Outline

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  - Approach

• Project Highlights
  - Metallic Cylinder Testing
  - Benefits to the Space Launch Systems (SLS)

• Next Phase: Composite Structures

• Concluding Remarks
Introduction
Large amount of cylinder testing occurred in the 1920s-1960s to help understand shell buckling

- Significant scatter in the buckling loads that were typically less than theoretical predictions

Differences between test and analysis are now primarily attributed to initial geometric imperfections (i.e., out-of-roundness)

Standard practice is to apply a design knockdown factor to theoretical predictions of perfect cylinder

Knockdown factor – lower-bound design recommendation
Shell buckling is the primary design driver in many recent NASA launch vehicle designs.

Conservative design factors have the potential to result in overweight structural designs.
Shell Buckling Knockdown Factor Project (SBKF)

NASA Engineering and Safety Center (NESC) assessment
- 2007 – Present

Objective
- To develop and validate new analysis-based shell buckling knockdown factors (KDF) and design guidelines for launch-vehicle structures
  - Metallic cryotank and dry structures (2007 – 2016)
  - Composite dry structures (2015 - ?)

Expected outcome
- Reduce structural mass and mass-growth potential
- Enable new structural configurations
- Increase KDF fidelity to improve design trades and reduce design cycle time/redesigns
Developing New Design Factors

- Validated high-fidelity analyses are being used to generate the design data (virtual tests)

- Testing serves to validate the analyses

- New factors will account for the following:
  - Initial shell-wall geometric imperfections (out-of-roundness) and nonuniform loading (caused by end imperfections)
  - Modern launch-vehicle structural configurations and materials
  - Relevant launch vehicle loads
  - Joints

- Implementation
  - Engage the user community to review and refine a technology development and implementation plan
Project Highlights

- Metallic Cylinder Testing
- KDF Implementation on SLS
Metallic Cylinder Testing
Subscale and Full-Scale Cylinder Testing

- Relevant metallic launch-vehicle-like structures
- State-of-the-art manufacturing, testing, and measurement techniques

Subscale (8-ft diameter) launch-vehicle cylinders

Full-scale (27.5-ft diameter) launch-vehicle cylinders

7 of 9 complete

2 of 2 complete
Predicted and Measured Buckling Response

Test and analysis results correlate well:

- Buckling loads predicted within 5% - 10%
- Physics of buckling initiation and propagation predicted accurately
- Validated high-fidelity analysis methods can be used to derive analysis-based design factors
KDF Implementation on SLS
Boeing Testimonials* and Return on Investment

- The Boeing Company (Boeing) has utilized our preliminary set of KDFs in the design of the Block 1 SLS Core Stage
- Testimonials from Boeing management state that the new KDFs enabled
  - 2,000 lb - 3,000 lb mass savings in the SLS Core Stage tanks (5% - 8%)
  - Reduced material costs by $300K - $400K per launch by using thinner plate material (machining cost reduction also expected, but not captured here)
  - Reductions in design and analysis cycle time by eliminating the need for detailed structural optimization of weld lands
  - Contributed significantly to on-time PDR

- Return on investment (ROI) rough order of magnitude (ROM) based on mass savings only
  - Assume 3,000 lb mass savings in Core Stage tanks
  - Assume core stage gear ratio = 5.5
  - Assume $10K/lb payload

\[
\text{ROI} = \frac{3,000 \text{ lb}}{5.5} \times $10K/\text{lb} = $5.45M \text{ savings per launch}
\]

*Boeing SLS Core Stage Design Technical Lead Engineer
Composite Structures
Engaged in a detailed planning phase

• Trade studies to identify design space

• Preliminary test planning
  – Considering 2.5-m to 4-m diameter cylinders
  – Assessing fabrication options
  – Assessing test facility options

• Looking for collaboration opportunities
  – Test article fabrication
  – Cylinder and cone geometry measurements
Preliminary Design and Imperfection Sensitivity Study

- **Ares V Interstage, honeycomb-core sandwich composite**

- **Design optimization**
  - Given facesheet layup and knockdown factor, optimize for facesheet and core thicknesses
  - Three facesheet layups
    - Quasi-isotropic (25% axial plies)
    - Tailored (43% axial plies)
    - Highly tailored (60% axial plies)
  - \(0.6 \leq KDF \leq 0.9\)
    - 500 lb - 1,000 lb (7%-15%) weight savings on Interstage

Optimized Designs

Not allowed by SP-8007 sandwich calculation

Potential new designs
Composite Cylindrical Test Articles

• **8-ft dia. honeycomb-core sandwich composite cylinder**
  – Nonreimbursable SAA with Northrop Grumman Corporation
  – Out-of-autoclave construction
  – Single piece (unsegmented)
  – Testing Oct. 2015

• **13-ft dia. fluted-core sandwich composite cylinder**
  – Nonreimbursable SAA with Boeing
  – Segmented in-autoclave construction
Concluding Remarks

• SBKF is using validated high-fidelity models to derive new analysis-based shell buckling knockdown factors for launch vehicles
  – NASA has implemented new knockdown factors on the SLS core stage
  – Demonstrated savings in mass, design cycle time, and cost

• Currently ramping up the SBKF Composites work

• We welcome your comments and participation
• Questions or Comments?