  - Environments can represent a range of missions and constituent properties (mass, natural frequency, etc…) by simulating a wide variety of expected configurations
  - Results can be sorted by location, constituent mass, constituent dynamic properties
  - Test specifications defined as Acceleration Spectral Density (ASD) base input and appropriate force limits

CBSA PROCESS



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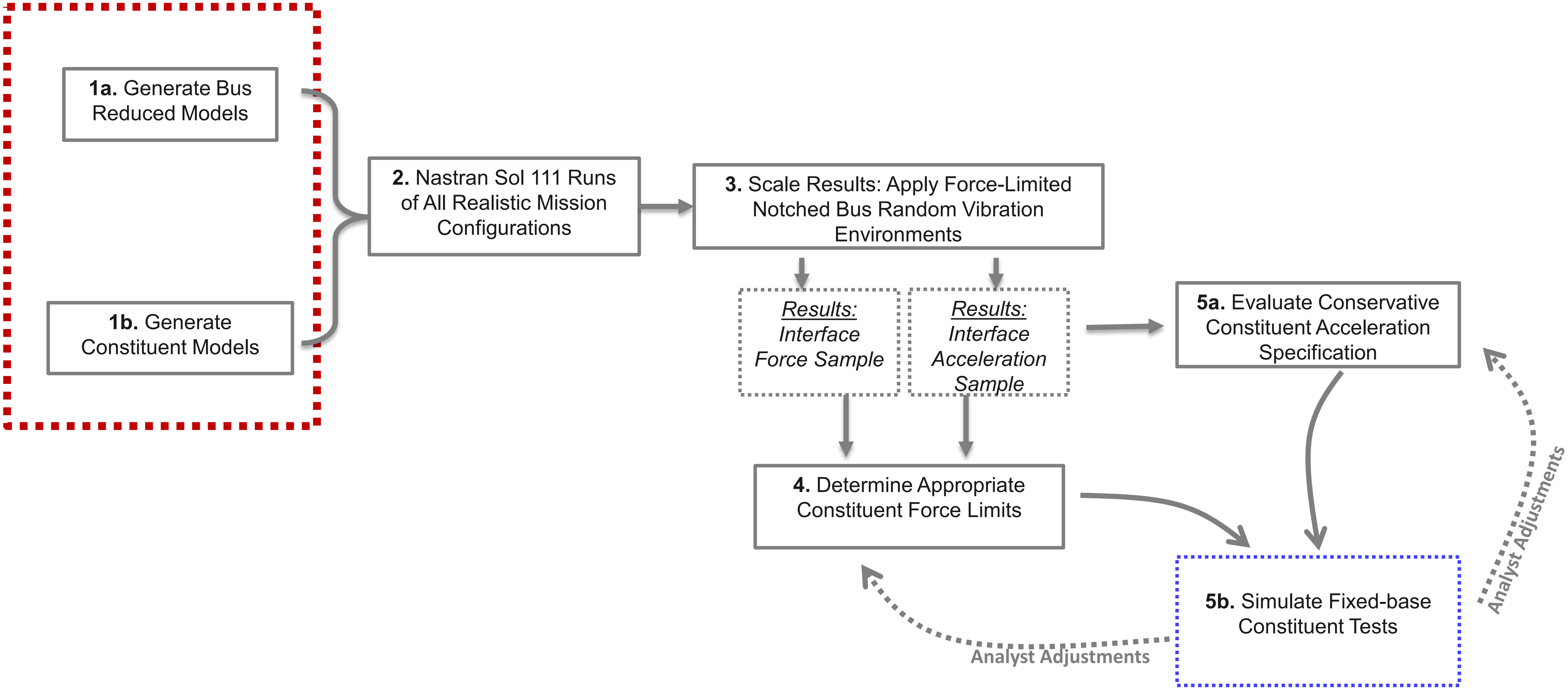
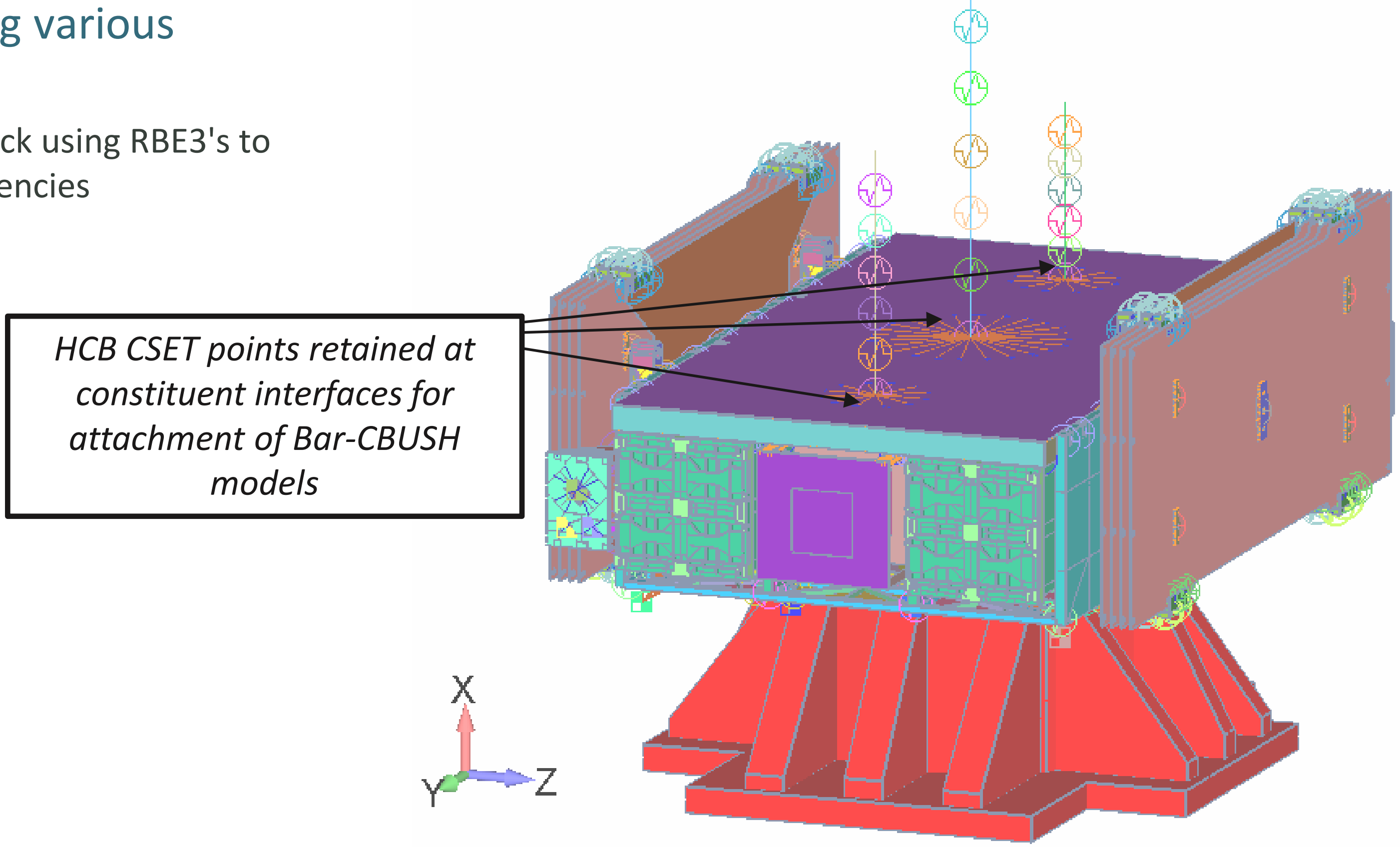
1. Modeling Approach



1. Modeling Approach – Bus HCB Reduction

- Analysis performed in Nastran
- Bus FEM reduced in various configurations using Hurty Craig Bampton (HCB) reduction
- Interface grids included in CSET for attaching various payloads
  - Constituent interface grids attached to payload deck using RBE3's to avoid over-constraining deck motion at high frequencies

Example Bus FEM With Simplified Bar/CBUSH Constituent Payloads Attached
(Explicit FEM Included for Visualization)



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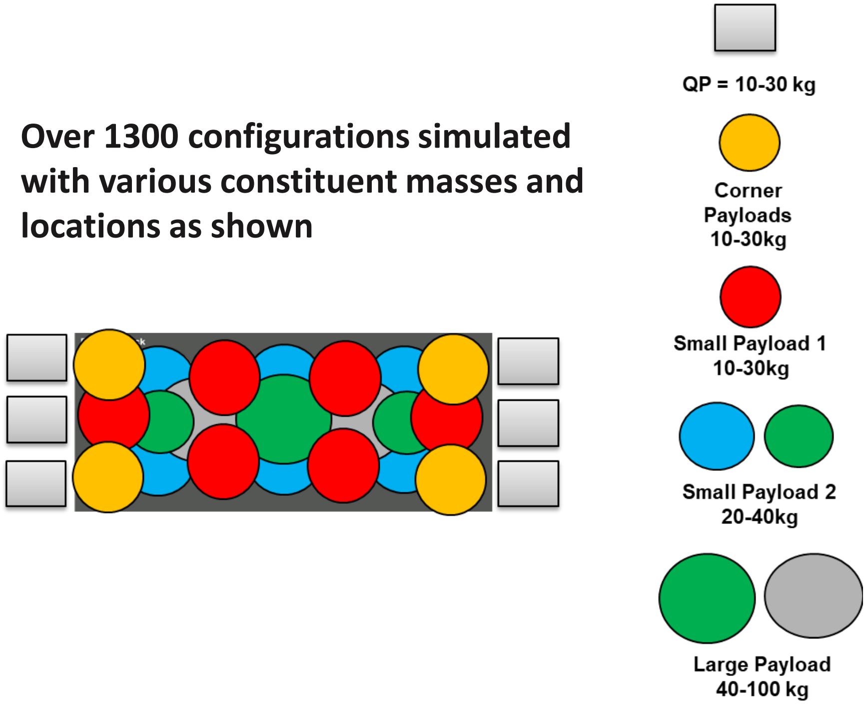
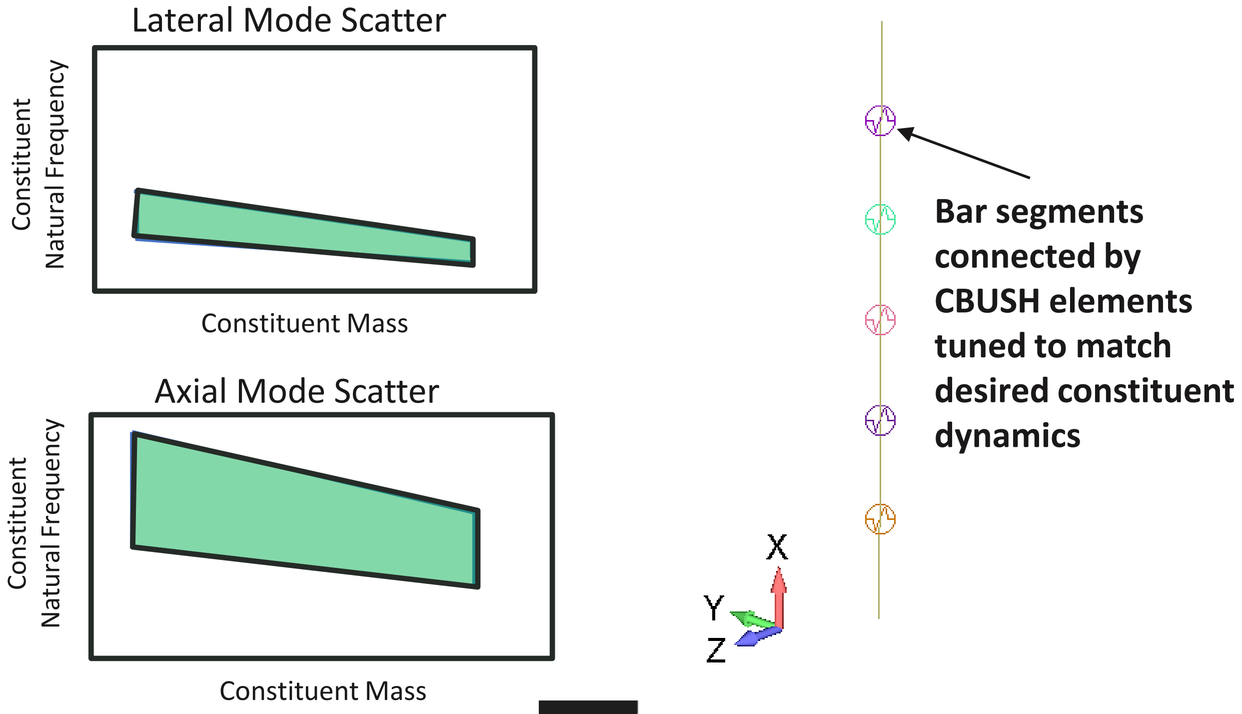
2. Modeling Approach – Constituent Models

- Tuned CBAR-CBUSH element models attached to bus HCB interface grids to represent dynamics of various constituents
- CBAR and CBUSH properties varied to populate expected mass/stiffness scatter
  - Each constituent model consists of 6 CBAR segments joined with CBUSH elements
  - CBUSHs required to decouple axial stiffness from modulus of bar elements

Over 1300 configurations simulated with various constituent masses and locations as shown



Constituent Dynamics Model



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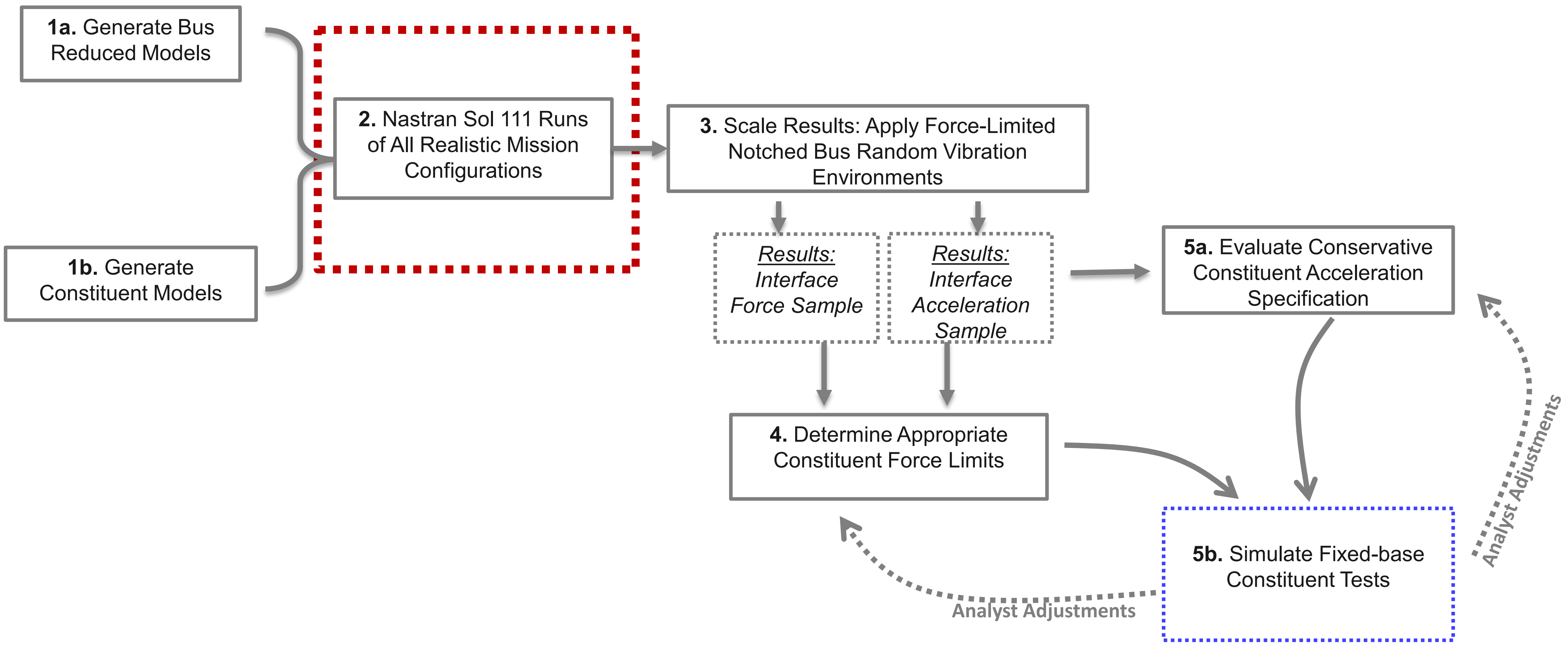
2. Run Generation



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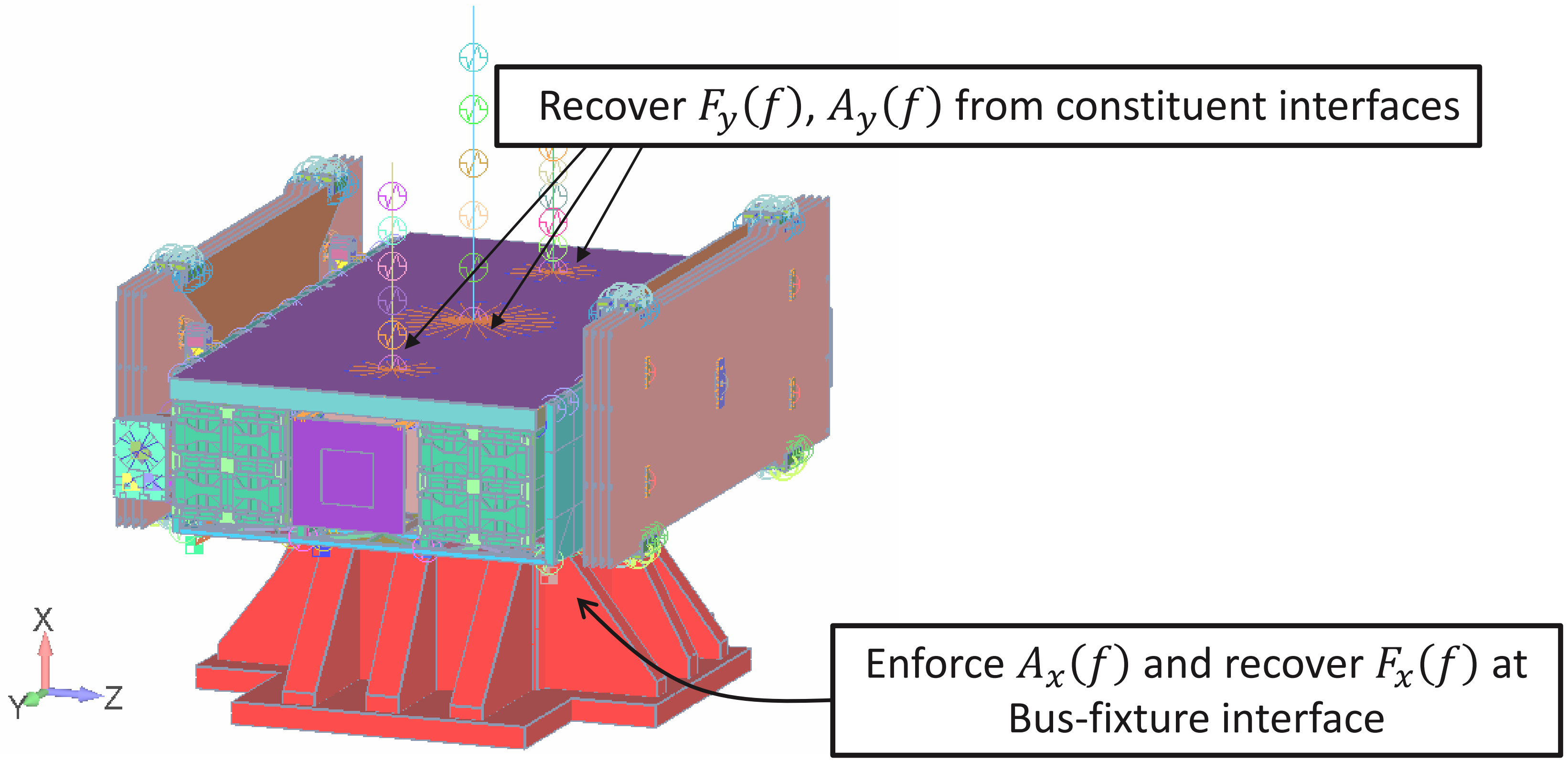
2. Run Generation [Coupled Runs]

- Automatically generated 1300+ Nastran decks representing every combination of payload mass, stiffness, and location
  - Transfer functions recovered in each axis independently using Solution 111 (frequency response) in frequency range of interest
  - Included modal damping based on past vibration test correlation



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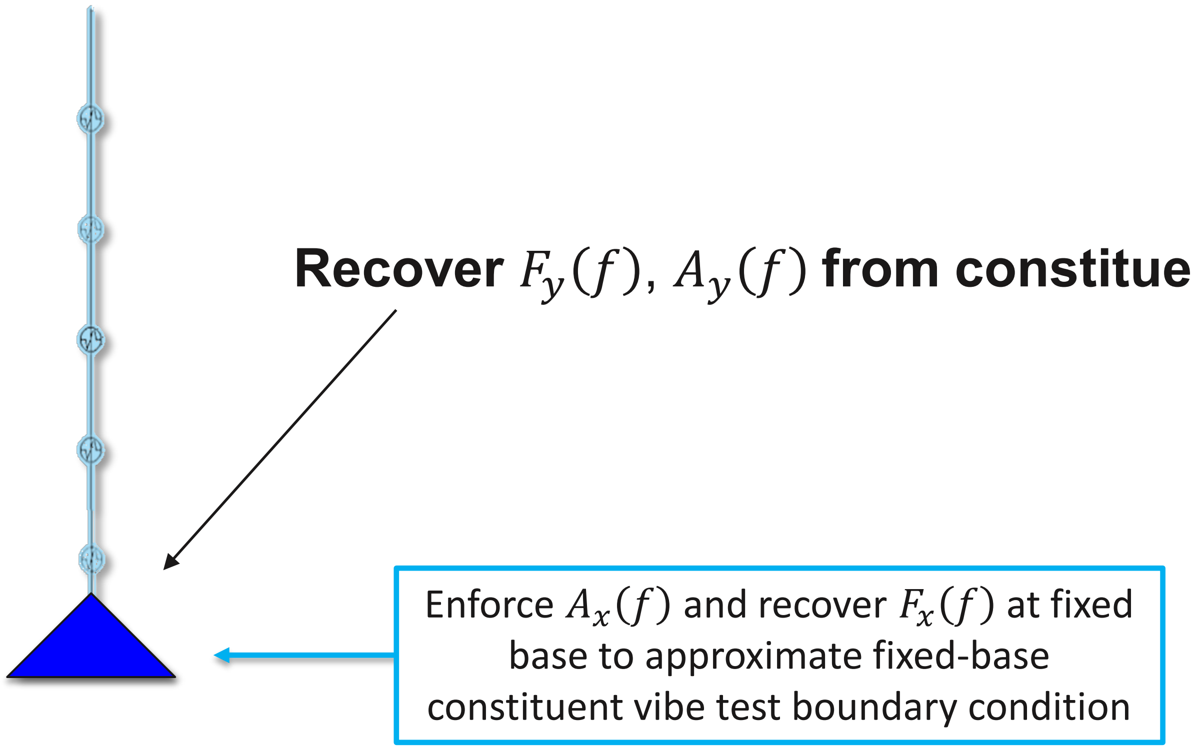
2. Run Generation [Fixed Base Constituent Runs]

- Also recovered fixed-base transfer functions of each constituent model
  - Fixed base results used to represent results from actual individual constituent tests
- Later applied ASD specification and force limits to simulate expected outcome of constituent tests



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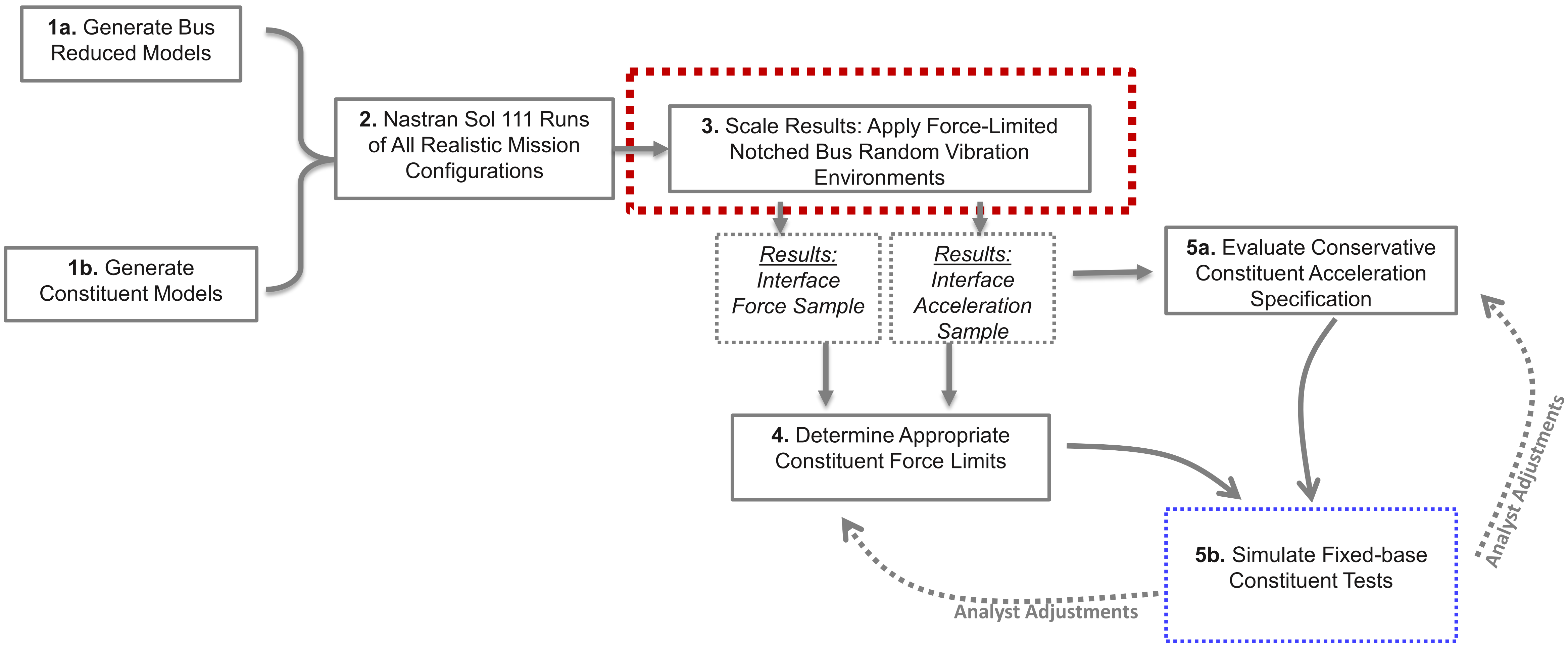
3. Apply Notched Bus Vibe Environment



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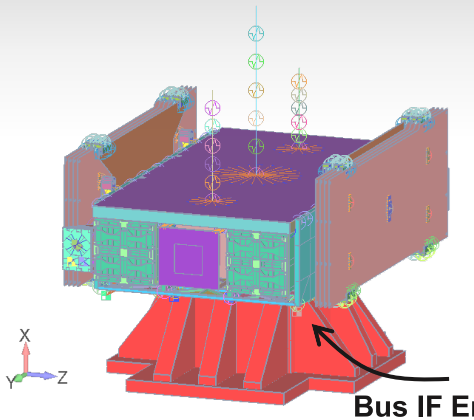
3. Apply Notched Bus Vibe Environment

- Applied bus interface random vibration environment to previously recovered transfer functions
- Automatically applied allowable notching to bus interface based on rideshare user's guide



Example SpaceX Rideshare RV MPE + 3dB

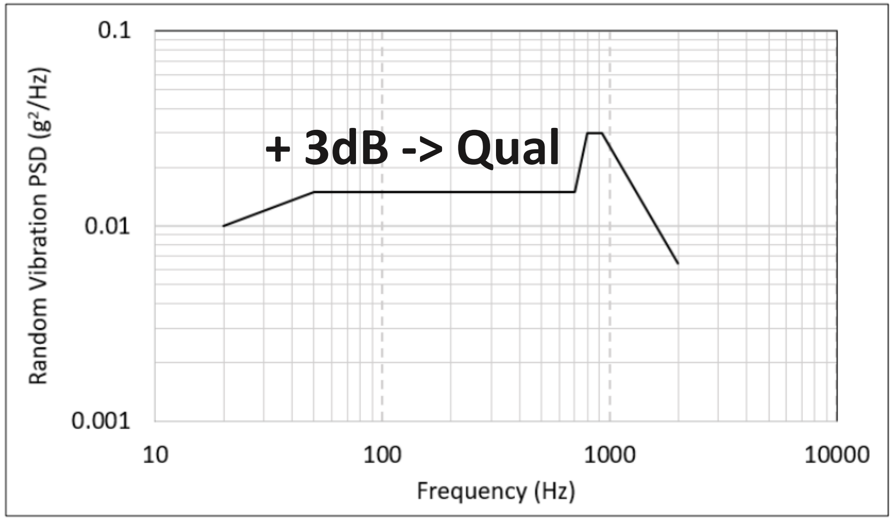
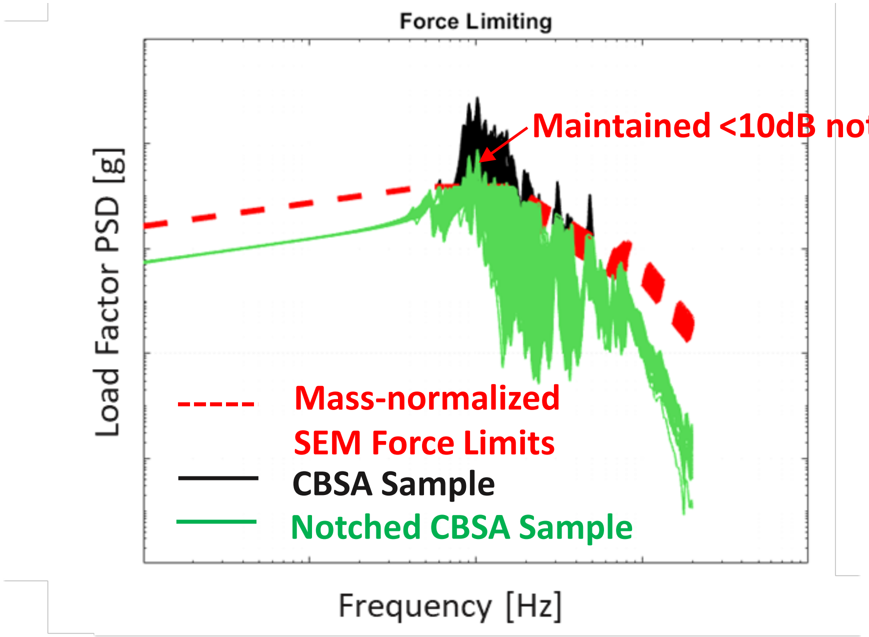


Figure 3-5: Random Vibration MPE

Example Bus Interface Force Limiting (Axial Cases)



Note: in this report, force PSDs are often normalized by mass so multiple constituent masses can be analyzed simultaneously

$$\text{Load Factor } S_{NN}(f) = \frac{S_{ff}(f)}{M^2}$$

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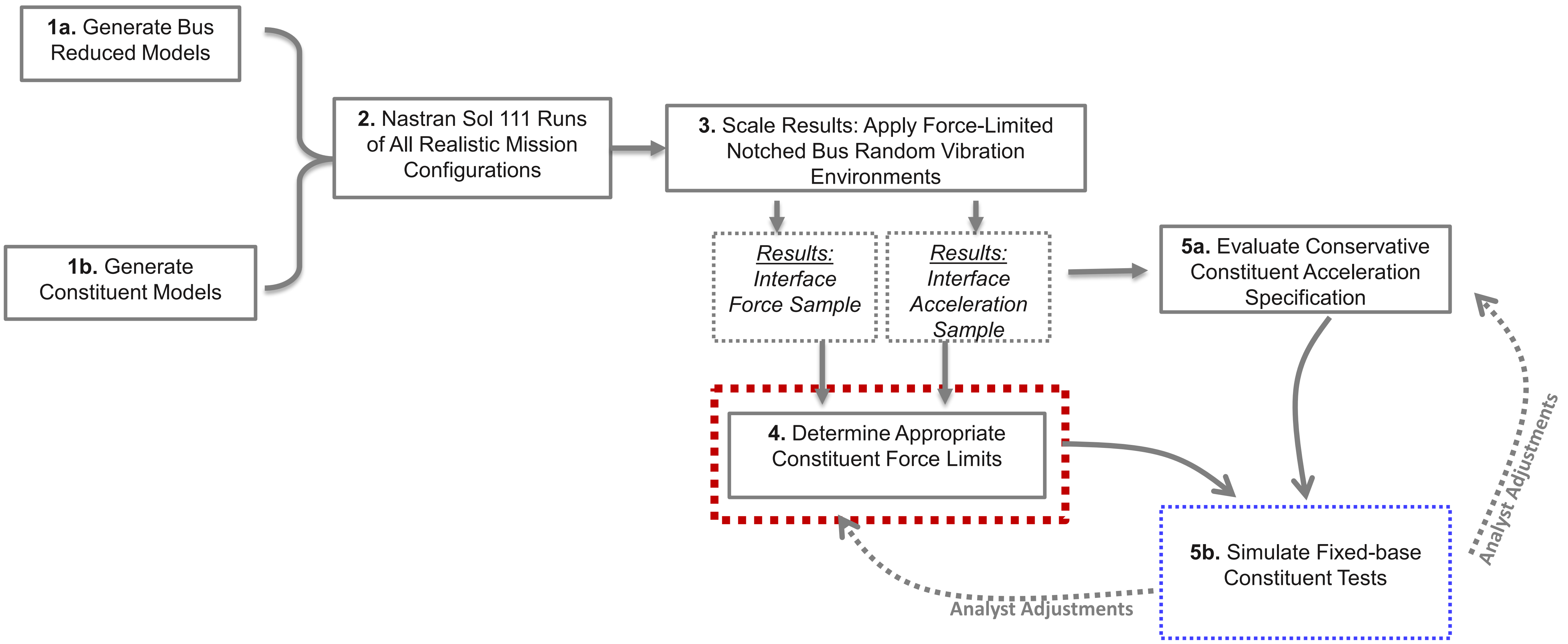
4. Determine Constituent Force Limits



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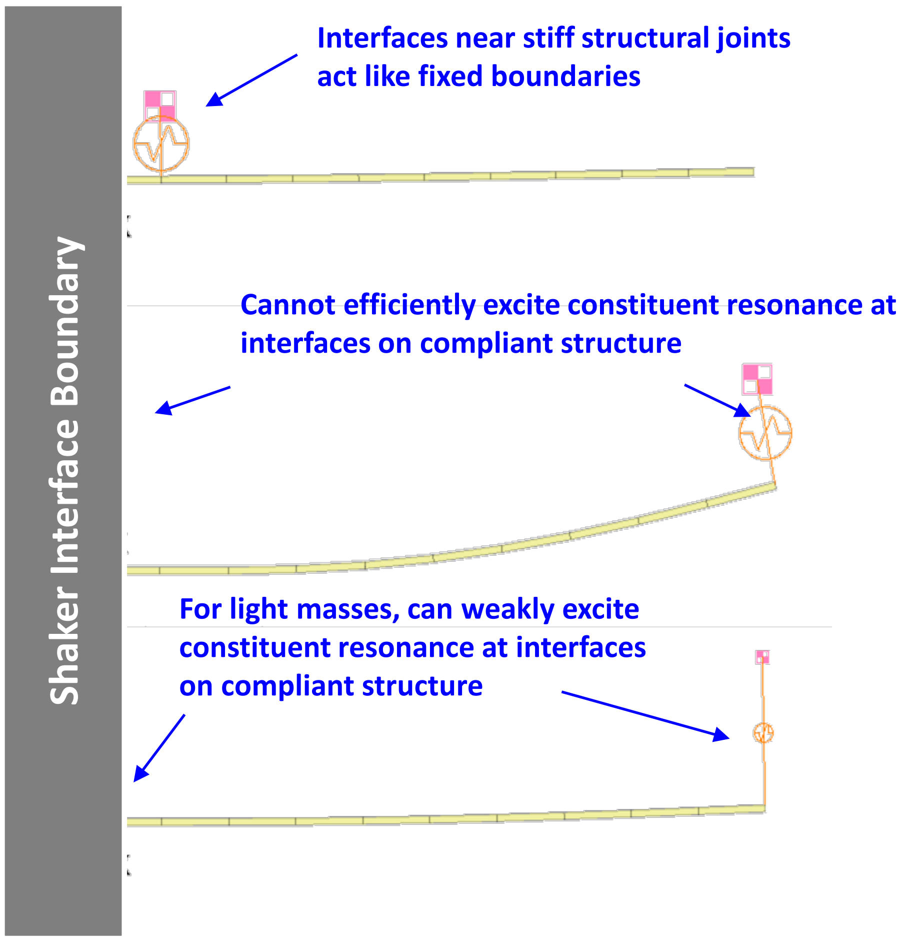
4. Determine Constituent Force Limits

- Fixed-base constituent test will never be able to reproduce in-axis coupled response due to incongruent interface impedance

- The coupled system interface (payload deck) may not have sufficient impedance to support & excite modal response of the constituent
  - Well known "vibration absorber effect" (VAE) documented by Scharton et. al.
  - Observable as acceleration anti-resonances at coupled interface
  - Dependant on mass, inertia, mounting location, natural frequency of constituent

- Force limits should aim to introduce correct amount of load into constituent's primary structural mode

Illustration of Transmissibility to Constituent Primary Resonance at Various Mounting Locations



4. Determine Constituent Force Limits

- The VAE is highly complex but the key property relevant to specification development is the expected transmissibility of force into the constituents primary structural mode

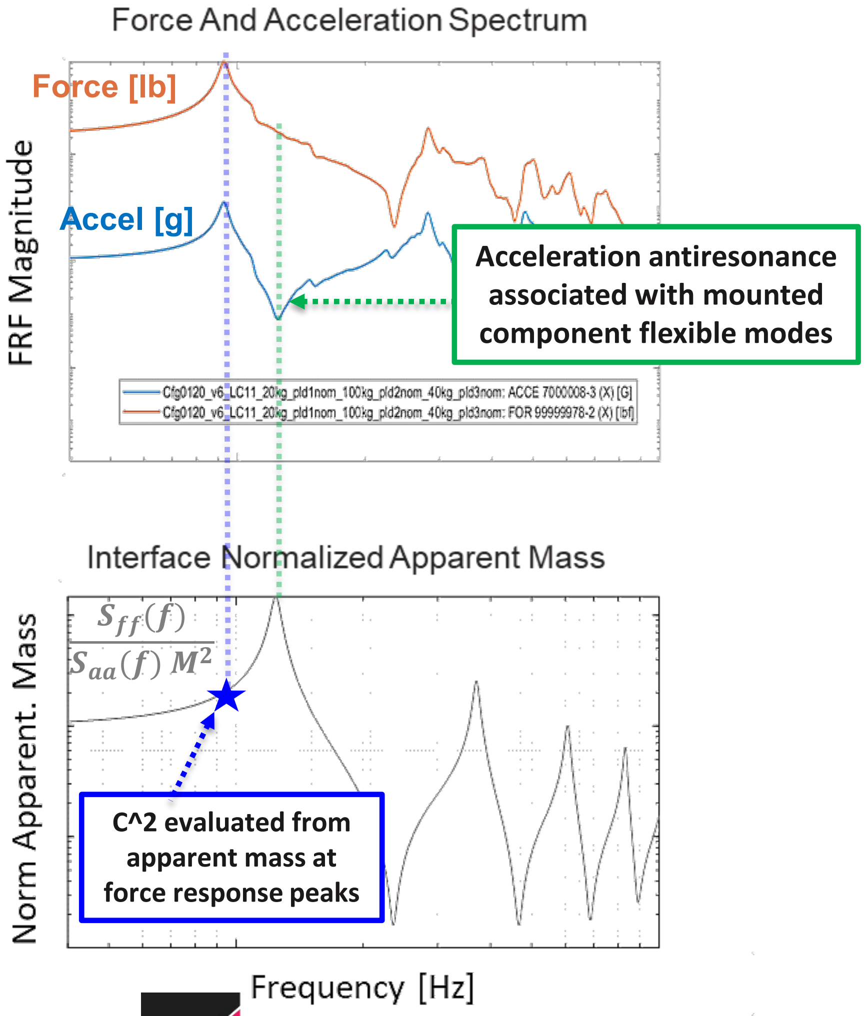
- RV Force limits can be algorithmically evaluated from CBSA as $\boldsymbol{C^2}$ consistent with the Semi-Empirical Method (SEM):
  - Relationship between interface force and acceleration is frequency-dependent apparent mass function
  - Since environment spectrum and RMS are often driven by force and acceleration *peaks*, we are most interested in this apparent mass evaluated at the peak interface force & acceleration frequencies of the coupled system – evaluated as $\boldsymbol{C^2}$ for random vibration
  - Appropriate $\boldsymbol{C^2}$ will achieve correct interface force magnitude and simulate VAE antiresonance

Standard Random Vibration SEM Force Limit (NASA STD 7004)

$$S_{FF}(f) = C^2 M_o^2 S_{AA}(f), \qquad f < f_b$$

$$S_{FF}(f) = C^2 M_o^2 (f_b/f)^{2n} S_{AA}(f), \qquad f \geq f_b$$

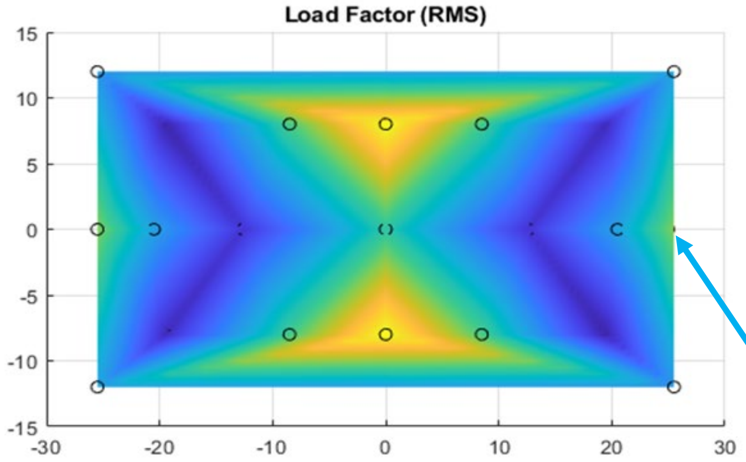
Vibration Absorber Effect



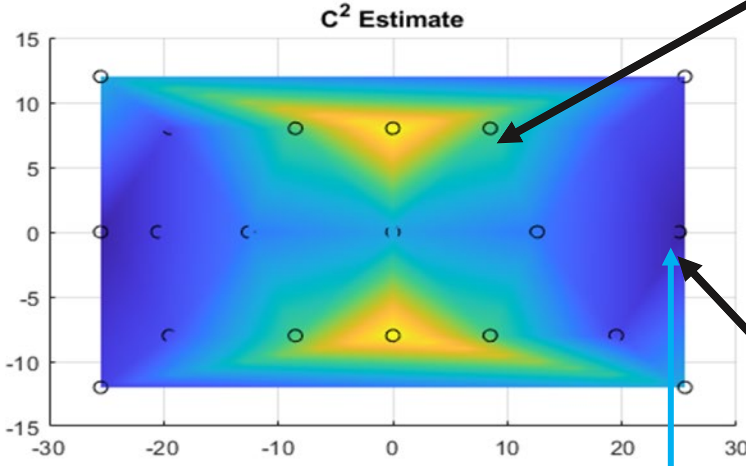
FORCE LIMIT TRENDS

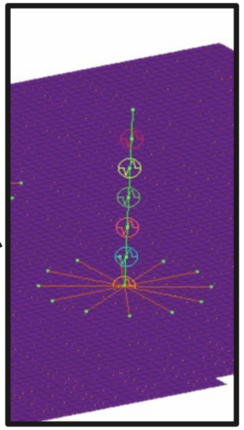
- Algorithmic C^2 evaluation results in distribution of C^2 values that can be analyzed statistically
  - Example of location trends shown below
- C^2 trends by location, mass, and natural frequency can help characterize dynamics of the bus structure and helps inform…
  - Appropriate segregation of environments and associated C^2 ranges
  - Placement of certain constituent payloads
- Observation: Low C^2 does not always result in lower loading
  - High interface force may be due to ~quasi-static vibration associated with high acceleration levels

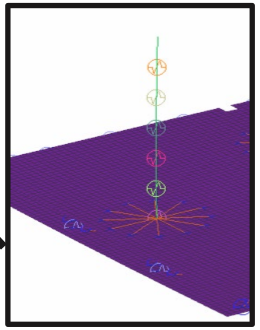
1-Sigma Load Factor (G-RMS)



Mean C^2

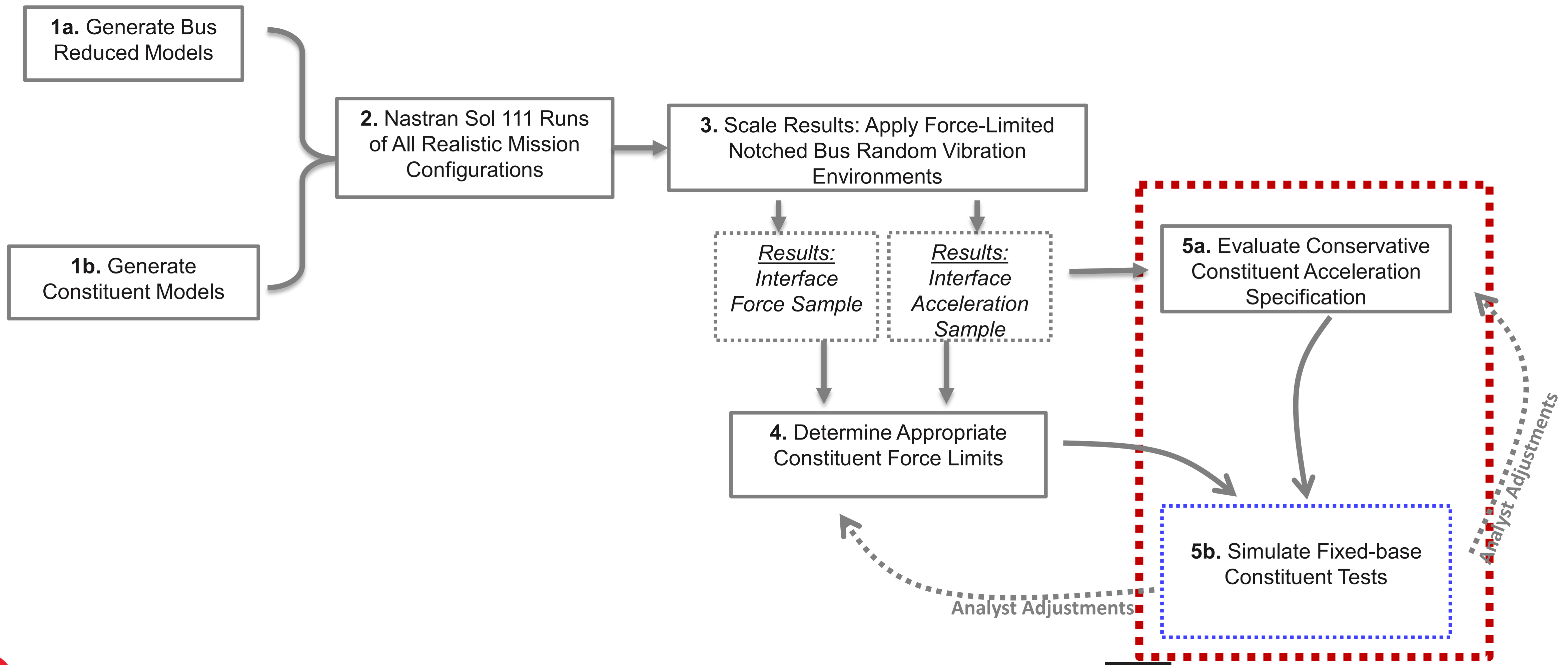






In some cases, high interface force can occur with low impedance (e.g. high acceleration)

5A. Evaluate Constituent Acceleration Spec



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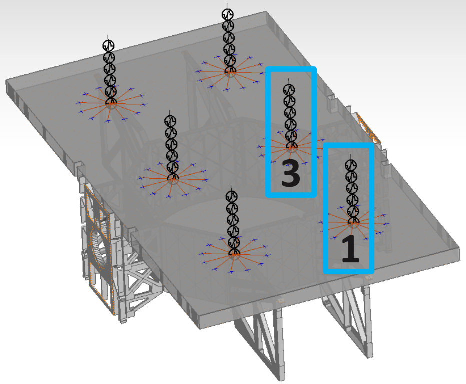
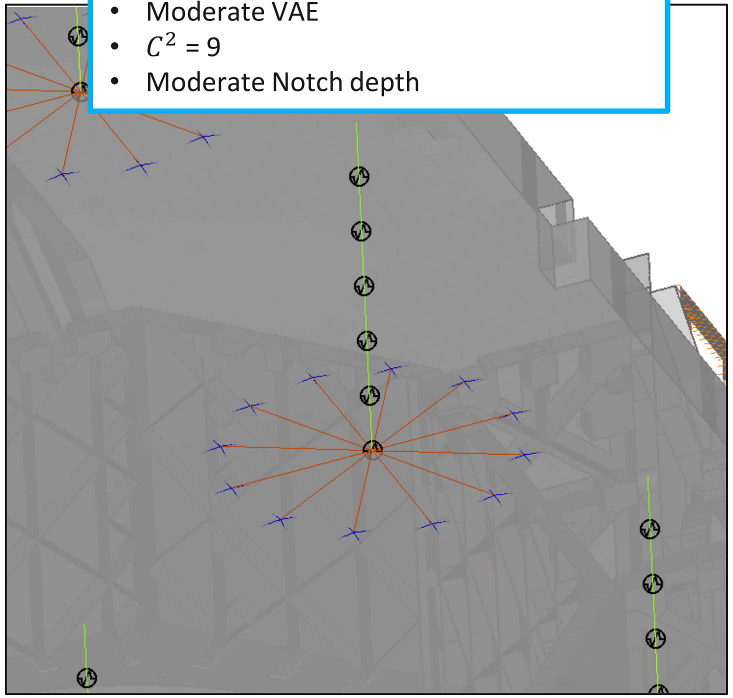
Interface Specification – Individual Constituent

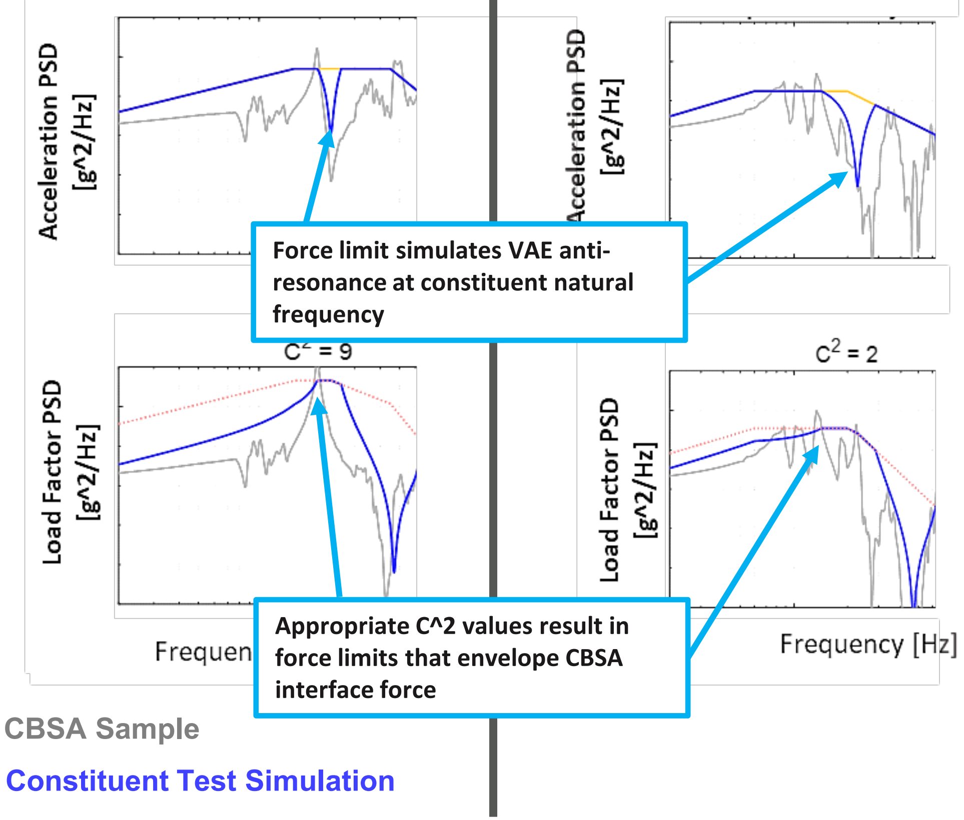


- Example ASD envelope and force limit implementation shown below for X-axis loading
  - In this example, the ASD specification is derived using industry standard approach (Spectral peak enveloping / FEMCI guidelines)
- For single constituent, force limit should limit force PSD to CBSA peaks and simulate VAE antiresonance



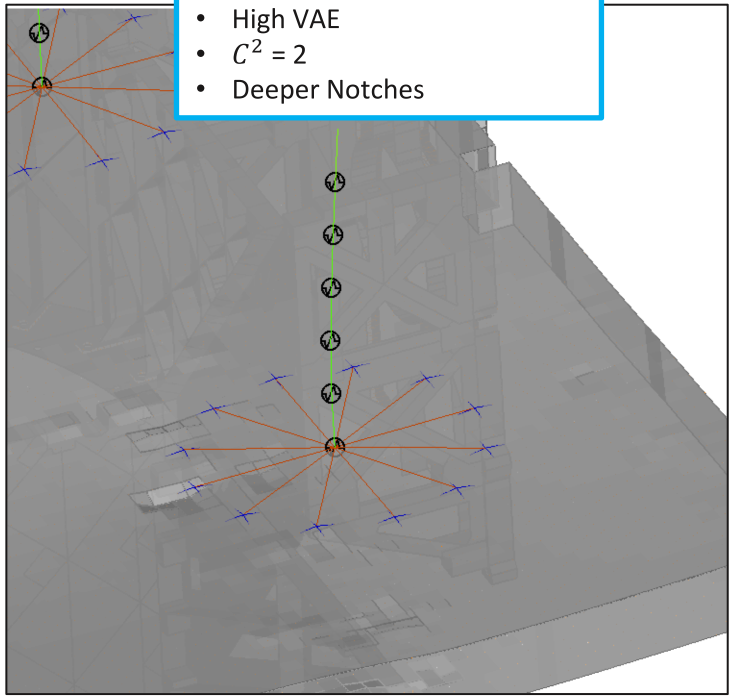
Force Peak @ Location 3:
- Moderate impedance
- Moderate VAE
- C^2 = 9
- Moderate Notch depth

Location 3: C^2 = 9 | **Location 1: C^2 = 2**



Force limit simulates VAE anti-resonance at constituent natural frequency

Appropriate C^2 values result in force limits that envelope CBSA interface force



Force Peak @ Location 1:
- Low impedance
- High VAE
- C^2 = 2
- Deeper Notches

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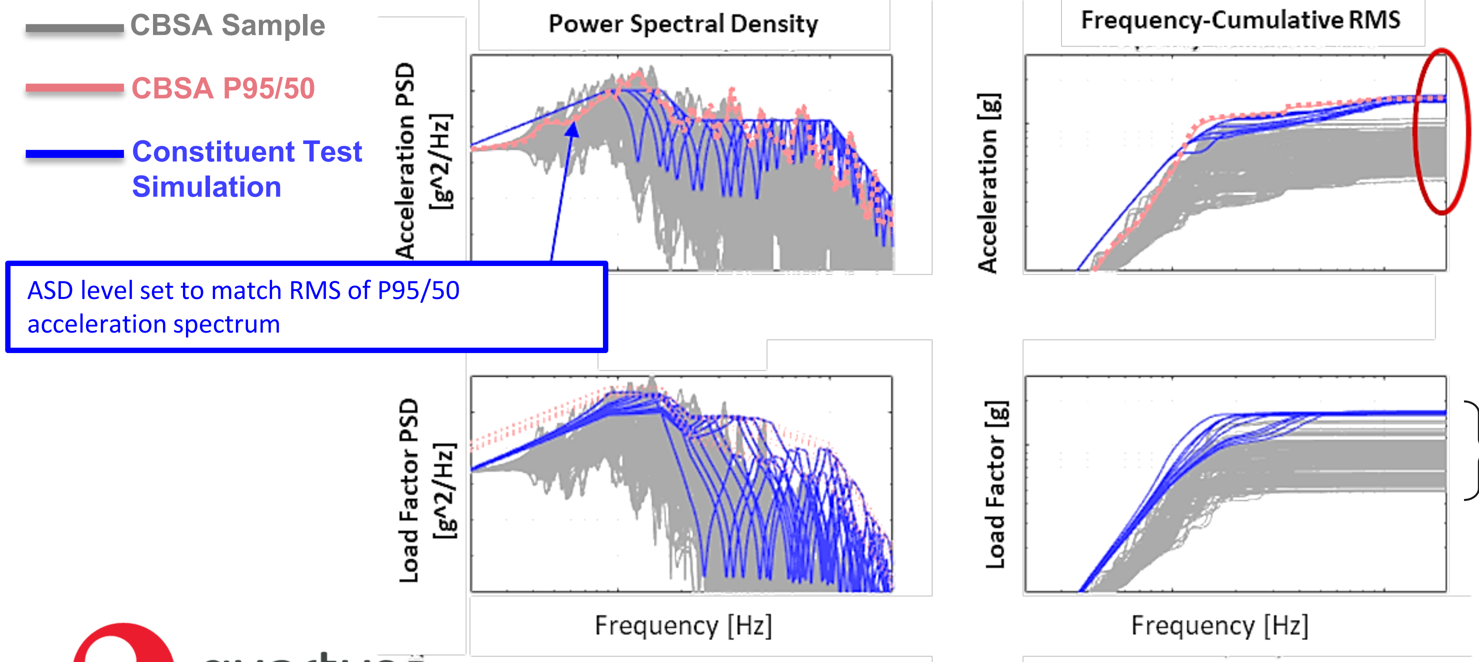
Enveloping Methods: Spectral Env. for Limited Sample

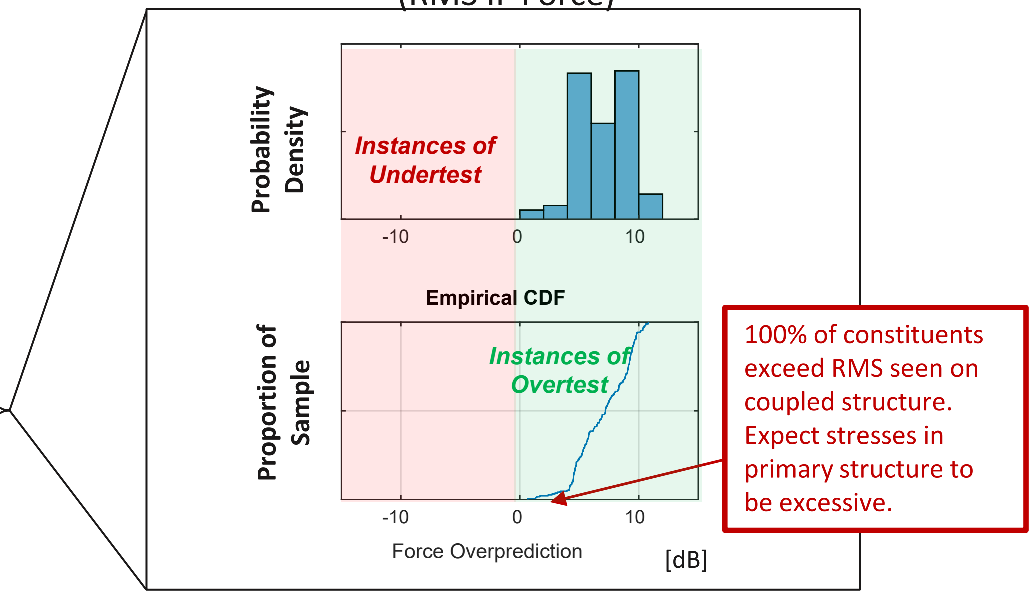
- Below example environment customized for payloads on outer edges of the payload deck (lower C^2 for X-axis loading)
  - C^2 allowed to vary within range informed by previous step to match observed CBSA limit load
  - ASD level set to match RMS of P95/50 acceleration spectrum and follow spectrum shape
- Peak-enveloping approach may be used for constituent samples that have similar dynamics, but RMS acceleration will contain excess conservatism
  - ASD specification RMS will contain excessive conservatism due to peak-driven enveloping
  - Resulting interface forces may match limit load, but case-by-case assessment shows primary structure of all constituents were overtested

Constituent Test Predictions VS CBSA Results



Case-by-case Overtest Analysis

(RMS IF Force)



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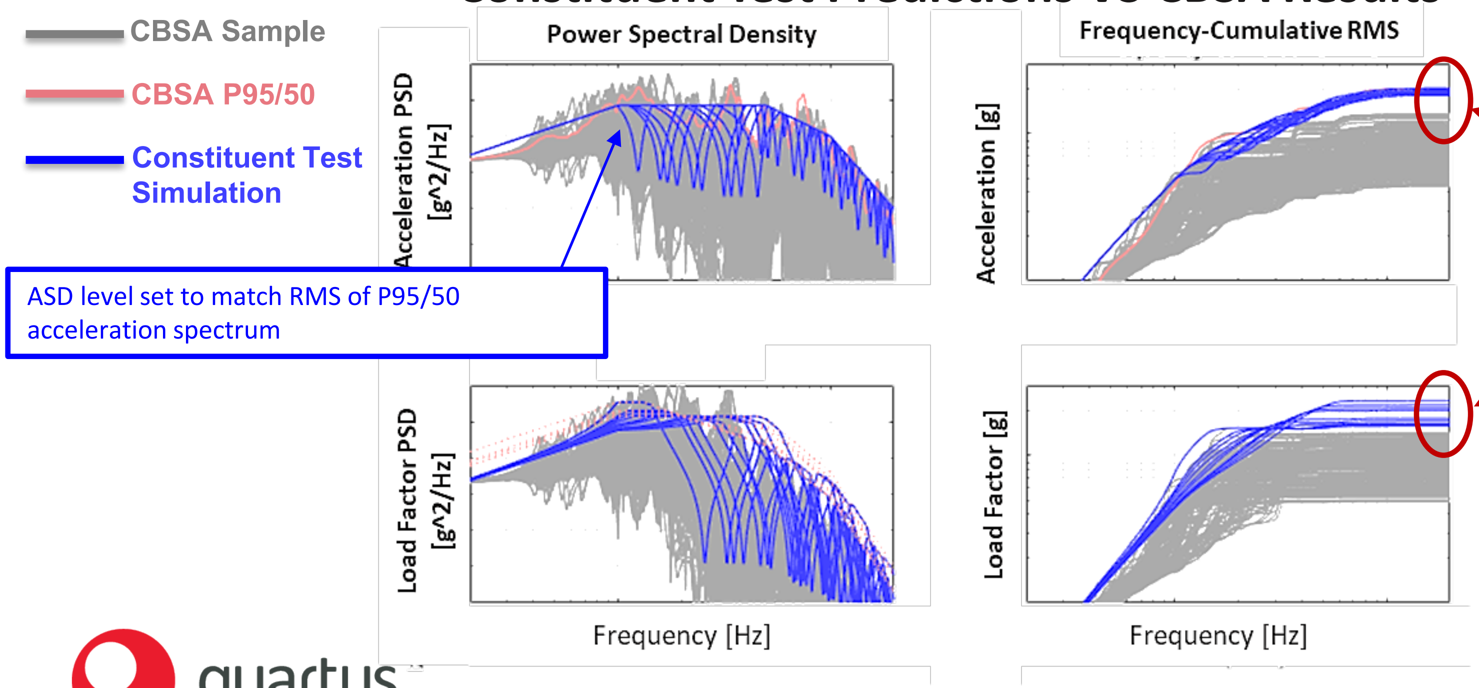
ENVELOPING METHODS: SPECTRAL ENV. FOR DIVERSE SAMPLE

- Below example environment includes all constituent locations, masses, and stiffnesses
  - C^2 allowed to vary within range informed by previous step to match observed CBSA limit load
  - ASD level set to match RMS of P95/50 acceleration spectrum and follow spectrum shape
- Peak enveloping approach for diverse sample of constituents will result in excessive conservatism in primary structure
  - Requires unrealistic reduction of C^2 to achieve correct interface loads
  - Expect constituent primary structure to be significantly overtested

Constituent Test Predictions VS CBSA Results



- Both acceleration specification and resulting interface forces will be excessively conservative for primary structure
- Reducing C^2 further to match interface force would be unrealistic based on acceptable range evaluated in previous step

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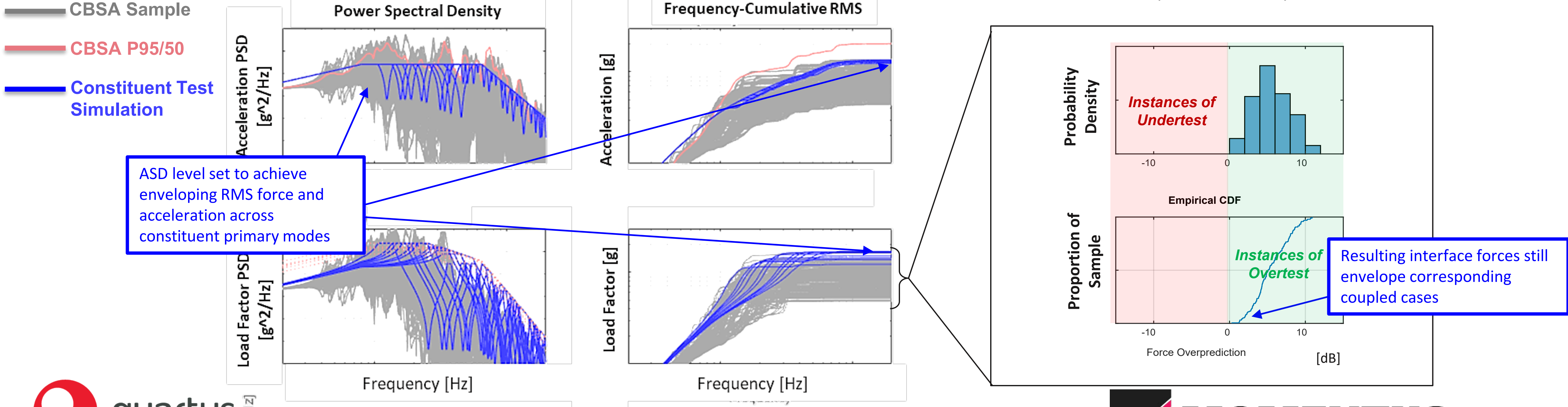
Enveloping Methods: RMS Env. for Diverse Sample

- Below example environment includes all constituent locations, masses, and stiffnesses
  - C^2 allowed to vary within range informed by previous step to match observed CBSA limit load
  - ASD level set to achieve desired Probability of Undertest (PoU) based on overall RMS
- RMS driven enveloping approach for diverse sample will maintain appropriate conservatism in primary structure, but introduces risk of undertesting small subcomponents (e.g. electronics)
  - Consider enforcing min workmanship environment floor or enveloping spectral peaks at high frequencies if this is of significant concern to the program

Constituent Test Predictions VS CBSA Results

Case-by-case Overtest Analysis

(RMS IF Force)



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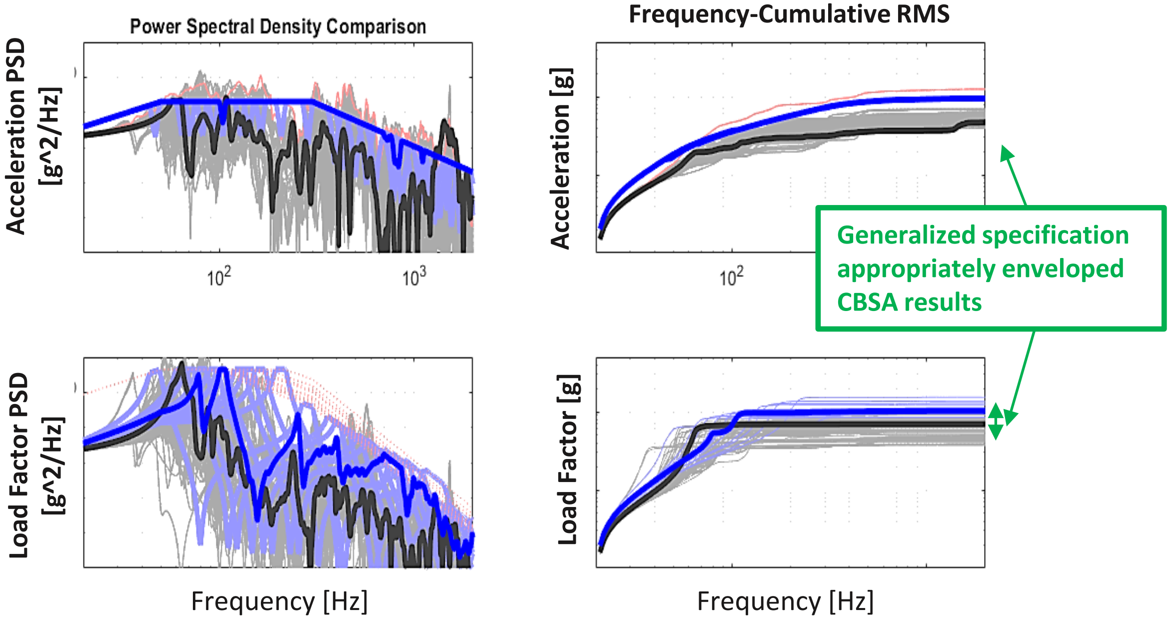
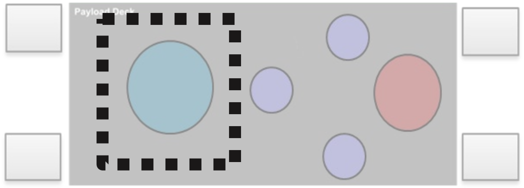
Validation Case Example [Generic]

- A limited sample of explicit FEM results should be compared with CBSA sample to build confidence in modeling assumptions and desired level of conservatism
- In this example…
  - Explicit fixed-base simulation successfully enveloped explicit CBSA RMS force, moment, and acceleration
  - Element-by-element stress field comparison shows that acceptable fraction of constituent was undertested (<5%)

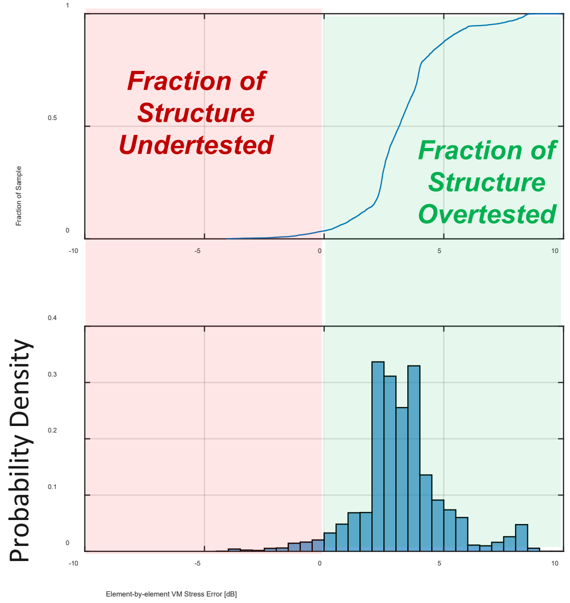
Explicit FEM of True Mission Configuration vs Generalized CBSA Sample





- **Explicit Spacecraft FEM**
- **CBSA Sample**
- **CBSA P95/50**
- **Constituent Test Simulation**

Element-by-element Stress Field Error From Generalized CBSA Specification



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Observations

- Coupled Base Shake Analysis (CBSA) can be performed to…
  - Generate random vibration environments and force limits for spacecraft across diverse range of configurations and constituent properties
  - Generate random vibration environments and force limits for spacecraft customized for specific mission configurations
  - Provide useful metrics for segregating environments (e.g. mass trends, impedance trends, etc…)
  - Aid in characterizing useful structural dynamics of bus structure

- A limited set of validation studies should be used to build confidence that…
  - CBSA produces results that bound desired output from explicit FEM analysis
  - CBSA produces
- When enveloping diverse CBSA samples, an RMS-driven enveloping approach may be desired to prevent excessive loads in primary structure
  - However, additional margin must be added depending on desired level of risk to ensure…
    1. High frequency enveloping of small subcomponent responses (e.g. electronics)
    2. Sufficient spatial coverage of envelope (i.e. account for incongruent load distribution – fixed base vs coupled)
- Future work:
  - Quantify uncertainties and limitations associated with CBAR/CBUSH/RBE3 based CBSA approach
  - Explore implications of varying modal mass distribution of constituent models
  - Can CBSA provide indicators of how well spatial distribution of responses will match between coupled and fixed-base constituent results?
  - Can CBAR internal VRS ensemble be used to build confidence in enveloping response of small subcomponents?
  - Create automated process for constituent payload placement optimization to reduce environments

REFERENCES

- Soucy, Dharanipathi, Sedaghati, “Investigation of Force-Limited Vibration for Reduction of Overtesting”
- Scharton, “Force Limited Vibration Testing Monograph”

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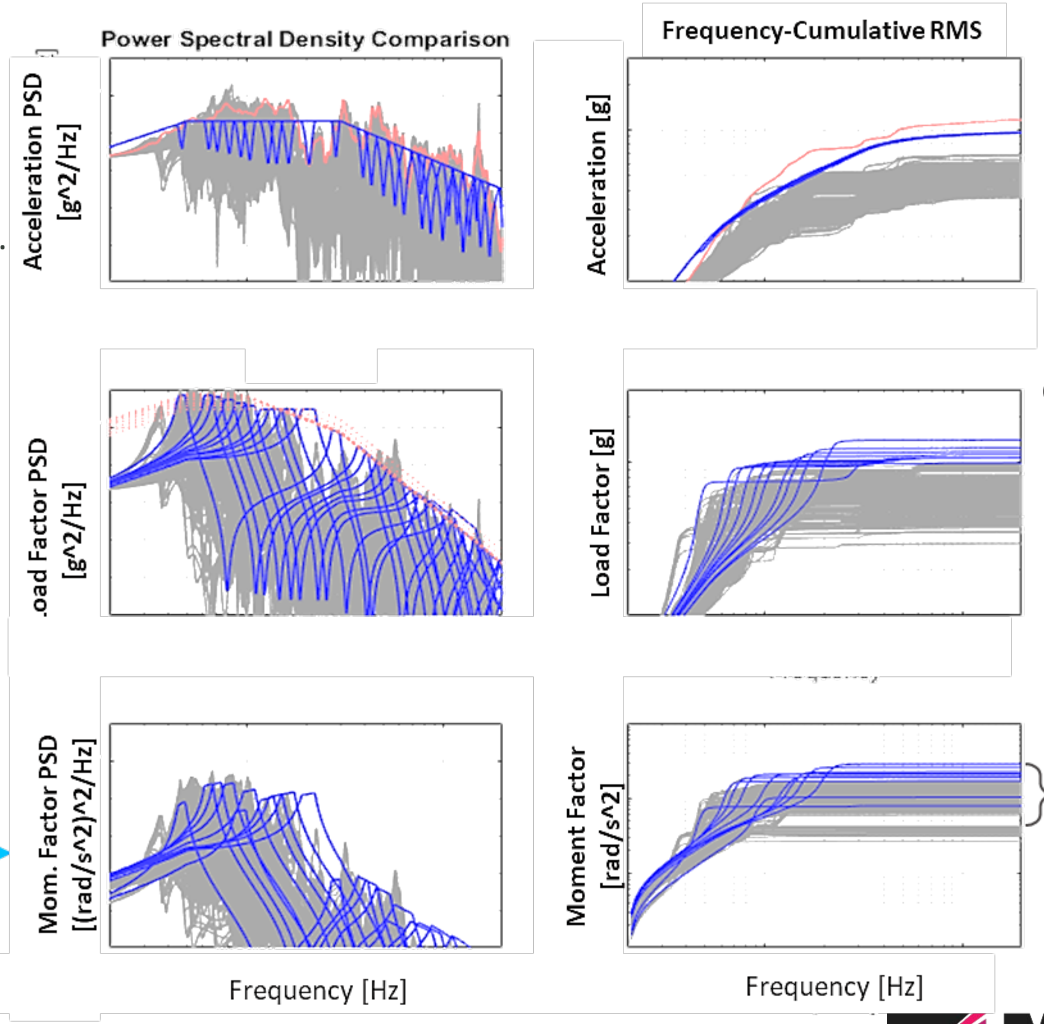
BACKUP

Lateral IF Specification Example

- Included moment comparison for assessment of lateral environments
- Observation: lateral loading associated with significantly higher force limits
  - Cross axis loading drives many force peaks (i.e. lateral force driven by vertical motion)
  - In practice, vibe test can only generate force peaks in-axis motion

Constituent Test Predictions VS CBSA Results (Lateral Loading)



CBSA Sample

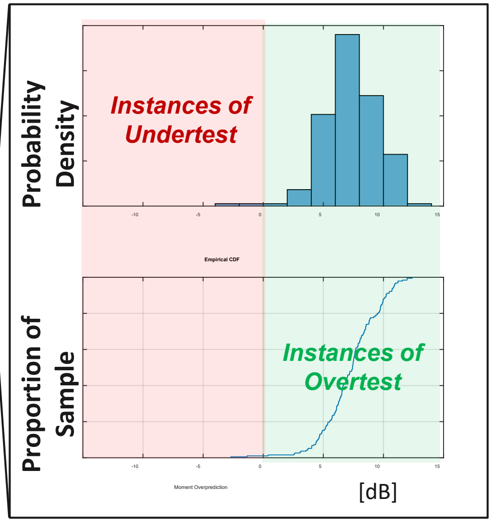
CBSA P95/50

Constituent Test Simulation

Lateral assessment includes comparison of moments

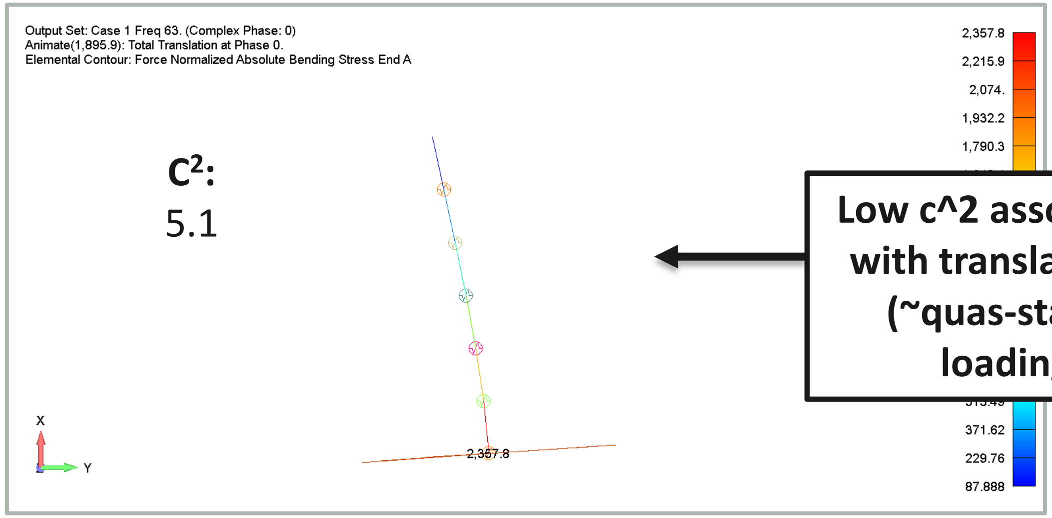
Case-by-case Overtest Analysis

(RMS IF Moment)



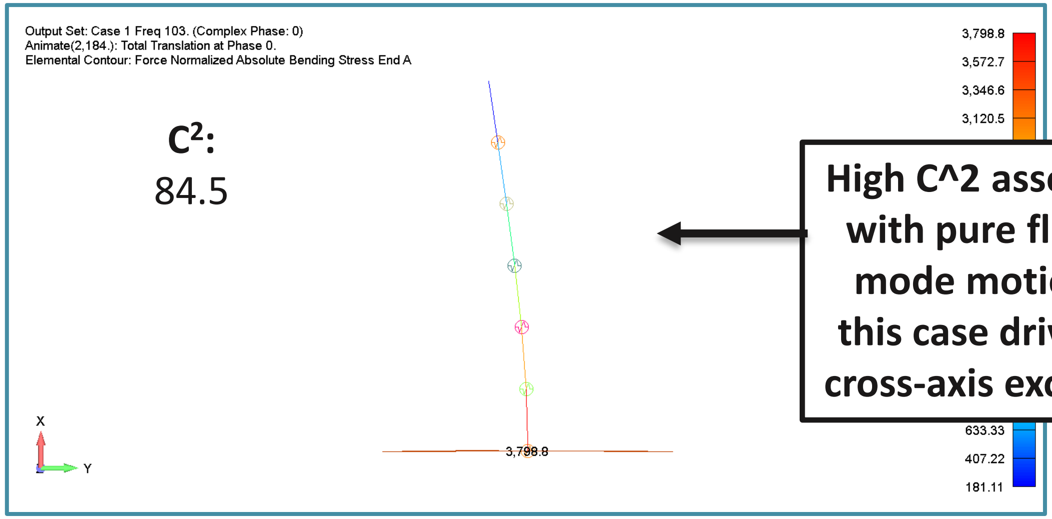
Cross Axis Effects on C^2 Evaluation

Freq 1

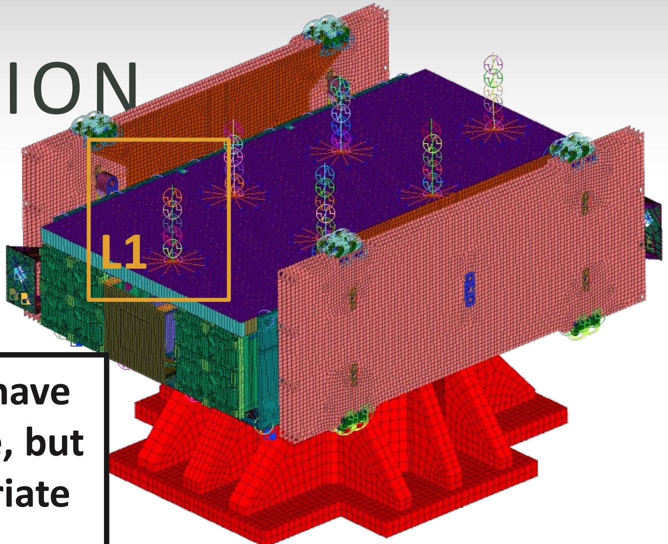


Low c^2 associated with translational (~quas-static) loading

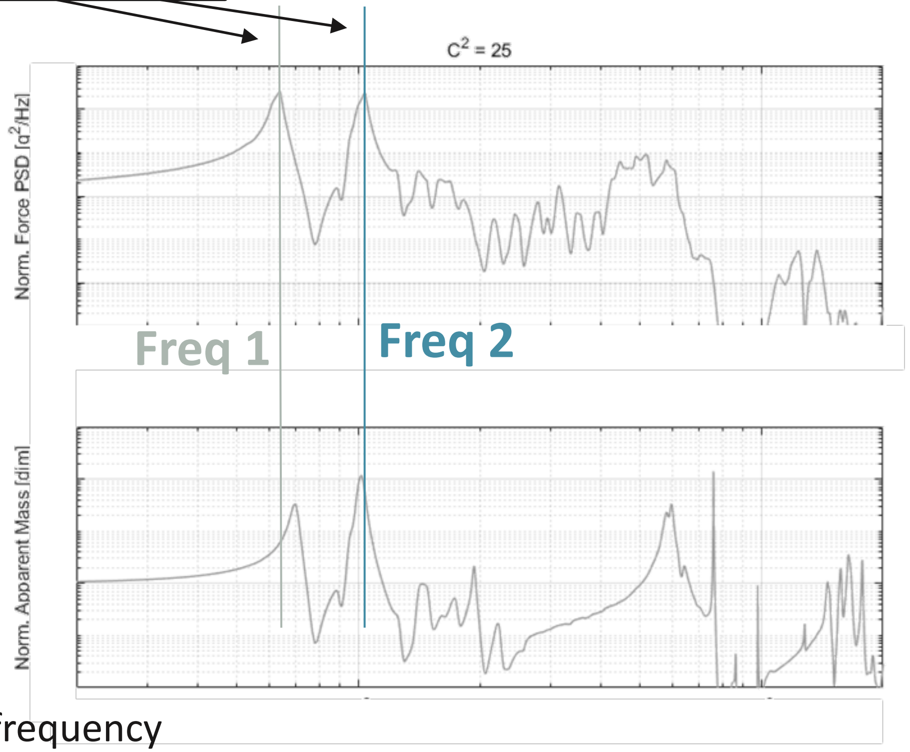
Freq 2



High C^2 associated with pure flexible mode motion, in this case driven by cross-axis excitation



Force peaks can have similar magnitude, but different appropriate c^2 values



Note: Stresses scaled by force peak at requested frequency

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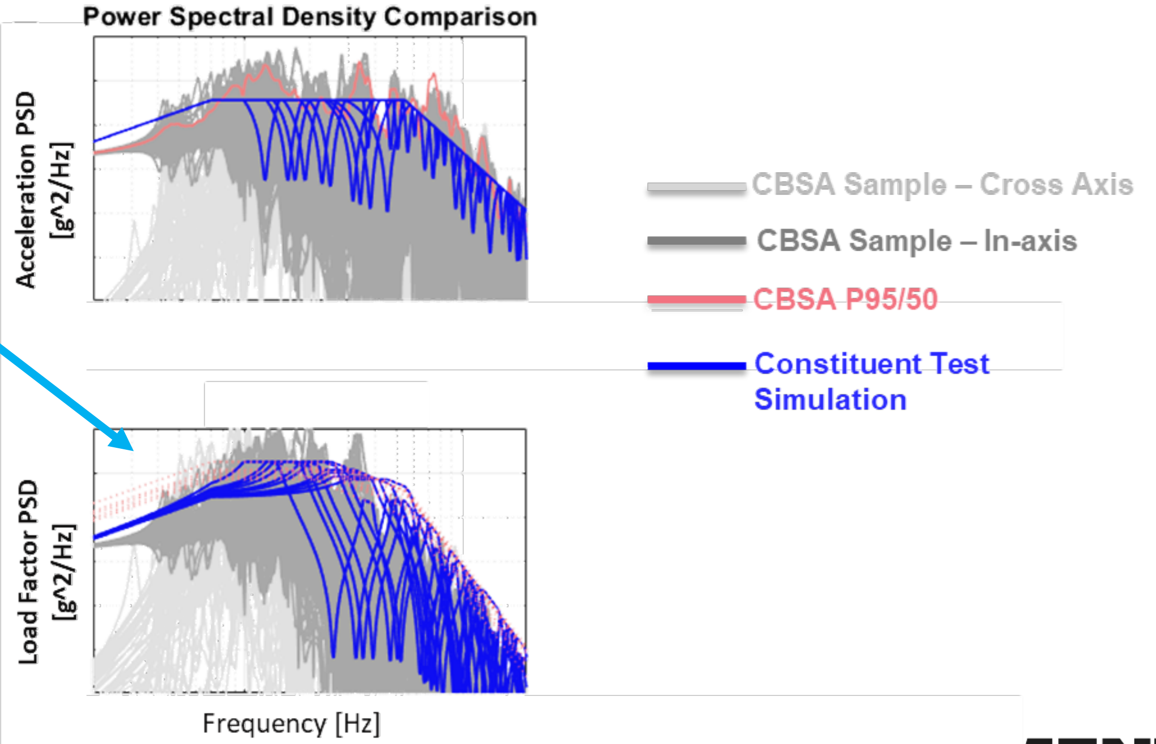
Cross Axis Response Checks

- Current process allows for inspection of cross axis responses
- Off axis responses can be enveloped with in-axis responses

Example of In-axis and Cross Axis Results (Axial Loading)

Example of cross axis peaks that exceed in-axis spectrum



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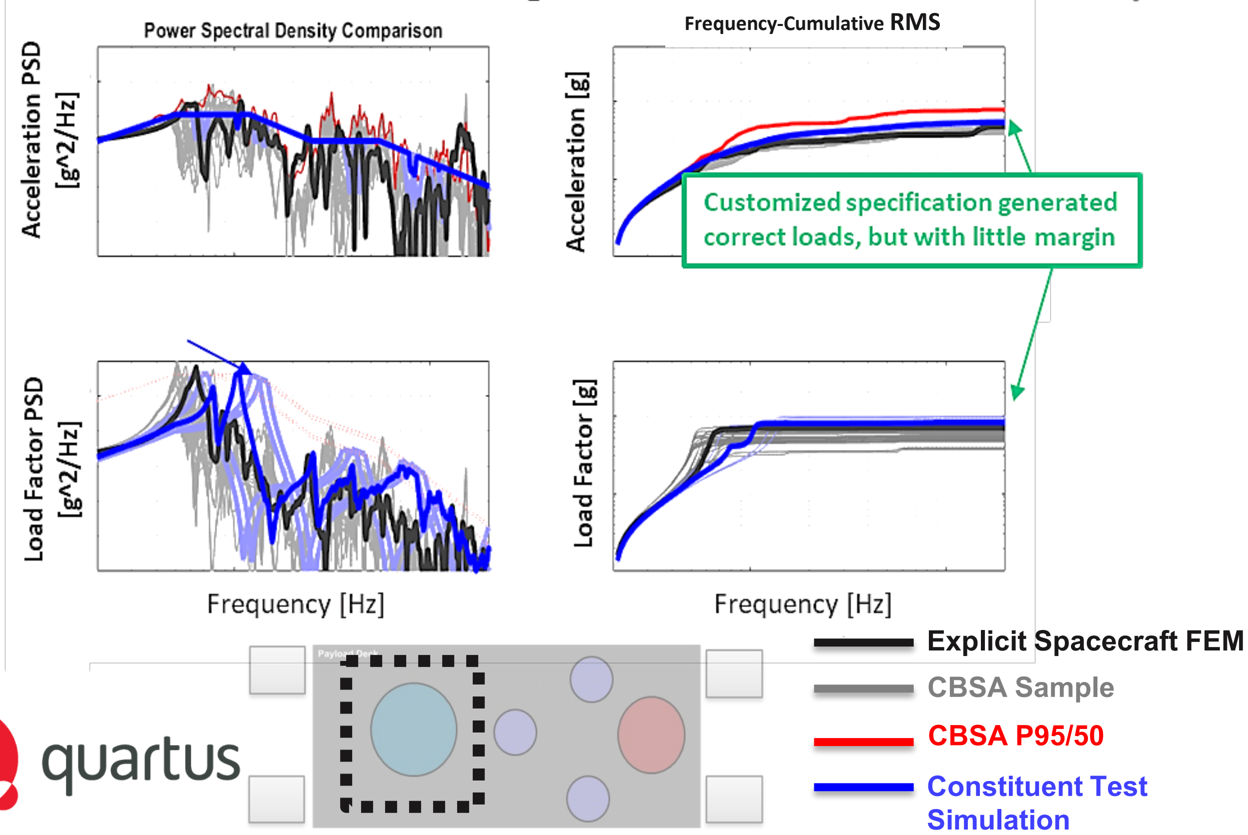
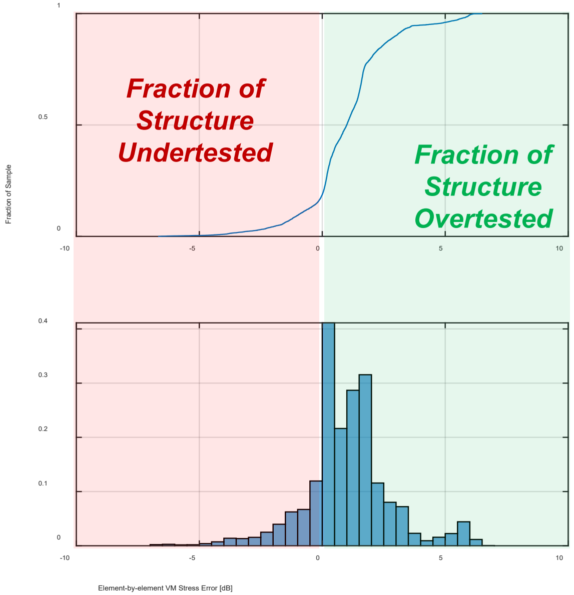
Validation Case Example [Customized]

- In this example…
  - A customized sub-sample of CBSA results was used to predict response of an explicit FEM
    - Subsample selected based on mounting location, mass properties, and natural frequency
  - Explicit FEA ASD and Force response fell within CBSA predictions, but some components on constituent structure were undertested
- Observation: Even if constituent reaches appropriate interface load, certain spatial regions of the structure may be undertested due to incongruent distribution of load

Explicit FEM of True Mission Configuration vs Generalized CBSA Sample



Element-by-element Stress Field Error From Generalized CBSA Specification



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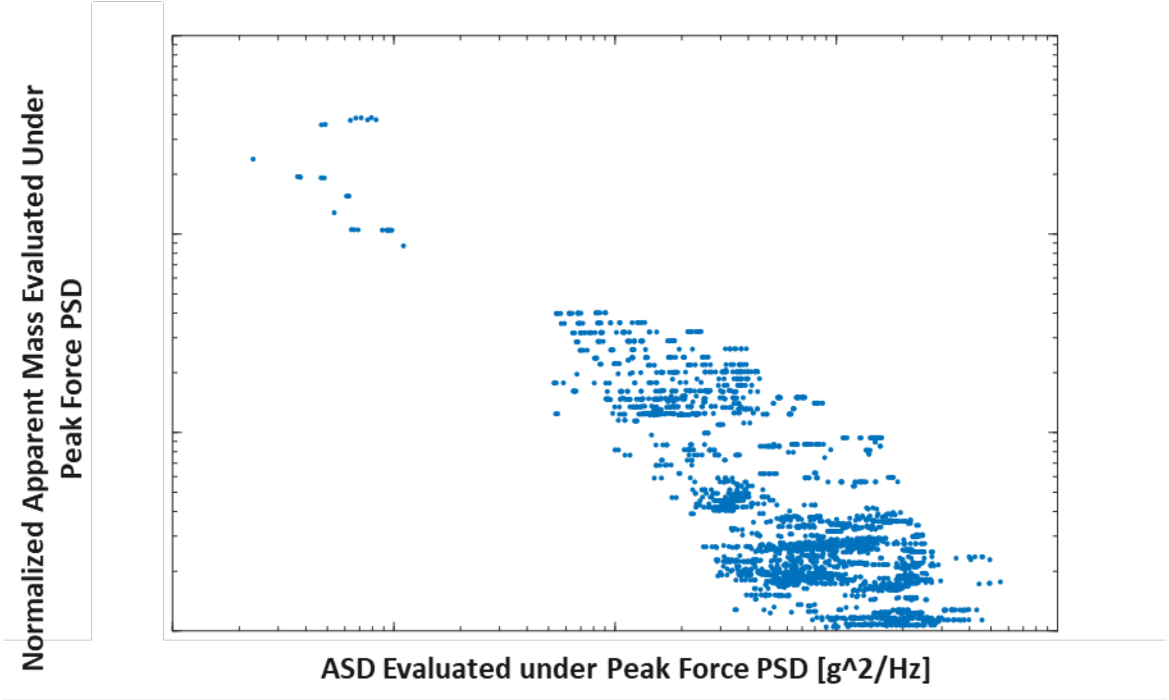
PEAK ACCELERATION PSD VS C^2 CORRELATION – AXIAL EXAMPLE

- Observed general trend of negative correlation between impedance (C^2) and interface ASD at frequency of peak force PSD
- Example below shown for all X-axis loading



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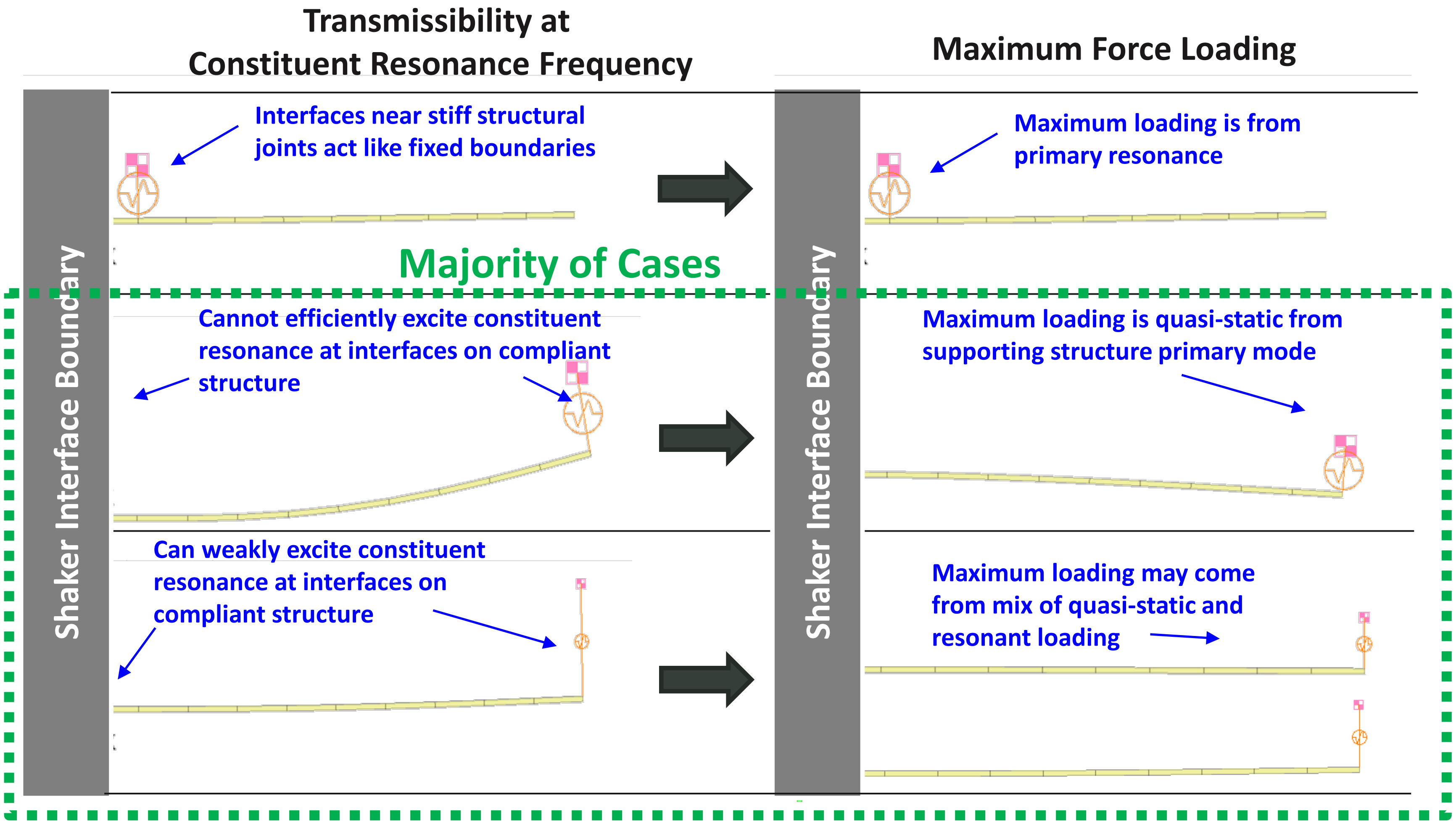
4. Determine Constituent Force Limits

- The VAE depends on 3 primary variables:
  - Mass & moment of inertia of constituent
  - Mounting location of constituent
  - Natural frequency of constituent

- Note: if the vibration absorber effect is present, it does not mean that the interface load will be low!
  - High quasi-static loading can come from supporting structure



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