Thermomechanical Fragmentation Model

James Beck, Ian Holbrough; Belstead Research
Tobias Lips, Bent Fritsche; HTG
Eddy Constant; R.Tech
Alan Flinton, Fluid Gravity Engineering
ESA Clean Space Days, Noordwijk, October 8-11th 2024
PR00070/D22

Thermomechanical Fragmentation Model

- Objectives
  - Construct a thermomechanical fragmentation model for large structures
- Knowledge
  - Some ideas / models for bottom-up fragmentation (joint failures)
  - Some testing of spacecraft joints
  - Is there a gap to large scale fragmentation (modules / appendages)?
- ESA Activity
  - HTG (lead, SCARAB)
  - BRL (modelling, SAMj)
  - FGE (CFD, test planning)
  - R.Tech (FEM, PAMPERO)
  - IRS (Testing)
- This presentation covers the modelling

Three Separate Aspects

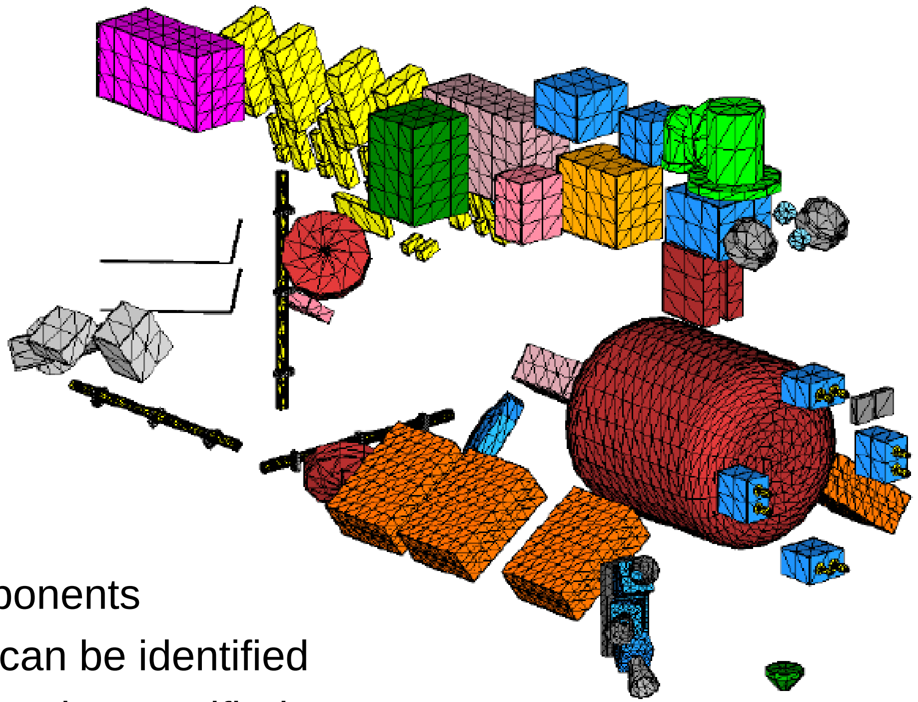
- Underlying Thermomechanical Physics Model
  - Heating (already done by tools), Forces (tentatively done by tools)
  - Major part of development work
- Model of Spacecraft Parts which Can Fragment
  - How do the critical parts need to be modelled?
  - How good can the guidelines be?
  - Separate from the physical model in the tools (but not really independent)
- Fragmentation Criteria to Determine Separation
  - When does the thermomechanical state indicate fragmentation?
  - How are these assigned?
    - Bookwork values?
    - Test data? (Will include phenomena such as strain effects)
    - Implicit through flight observation data?

Generic Schematic of Model

Context	Physical Model	Break-up Criteria	Results
Spacecraft model Components Joints Position Velocity Orientation Rotation	Component Forces (aero) Joint Forces Component Forces (total)	Comparison against thresholds Genesis model for components	Joint Failure Component Failure Genesis
Provided by Tools	Calculated by Model	Critical Value Data	For Tools to Generate Fragments

INPUTS → … → OUTPUT

Inputs



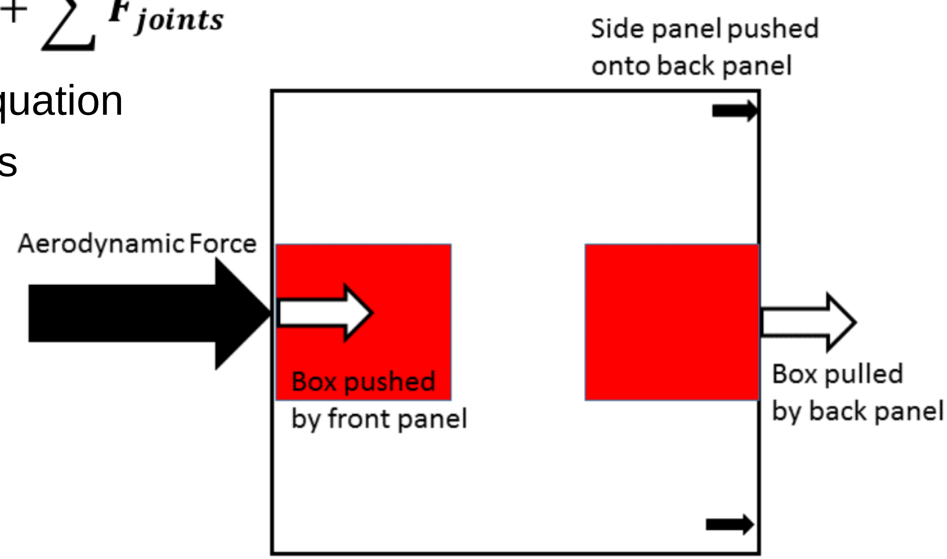
- Spacecraft Model
  - Component-joint
    - Description as components
    - Joined by joints
  - Panel-based conversion needed
    - Group panels into components
    - Joints are virtual
      - Connect exactly two components
  - Components (primitive collections) can be identified
  - Locations of joint connections need to be specified
- Trajectory Data
  - Position, velocity, orientation, rotation rate
    - Inherently 6dof data required
    - Orientation of force/moment important
    - Rotation of spacecraft important

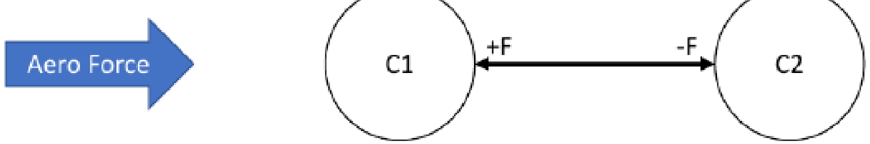
Model

- Acceleration of vehicle is known
  - Net acceleration of all objects is known (rigid body)
  - Acceleration from aerodynamics of each component is known
    - Non-zero only for components in flow
    - Other force must be transmitted through the joints
    - For each component

$$m\boldsymbol{a} = \boldsymbol{F}_{aero} + \boldsymbol{F}_{centrifugal} + \sum \boldsymbol{F}_{joints}$$

    - As rigid body, one redundant equation
    - n-1 equations for n-1 joint forces





Belstead

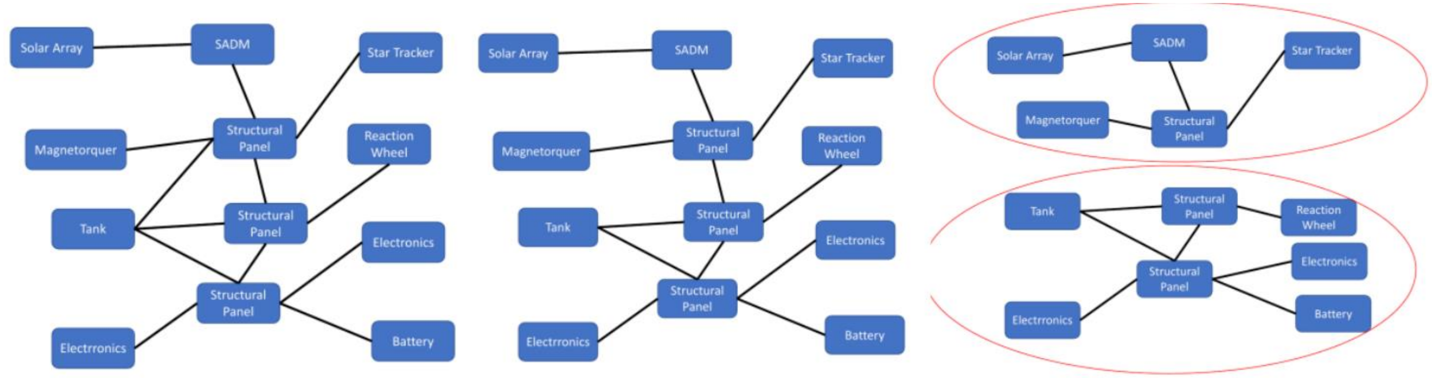
Solution

- Network Structure
  - More joints than equations – multiple solutions
  - Singular Value Decomposition method proposed $Ax = b$
    - x is unknown joint forces
    - b is known component forces
    - A is a matrix which defines which joints are linked to which components

$A_{ij} = 0$ if joint j is does not connect component i

$A_{ij} = 1$ if joint j has component i designated as 'component 1'

$A_{ij} = -1$ if joint j has component i designated as 'component 2'



Moments

- Originally derived directly from local forces

$$M_j = \sum r \; x \; f$$

- Action-at-a-distance inadequate
  - Require impact across spacecraft (as obtained for forces via SVD method)
  - Use SVD approach
- Write similar equation for moments
  - $I\ddot{\theta} = M_{aero} + \sum M_{joints}$

    $$ma = F_{aero} + F_{centrifugal} + \sum F_{joints}$$

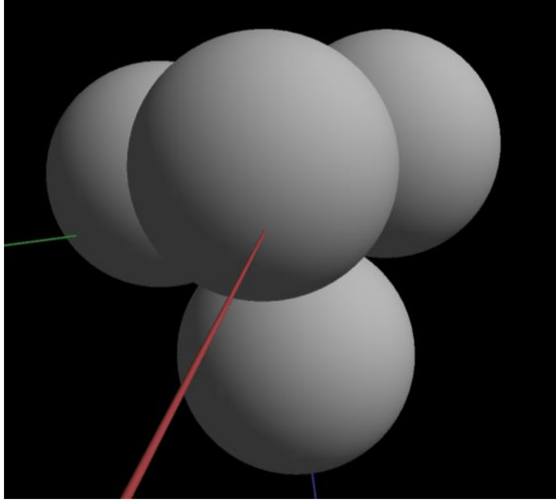
    - Note moments are around spacecraft Cg
  - Use SVD similarly to calculate moments in joints (about Cg)
  - Move moment reference centre to joint location
    - $M_j = M_{cg} + rxF$
  - Captures required effects

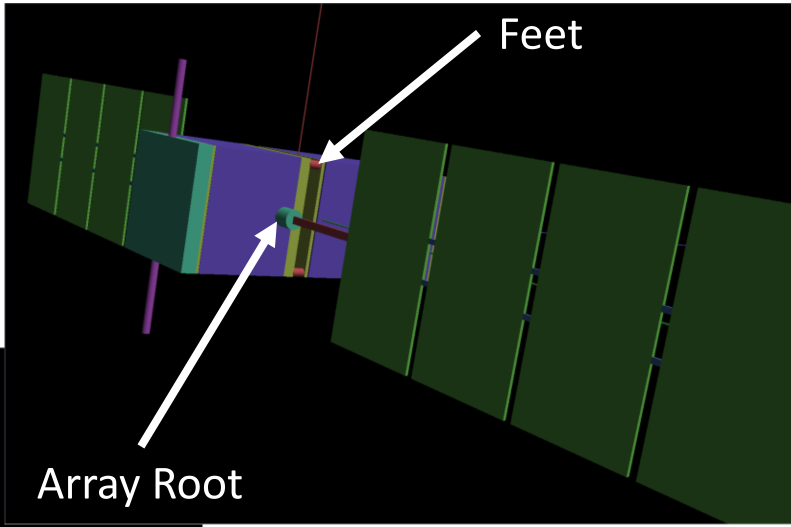
Fragmentation Events

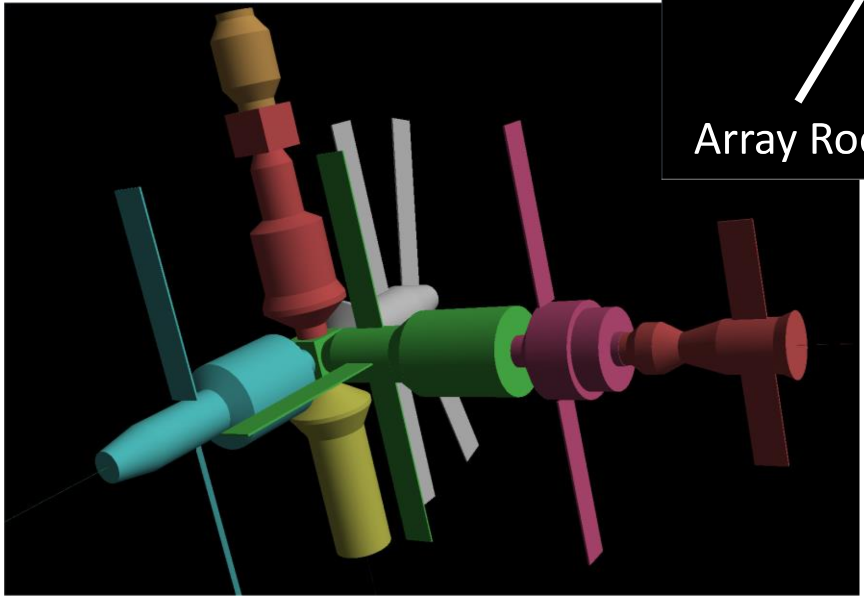
Failure Thresholds	Type	Note
Temperature	Joint	Failure on reaching a fixed temperature
Temperature / time	Joint	Failure once the threshold temperature has been exceeded for a specified time
Mass loss	Component	Failure on fractional mass loss of a component Allows fragmentation before complete demise
Tension	Joint Component	Failure at a given tensile stress Joints expected to be stronger in compression
Tension / temperature	Joint Component	Failure at a given tensile stress at the current temperature
Tension / temperature / time	Joint Component	Failure at a given tensile stress at the current temperature on condition that a fixed temperature has been exceeded for sufficient time
Absolute force	Joint Component	Failure at a given total stress
Absolute force / temperature	Joint Component	Failure at a given total stress at the current temperature
Absolute force / temperature / time	Joint Component	Failure at a given total stress at the current temperature on condition that a fixed temperature has been exceeded for sufficient time
Shear	Joint	Failure at a given shear stress
Shear / temperature	Joint	Failure at a given shear stress at the current temperature
Shear / temperature / time	Joint	Failure at a given shear stress at the current temperature on condition that a fixed temperature has been exceeded for sufficient time
Bending moment	Joint	Failure at a given bending moment
Bending moment / temperature	Joint	Failure at a given bending moment at the current temperature
Bending moment / temperature / time	Joint	Failure at a given bending moment at the current temperature on condition that a fixed temperature has been exceeded for sufficient time
Torsion	Joint	Failure at a given torsion
Torsion / temperature	Joint	Failure at a given torsion at the current temperature
Torsion / temperature / time	Joint	Failure at a given torsion at the current temperature on condition that a fixed temperature has been exceeded for sufficient time

Three Application Test Cases

- Application Test Cases
  - Tetrahedron
    - Simple case to compare forces/moments
  - JASON
    - Array root (moment)
    - Feet (compression)
  - MIR
    - Array-module
    - Module-module

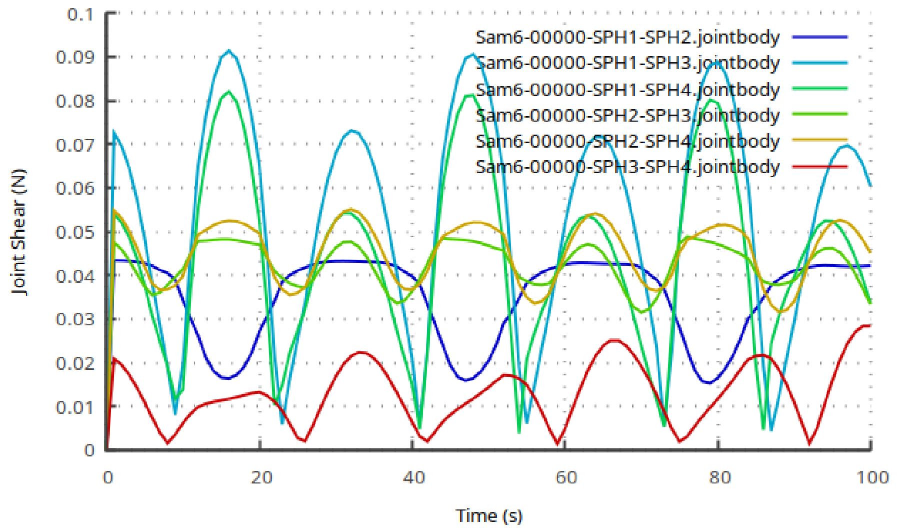


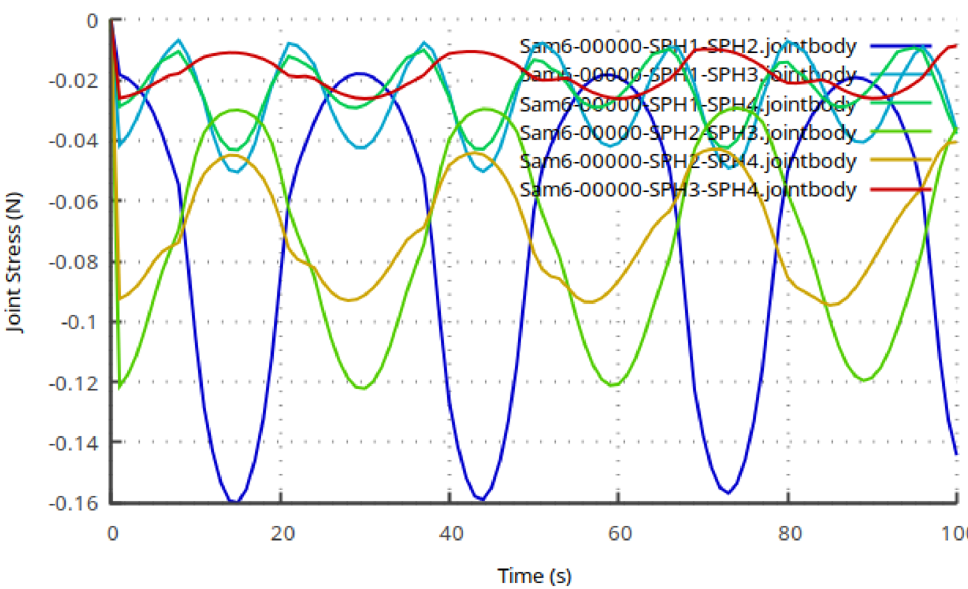


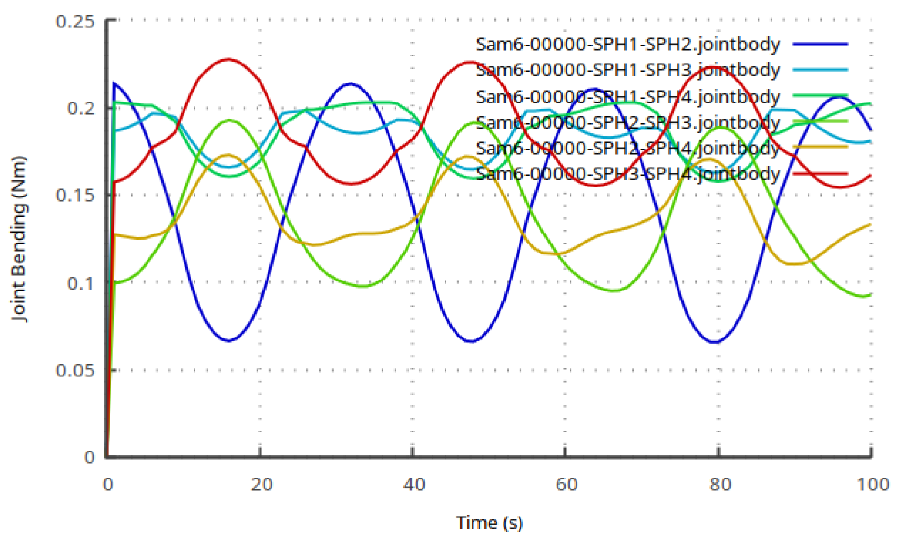


Tetrahedron Case

- Tensile force
- Shear force
- Bending moment
- Results good (Codes comparison)

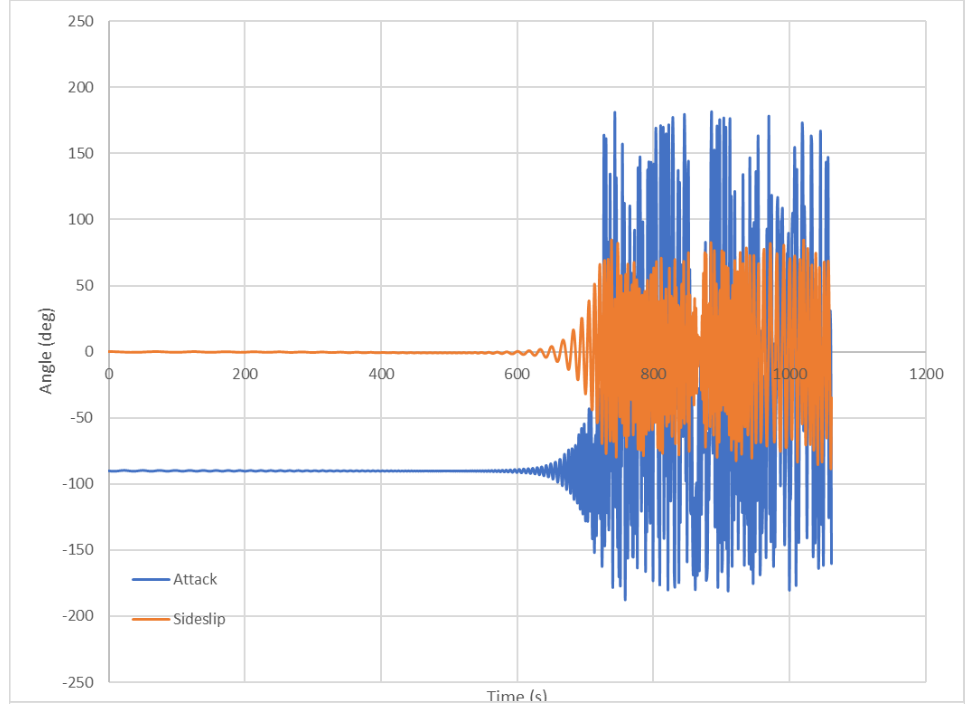


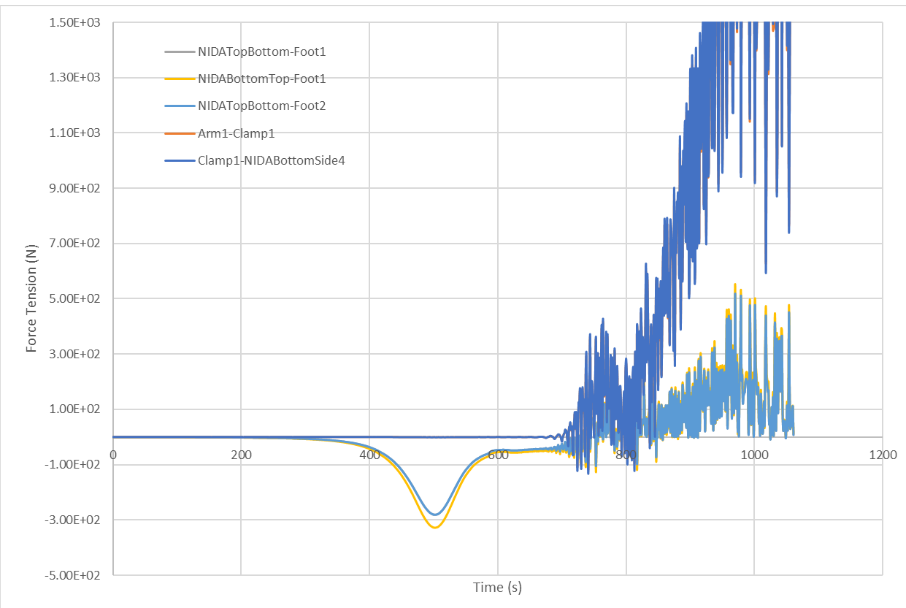


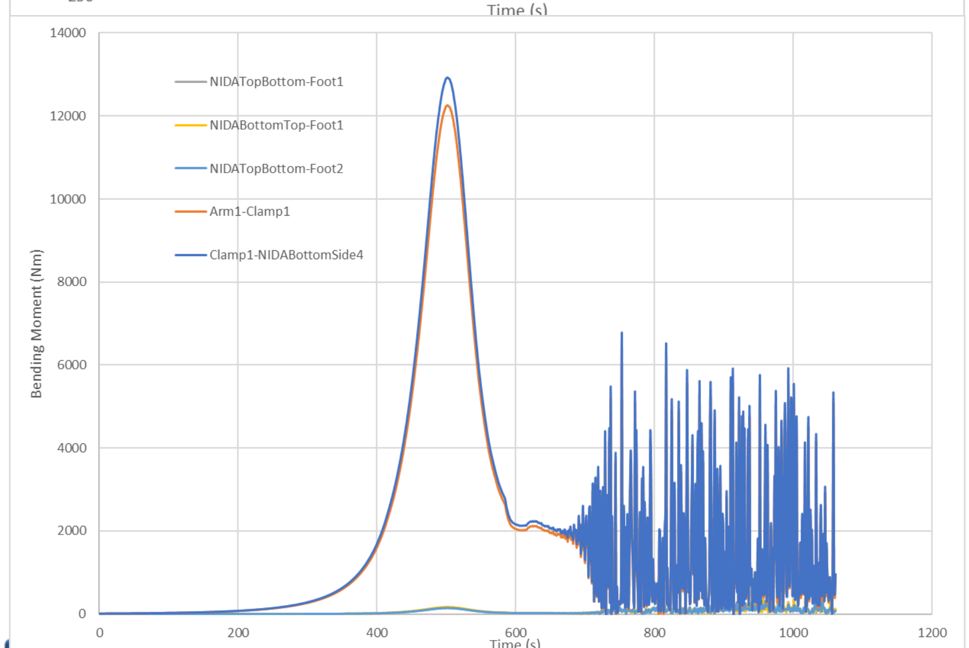


JASON

- Motion is Stable
  - Very heavy launch adaptor leading
  - Peak dynamic pressure ~500s
    - ~60km
  - Feet compressed
  - Large bending moment on array

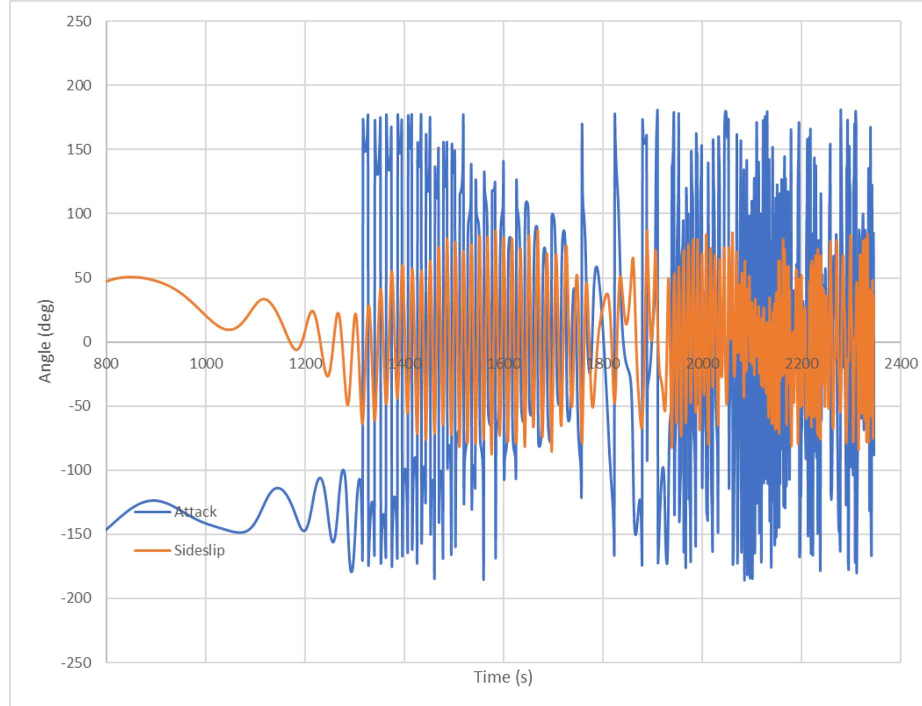


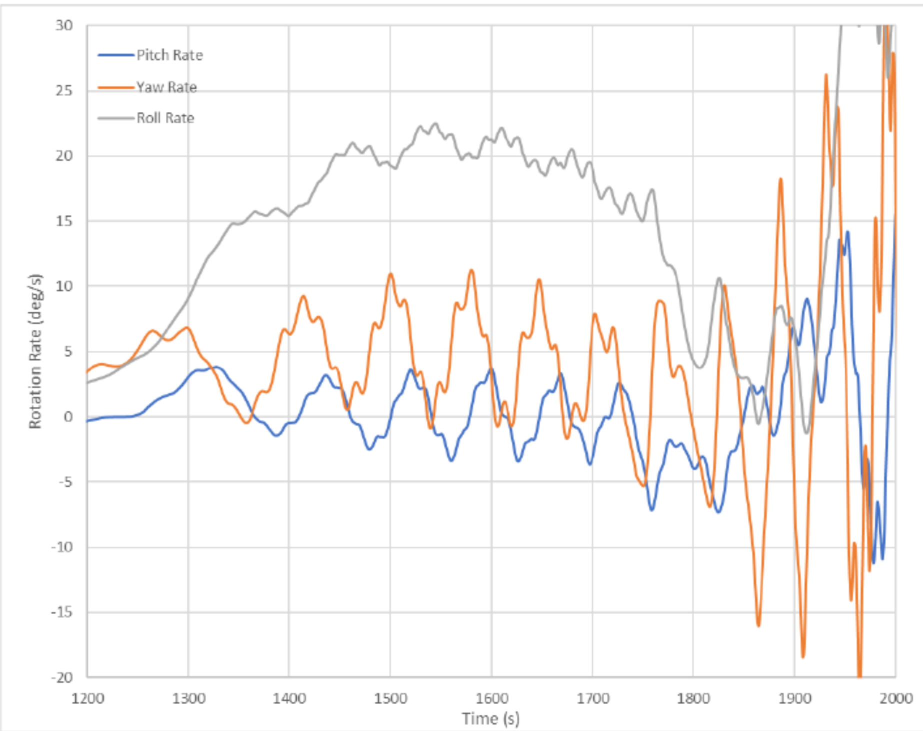


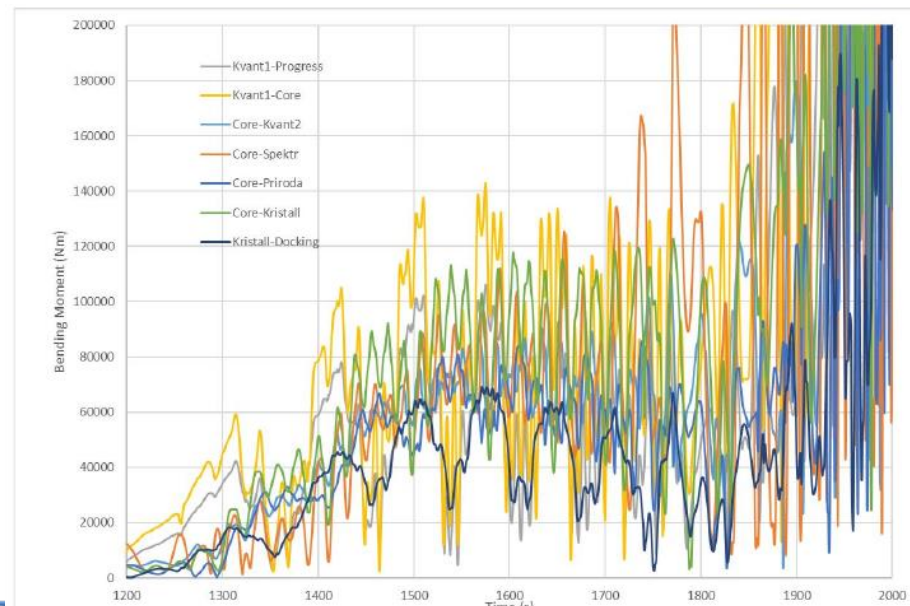


MIR

- Stable to ~95km
  - Tumbling through peak dynamic pressure ~40km (very late)
- Moments depend on rotation







Fragmentation Criteria

- Extremely Difficult to Assess
  - No clear extraction from test data
  - Bookwork values do not provide immediate answer
  - Very dependent on nature of model
- First order assessment inferred from MIR observation data
  - Reasonable solutions obtained
  - Very high uncertainties (at least an order of magnitude)
- Phenomenology not understood
  - Influence of local hot spots?
  - Which part of the structure actually fails?
  - Observation data current best guess

Summary

- Component based fragmentation model devised
  - Applicable to panel based tools
- Force/moment calculations based on rigid body motion
  - Good first order approximation
- Implementation successful
  - Across all tools
- Fragmentation criteria
  - High uncertainty
  - Use of bookwork strength values does not seem to be appropriate
  - Observation correlation current approach