



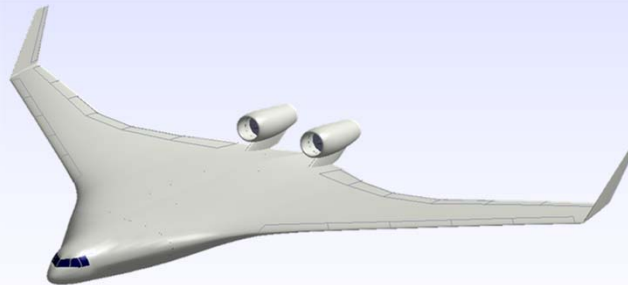
Testing and Analysis of a Composite Non-Cylindrical Aircraft Fuselage Structure Part II: Severe Damage

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Outline

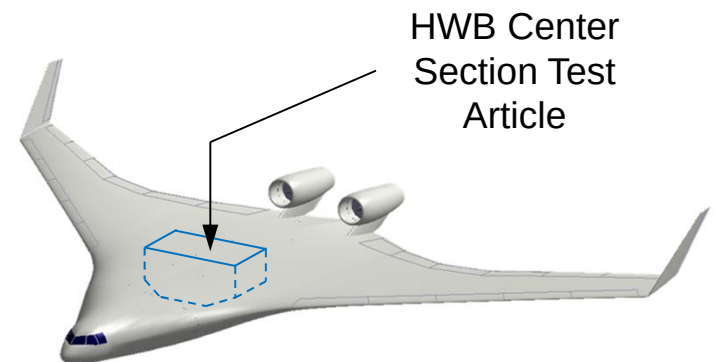
- **Introduction**
- **Pultruded rod stitched efficient unitized structure (PRSEUS) concept**
- **Hybrid wing body (HWB) center section test article**
- **Finite element model (FEM) with discrete source damage**
- **Test article instrumentation**
- **Comparison of test versus finite element analysis (FEA) results**
- **Conclusions**

Introduction – Objectives

- **Environmentally Responsible Aviation (ERA) Project**
 - **NASA and The Boeing Company collaboration on damage arresting composites**
- **10% airframe weight reduction can provide significant reduction in fuel burn and emissions**
- **Incremental improvements to conventional “tube & wing” configuration insufficient to meet the goals**
- **HWB configuration promises significantly improved aircraft performance**
- **HWB requires pressurized composite airframe with nearly flat panels that transfers significant mechanical loads**
- **Explore PRSEUS as the primary structural concept for HWB**

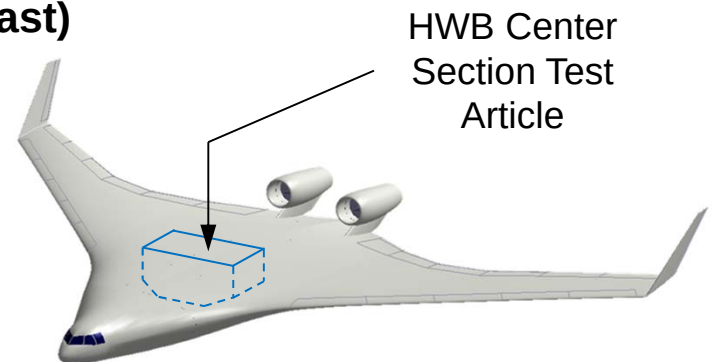
Introduction – Approach (cont'd)

- **Series of building block tests conducted in the past 6 years**
- **An 80%-scaled HWB center section test article built for structural testing under combined pressure and mechanical loads**
- **FEA used to support design**
- **Maturation of the manufacturing process**
- **Data for predictive analysis validation**
- **Ultimate proof of concept**
 - **Technology readiness level (TRL) 5**



Introduction – Approach

- **Testing in the Combined Loads Test System (COLTS) Facility at NASA Langley Research Center (LaRC)**
 - **Five critical load conditions exercised first in pristine and barely visible impact damage (BVID) condition, including mechanical, pressure, and combined mechanical with pressure loads tested up to 150%-165% design limit load (DLL)**
 - **Final test to failure with discrete source damage (DSD) under the wing up-bending load (2.5-g)**
 - **Severed crown panel frame (no compression test with severed frame exercised in the past)**
 - **No pressure load since DSD precludes pressurization**
 - **Demonstrate ability to redistribute and sustain loads of at least 70% DLL**
 - **Demonstrate improved damage tolerance resulting from through-the-thickness stitching**



PRSEUS Concept

- Highly integrated and light-weight (fewer joints)
- Damage tolerant (delamination- and crack-arresting capabilities)
- Cost effective (made of stitched dry fabric preforms, resin infused, no metal inner moldline tools and no autoclave required)

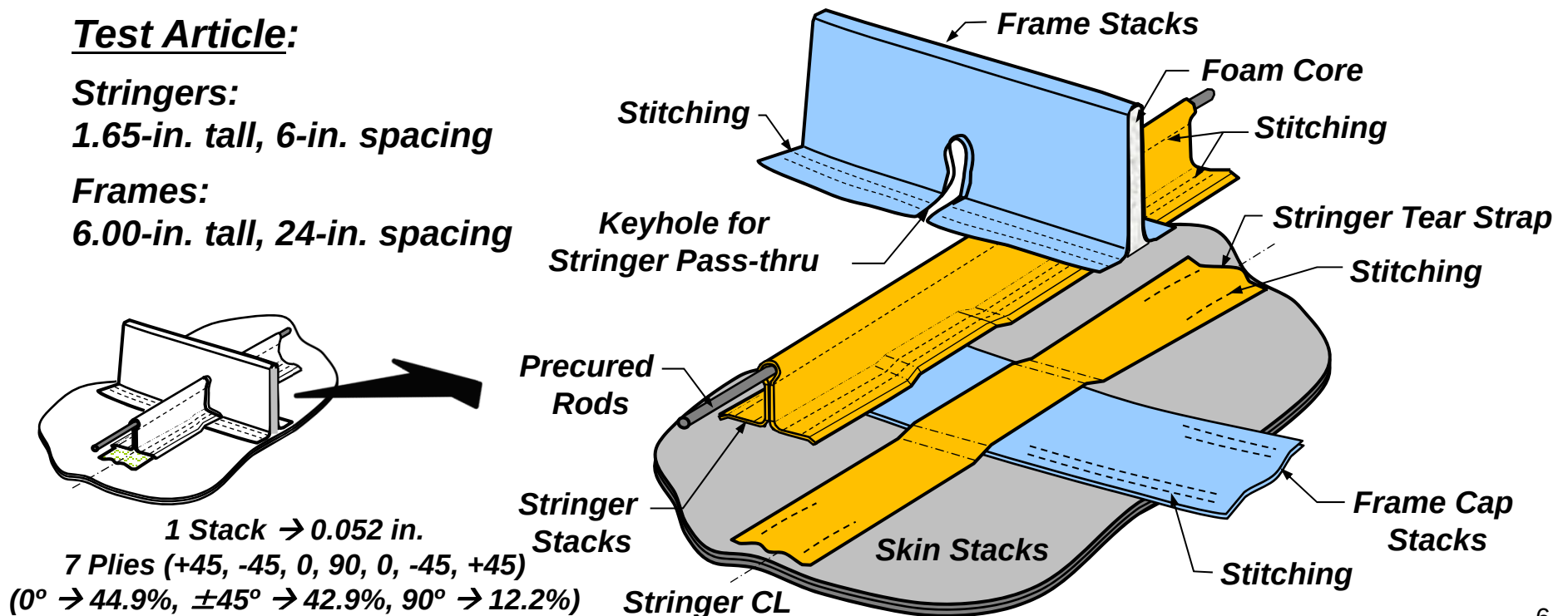
Test Article:

Stringers:

1.65-in. tall, 6-in. spacing

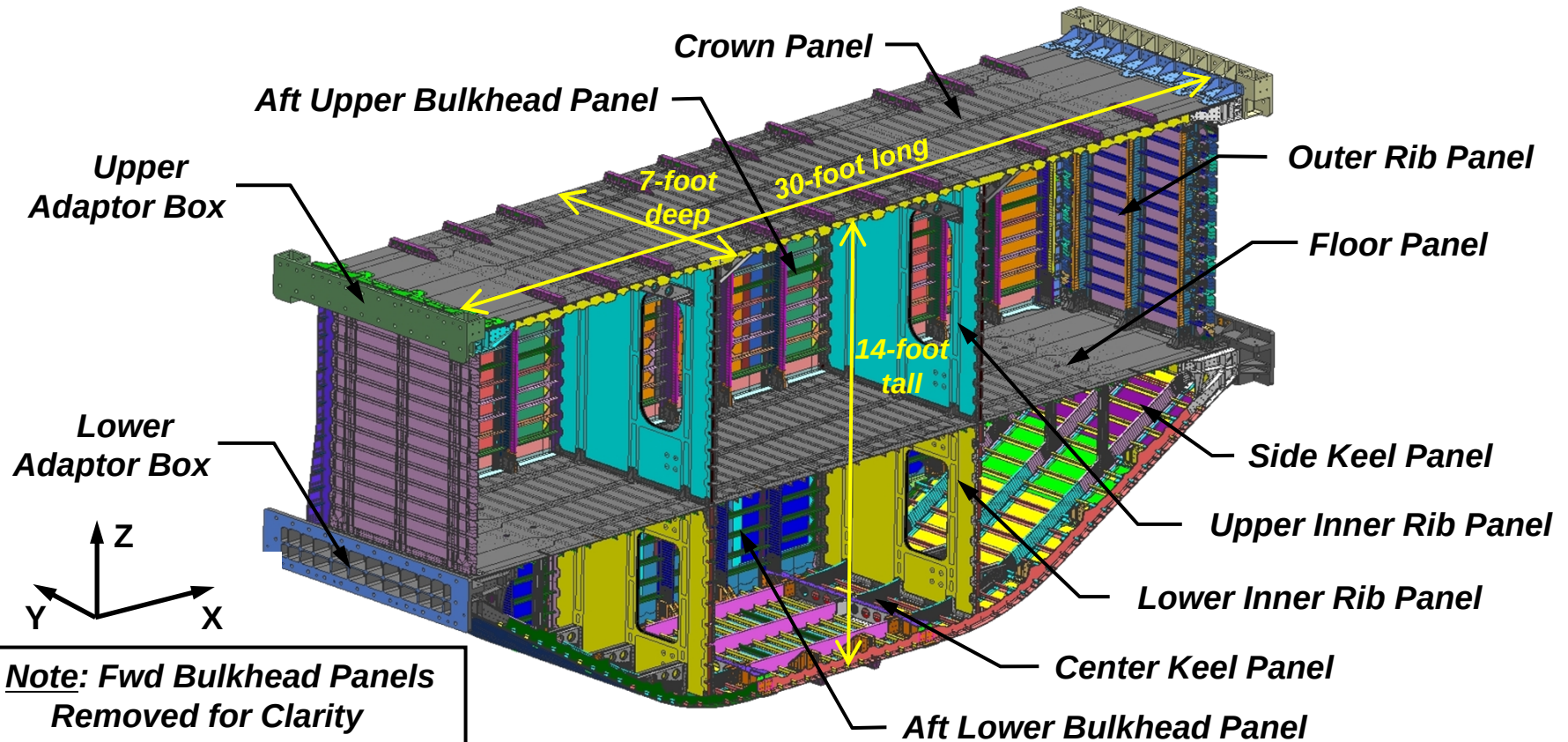
Frames:

6.00-in. tall, 24-in. spacing



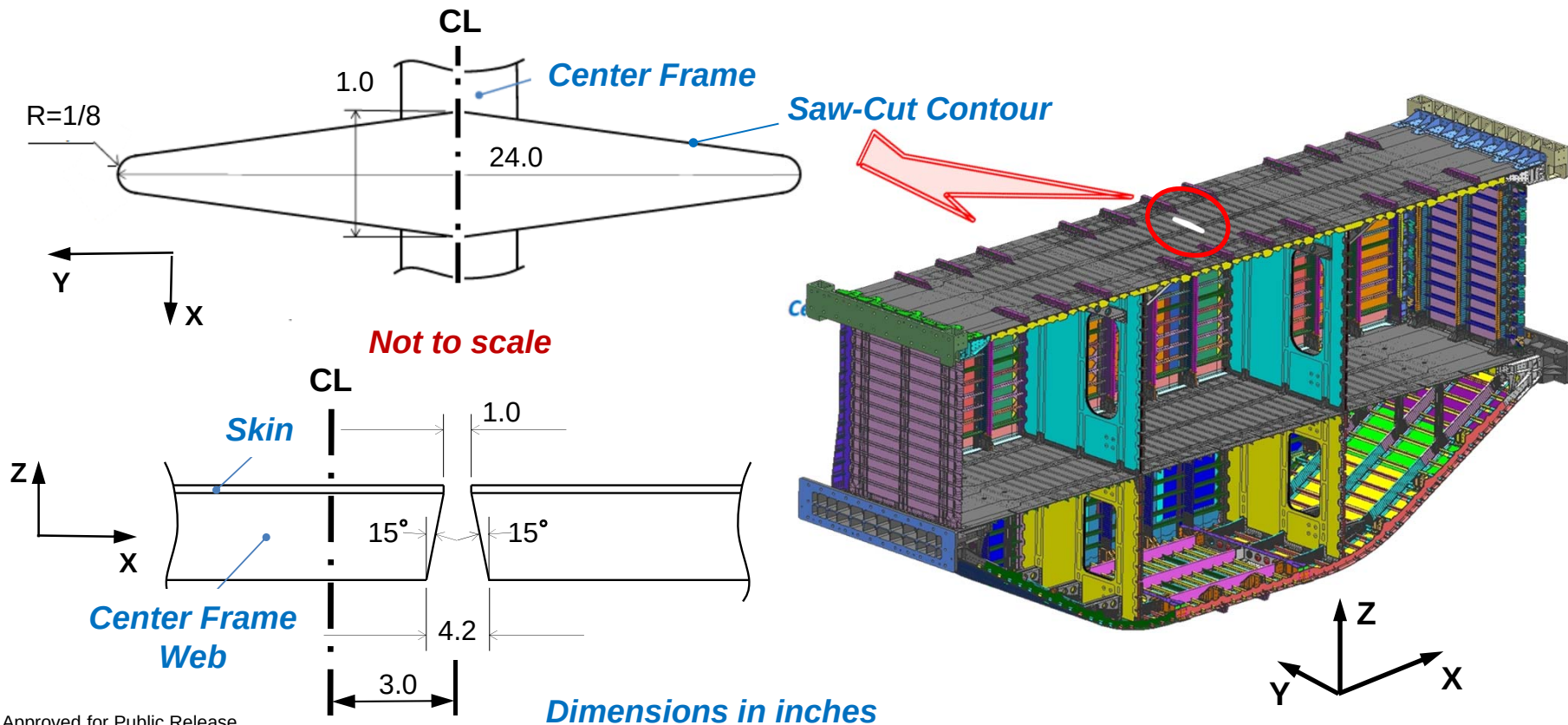
HWB Center Section Test Article

- 11 PRSEUS panels and 4 composite sandwich panels
- Composite panels are joined by metallic fittings and fasteners



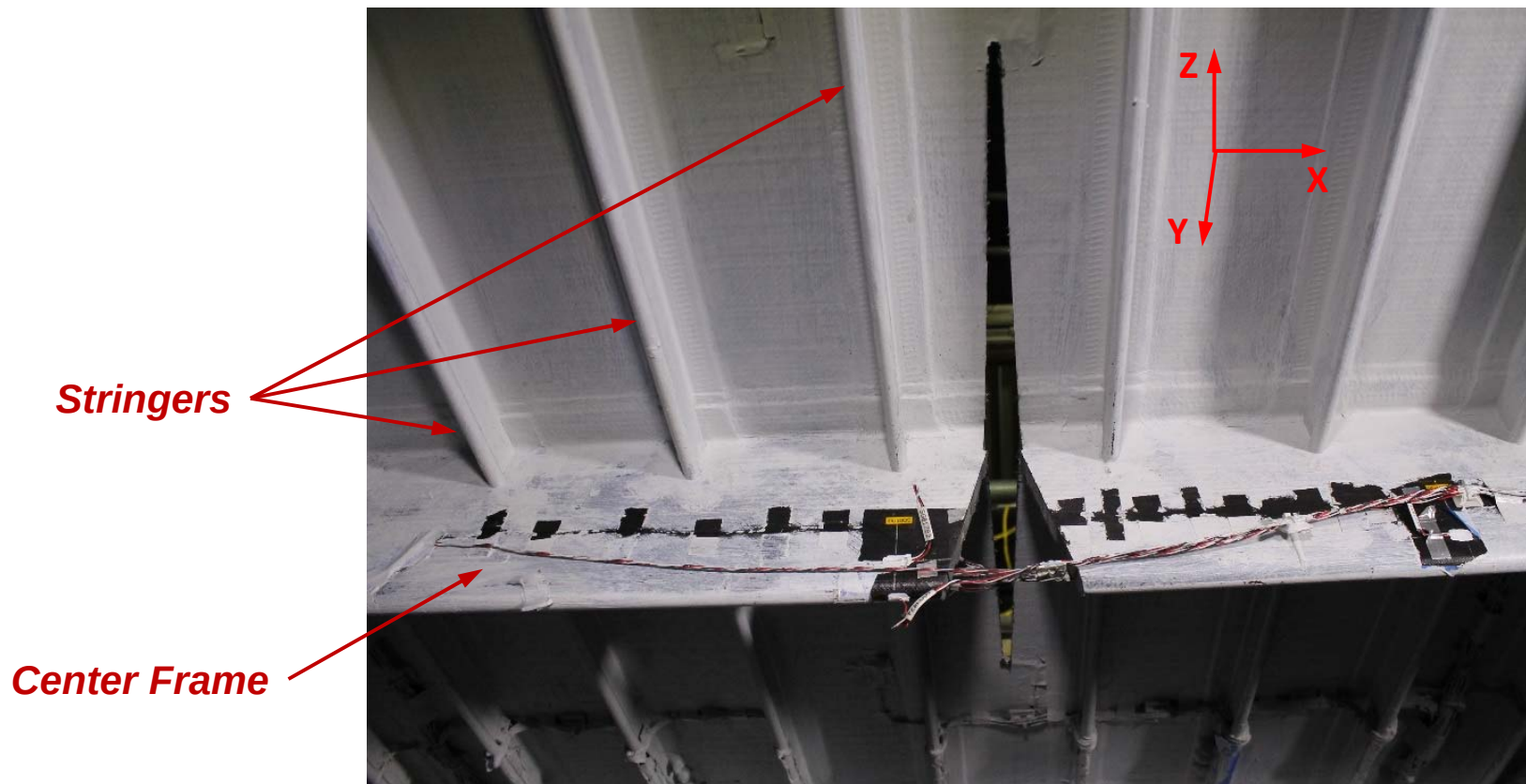
Discrete Source Damage

- Crown panel diamond-shaped cut
- Mid-bay to mid-bay including cutting the center frame
- 3 in. off mid-span centerline (CL)



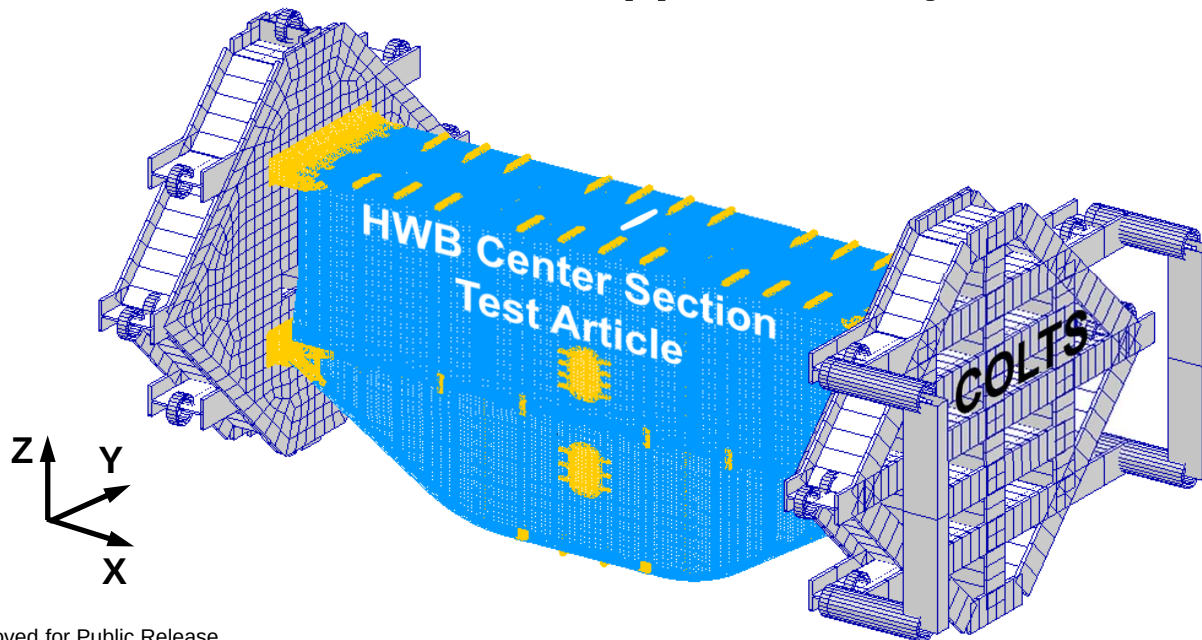
Discrete Source Damage

- View from the inside of the test article



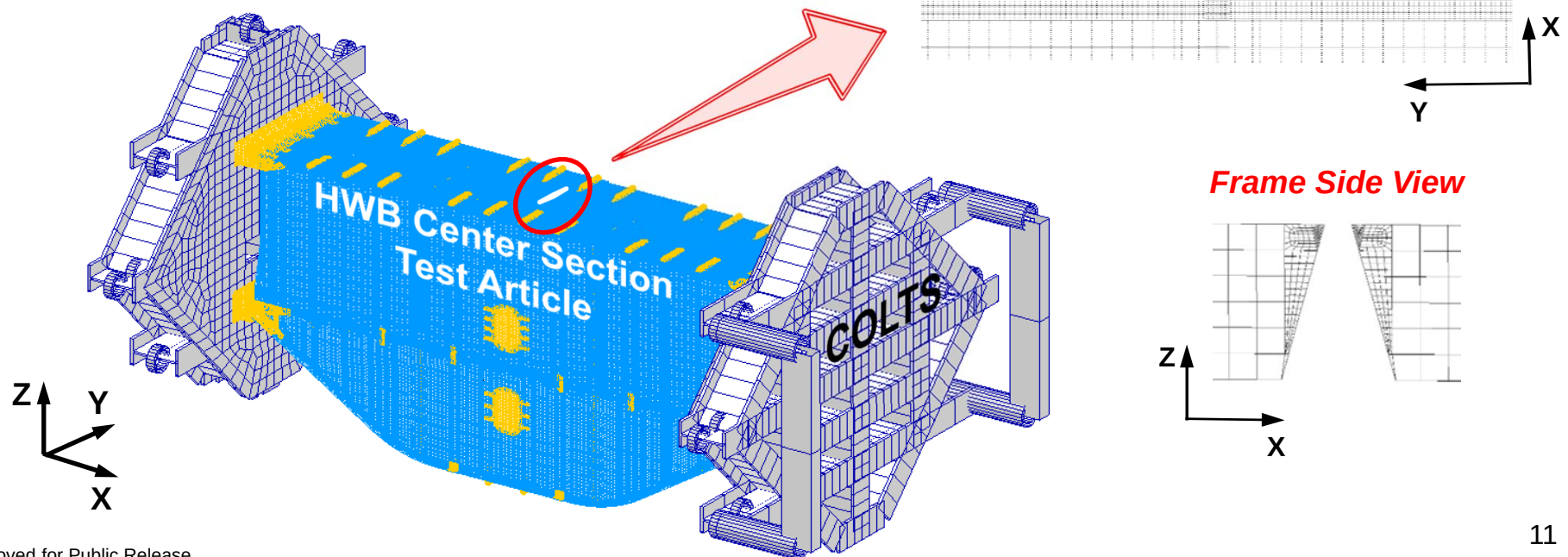
Finite Element Model

- **Element types used in the FEM (MSC.Nastran)**
 - 1-D (bar) elements used for pultruded rods and frame tops
 - 2-D (shell) elements used for composite panels and metallic fittings
 - Fastener (connector) elements used for bolted joints
- **Typical element size approximately 1 in.**
- **Total model size approximately 4.5 million degrees of freedom**



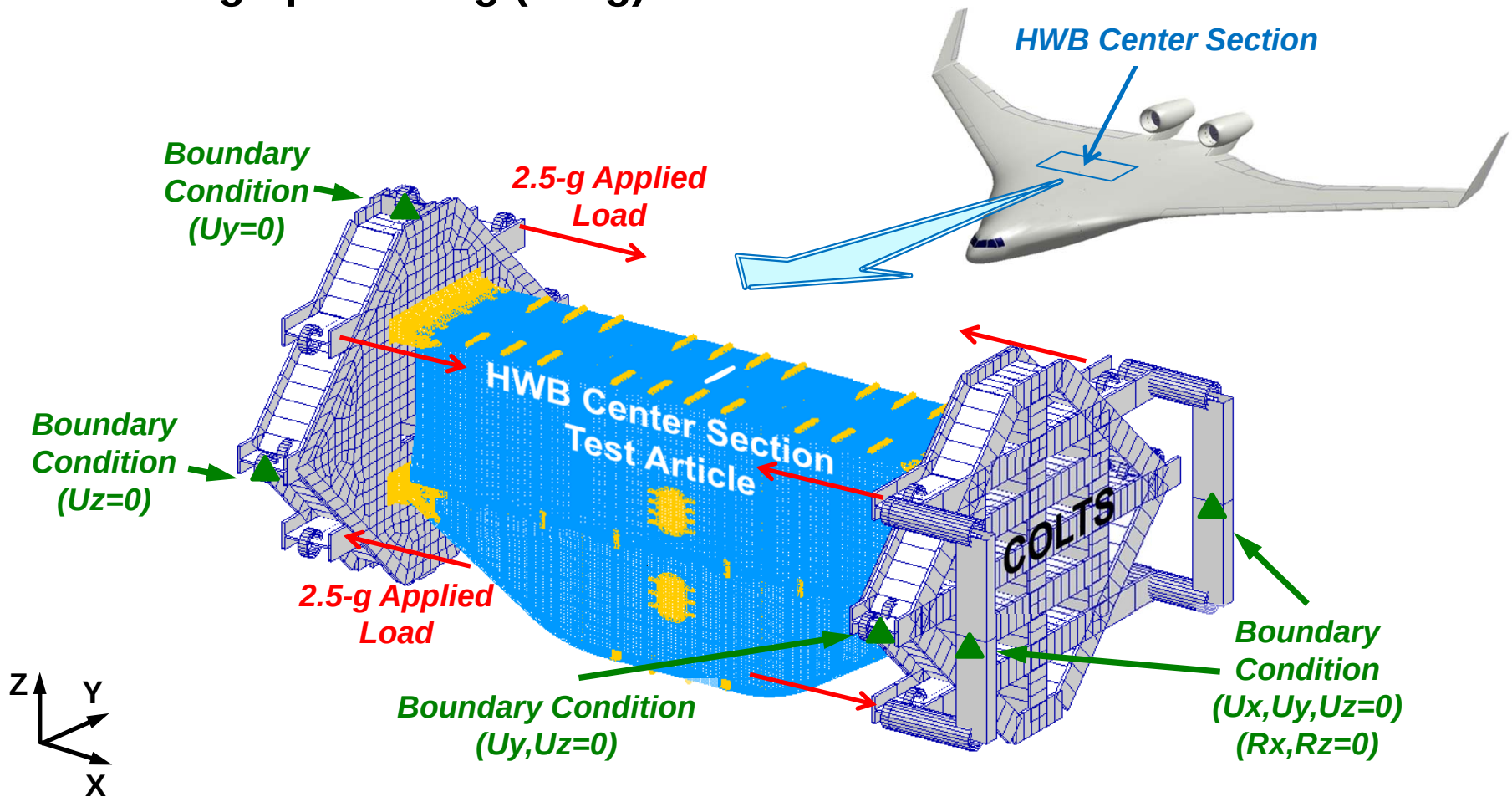
FEM in the Vicinity of Discrete Source Damage

- Element edge size at saw-cut tips ~ 0.05 in.
- Saw-cut skin bay element edge size ~ 0.25 in.
- Refined mesh connected to coarser mesh away from DSD using nodal values interpolation (RSPLINE functionality)

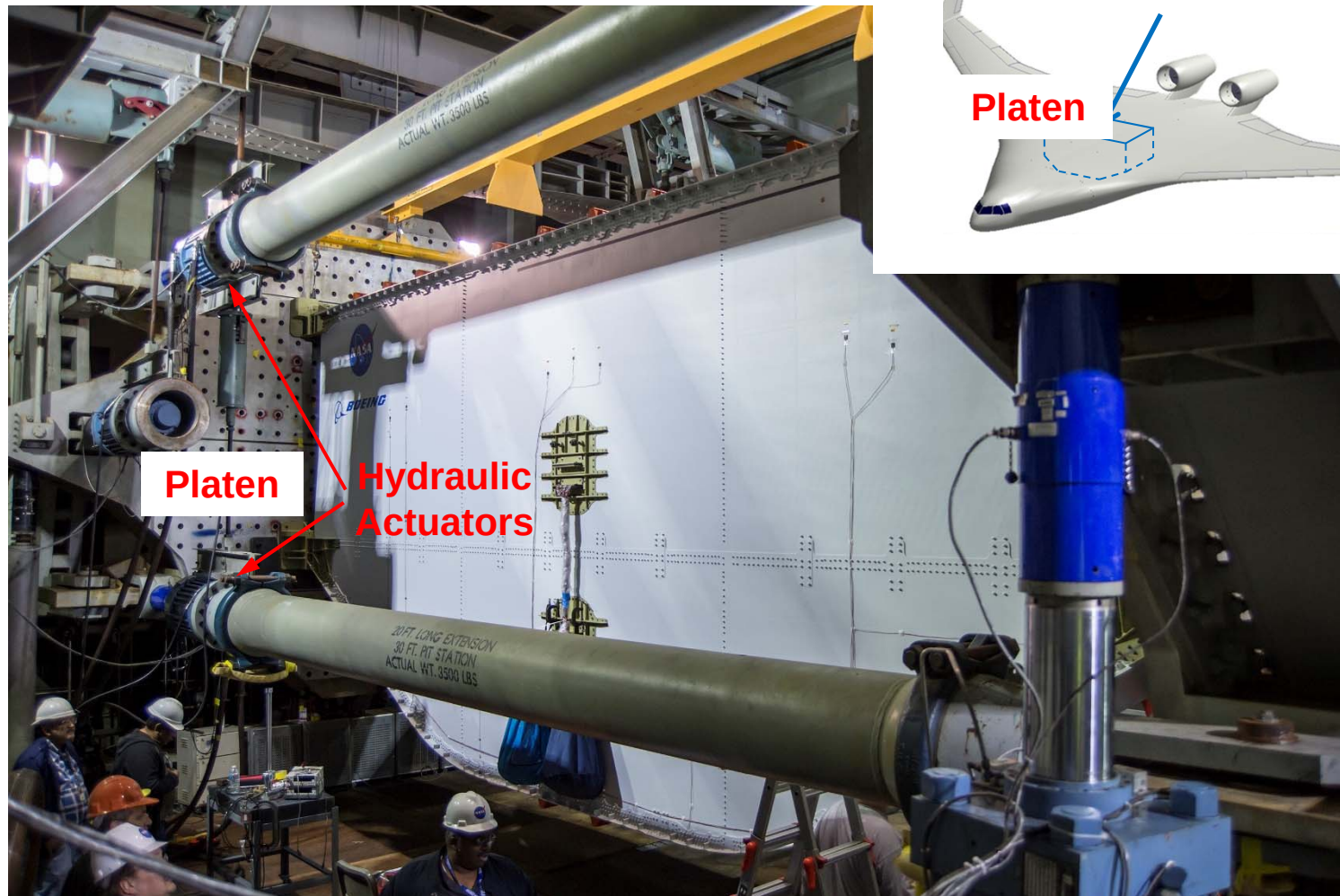


Load Application and Boundary Conditions

➤ Wing up-bending (2.5-g)



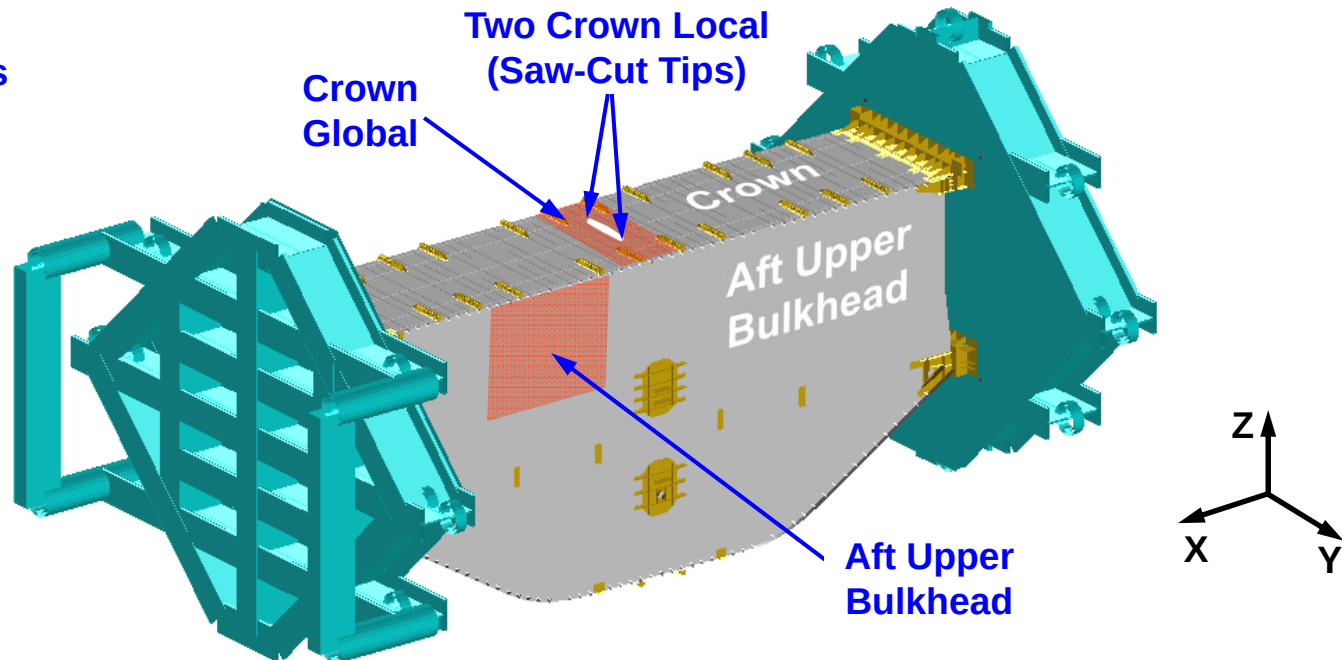
HWB Test Article Installation in the COLTS Facility



Test Article Instrumentation

- Results to be discussed
 - Video image correlation in three dimensions (VIC-3D) full field displacement acquisitions on the outer moldline (OML) surfaces of crown and upper bulkhead panels
 - Strain gages (380 unidirectional and 36 rectangular rosettes, total of 488 channels)

VIC-3D
Systems

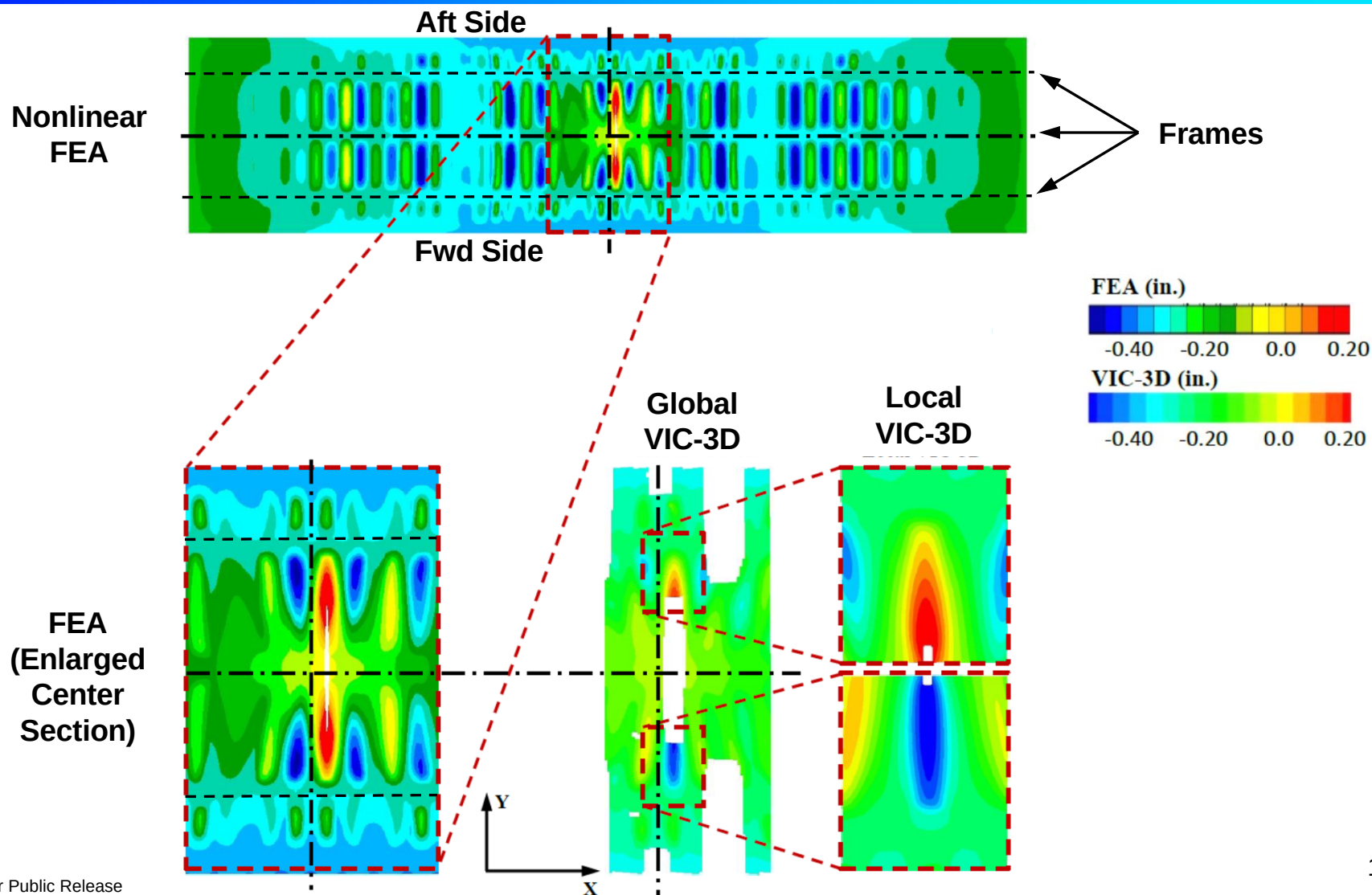


Summary of Test Results

- **First damage identified at 130.3 kips actuator load (81.9% DLL)**
- **Final failure at 241.8 kips (152.1% DLL)**
- **Several indications of damage progression identified between the initial and final failure**
- **FEA executed up to 238.5 kips (150% DLL)**

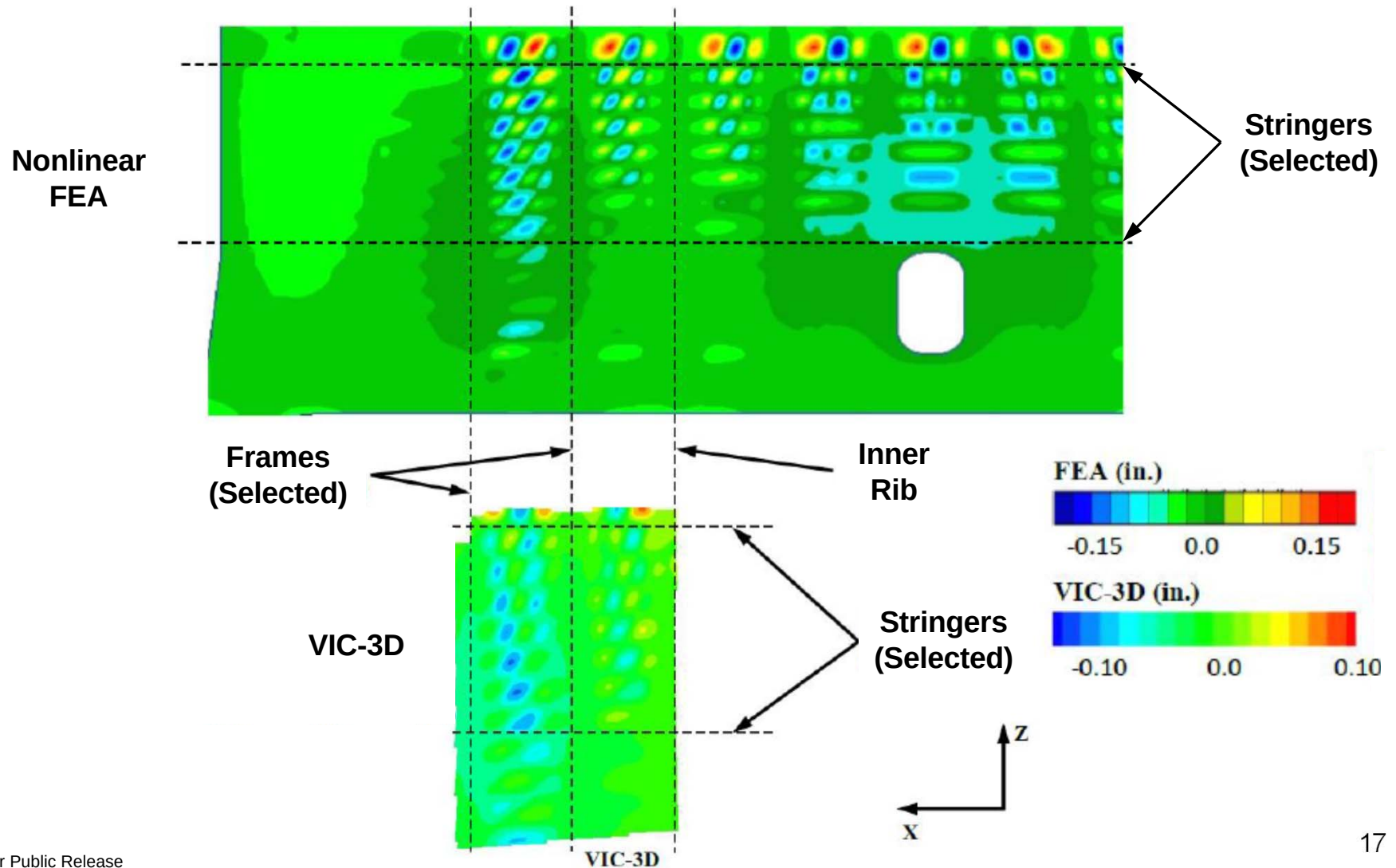
Crown Panel

Out-of-Plane Deformation at 150% DLL



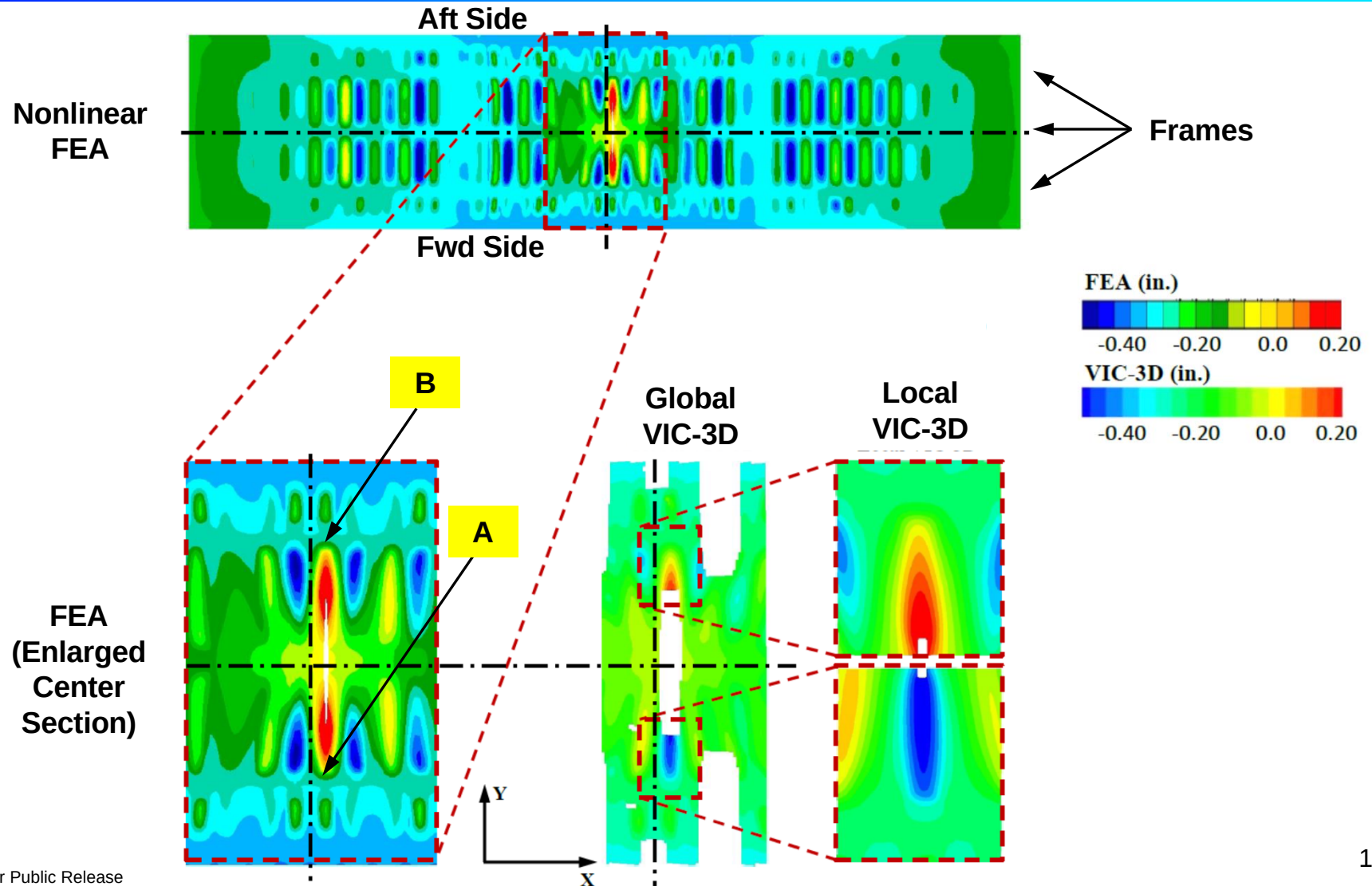
Aft Upper Bulkhead Panel

Out-of-Plane Deformation at 150% DLL



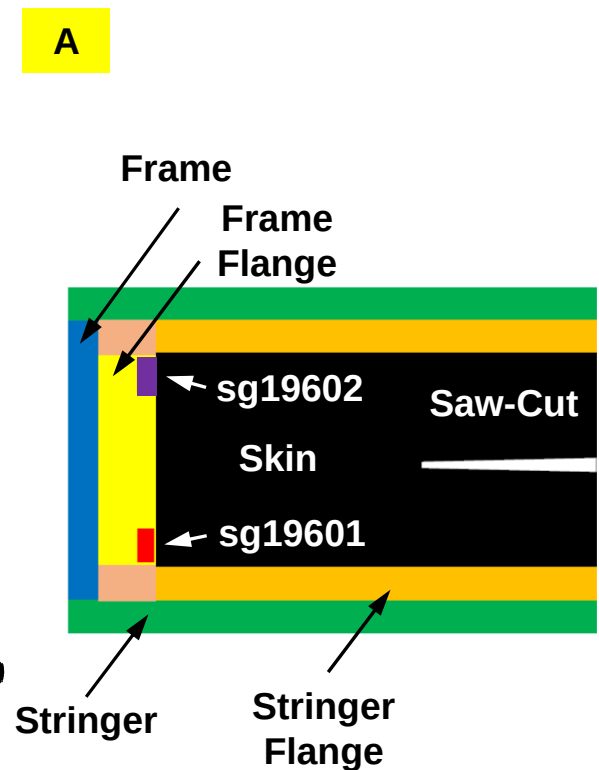
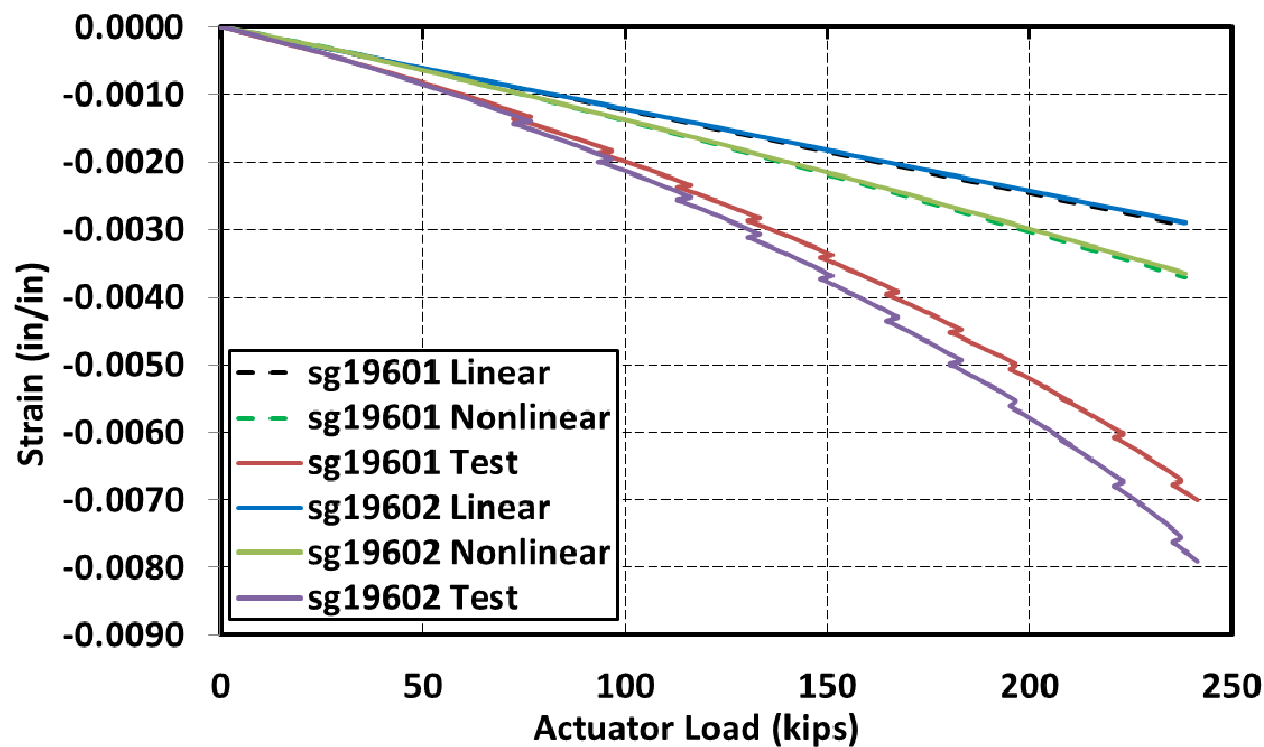
Crown Panel

Strains in Flanges of Side Frames



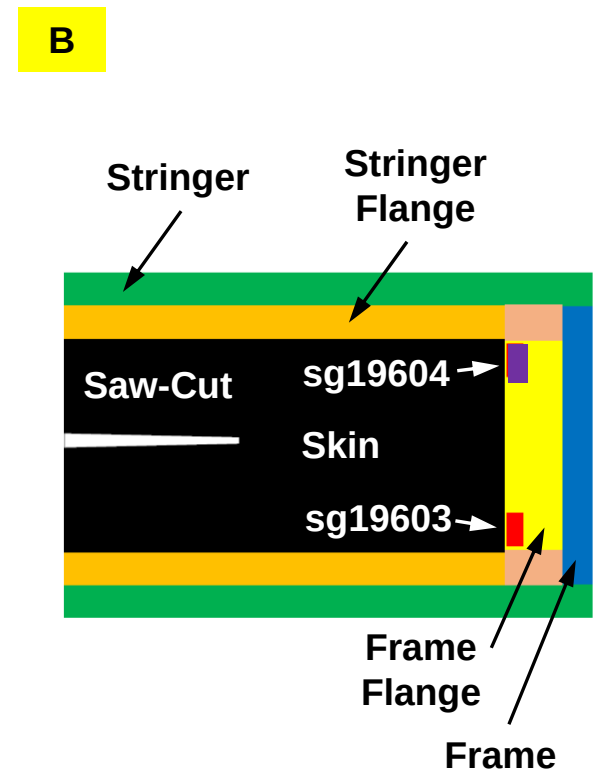
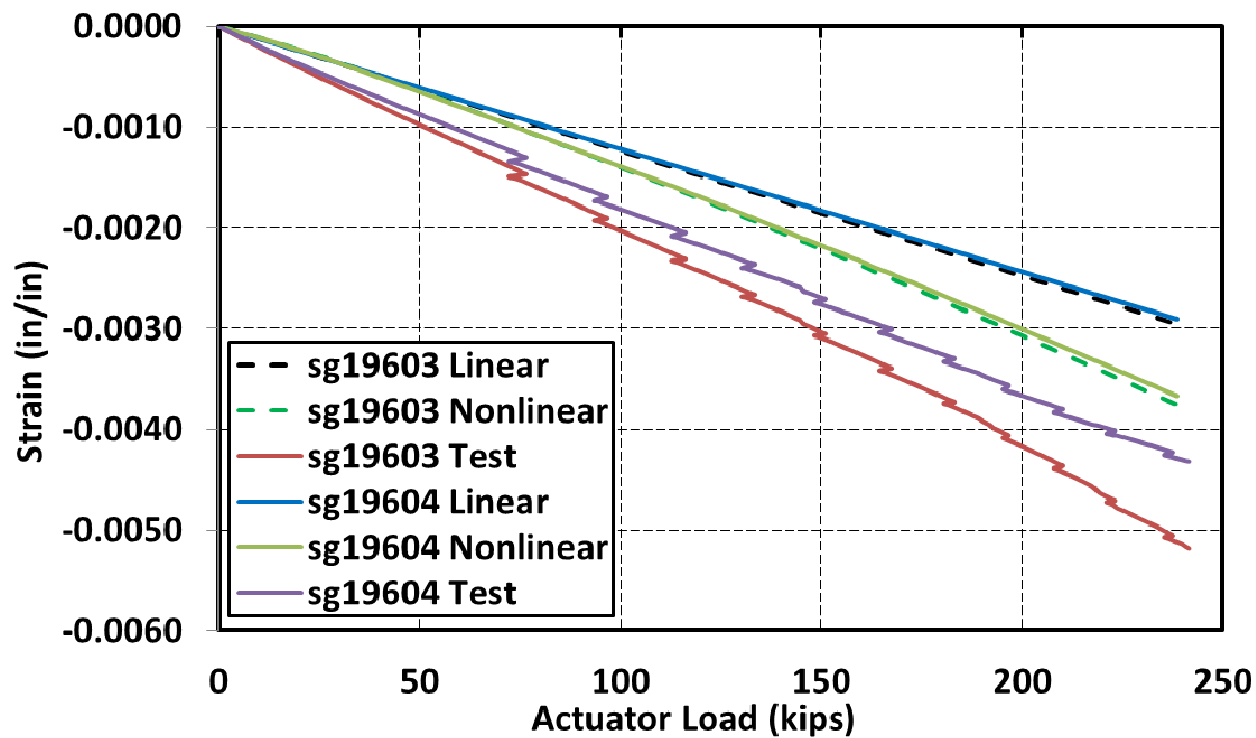
Crown Panel

Strains in the Forward Frame Flange

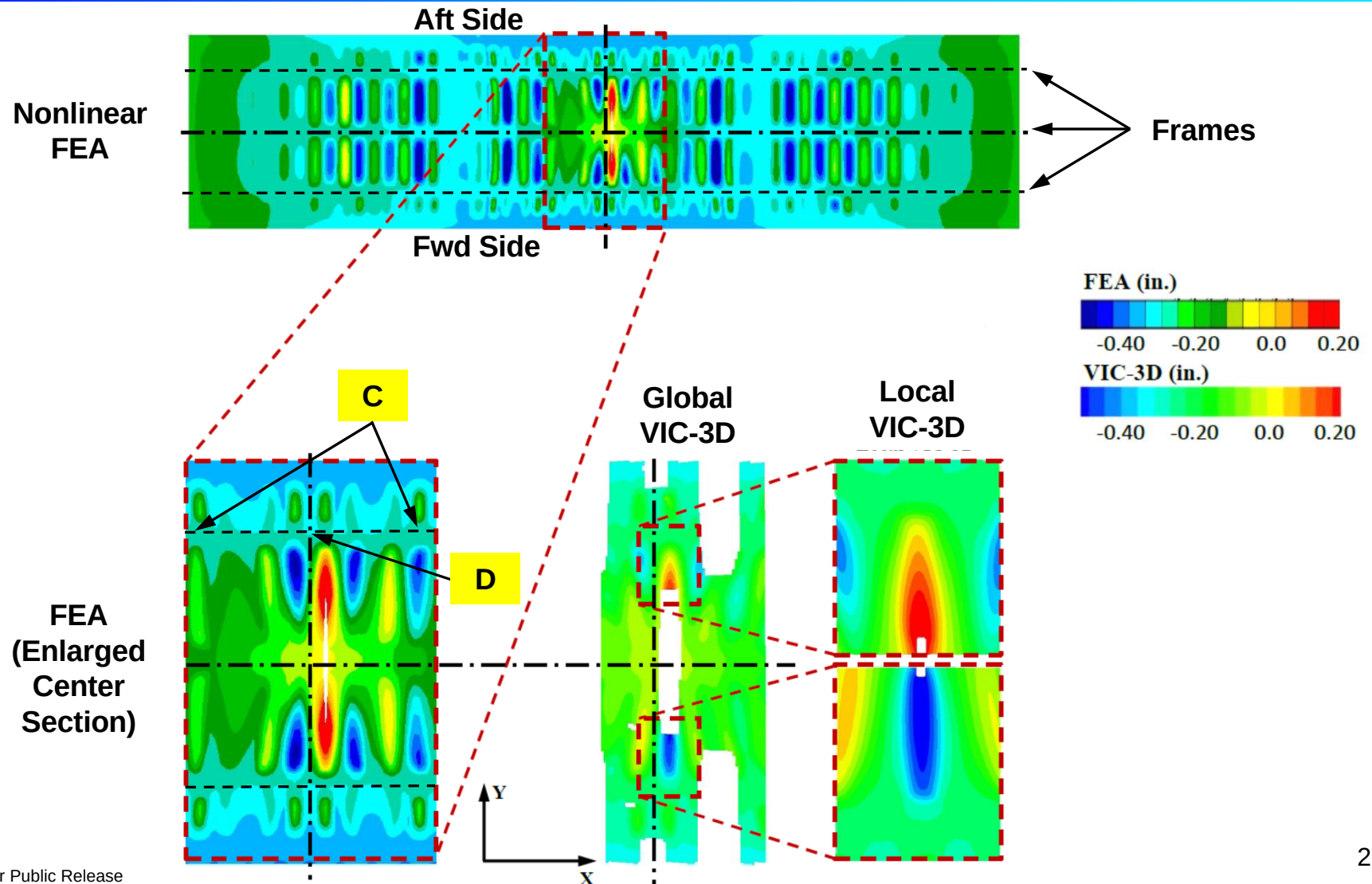


Crown Panel

Strains in the Aft Frame Flange

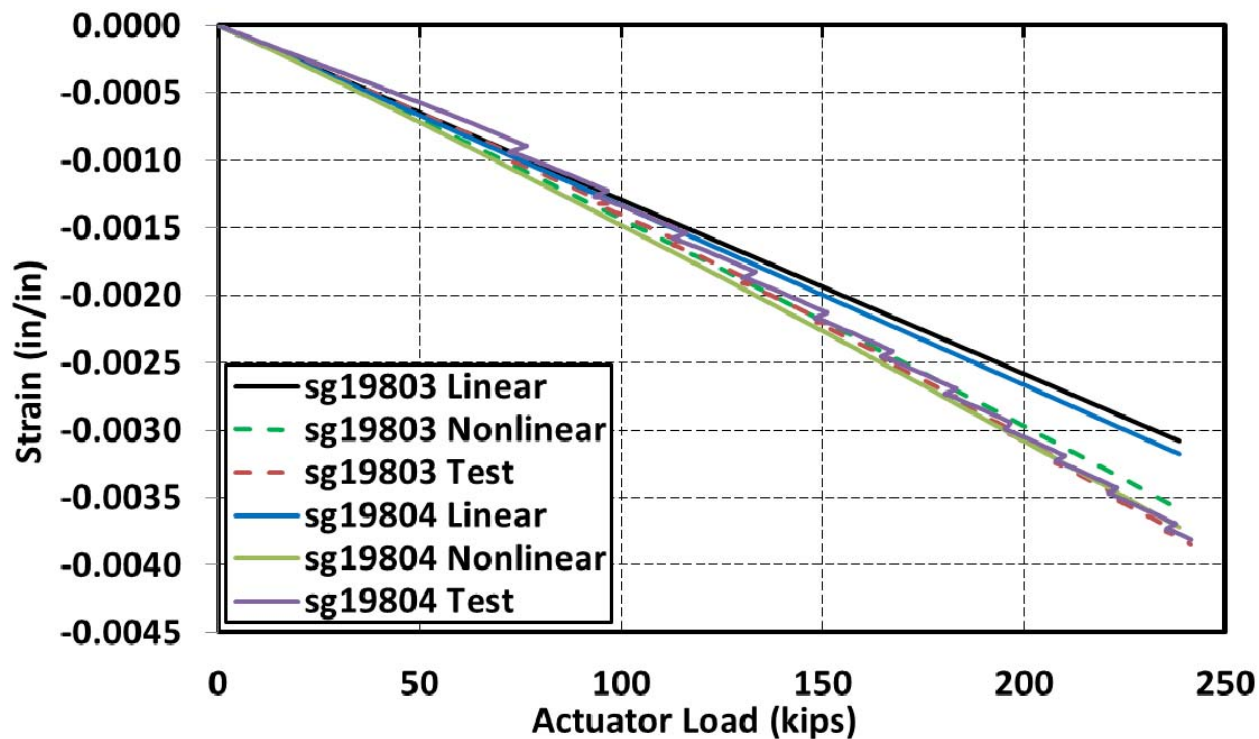


Crown Panel Strains in the Aft Frame

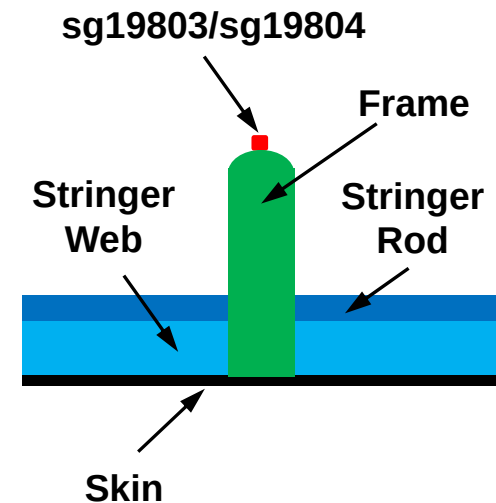


Crown Panel

Strains at the Top of the Aft Frame

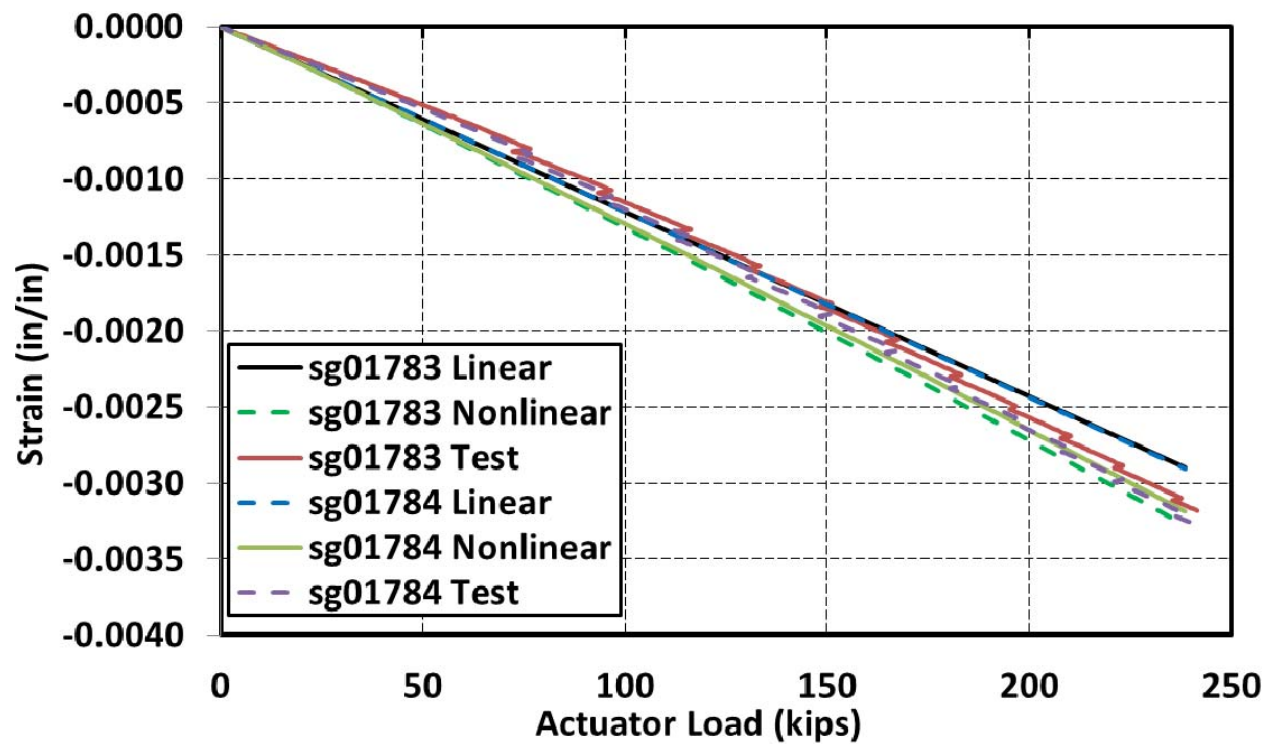


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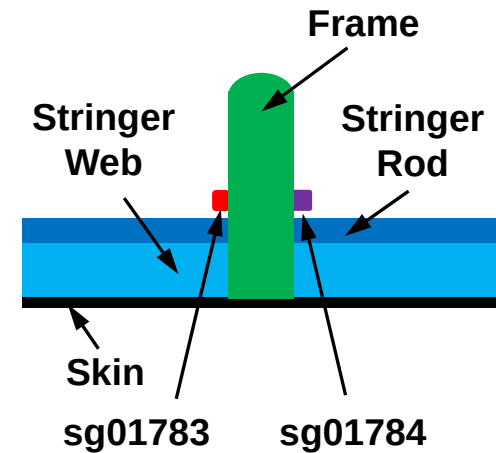


Crown Panel

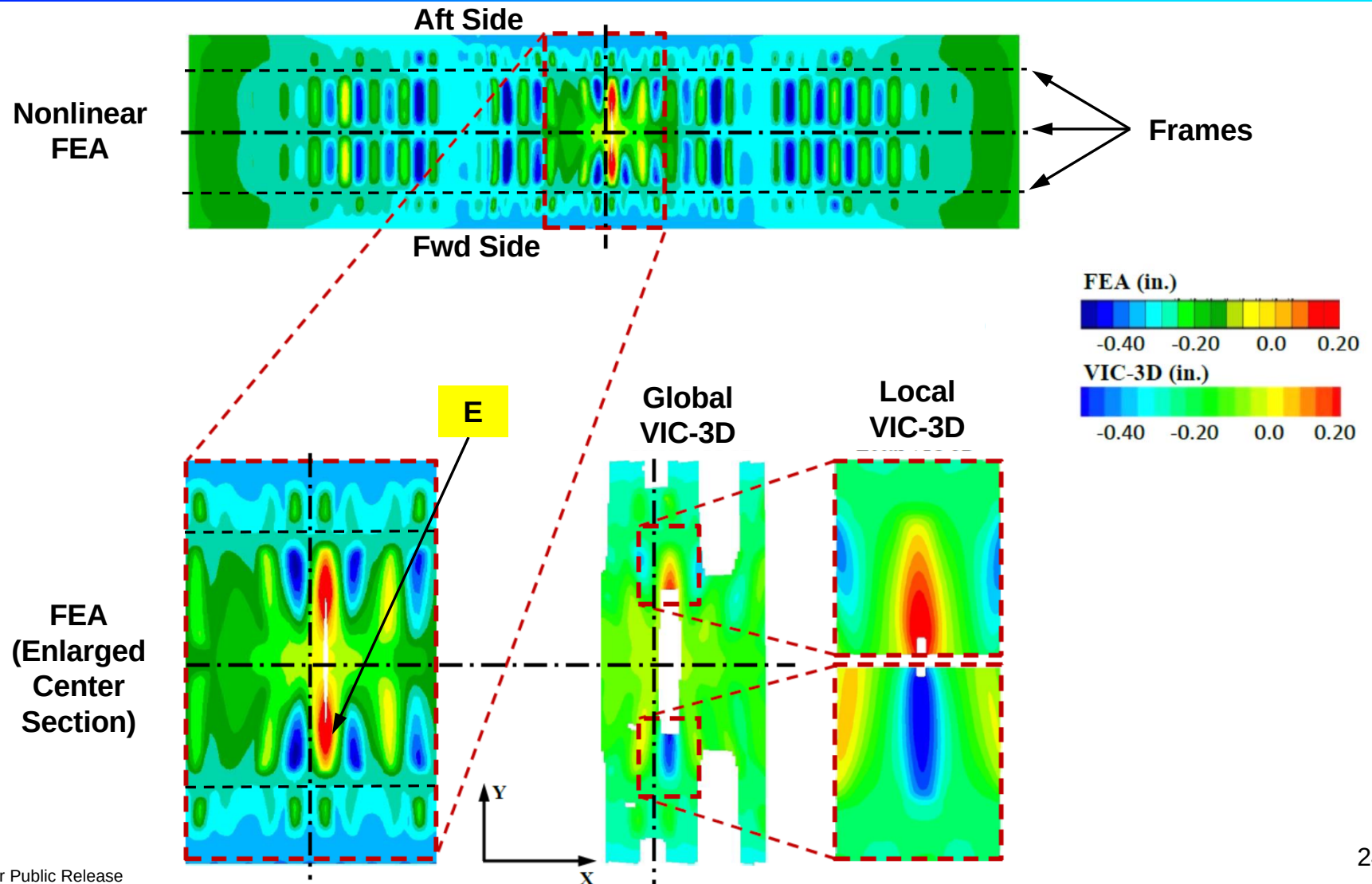
Strains in the Aft Frame Web



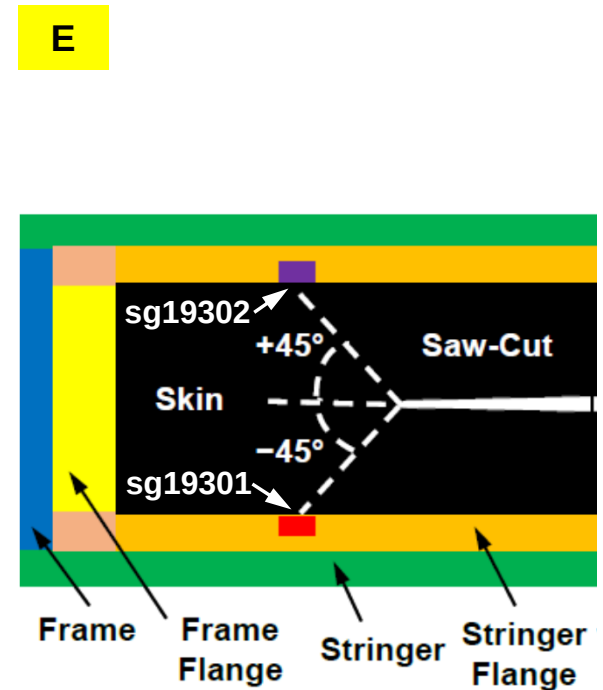
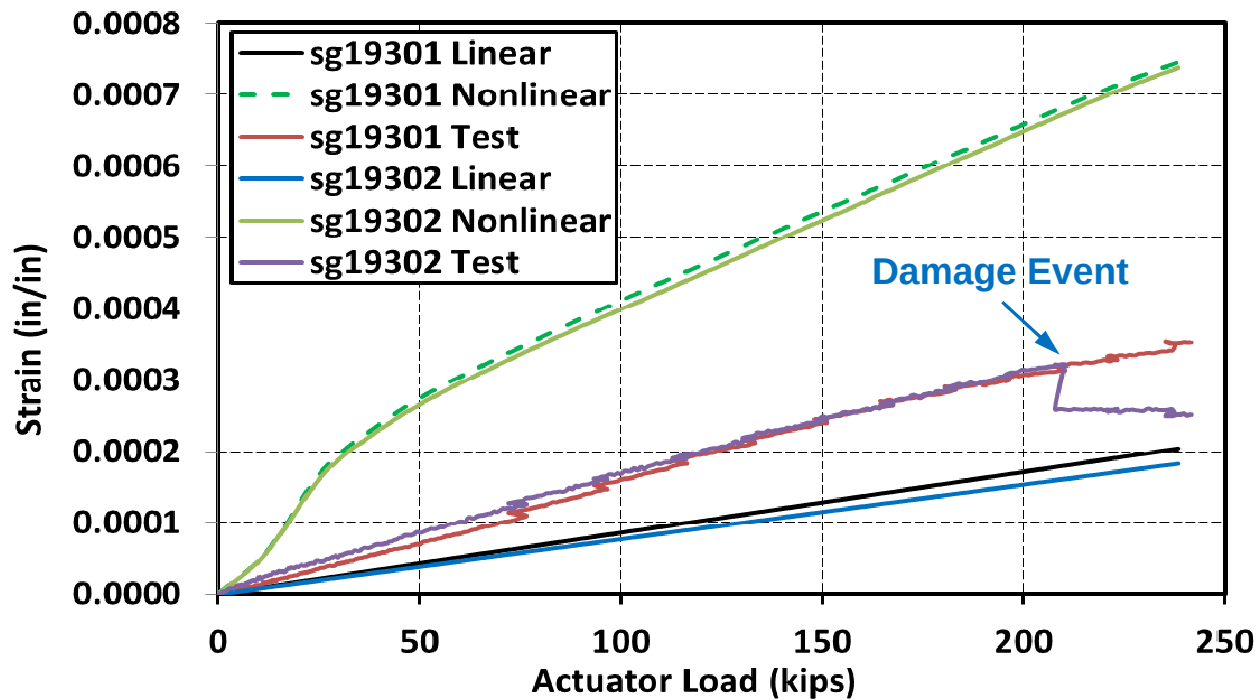
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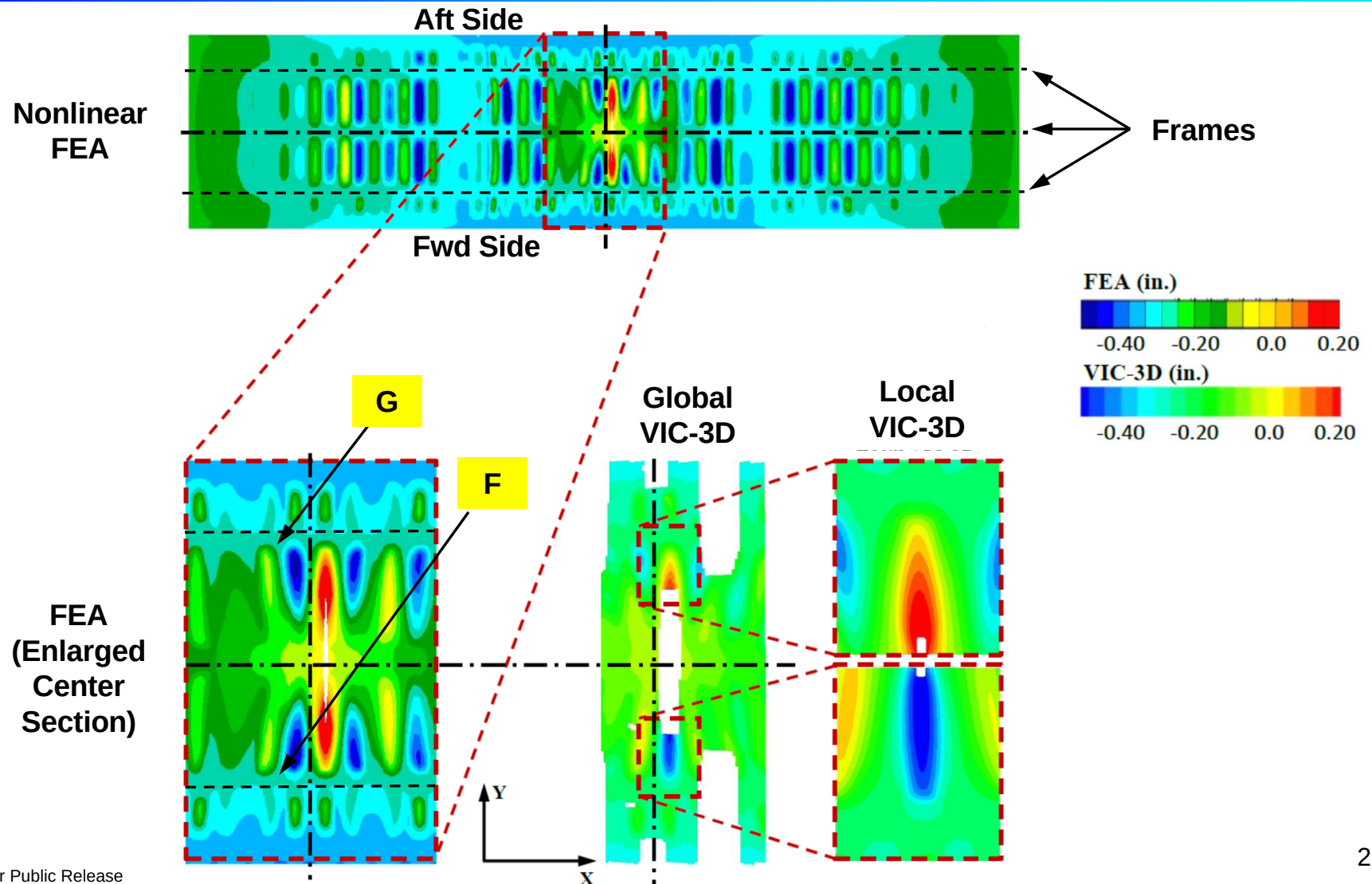
Crown Panel Strains in Stringer Flanges



Crown Panel Strains in Stringer Flanges

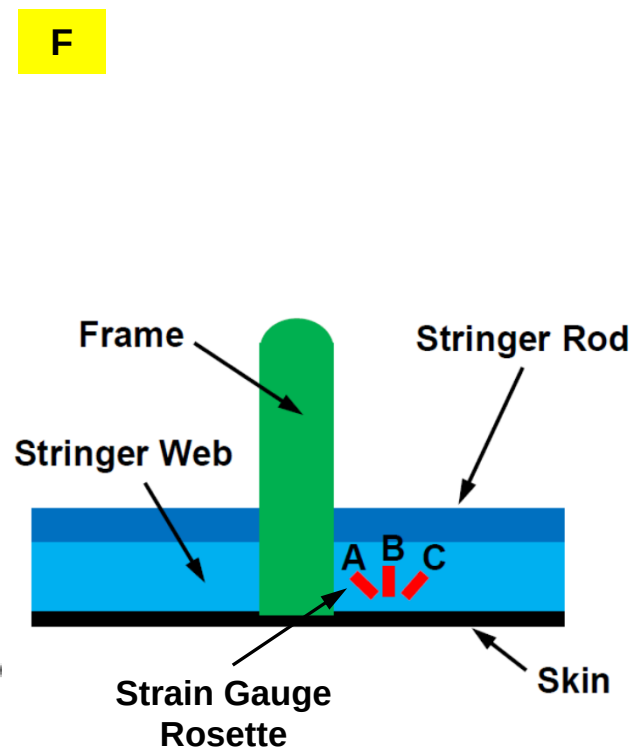
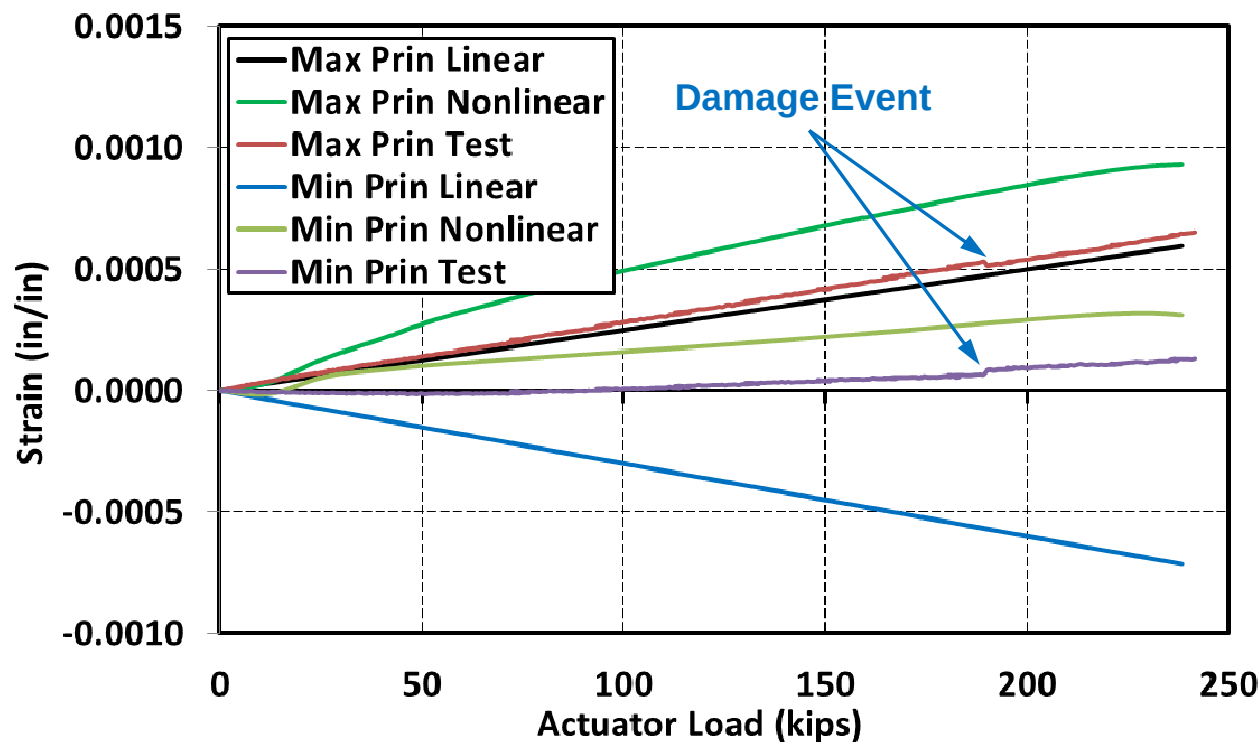


Crown Panel Strains in Stringer Webs



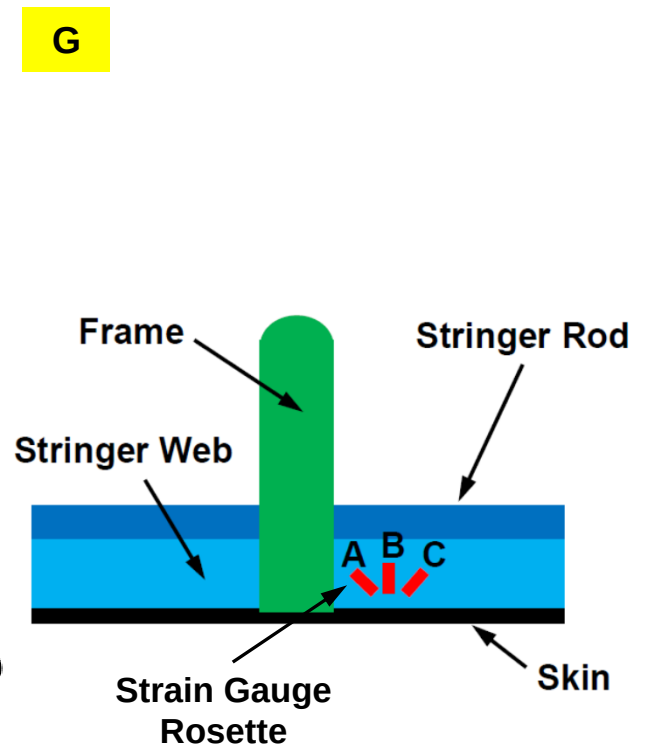
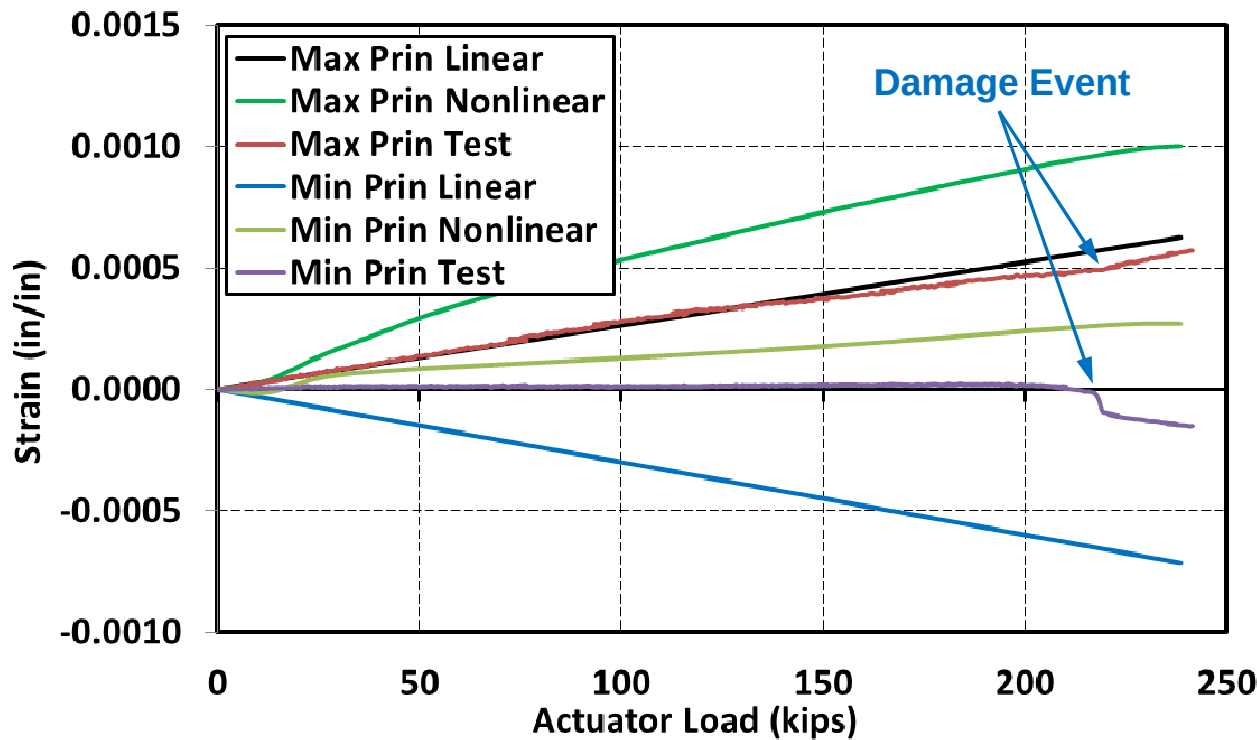
Crown Panel

Strains in the Forward Stringer Web

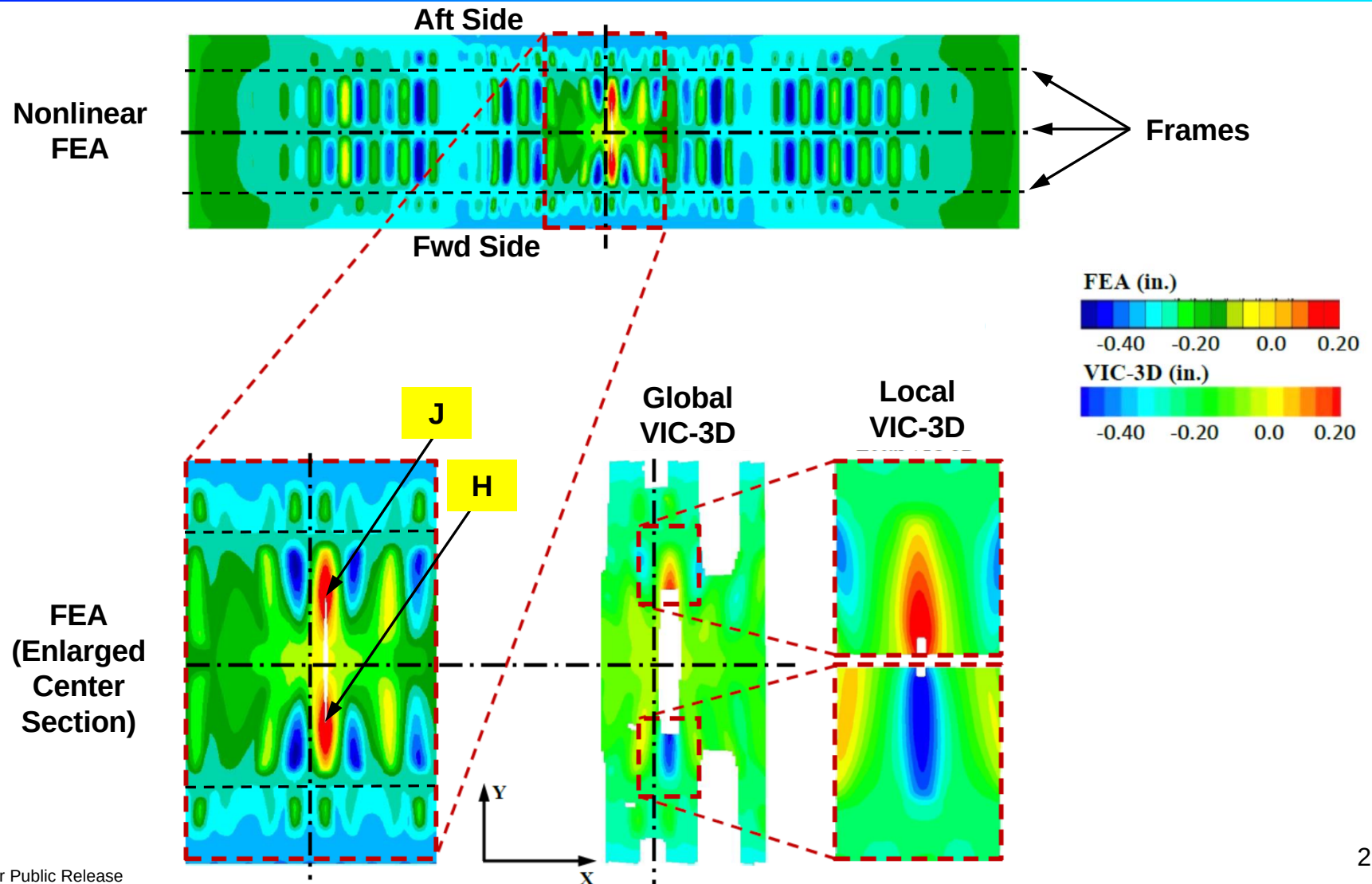


Crown Panel

Strains in the Aft Stringer Web

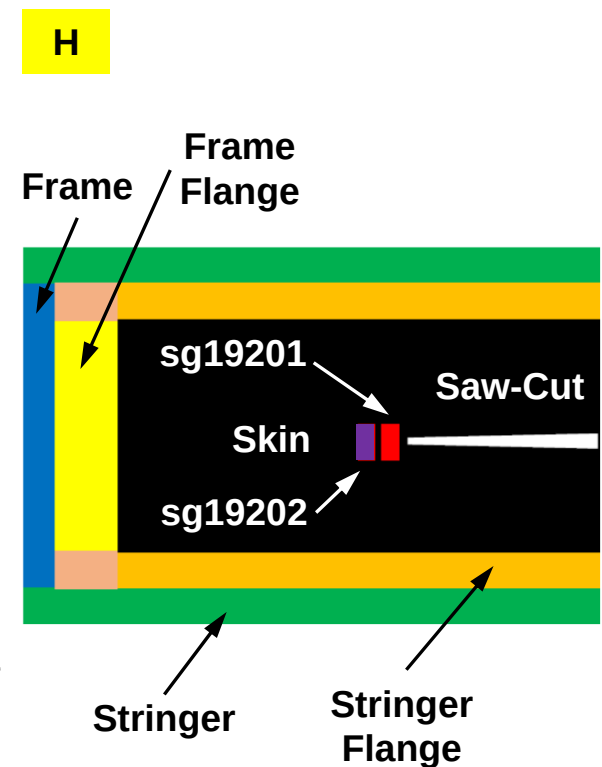
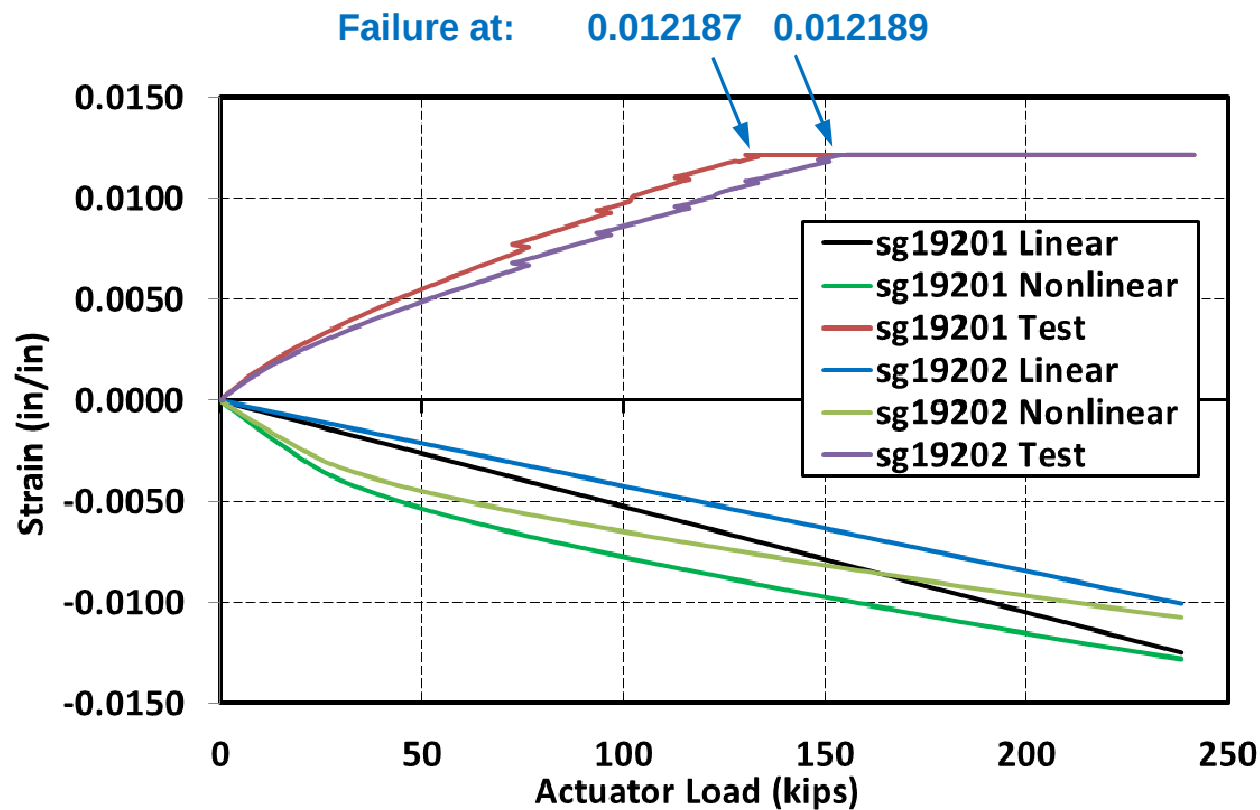


Crown Panel Strains at Saw-Cut Tips



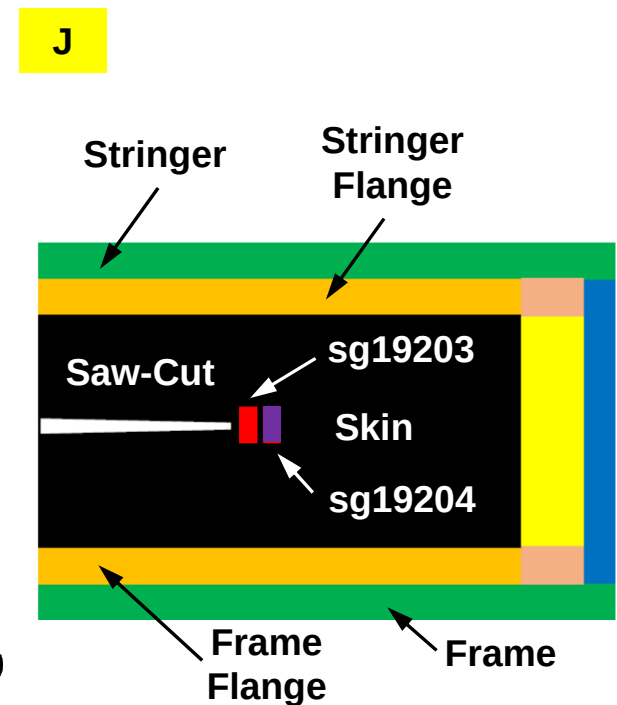
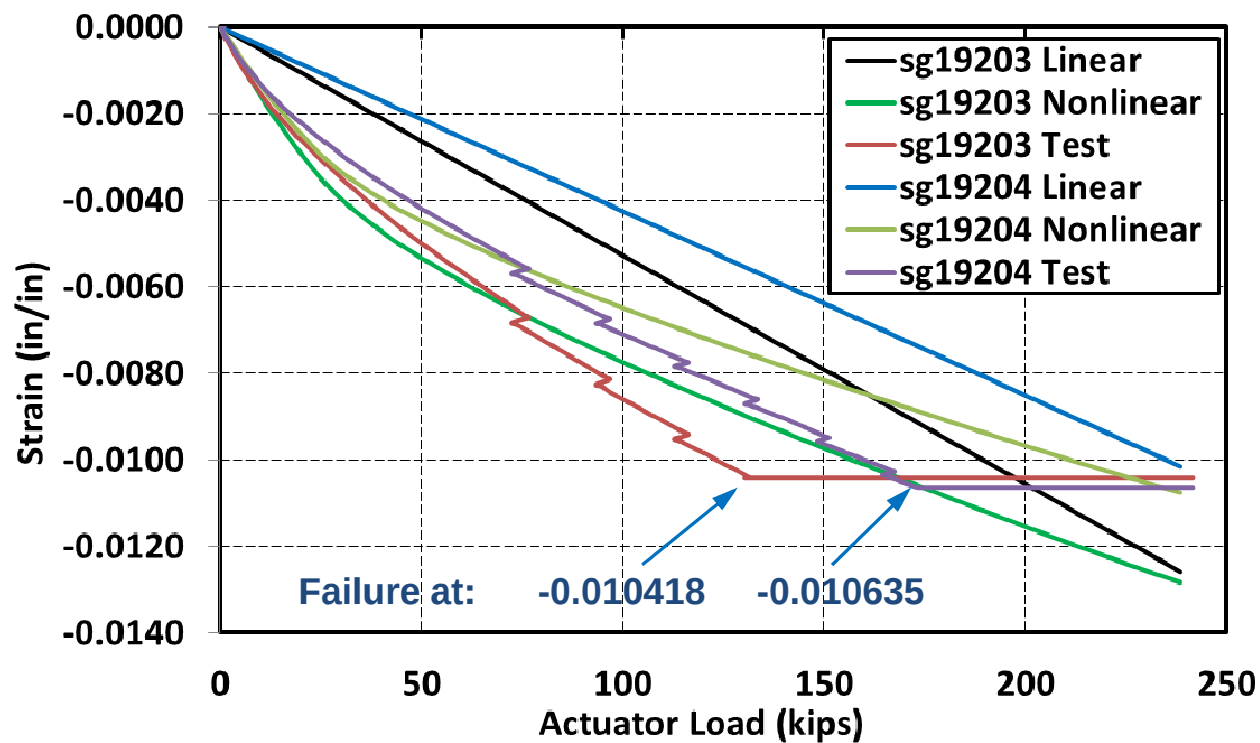
Crown Panel

Strains at the Forward Saw-Cut Tip



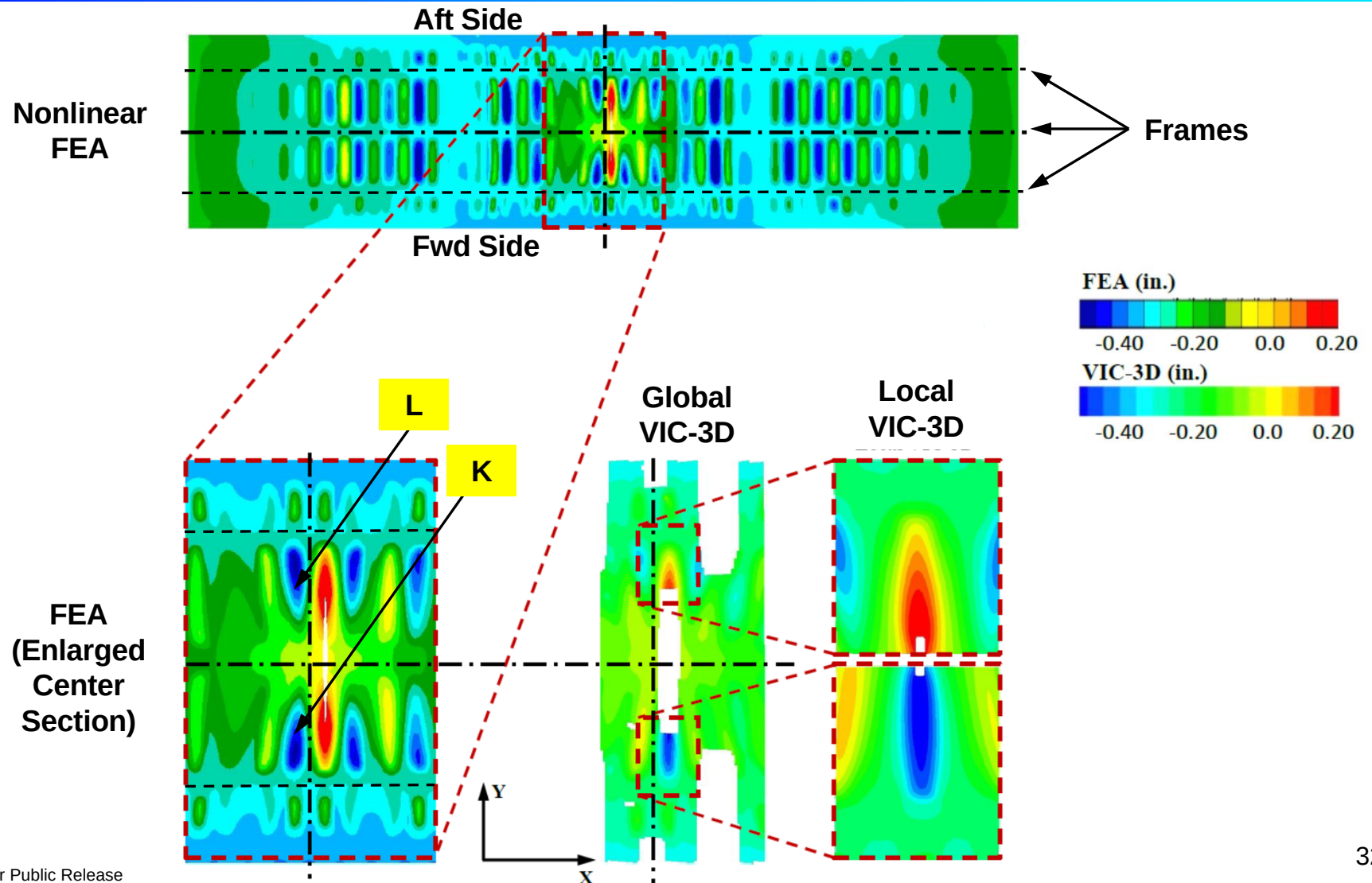
Crown Panel

Strains at the Aft Saw-Cut Tip



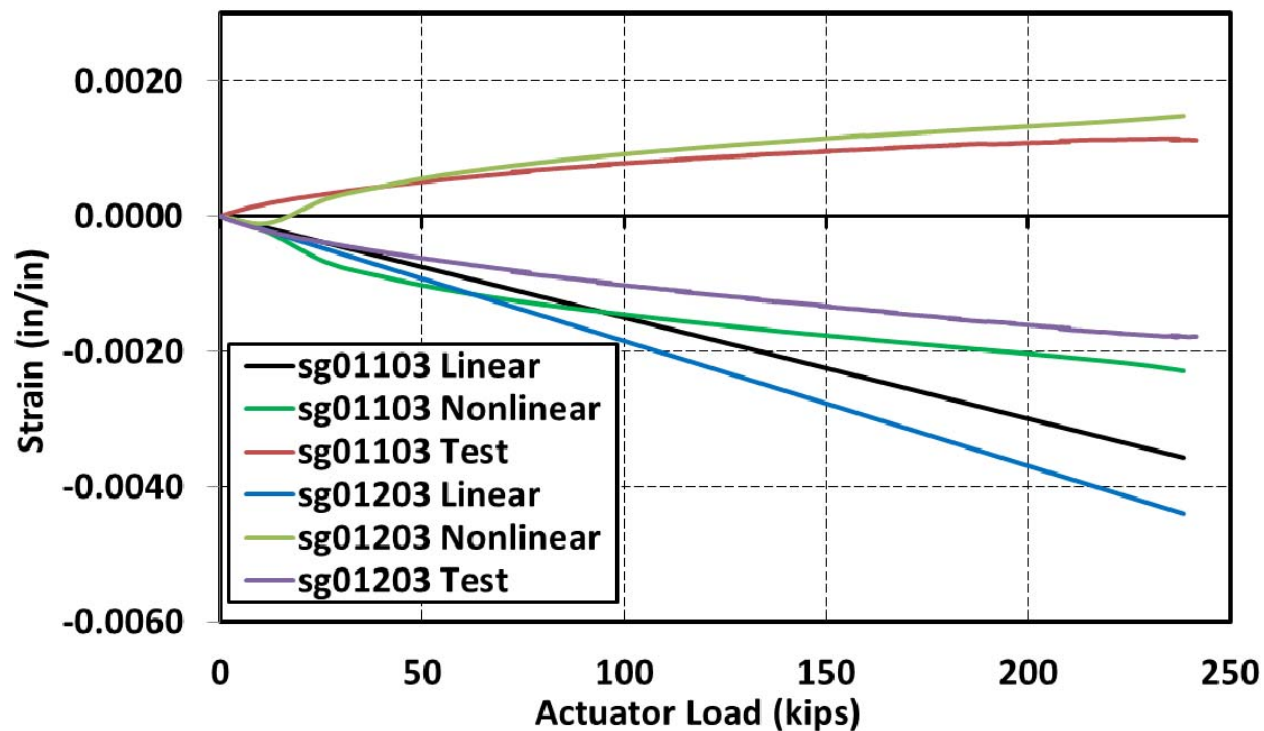
Crown Panel

Back-to-Back Strains in Skin Bays

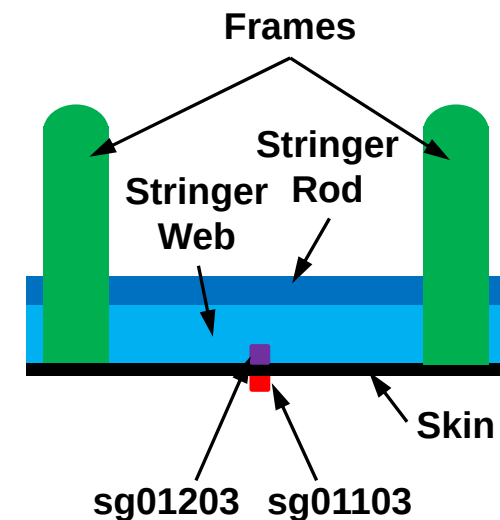


Crown Panel

Back-to-Back Strains in the Forward Skin Bay

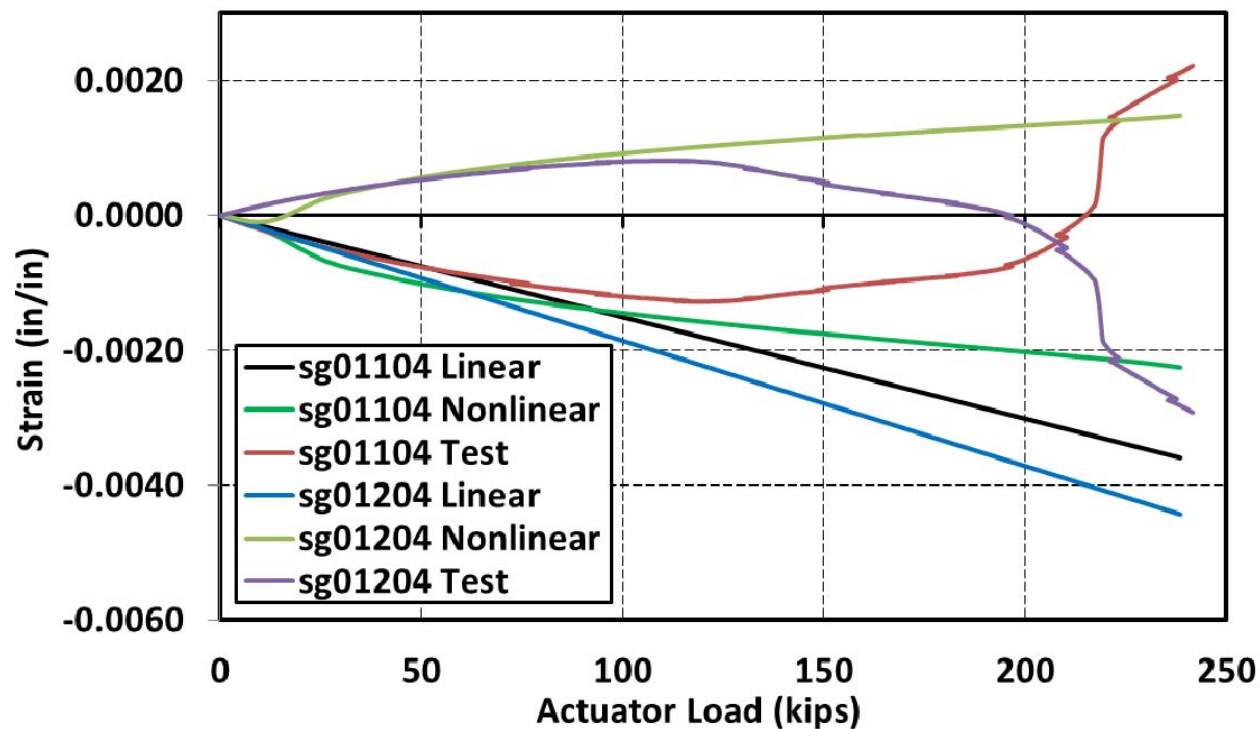


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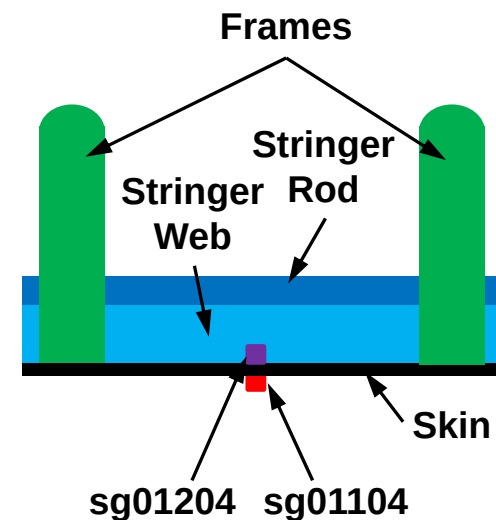


Crown Panel

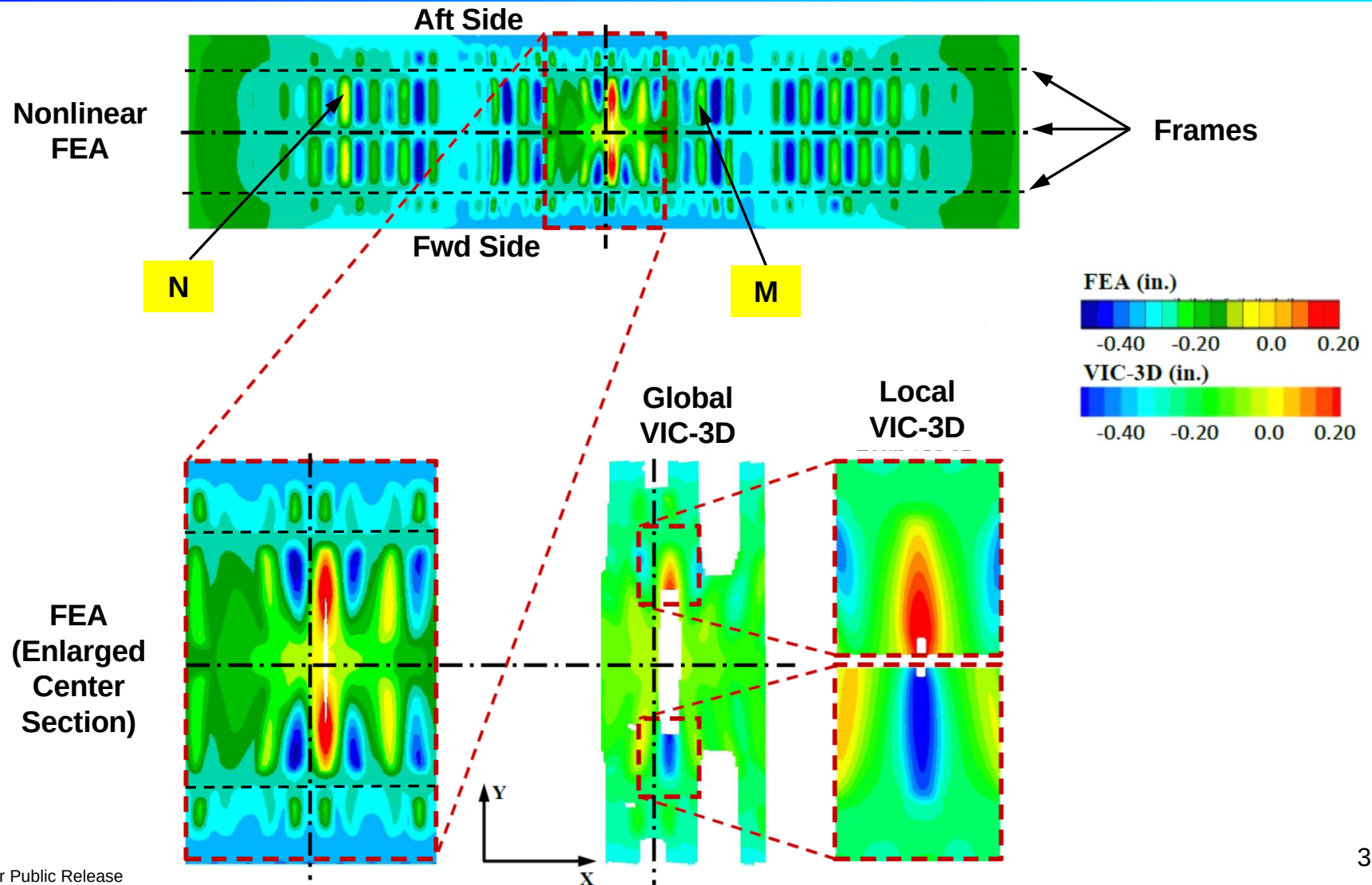
Back-to-Back Strains in the Aft Skin Bay



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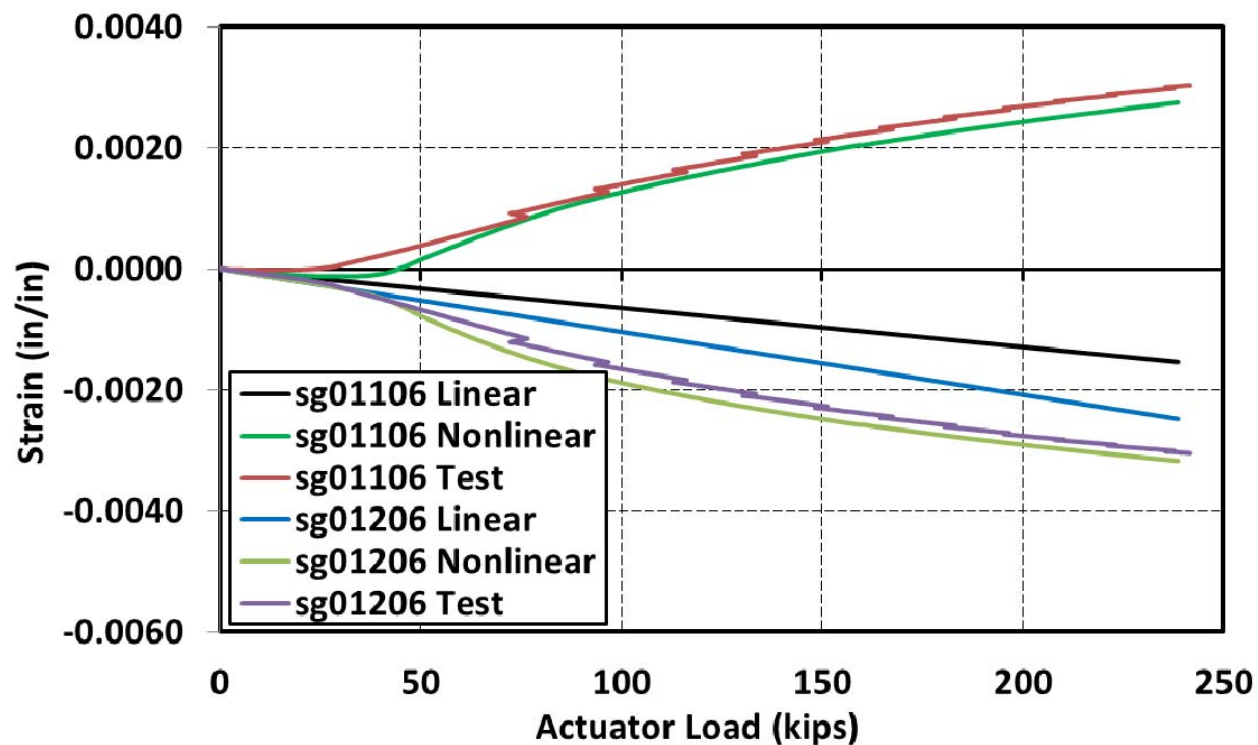


Crown Panel Far Field Skin Strains

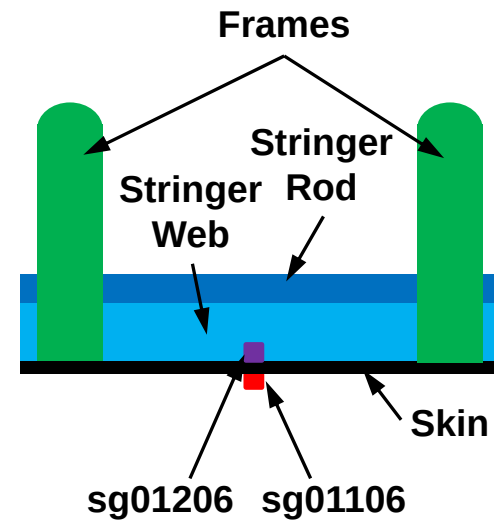


Crown Panel

Far Field Back-to-Back Skin Strains

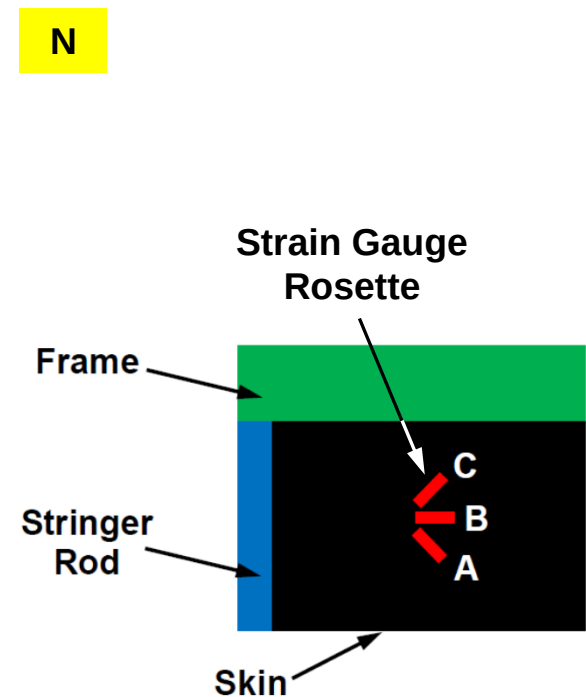
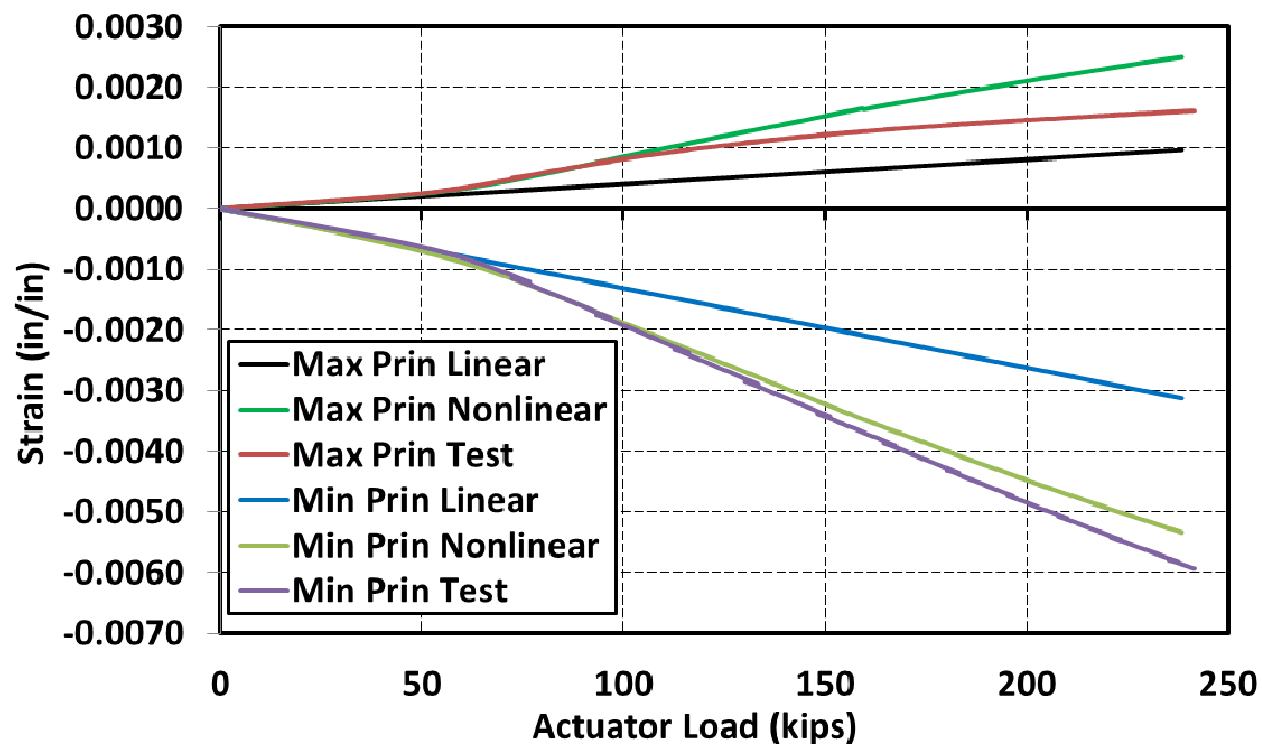


M



Crown Panel

Far Field Skin Principal Strains



Conclusions – Testing

- **Successful completion of the HWB center section article testing in pristine and BVID conditions enabled final test to failure with DSD**
 - **First localized skin damaged observed at 130.3 kips (81.9% DLL) at the saw-cut tip**
 - **Several other incremental damages identified in the vicinity of the DSD before the final failure at 241.8 kips (152.1% DLL)**
 - **Failure load exceeded condition representative of transport category airframe certification standards with DSD (70% DLL)**

Conclusions – FEA

- **FEA analysis without damage progression capability rapidly developed and successfully applied to determine DSD geometry and guide test article instrumentation**
- **Favorable comparison of test data and nonlinear analysis results obtained in far field and before incremental damage development identified**
- **As the damage progressed, the agreement between test and analysis gradually deteriorated, nevertheless overall response characteristics accurately captured**
 - **Buckling of skin bays before damage development**
 - **Initial damage at saw-cut tips**
 - **Final failure location and mode – frame crushing rather than buckling (i.e., exceeding strength capabilities rather than failing in stability mode) and originating at frame base (flange) rather than top**

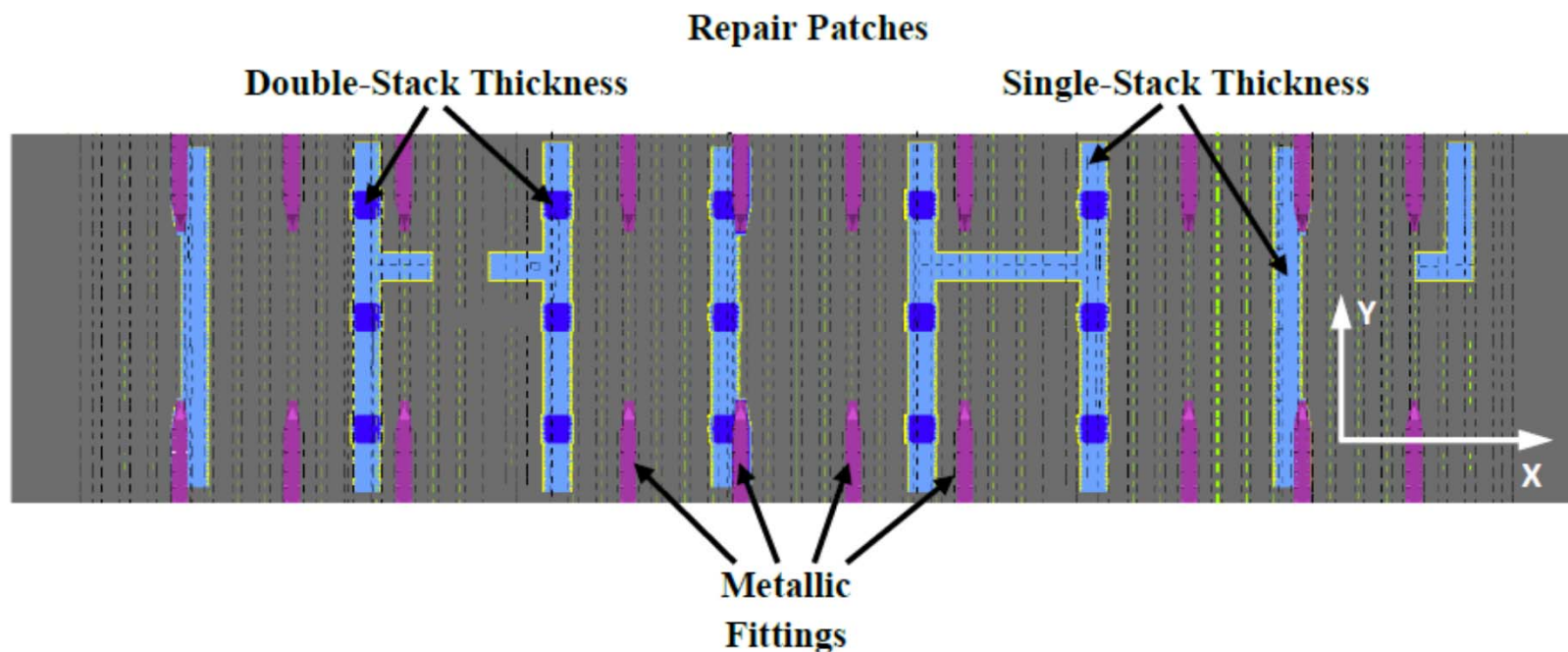
Questions



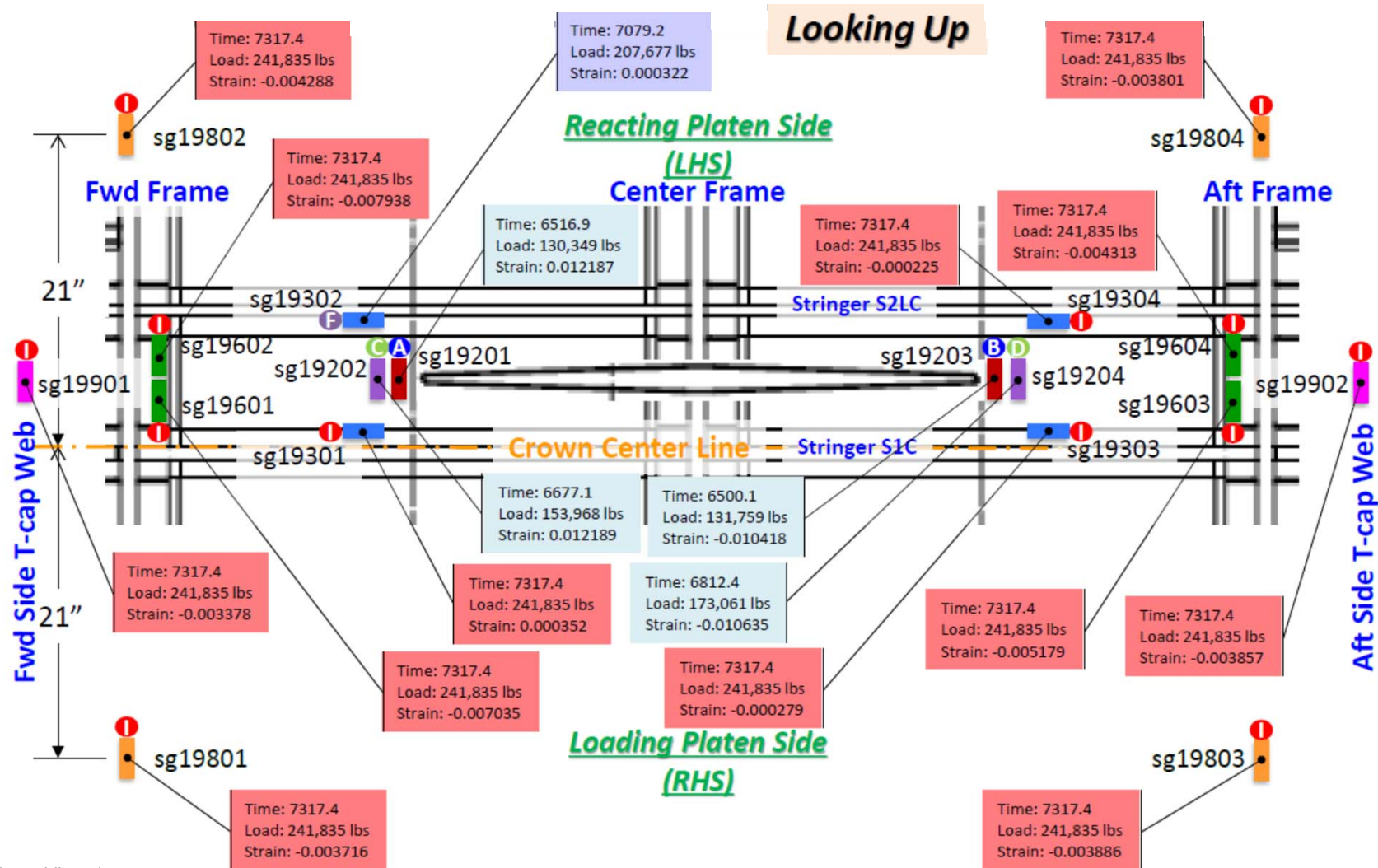
Supplemental Material

Crown Panel Rework

- Bonded patches (dry-to-dry) in blue
 - Single stack thick (light blue)
 - Double stack thick (dark blue)
- Metallic fittings (magenta)



Strains in the Proximity of the DSD



HWB Center Section Test Article

Long Beach, CA to Hampton, VA



MBB loaded on K-Loader
at Boeing Long Beach



MBB loaded into
Super Guppy at Boeing LB



MBB unloaded from
Super Guppy at NASA LaRC



MBB unloaded from
K-Loader at NASA LaRC

HWB Center Section Test Article Set Up in COLTS

