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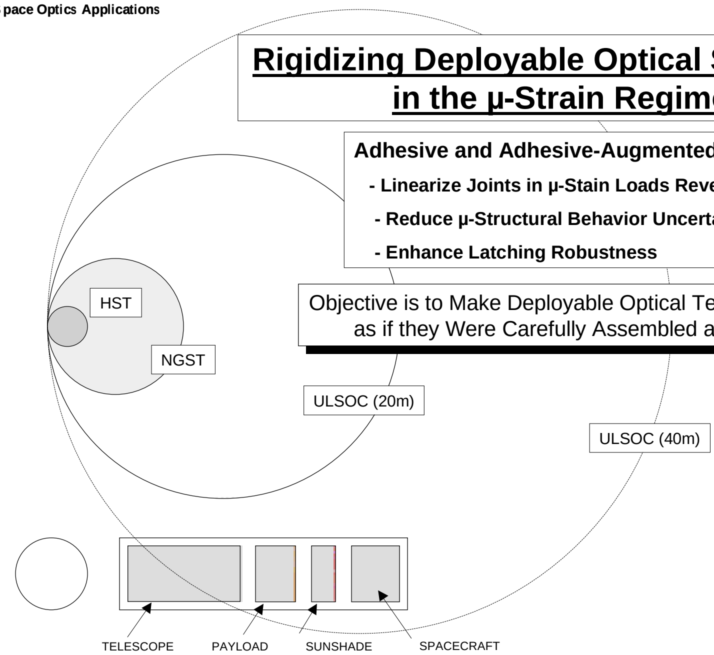
Rigidizing Deployable Optical Structures in the μ-Strain Regime

Adhesive and Adhesive-Augmented Latches to :

- **Linearize Joints in μ-Stain Loads Reversal Regime**
- **Reduce μ-Structural Behavior Uncertainties**
- **Enhance Latching Robustness**

Objective is to Make Deployable Optical Telescopes Behave as if they Were Carefully Assembled at the Factory



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Overview of the Concept

Erecting or deploying 20 to 40m-class optical telescopes from a stowed configuration that fits within 4 to 5m diameter and possibly 10m long launcher-defined payload volumes challenge designers to find ways to lock them together without introducing unacceptable levels of flexibility or positional instability. This paper describes an emerging concept where dry film, heat activated adhesives or two-part epoxies are used to make these connections, replacing and/or augmenting mechanical latches or other mechanism-related approaches. A plan for developing and characterizing these joints in the small-strain or micro-dynamics regime is presented.

The title, “Rigidizing Deployable Optical Structures” isn’t intended to imply that these structures will be any stiffer than they would be if they weren’t deployable. Rather, it means that the joints and latches needed to implement the deployment and lock-up functions are, conceptually, designed not add flexibility to perhaps an already very flexible structure. Arguably more important, ‘rigidizing’ also means that any incipient looseness associated with vibration and loads reversal and non-repeatible and/or non-linear behavior will be eliminated or minimized in the critically important, to precision optical systems, micro-to-nano strain regime. In other words, the goal is to make the design behave as the designer intended.

This paper is presented as a set of briefing charts which are largely self-explanatory. We begin with a definition of the issues that tend to set precision optical structures apart from ordinary spacecraft structures, particularly in the realm of micro-mechanics and micro-dynamics. A brief summary of those attributes which are desireable, if not mandatory, to make the deployed telescope behave as if it were carefully assembled in the factory is presented. We then describe several different classes of joints that might be employed in the design of a a large deployable optical telescope and how they approach these the objectives. One conclusion reached is that if the telescope was a factory assembled monolith, its construction would employ adhesive bonded continuous joints as opposed to a pinned and bolted design or an integrally machined jpintless unit. These approaches are perhaps best exemplified by the 5m long x 2.8m Hubble Secondary Mirror Truss and the all-beryllium ITTT/SIRTFcryogenic telescope. Like edges, joints are an anathema to deployable optical systems.

The question was whether we could devise a way to “glue” the deployed components together in space and achieve what we might in the factory. Several approaches to accomplishing this for different classes of joints are illustrated here and it appears that this idea, to 1’st order, is feasible, meriting further study and evaluation. We show that the bond-line proportions for a ‘glued in space’ joint will not degrade stiffness. Loads transfer is accomplished over a broader area than is practical with mechanical joints, thus precluding local flexibility in the surrounding local structural areas. We also show that the tight tolerances required to ensure that a ‘system’ of latches separated by possibly meters of structural path length do indeed fully engage are relaxed with this approach.

Finally a suggested plan for bringing the idea from a paper stage to a series of proof-of-principle experiments is presented.

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"….like edges, joints are an anathema to deployable optical systems." *anon*

Why? Because they are potential sources for performance degradation and/or uncertainty in the optically important micro-strain and micro-dynamics regime!

They:

- add more flexibility to potentially already very flexible systems
- have uncertain and sometimes non-repeatable micro-vibration transmission characteristics
- may exhibit non-recoverable deformations and multiple small-strain equilibrium states
- may have non-linear and non-repeatable small-strain stiffness and damping characteristics
- …. and thereby complicate any feed-back control systems
- are hard to account for analytically at the overall OTA level
- and in general, are poor substitutes for careful factory assembly

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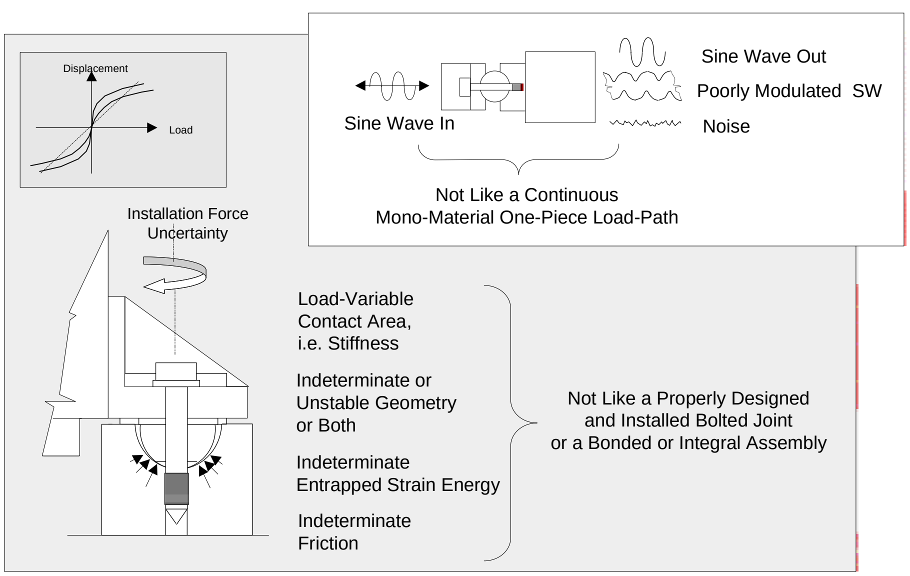
Some Micro-Mechanical Concerns with Mechanical Latches, When 0.01 μm is Important



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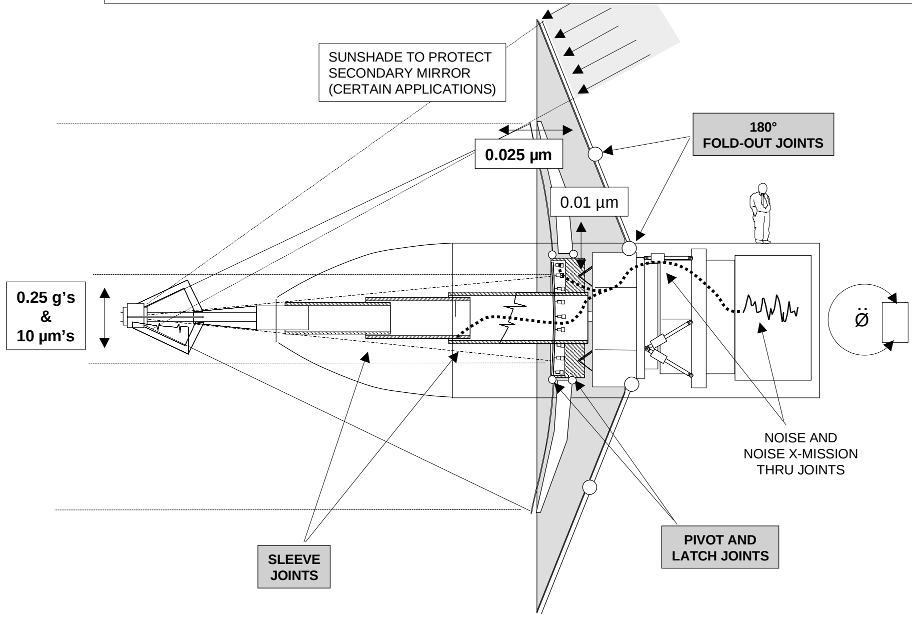
Three Classes of Joints & Why 10 nm is Mechanically Important

(Shown for a Generic 12m Telescope)



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Three Classes of Joints….cont'd

- **Fastening a <u>Secondary Mirror</u> Support Tower Together**
  - Distributed Structure, Therefore Continuous Joints Desirable
    - re. Structural Efficiency
  - Subject to Significant Lateral Loads During Repointing
    - Can be a Major Image Jitter and LoS Error Source
      - FSM and/or Active Damping
  - As Little as <u>0.01mm</u> Hysteresis Can Exceed WF Requirement
    - Rapid Error Sensing & Correction Req'd, Some Applications
  - An Old Problem Has Gotten Tougher
- **Rotating and Locking Deployable <u>Primary Mirror Segments</u> in Place**
  - Jitter Limits 'otoo' 0.015 λ rms WF or 0.12 λ P-P Tip Displacement
    - Much Tighter than SM Static or Dynamic Tolerances
    - Equivalent to 0.02 λ or <u>0.01µm</u> (0.0000004") motion of latch or pivot region motion
    - Not Correctable with FSM's or Similar Methods
  - A New and Tough Problem
- **Folding Out and Locking <u>Appendage</u> Support Struts**
  - Looseness to be Avoided re. CS Feedback

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In View of the Foregoing, Here Are

Some Attributes of a Desirable 0-g Deployable Joint

- **Predictable and Repeatable μ-Dynamics and μ-Mechanical Behavior**
  - Smooth Strain Flow and Structural Continuity
    - Minimize Additional Flexibility & 'Elastic Hinging"
      - In the Latches, In the Local Strain Diffusion Structural Path
  - Linear Elastic Small-Strain Properties
  - Minimal Entrapped Strain Energy
    - Avoidance of Multiple Equilibrium States
- **CTE Continuity**
  - A 'sometimes' problem with in-loadpath mechanisms
- **Testable at 1-g**
  - No differences in 0-g
- **Other Design Considerations:**
  - Harness and Cabling Compatibility
  - Assured Latching
  - Weight
  - Number of Parts
  - Temperature
  - Launch Survivability where Applicable
  - etc.
- **Should Have Characteristics of a Factory-Assembled Monolith**

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Which Leads Us to Bonded Deployable Connections,

An Emerging Concept

- Primary Loadpaths Where:
  - adequate shear area is available
  - loads are relatively low
  - configurations are compatible with good bonding geometry
- Parallel or Secondary Loadpaths Where:
  - bondline is primarily to eliminate potential looseness
  - geometry is not well suited to good bonding practice
    - partial loss of bondline integrity is tolerable
    - rigidizing a journal pivot, for example
- Provides Solutions to Some Applications, Not All

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Adhesive Options Under Consideration

Two-Part Epoxies	Gap Filler for Journal Pivots Plus Other …...
Heat-Activated Dry Film Adhesives	Lap Shear Applications
Solvent-Activated Dry Adhesives	??….aka postage stamps….Contamination
Pressure-Activated Tacky Adhesives	Handling and Application Problems…aka duct tape
Single Part Adhesives	B-Staged Epoxy, for example…..Shelf-Life Limited

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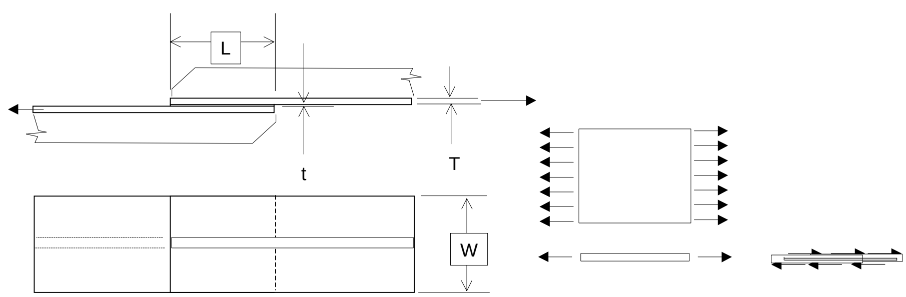
Bondline Itself Does Not Add Flexibility…..



Kb = WLG / t

Km = WTE / L

For Equal Stiffness,
t " L^2 G / E T

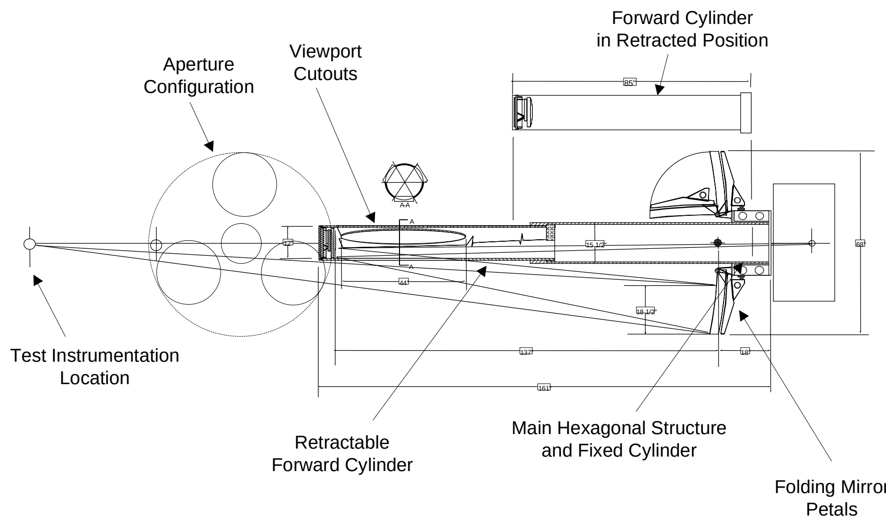
Adhesive stiffness equal to or greater than the material it replaces, if proportioned properly

L = 1in
G adhesive = 0.1Mpsi
E adherend = 12 Mpsi
T = 0.1 in"

t " 0.08 in.

Some Bonded Connection Application Examples

Stowable SM for a Proof-of-Concept Jitter-Defeating Experimental Telescope



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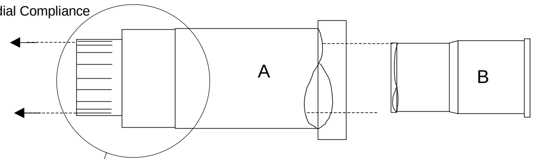
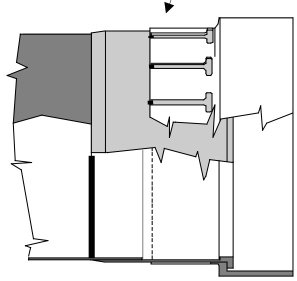
Initial Concept for Sleeve Joint

Slotted for
Radial Compliance





In Principle, Overtly Simple:

- Excellent Structural Continuity
- Deterministic CTE Continuity
- Compact

But…..:

- Impractically Tight Tolerances for Large Diameters Even With Slotted Skirt
  - Leading to High Variability Bonding Pressure
  - And Therefore Poor Bonding Conditions

Led to the Broad-Tolerance "Glue-Shoe" Design

- (next chart)

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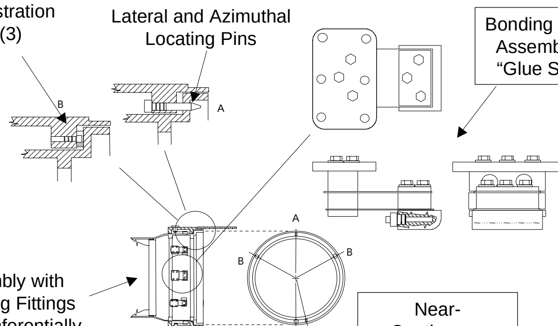
Anatomy of the Joint , and the "Glue Shoe"

Axial Registration
Lands (3)

Lateral and Azimuthal
Locating Pins

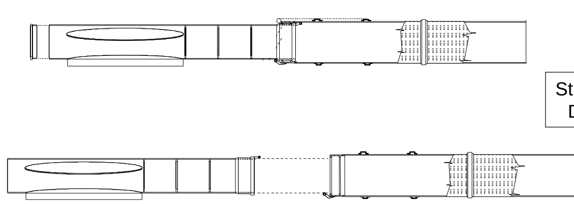
Bonding Fitting
Assembly or
"Glue Shoe"

Position
Determinancy
Provisions



Joint Assembly with
Eight Bonding Fittings
at 45° Circumferentially

Near-
Continuous
Loads Transfer



Structure with Cable
Deployment Drive

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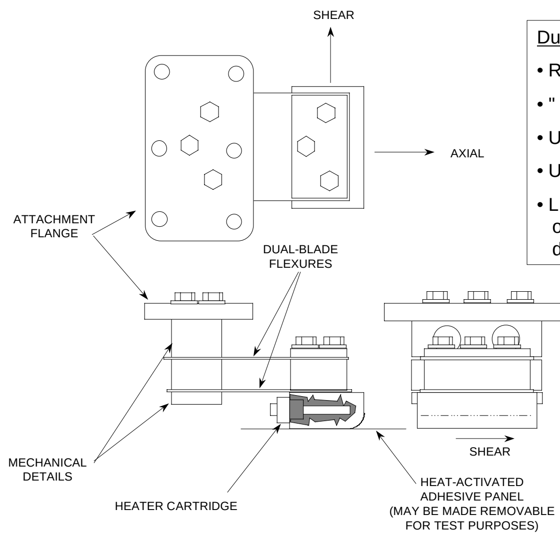
The "Glue Shoe" Concept



Dual Flexures Provide:

- Radial Translation with No Rotation
- " 15 psi clamping pressure for cure
- Uniformity of pressure over shoe area
- Uniform bond-line thickness
- Liberal tolerances between inner and outer joint halves over 'large' diameters

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Joint Design Characteristics,
for a Specific Example

Flexure Length and Width	1" x 1"
Thickness	0.02"
Material	Titanium
Axial Stiffness	5.1Mp/in
E x MoI	228 M lb in^2
E x MoI without Joint	244 M lb in^2
Bending Frequency with Joint	10.22 Hz
Bending Frequency without Joint	10.30 Hz
Clamping Pressure	13 lbs (nearly 1 atmosphere, typical bonding condition)
Flexure Offset	0.05"
Flexure Stress	97,000 psi (OK for Titanium)
Activation Temperature (typical)	____ °C
Power Required	____Watts for ____ Minutes
Softening Temperature	____°C

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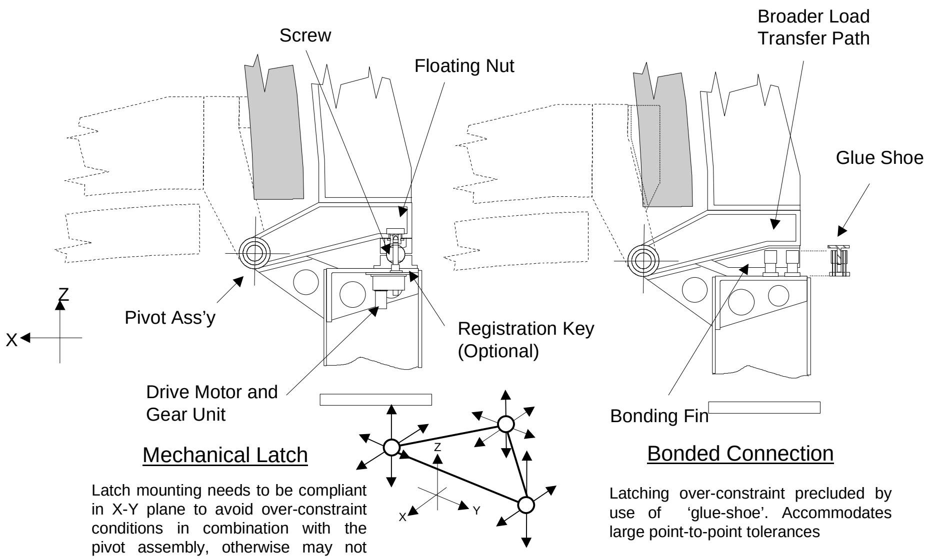
‘Glue Shoe’ Applied to Pivot and Latch Joint



Mechanical Latch

Latch mounting needs to be compliant in X-Y plane to avoid over-constraint conditions in combination with the pivot assembly, otherwise may not fully seat. Details not shown.

Bonded Connection

Latching over-constraint precluded by use of ‘glue-shoe’. Accommodates large point-to-point tolerances

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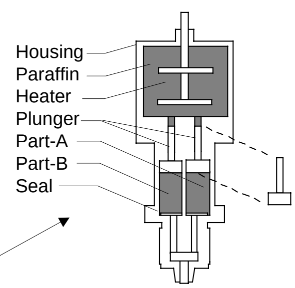
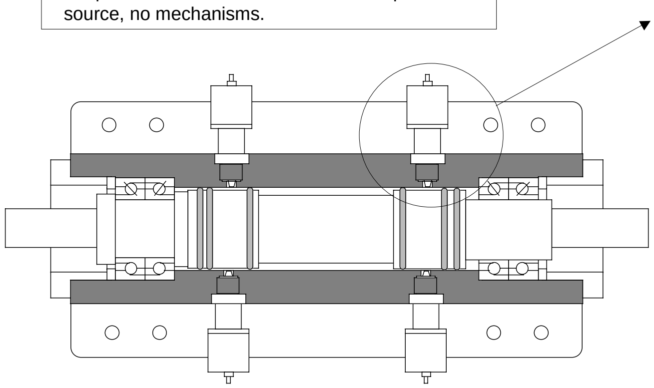
Rigidizing the ° Pivot
Sealed Two-Part Adhesive Cartridge

- Largely Tolerance Insensitive
- Unlimited shelf life in vacuum
- Accommodates various adhesive types for different applications
- Built-in mixing chamber
- Simple, automobile radiator thermostat, pressure source, no mechanisms.





Example:
V = 0.75”Ø x 0.75L
?T=100°F
Bore = 0.16”Ø each
Stroke= 0.5 inches
Power= _____

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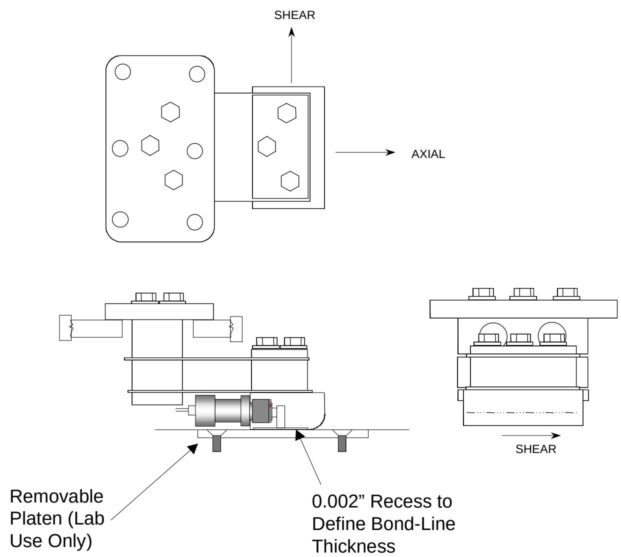
The Adhesive Cartridge Applied to the 'Glue Shoe'



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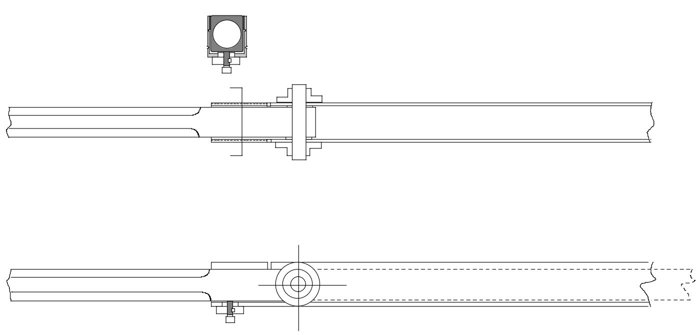
"Carpenter's Ruler" Joint,
Using Heat Activated Dry-Film Adhesive



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Recommended Development Activities

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Heat-Activated Dry Film and Adhesive Cartridge 'Glue-Shoe', Experiments

As-Cured Strength and Shear Stiffness for Candidate Adherends Over a Range of:

- Cure Temperatures and Durations
- BondlineThickness'
- Cure Pressures
- Pre-Cure Vacuum Durations

Determine range of conditions over which the adhesives can for 'factory-like' or at least dependable bonds. Power Req'ts

Measure Outgassing Quantity and Species

- Part of Overall Material Selection Investigation

Verify low cure products and/or effectiveness of edge closures

µ-Dynamics & µ-Mechanics Behavior:

- Micro-Noise Transmission (MMTF) vs. …..
- Damping vs. Frequency vs. Amplitude
- Damping vs. DC Stress Level *aka* 1-g vs. 0-g

Characterize micro- and nano-characteristics of the joints

Engineering Model Joint Assemblies

System Level Applications

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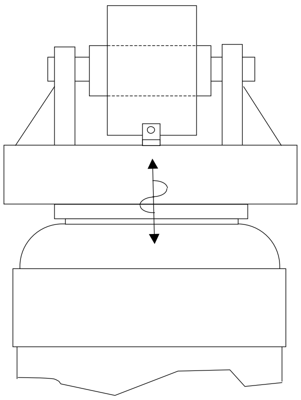
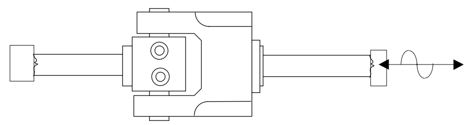
Pivot Rigidizer Experiments





Micro-Dynamics Measurements
Post-Macro Survivability Verification in 'Strut Tester' after Energizing the Adhesive Cartridge(s)

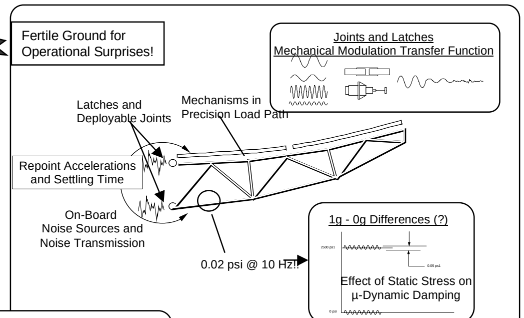
Macro-Dynamics Survivability
Prior to Injecting Adhesive

Raytheon

The "Strut Tester" : Overcoming Superstition with Science in Structures Technology

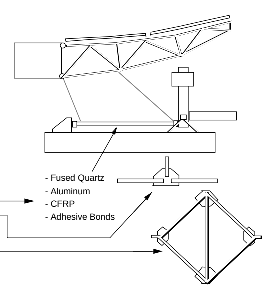
MicroDynamics and Jitter in Large Deployable Telescopes

- Segment Vibration….10X as critical as SM or LoS Jitter which is SoA re. SBL
- Fractional 'psi' stresses…. in Large Structures means Optically Large Displacements
- Mechanisms & Elasticity…Do mechanisms in precision load paths behave as designers expected?
- Testability….will fractional psi strain regime dynamics be the same at 0g as they were at 1g?
- Cryogenics….what dynamics and damping differences between RT and 50K?



MicroDynamics Experiments at Raytheon

In-situ Loading and Boundary Condition Simulations
Damping vs. Amplitude
1g vs. 0g Damping "²'s"
Small Strain Elasticity
Effect of Temperature
Effect of Vacuum (Dryout)
Effectiveness of Damping Augmentation at Nano-Strain Levels, et al
Experiments Include:
Struts of Different Mat's
Struts with Joints
Simple Structures
Mechanisms and Actuators in Load Path



Raytheon Micro-Dynamics Research

- Laboratory Determination of Component-Level Nano-Dynamics Characteristics
- Incorporate into Structural Models, Early
- Avoid Costly Over-Design
- Avoid More Costly Under-Design!
- Improve Confidence in Designs for the Unprecedented NGST conditions
- Increase Certainty in Cost-to-Launch Estimates
- Increase Certainty in Operational Success

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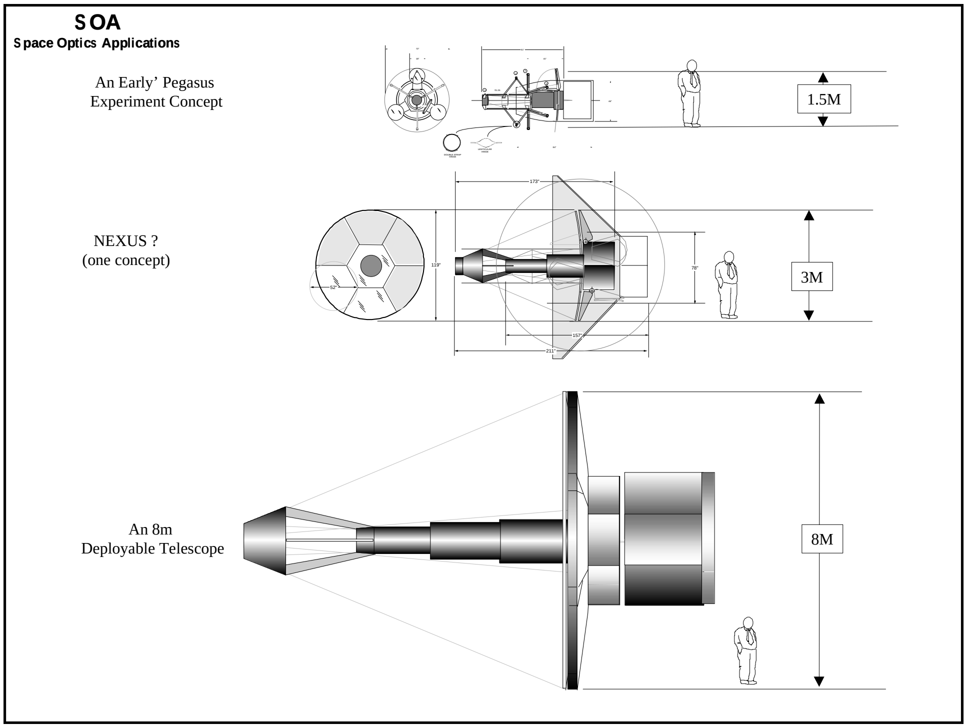
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An Early' Pegasus
Experiment Concept
1.5M
NEXUS ?
(one concept)
3M
An 8m
Deployable Telescope
8M