Joint Fragmentation; Phenomena Testing and Assessment

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Motivation

- Spacecraft Fragmentation
  - Vital aspect of Design-for-Demise
  - General agreement that early component release reduces ground casualty risk
  - Subsystem demise from given altitude requirement in many CleanSat studies
- Importance of Joints/Fasteners
  - Weak points; mechanically, and often thermally
  - Intuitive expectation that fragmentation occurs at weak points
    - Basis of unique SAM fragmentation model
    - No (previous) data to support/deny this assertion

Outline

- Selected Joints
  - Sandwich material adhesive
    - Initial main structural failure
  - Insert potting material
    - Equipment release
  - Bolts and brackets
    - Subsystems release
    - Possible thermal stress effects
- Test Conditions
  - Assessment of expected forces in re-entry
    - Rapid force increase at about 80km
  - Assessment of expected temperature rise rates in re-entry

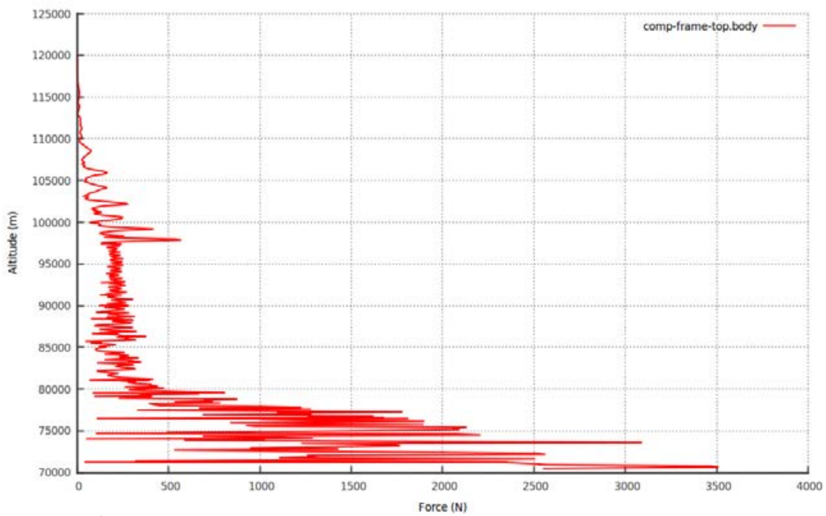
Atmospheric Conditions

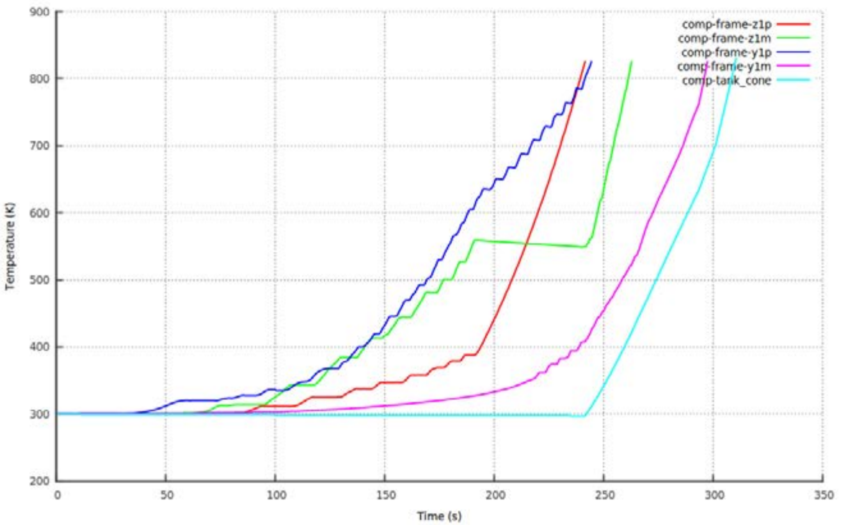
- Interest is in failure above 70km, higher is better
  - For well-mixed region up to about 120km, US76 is good
  - Speed reduction is small until 80km due to low density
  - For a 7.8km/s entry:

Altitude (km)	Density (kg/m^3)	Dynamic Pressure (Pa)	Max. Surface Pressure (Pa)
100	5.6e-7	17	34
95	1.4e-6	43	86
90	3.4e-6	100	200
85	8.2e-6	250	500
80	1.8e-5	550	1100
75	4.0e-5	1200	2400
70	8.3e-5	2500	5000

Re-entry Conditions

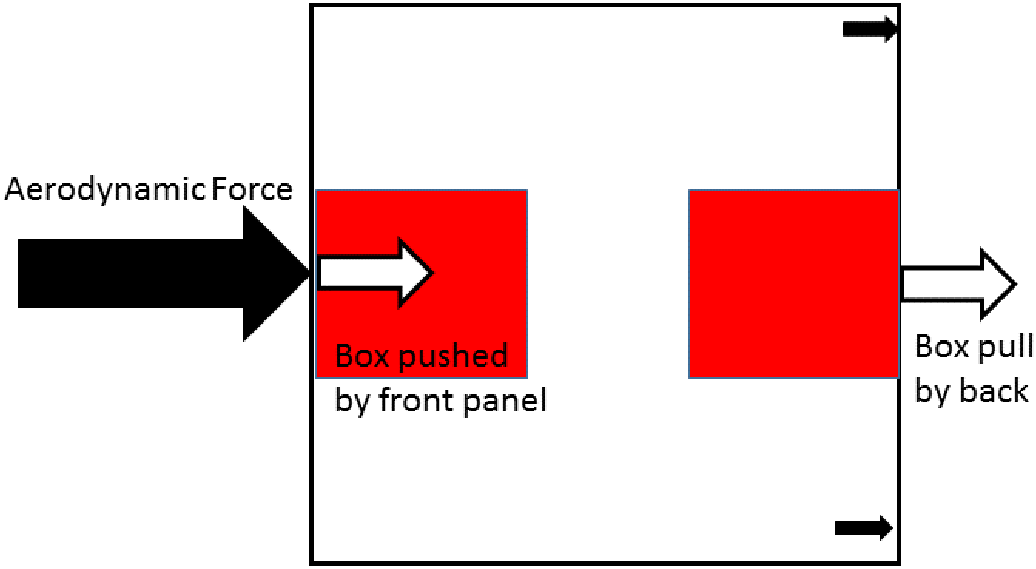
- Forces are Low
  - Tens of Newtons interesting
  - Rapid increase after 80km
  - Catastrophic break-up assumption usually 78km
- Temperatures are Reasonably High
  - Temperature rise is ~200-400C/min





Force Assessment

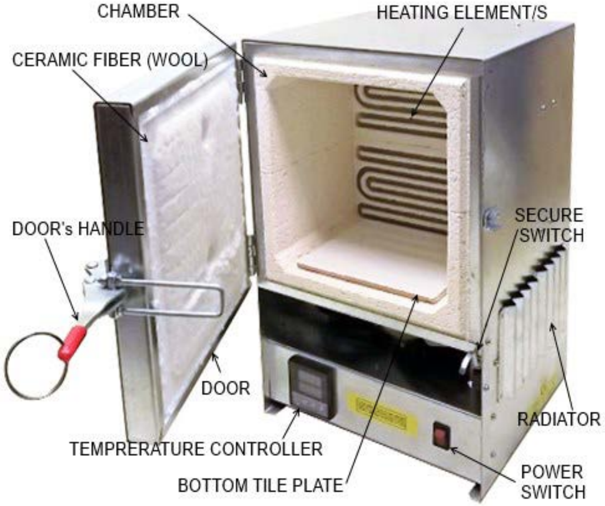
- Forces are Mainly Compressive
  - Spin rates are relatively slow (tens of degrees/sec)
  - Heating occurs where aerodynamic force applies
  - Heated parts usually compressed
    - Guaranteed separation on melt?



Test Campaign

- Initial Phenomenology
  - Epoxy behaviour
  - Test set-up
- Facesheet Testing
  - Peel tests
  - Shear tests
- Insert Testing
  - Pull tests
  - Screws included in inserts
- Bolt/Bracket Testing

Brazing Torch



Home Kiln

Phenomenology Tests

- Epoxy Material
  - Initial discolouration to light straw colour at 200-220^{0}C
  - Darkening by 270^{0}C
  - Bubbling and outgassing evident at 270^{0}C
  - Gassing complete by 400^{0}C
  - Pyrolysis gases did not self-ignite, but could be lit by direct application of the torch flame

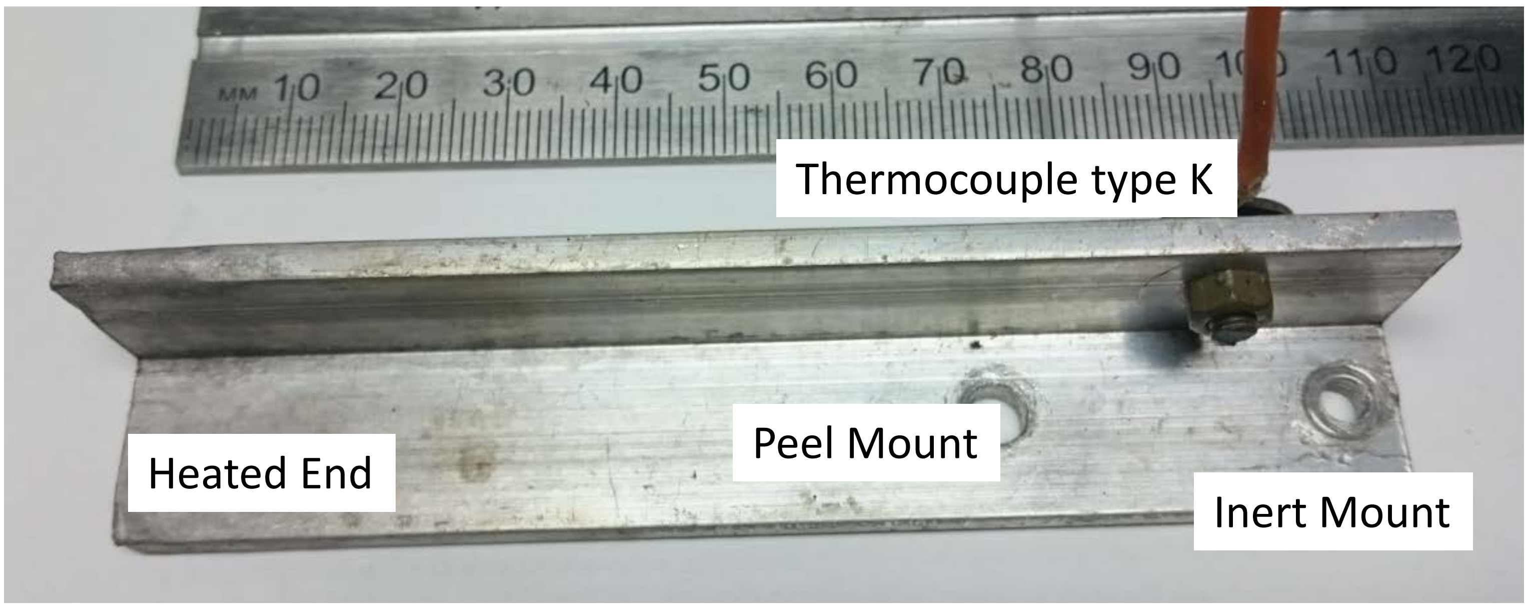
336^{0}C discoloration evident; conduction slow

438^{0}C large outgassing

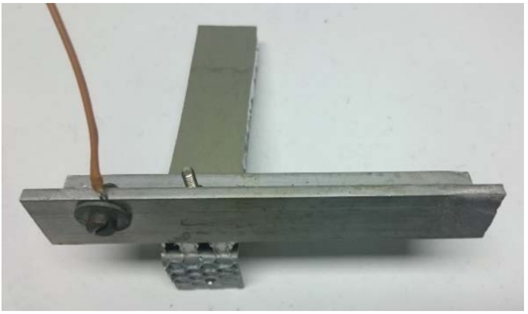
478^{0}C blackened insert

Heatsink Setup

- Use of heatsink allows controlled tests
  - No contact with torch flame
  - Consistent heating of area of interest

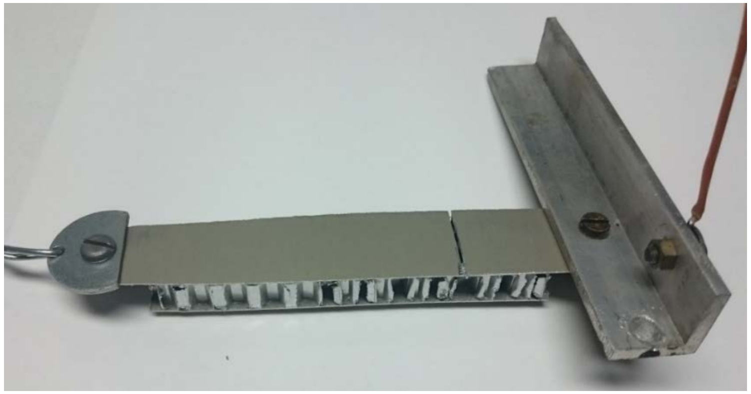


Facesheet Tests



- Peel Tests
  - 2cm thick cut samples (aluminium skin)
  - Top side heated, force on lower side
  - Catastrophic unzip of facesheet
  - Failure at low loads (50-150N) and low temperatures (180-230C)
  - Cold side failures at lower loads indicates conduction
  - Highly likely failure regime

Facesheet Tests



- Shear Tests
  - 2cm thick cut samples, 2cm length
  - CFRP more resistant than Al
  - Some debond at cold side
    - CFRP fails at front and back (?radiation)
  - Direct heat gives fast fail; little epoxy reaction
  - Gradual heating gives clear epoxy colour gradients; heat soaks

Sandwich Panel Failure

- Possible Modes

Heating of skin

Thermal Barrier
(Glue melt + air gap)
↓
Skin failure promoted
↓
Honeycomb failure
(conduction path to glue)
↓
Inner Skin Failure

Most Likely Process?
Failure is closer to panel level

No Thermal Barrier
(Conduction to honeycomb)
↓
Panel failure delayed
↓
Hole forms in complete panel

Slowest Process
Does Panel Release?

Immediate Skin Failure
(Release glue melt + force)
↓
Honeycomb failure/ stiffness loss / bending failure
↓
Inner Skin Failure

Fastest Process
Unbolted section of panel?
Cut skin?

Sandwich Panel Failure

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Thermal Barrier (Glue melt + air gap)
→ Skin failure promoted
→ Honeycomb failure (conduction path to glue)
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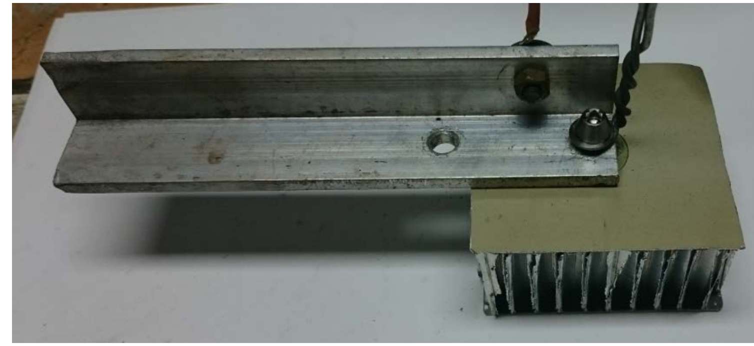
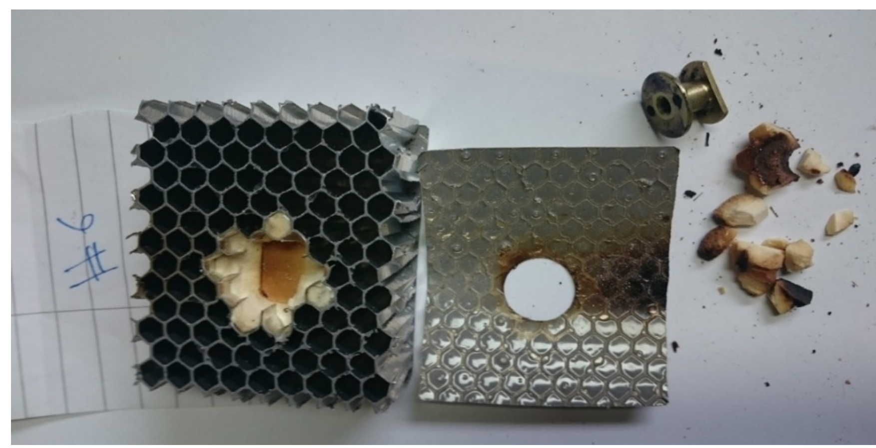
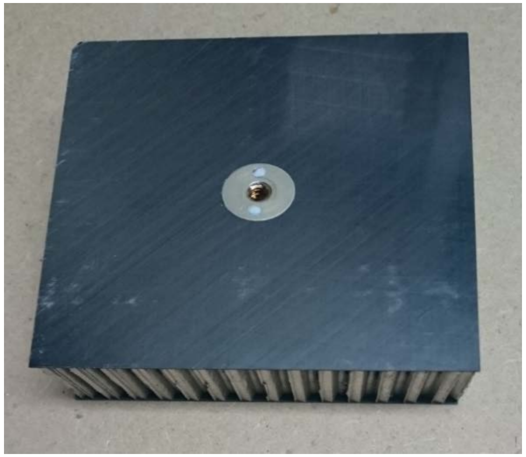
Insert Tests



- Pull Tests
  - Aluminium skinned samples
  - Heat soak time into epoxy required
  - Heat to 400C, then maintain temperature
  - Loose in ~1 minute, but delayed release to ~4 minutes
  - Larger load can pull off front skin as well



Insert Tests



- Pull Tests
  - CFRP skinned samples
  - Heat soak time into epoxy required
  - Heat to 400C, then maintain temperature
  - Pull out directly after 45s
  - Damage to CFRP evident around holes (thermal stress/bending)

Sandwich Insert Failure

- Possible Modes

Heating of Insert

Conduction to Glue → Pull out of insert (Force based)

Fastest Process
Insert installation to promote pull out?

Conduction to Glue → Residual stickiness/snag (Forces too low) → Delayed pull out

Most Likely Process
Required Force/Delay Time?

No conduction → Insert does not fail → Failure at panel melt

Slowest Process
Realistic?

Sandwich Insert Failure

- Possible Modes

Heating of Insert

Conduction to Glue

Pull out of insert
(Force based)

Fastest Process
Insert installation to
promote pull out?

Conduction to Glue

Residual stickiness/snag
(Forces too low)

Delayed pull out

Most Likely Process
Required Force/Delay Time?

No conduction

Insert does not fail

Failure at panel melt

Slowest Process
Realistic?

Bolt/Bracket Tests

- Aluminium Bracket/Titanium Bolt
  - Bolts torqued
  - Oven used at fixed temperature
  - Bolts loosened substantially (~350C)
  - Damage seen on threads
  - Damage seen on brackets
  - Thermal stresses are high
  - Dynamic environment
    - Loose bolt -> high load
    - Fast damage and fail
    - No melting will be required
    - Hot, dynamic testing required

Bolt/Bracket Failure

- Possible Modes

Heating of Bolt/bracket

Path 1:

CTE compatible
Low Thermal Stress
↓
Strength dominates
Reduces with Temperature
↓
Failure at low strength
Before lower melt point

Most Likely Process?
Required CTE difference?
How far before melt?

Path 2:

Lower CTE compatibility
Higher Thermal Stress
↓
Sufficient stress to either
Damage bracket or
Break bolt
↓
Failure CTE driven

Fastest Process
Analysis suggests possibility

Path 3:

CTE compatible
Low Thermal stress
↓
Strength dominates
Retained to melt point
of bracket
↓
Failure at melt

Slowest Process
Realistic?

Bolt/Bracket Failure

- Possible Modes

Heating of Bolt/bracket

CTE compatible
Low Thermal Stress

↓

Strength dominates
Reduces with Temperature

↓

Failure at low strength
Before lower melt point

Most Likely Process?
Required CTE difference?
How far before melt?

Lower CTE compatibility
Higher Thermal Stress

↓

Sufficient stress to either
Damage bracket

↓

Loose bolt has high
dynamic forces

↓

Failure CTE driven

Fastest Process
Analysis suggests possibility

CTE compatible
Low Thermal stress

↓

Strength dominates
Retained to melt point
of bracket

↓

Failure at melt

Slowest Process
Realistic?

Final Phenomenology Tests

- Direct Application of Heat to Sandwich
  - High heat fluxes
  - No forces applied – all failures under own weight
- Sequential Failure
  - Facesheet collapse (~6-10s for aluminium)
    - Final part becomes oxidised and falls when glue fails
  - Honeycomb collapse
  - CFRP is much more robust than aluminium
    - Slower heating oxidises honeycomb; gains heat resistance
    - Pyrolysis gases burn for 30s – sample intact after flame stop
    - Failure at about 2 minutes

Final Phenomenology Tests

- Aluminium

- CFRP

Fragmentation Concepts

- Spacecraft Fragmentation modes
  - VAST/VASP worldview
    - Panels/components reach (relatively) high temperature
    - Mechanical force increases as altitude decreases
    - Resultant catastrophic breakup
    - Occurs at point that forces are sufficient
  - Gradual fragmentation worldview
    - (Almost) all failures are purely thermal and occur as the components reach melt
- Tests support breakup in narrow altitude zone
  - Weakening temperatures are low relative to (aluminium) melt
  - Even bolts/brackets can be expected to fail >350-400C

Design Implication

- Panel failure expected at panel level
  - Facesheet peel removes stiffness, panel will bend especially with equipment mass attached
  - Shielding of internal components will be different
- Below TBD (~78km?) Forces expected to Fail Joints
  - Melt model is not appropriate
  - Work on shielding / late item release below TBD (~70km?) questionable
- Promotion of High Altitude Failures
  - Current design based on melt driven failure
    - Temperature / force balance to be established – no certainty
    - Note forces are mainly compressive; separation is issue
  - Suggests use of preloads which are small, but enough when hot

Next Steps

- Testing Work
  - Understanding of Force/Temperature/Separation
  - Thermal stress effects
  - Improved quantification from detailed measurements required
  - Understanding of ‘Chain of Failures’
    - How do failures induce other failures?
    - Stiffness loss / Bending / thermal stress
- Modelling Work
  - *Equivalent Phenomenology* Modelling Required
    - Equivalent material shown to be insufficient (eg. CFRP)
  - Construct force/temperature failure criteria based on data
  - Modelling rooted in real test data, and extended
  - Capture ‘chain of failures’