

HIGHLY LOADED COMPOSITE STRUT TEST DEVELOPMENT AND RESULTS

K. Chauncey Wu and Dawn C. Jegley

NASA Langley Research Center, Hampton, Virginia

James E. Phelps and Martin J. McKenney

ATK Space Systems Inc., Hampton, Virginia

Ansley Barnard

Washington Space Grant Consortium, Seattle, Washington

ACCIS DTC

University of Bristol, Bristol, UK

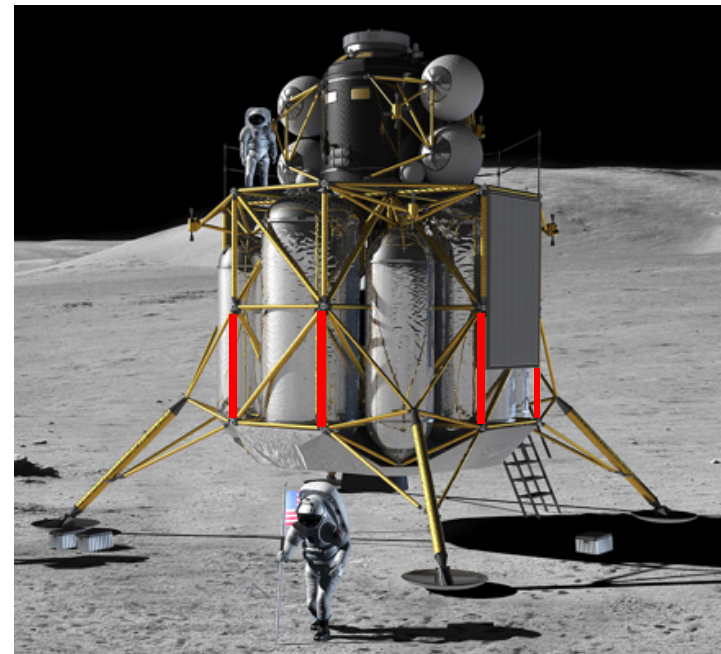
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HIGHLY LOADED COMPOSITE STRUT TEST DEVELOPMENT AND RESULTS

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- Test facility requirements
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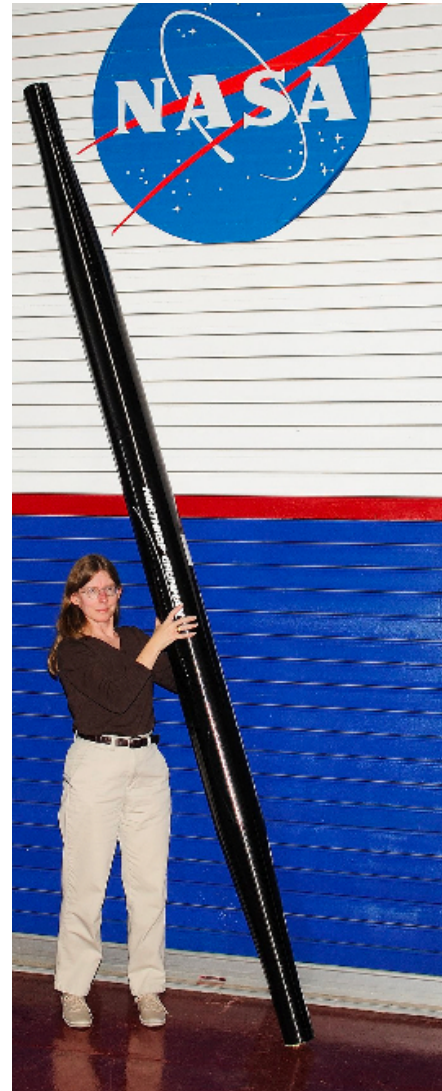
Introduction

- NASA Advanced Composites Technology program initiated in 2008 to support Constellation space exploration program.
- ACT program goal is to develop and advance state-of-the-art for composite structures technology.
- Selected applications include Ares V intertank/interstage dry structures, and Altair lunar lander truss struts.
- Altair descent stage concept has 200 struts, subdivided into 30 groups by their lengths and loads.
- Largest ultimate loads are 60.2 klb tension and -107.6 klb compression in the struts highlighted in red. Limit = $DUL/1.4$ FS.



Introduction (2)

- Heavily Loaded Struts task initiated under ACT to design, develop and manufacture composite struts with tapered ends, allowing attachment of many struts to a common node.
- Phase 1 entailed strut concept development, analytical structural performance studies, and fabrication of manufacturing demonstration hardware (example shown in photo at right).
- Phase 2 entailed strut hardware detail design, additional structural performance studies, and fabrication of strut hardware capable of carrying Altair design ultimate loads.
- Completed struts were delivered to NASA for evaluation and structural testing using the test capability developed and described here.

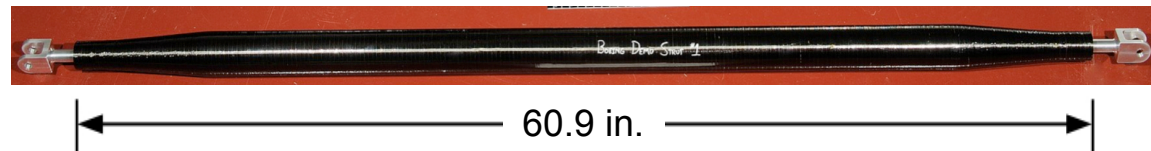


Phase 1 mfg. demo.

Composite Strut Description

- Ten struts were designed, analyzed and built by Boeing and Northrop Grumman under contract to NASA.
- Strut lengths ranged from 61 to 127 inches, with predicted compressive loads from -2 to -140 klb.
- Strut bodies fabricated from IM7/8552 prepreg tow and tape using hand layup, and then autoclaved or oven-cured.
- Tapered ends of struts incorporated titanium end fittings.

Phase 1
mfg. demo.



Phase 2
high-load
struts

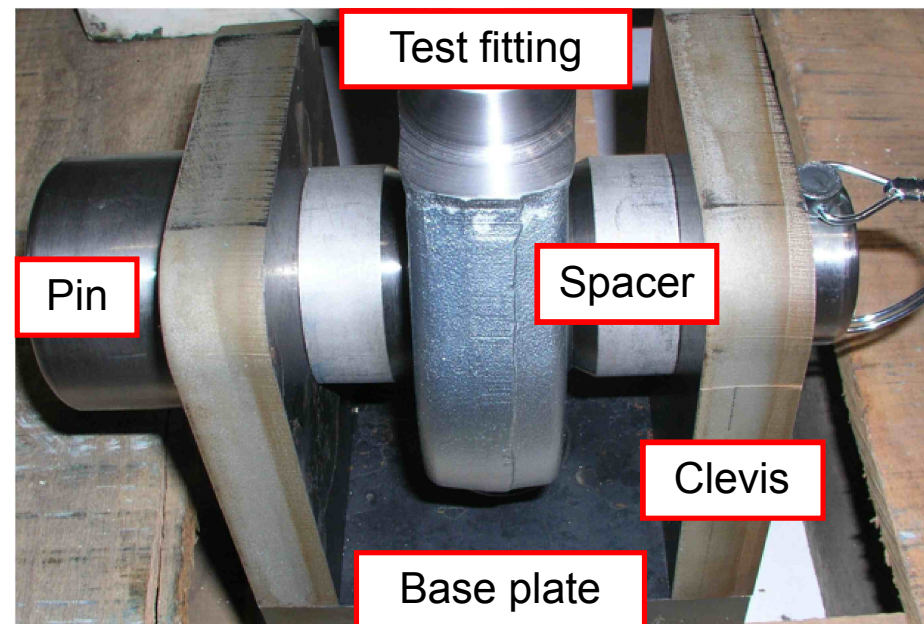
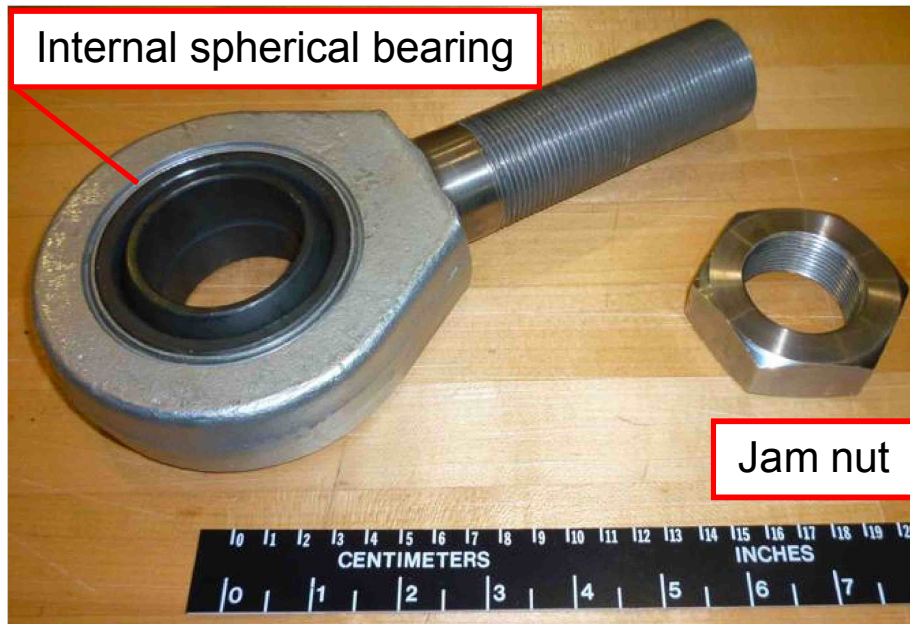


Test Facility Requirements

- Test facility must be capable of accommodating struts of different lengths with minimal modifications.
- Test hardware must be capable of applying both axial tension and compression loads of up to 150 klb.
- Test facility must have high stiffness to minimize structural deflections, and have sufficient strength to prevent failure of hardware and ensure safety of personnel.
- Test hardware must be adjustable to allow the composite strut to be aligned parallel to gravity.
- Test hardware must permit quick assembly and installation of the strut, as well as positioning of test instrumentation.
- Test hardware must not artificially constrain strut structural response (e.g., permit elastic Euler buckling).

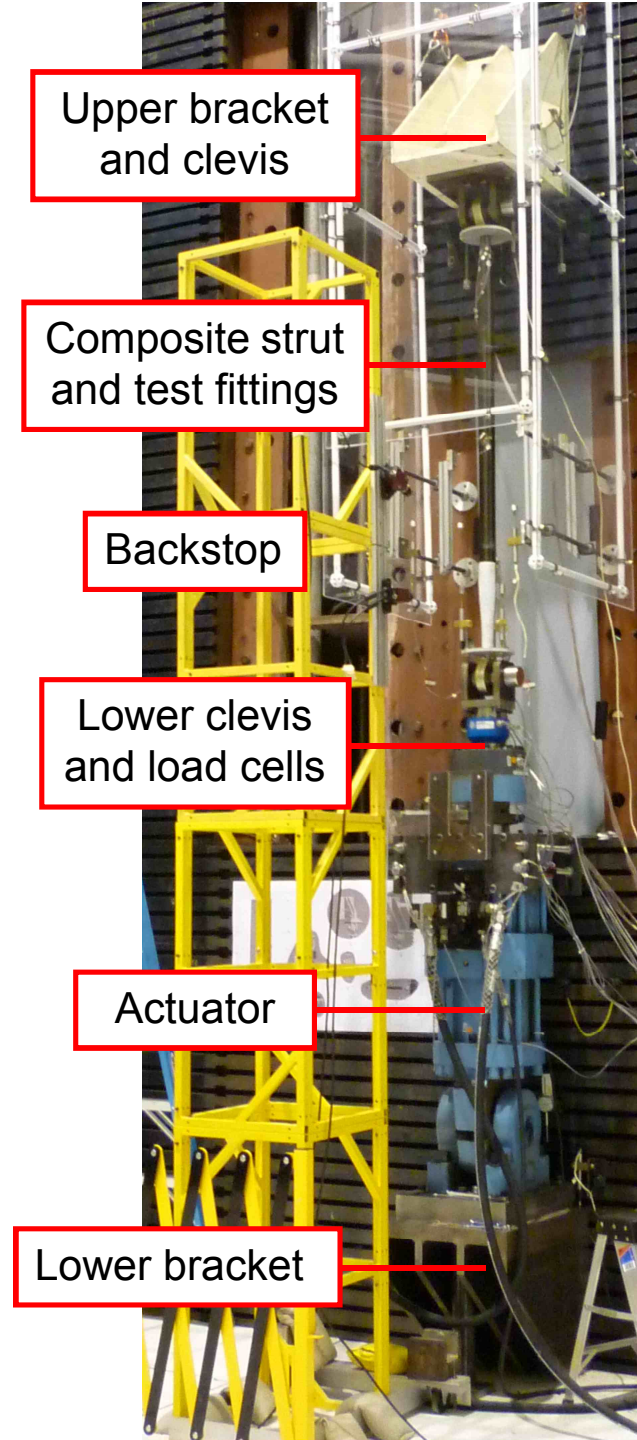
Test Fitting Development

- The interface between composite strut and the test facility was critical to satisfying many of the requirements just described.
- Different options considered for these strut test fittings included cup-and-cone fittings, coupler bearings, and single-DOF hinges.
- High-load rod end bearings selected and modified for the test fittings, and integrated into a double shear, tang and clevis joint.

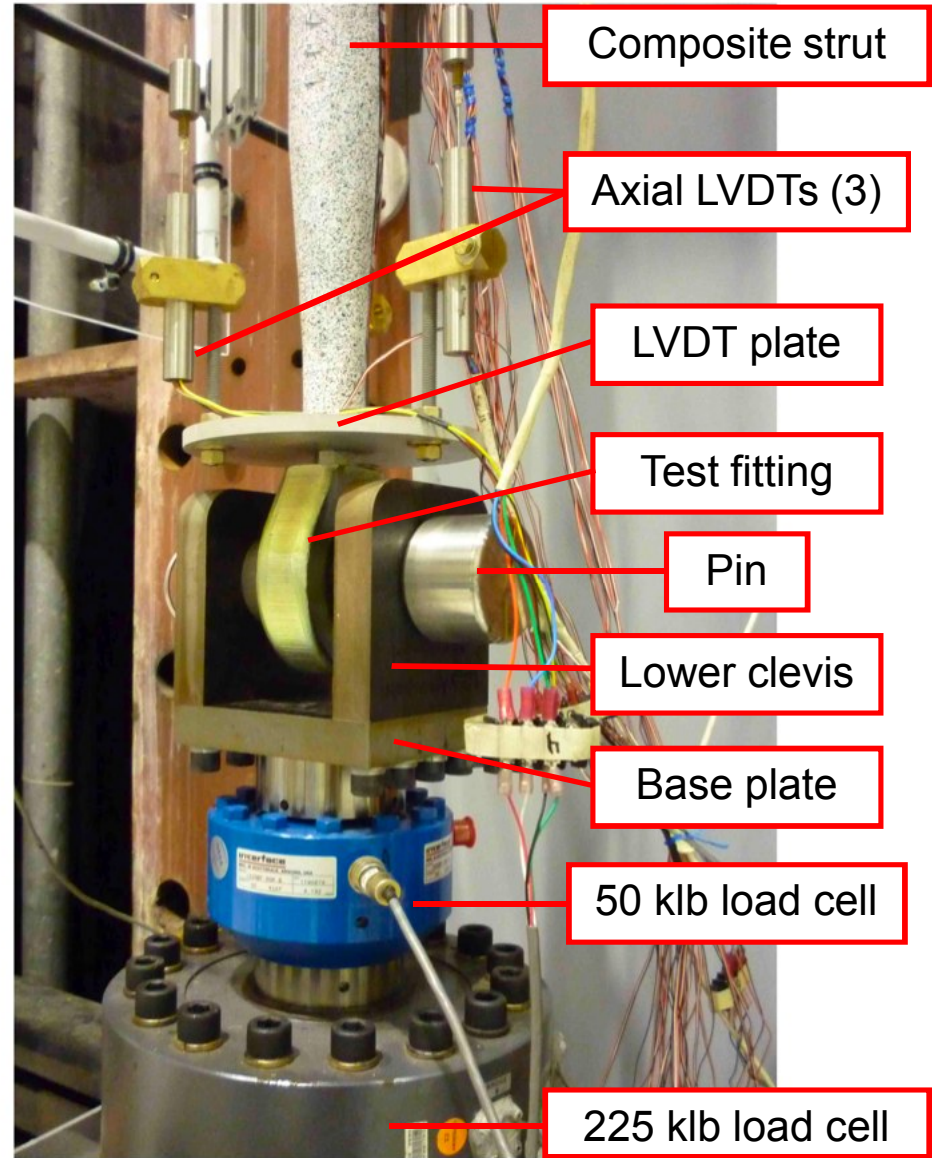
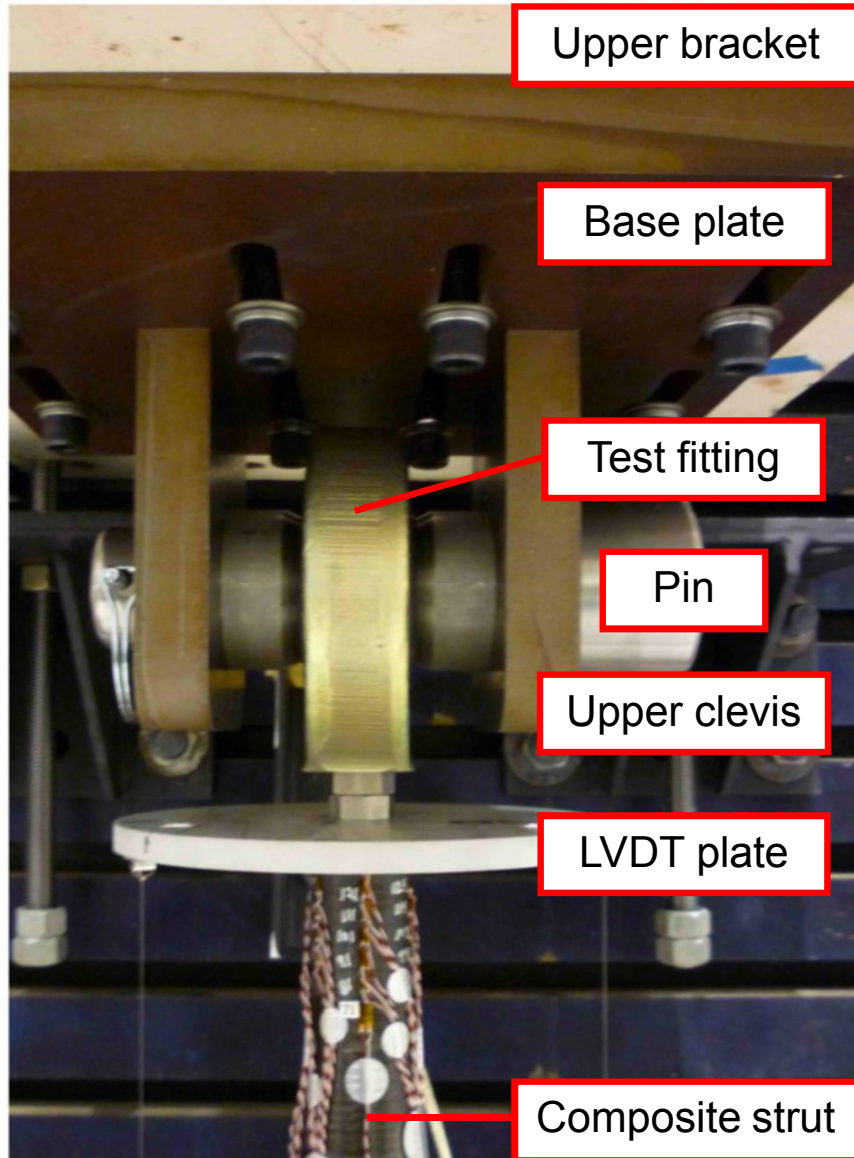


Test Facility Development

- Adjustable upper and fixed lower brackets bolted to stiff structural backstop.
- Composite strut with attached test fittings connected to clevises bolted to brackets.
- Axial forces measured with an integral 225 klb-capacity load cell for high loads, or a removable 50-klb load cell for lower load levels.
- 225 klb-capacity hydraulic actuator run in displacement control to load the strut.
- Displacement transducers (LVDTs) and strain gages (SGs) deployed to measure strut structural response.



Test Facility Development (2)



System Checkout Tests

- Aluminum struts fabricated for system checkout tests. One strut was buckled plastically by accident. Incorporated load and displacement limits in control system.
- Tension testing over 30 klb revealed bending of lower base plate when test fitting was trapped in clevis. Two base plates were then bolted together to increase bending stiffness.
- Measurements of upper bracket axial motion indicated that fixture was slipping along the backstop until the mounting hardware made contact. Special hardware was installed to reduce deadband and help mitigate this problem.
- Test procedures were also modified to reduce effect of upper bracket motion. A "pretest" load of 30 klb was applied before the test load to seat the hardware and reduce deadband.

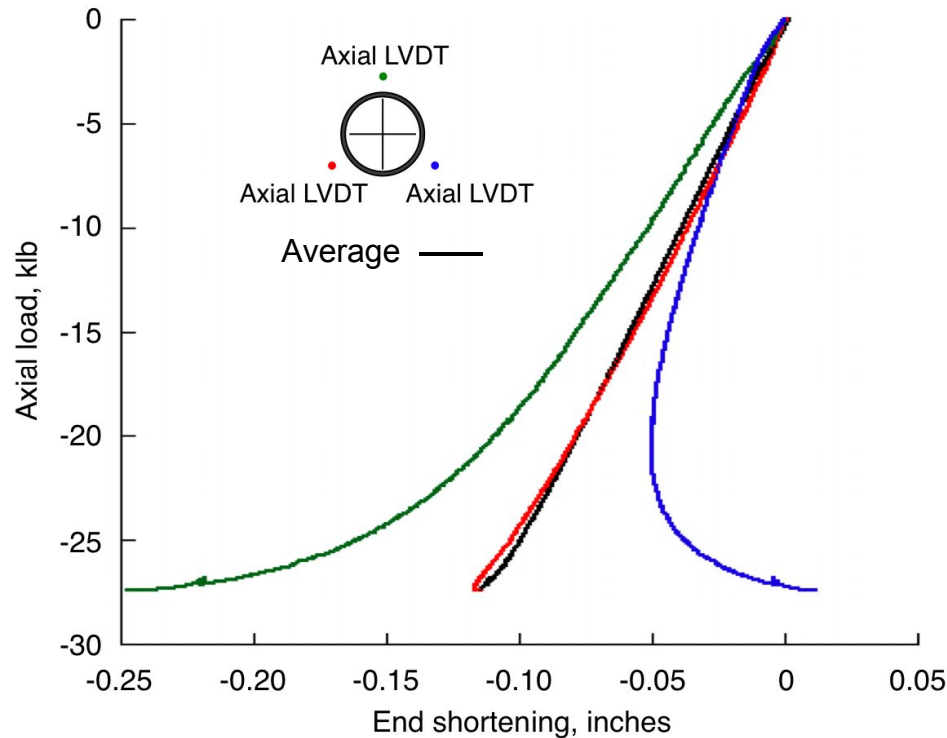
System Checkout Tests (2)

- Final checkout tests were performed using the three composite struts developed as MDUs during the Phase 1 study.
- Two composite struts were 61 in.-long and 2.5 in.-OD. (shown at left), and one strut was 127 in.-long and 6.2 in.-OD (shown at right).
- These composite struts were tested in both tension and compression, but only compression test results are presented here.

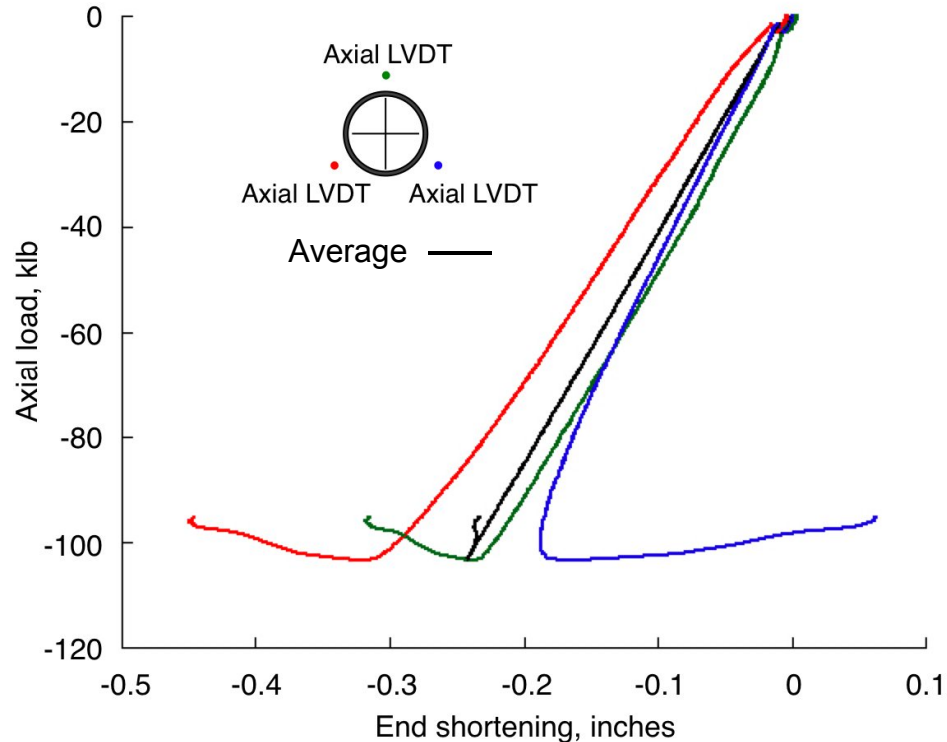


Test Results - Axial Displacement

Three axial LVDTs equally spaced around strut circumference.
Average axial end shortening is linear to maximum load.



Short strut (typical)

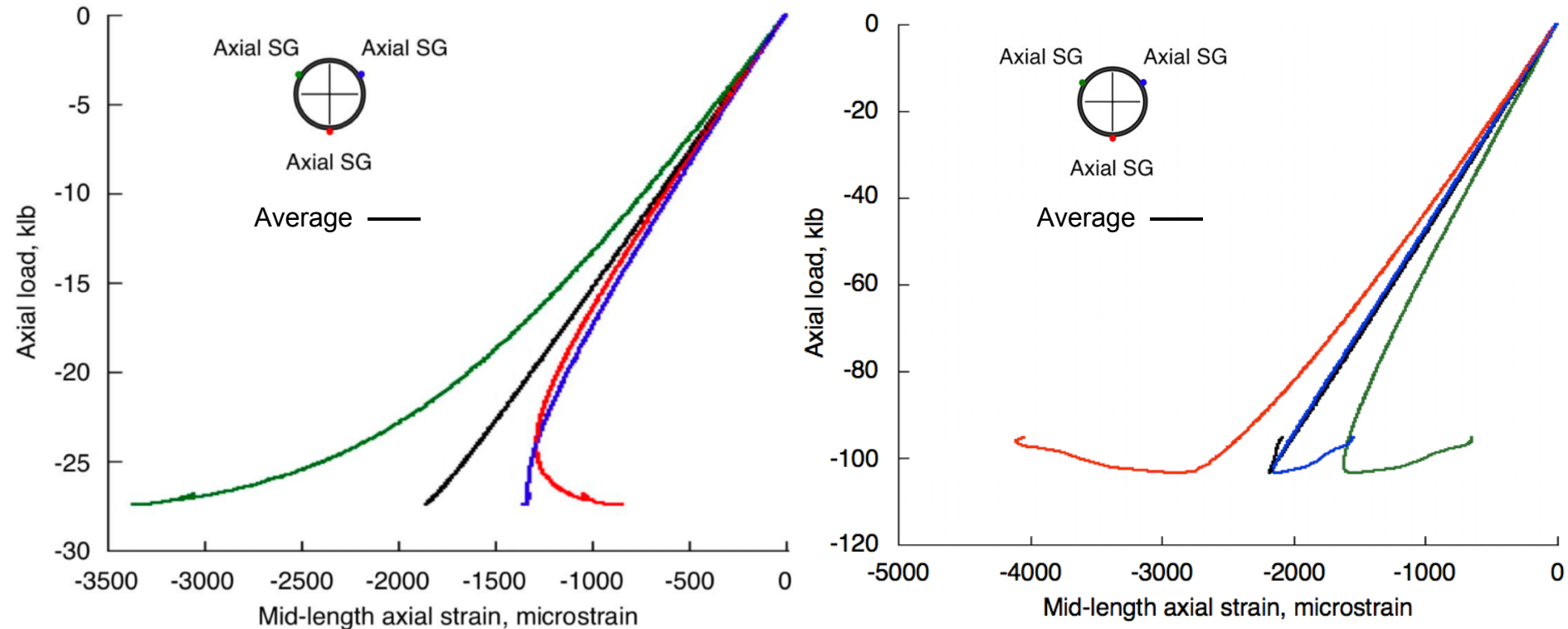


Long strut

Short strut displacements are nonlinear, asymptotic to -27.4 klb.
Long strut displacements roughly linear to buckling at -103.6 klb.

Test Results - Axial Strain

Three axial strain gages equally spaced around strut mid-length circumference. Average axial strain is linear to maximum load.



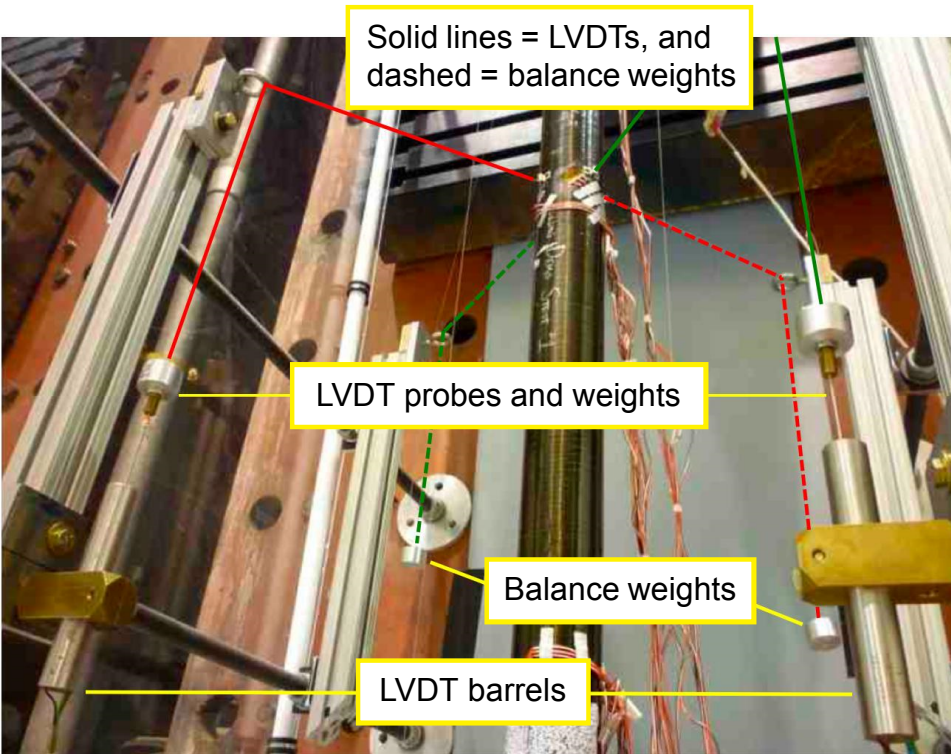
Short strut (typical)

Long strut

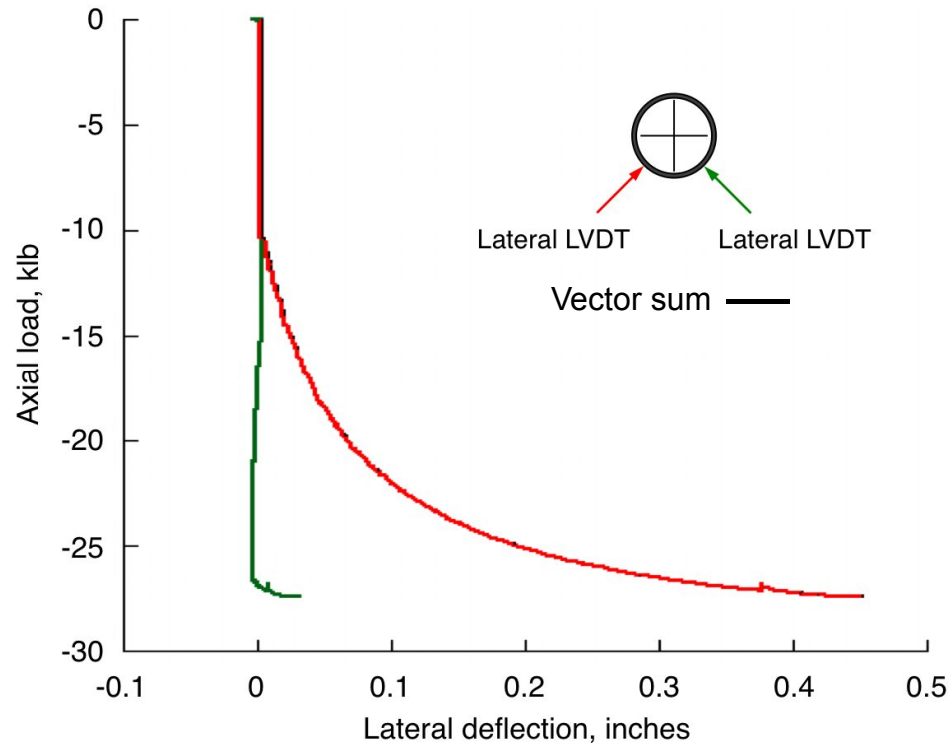
Short strut results indicate large bending throughout test.
Long strut results show less bending prior to buckling.

Test Results - Short Strut Lateral Deflections

Lateral deflections at strut mid-length measured using two LVDTs mounted at right angles normal to the strut axis.



Test setup

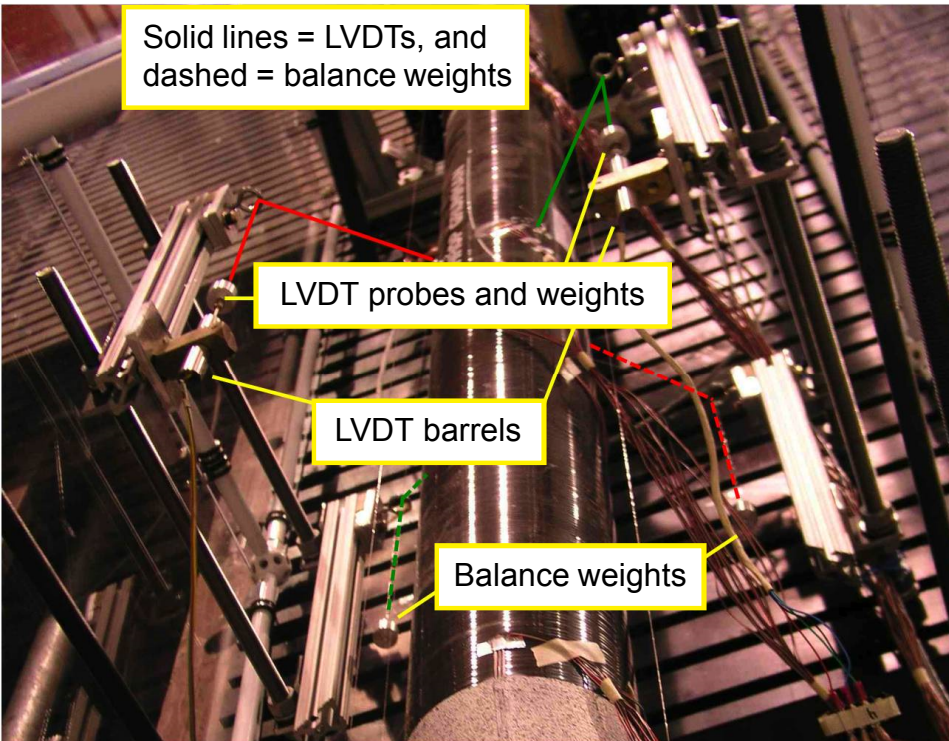


Short strut (typical)

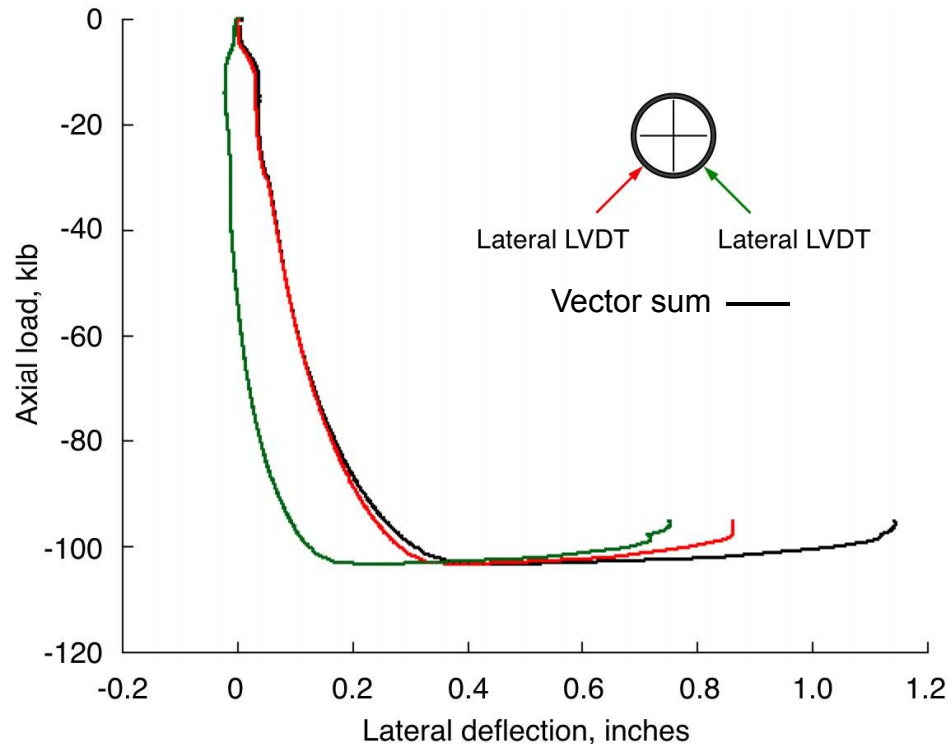
Measured lateral deflection/length ratio of about 1/120.
Strut deflections in plane inclined 45 deg. to backstop.

Test Results - Long Strut Lateral Deflections

Lateral deflections at strut mid-length measured using two LVDTs mounted at right angles normal to the strut axis.



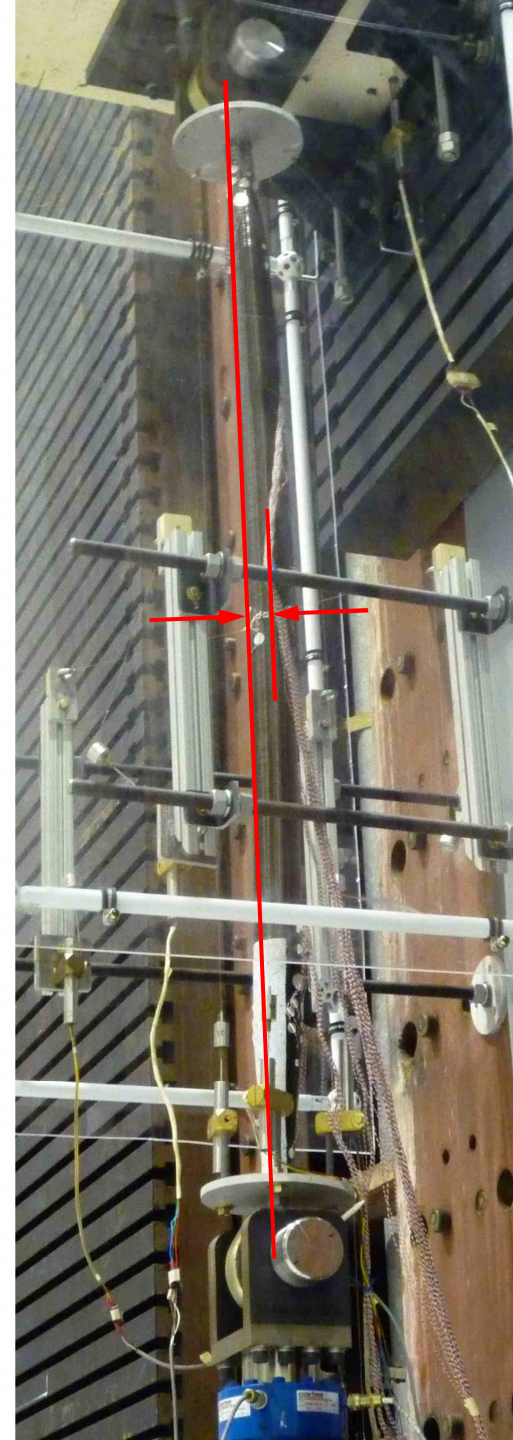
Test setup



Measured lateral deflection/length ratio of about 1/500.
Strut deflections occur in plane perpendicular to backstop.

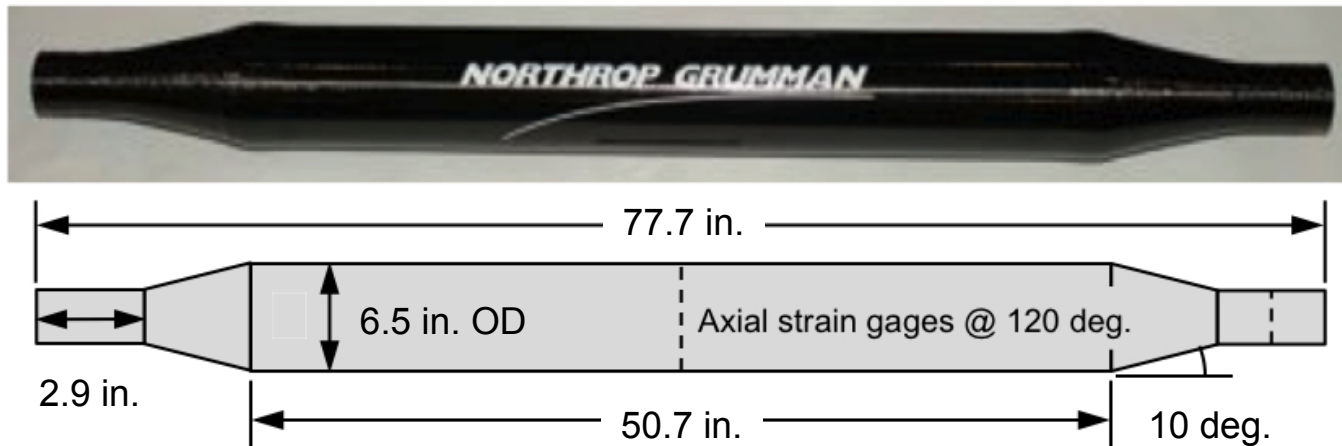
Test Results - Strut Failure

- The three composite checkout struts tested all failed elastically in Euler buckling.
- The two 61-inch short struts buckled at -27.4 and -23.3 klb. Lateral deflection of strut under load is shown at right.
- The 127-inch long strut buckled elastically at -103.6 klb.
- After loads were removed, all three struts returned to their approximate pre-test configurations. No post-test QA performed.
- These results indicated the test capability was suitable for testing the heavily loaded struts developed under Phase 2.



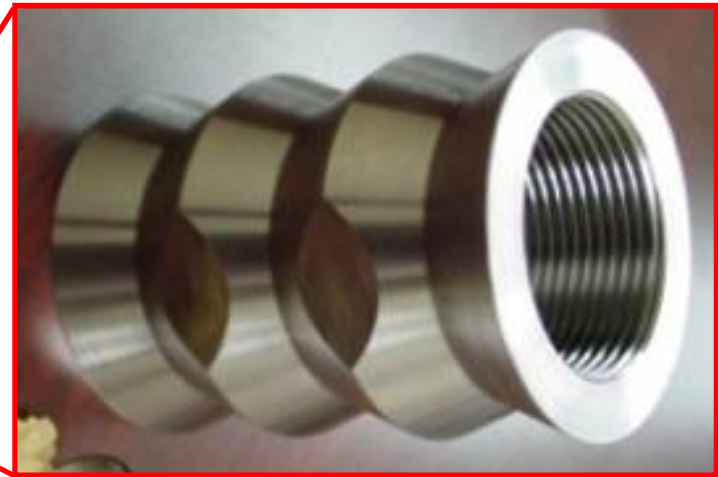
Selected Phase 2 Composite Struts

- Struts were designed and analyzed by Northrop Grumman and Boeing under contract to NASA.
- Park Aerospace fabricated two identical heavily loaded struts under subcontract to Northrop Grumman.
- 17-ply $[90/0_2/\pm 45/0_3/\overline{90}]_S$ laminate of cylindrical strut body fabricated using IM7/8552 prepreg tow and tape material.
- Both tapered ends of the strut contain titanium end fittings.



Selected Phase 2 Composite Struts (2)

- Patented internal titanium end fittings provided interface between strut and test hardware. They were completely integral with the composite strut ends.
- End fittings were aligned with plaster mandrel axis, and composite material was hand-placed over them.
- Additional hoop tows were wrapped around end fittings to provide a smooth OML. After shrink-wrapping, assembled strut was cured in an oven.
- Mandrel washed out from inside of cured strut.



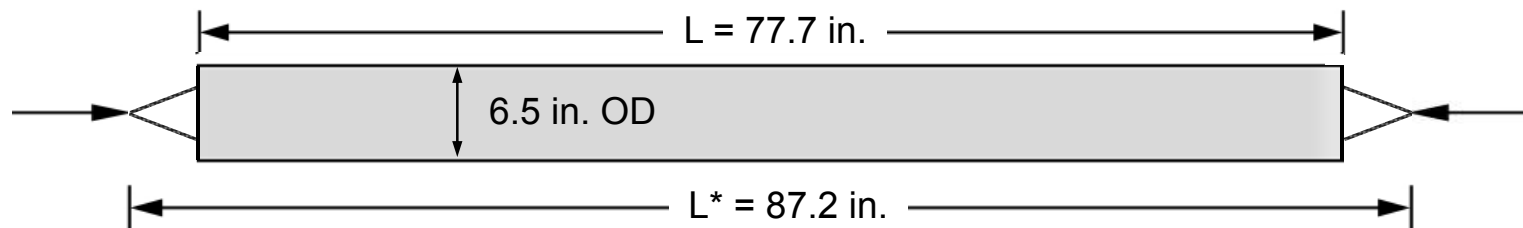
Strut Structural Analysis

- Estimate prismatic tube stiffness and buckling load using classical lamination theory and structural mechanics.
- Laminate axial modulus $E = 14.11 \text{ Mlb/in}^2$ calculated from assumed IM7/8552 compressive ply properties.
- 17-ply laminate thickness of 0.088 in. gives stiffnesses $EA = 24.95 \text{ Mlb}$, $EA/L = 321.2 \text{ klb/in.}$ and $EI = 126.53 \text{ Mlb-in}^2$.
- After inclusion of test fitting lengths, tube Euler buckling load $P_{cr} = \pi^2 EI / (L^*)^2$ is estimated to be -164.3 klb (~1.5x greater than the -107.6 klb strut DUL).

Test hardware



Analysis
model

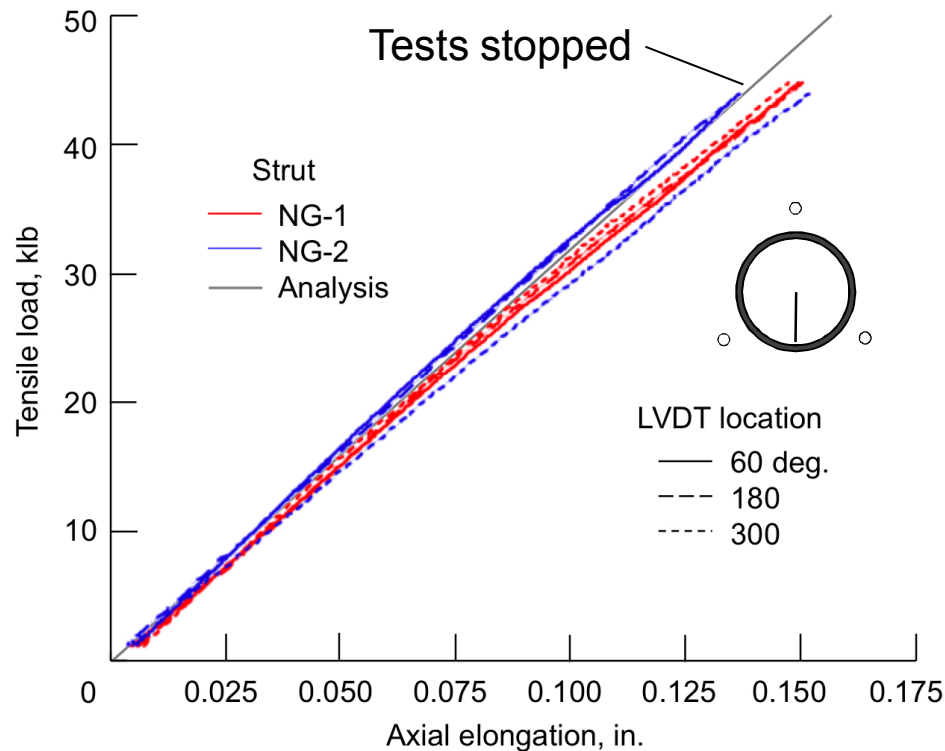


Strut Structural Analysis (2)

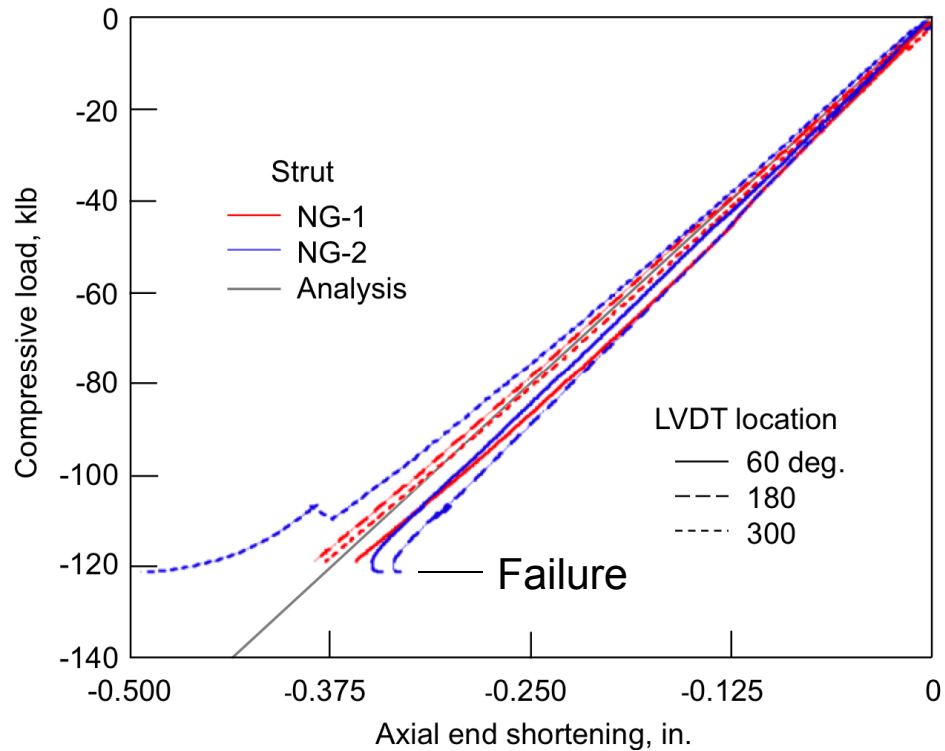
- Estimate prismatic tube first-ply failure load using classical lamination theory and composite mechanics.
- Undamaged strength allowables assumed for IM7/8552 ply (all klb/in²). Tensile $X_t = 363$, $Y_t = 9$; compressive $X_c = -249$, $Y_c = -41$; shear $S = 13$.
- Strength analysis of 17-ply laminate with $[90/0_2/\pm 45/0_3/\overline{90}]_s$ layup predicts Hill-Tsai first-ply failure in 0-degree plies at $P_{\text{fpf}} = -296$ klb axial load.
- Predicted strength failure is almost 2x times predicted global instability load. Therefore, acreage tube strength should not be dominant failure mode.

Test Results - Axial Displacement

Struts were first loaded to tensile DLL (44.3 klb average), then loaded to failure in compression (-120.5 klb average).



Tension tests

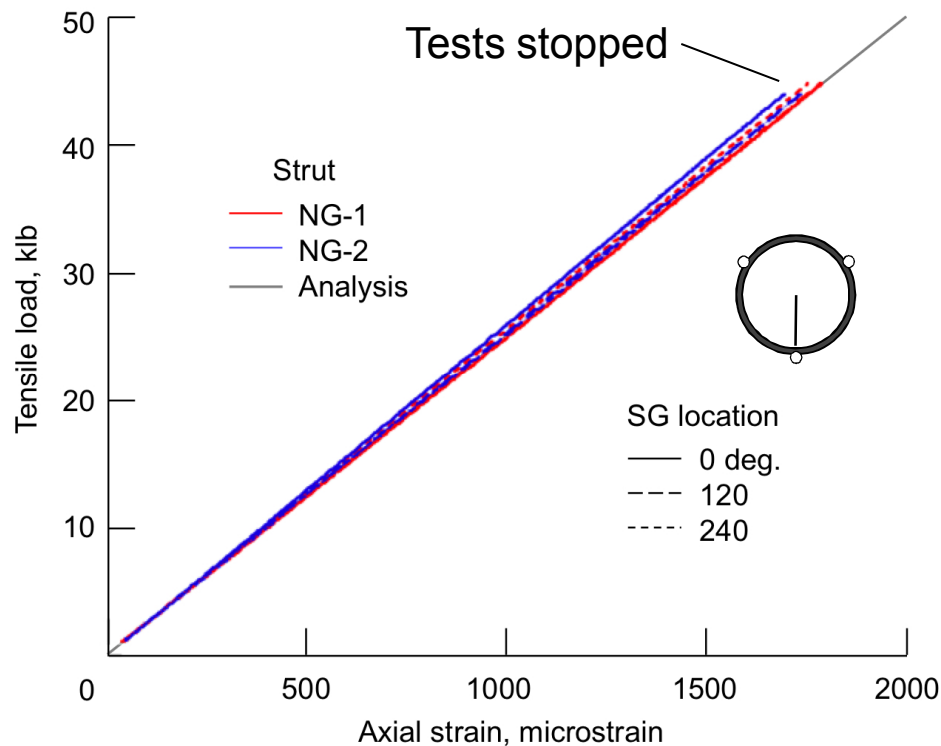


Compression tests

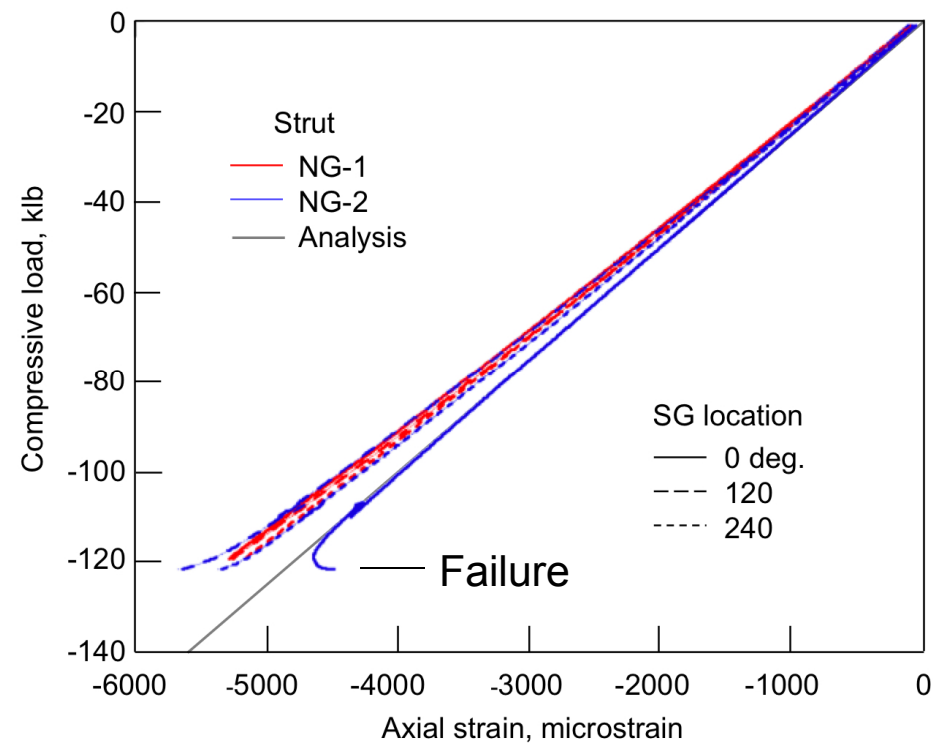
Measured strut axial displacements are linear to near failure.
Averaged slopes 1.4 percent below predicted strut stiffness EA/L .

Test Results - Axial Strain

Three axial strain gages deployed around strut mid-length circumference to measure elongation and bending.



Tension tests



Compression tests

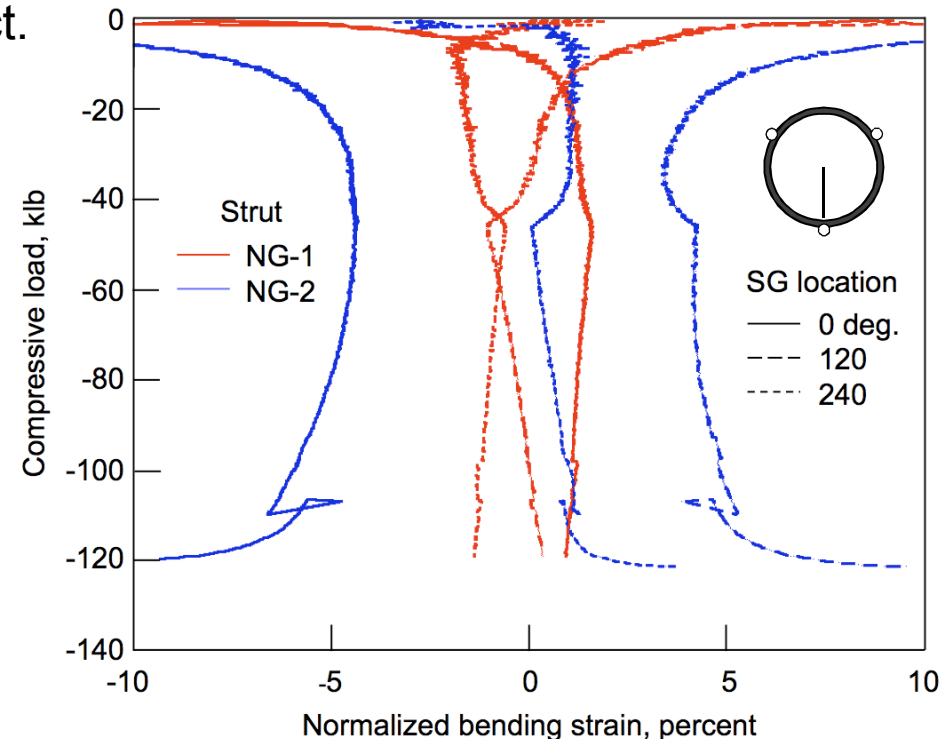
Measured strut axial strains linear to near failure. Averaged slopes 2.5 percent below predicted cross-section stiffness EA.

Test Results - Normalized Bending Strain

- Normalized bending strain at strut mid-length is defined as the ratio of bending strain to axial strain, calculated as:

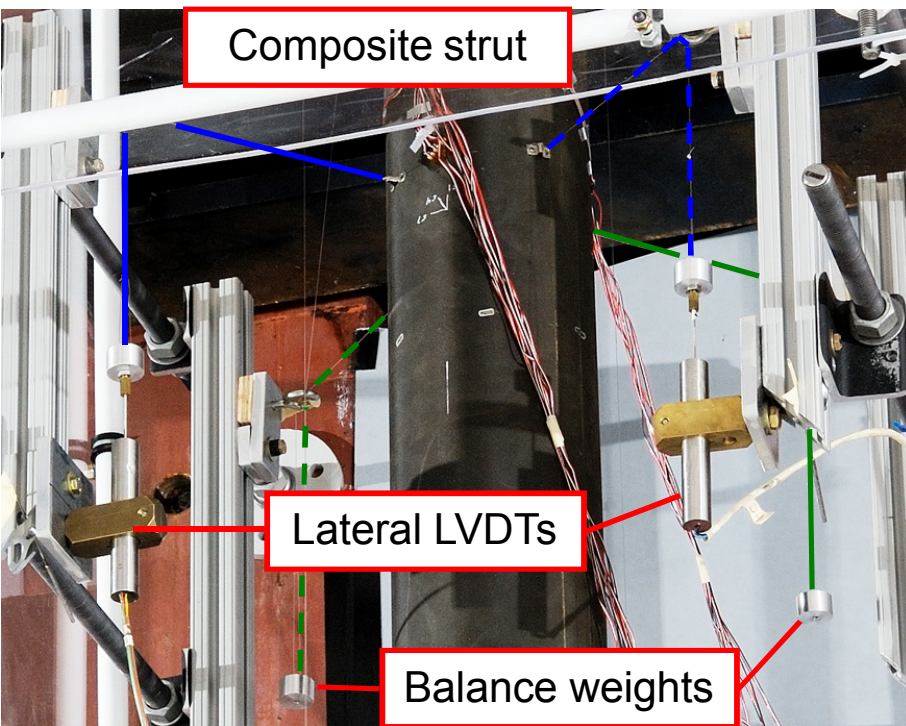
$$\frac{\text{axial strain} - \text{average strain}}{\text{average strain}} \times 100 \text{ pct.}$$

- Compression test loads are plotted at right vs. the normalized bending strains.
- Large strain variations at low loads are not considered significant.
- Normalized bending strains are bounded by about ± 5 percent up to failure, indicating that little strut bending was occurring.

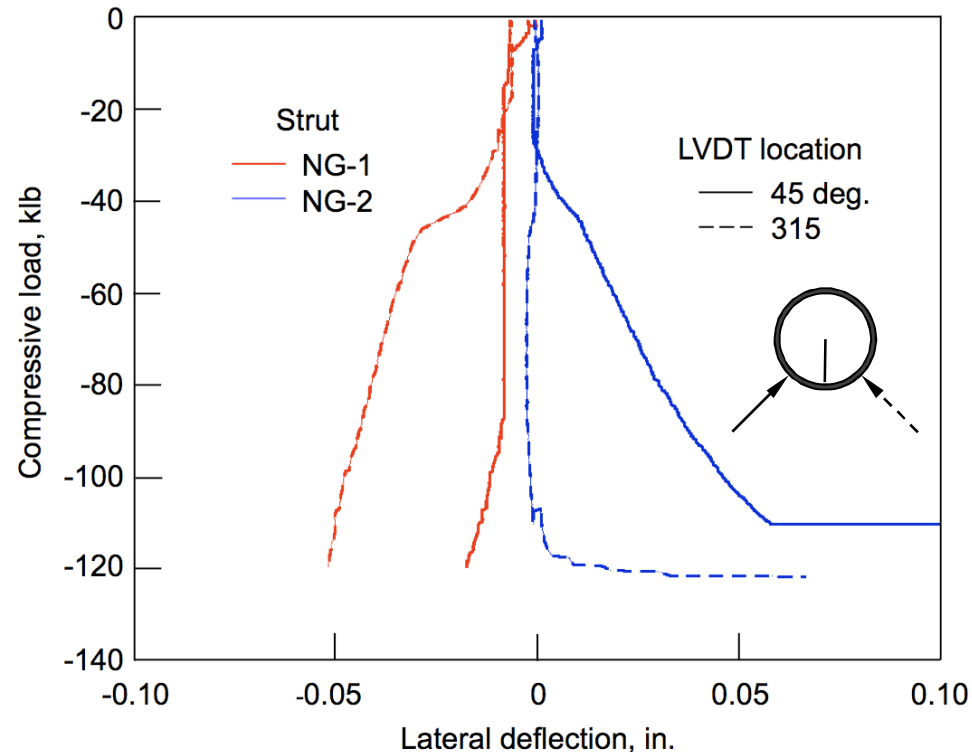


Test Results - Lateral Deflection

Lateral deflections at strut mid-length measured using two LVDTs mounted at right angles normal to the strut axis.



Test setup

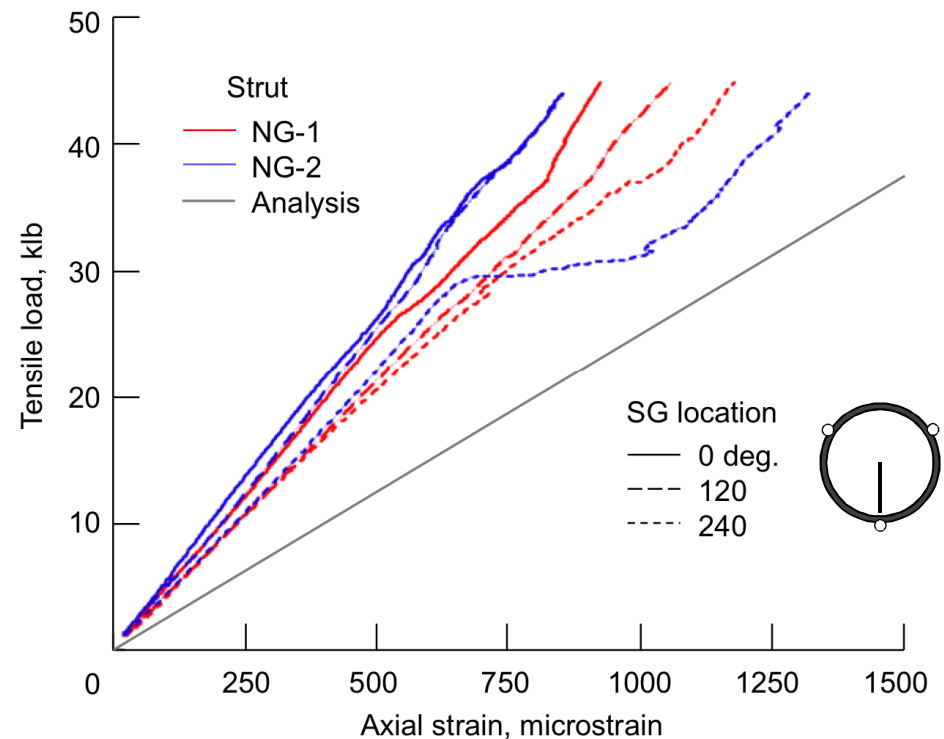


Compression tests

Measured lateral deflections were small ($\sim L/1550$ max.), so minimal strut bending was occurring prior to failure.

Test Results - Tensile Strain At Strut Upper End

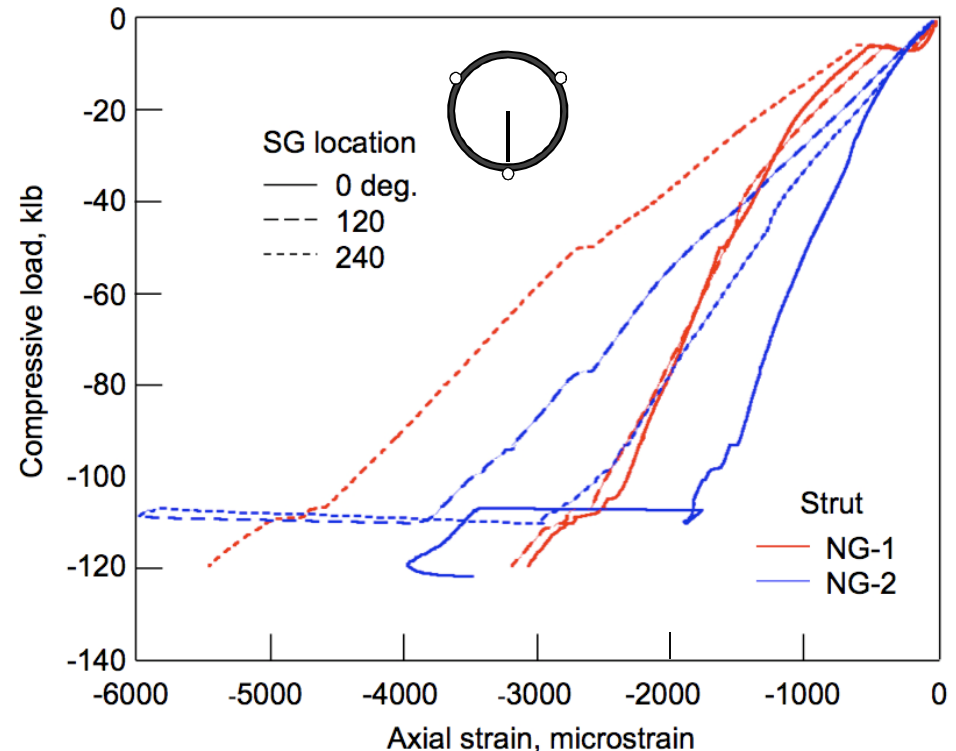
- Strut tensile loads are plotted below vs. axial strains from gages located around the upper end fittings.
- Variations in axial strains from tension tests suggest possible internal damage.
- Slopes are $\sim 2\times$ greater than predicted strut cross-section stiffness EA . Joint region is much stiffer than cylindrical tube.
- Damage appears localized to upper end fittings of struts. However, no NDE of struts was performed after tests.



Tension tests

Test Results - Strut Compressive Failure

NG-1 strut test stopped after sudden load drop at -119.3 klb.
NG-2 loaded past -110 klb load drop to collapse at -121.7 klb.



Compression tests

NG-2 failed upper end fitting
(no visible damage on NG-1)

Data from axial strain gages deployed around upper end fittings.
Measured strains nonlinear; large variations near NG-2 failure.

Concluding Remarks

- Test capability developed to load composite struts to 150 klb in both axial tension and compression.
- Hardware was adaptable for testing full range of strut lengths.
- System checkout tests were performed to identify issues with test hardware, which were then successfully mitigated.
- Three composite struts were successfully tested to high loads in axial compression, verifying system capability.
- Column buckling in multiple planes indicated that the rod end bearing test fittings provided desired pinned-end boundary conditions for the struts.
- This test capability was successfully used to test the heavily loaded composite struts developed under Phase 2.

Concluding Remarks (2)

- Heavily loaded composite struts were tested to tensile DLL, and also carried compressive loads to 112 percent of DUL.
- Axial displacements and strains were linear to near failure, and correlated well with simple analytical predictions.
- Titanium end fittings showed robust structural performance, with good tolerance to internal damage.
- Strut failure was characterized as strength-based, and was localized to the end fitting region. Struts did NOT fail in stiffness-driven buckling or acreage strength.
- This strut concept met the structural requirements, and shows great potential for structural applications on the Altair lunar lander, an application where minimum mass is critical for mission success.

Thank you!
Questions?