Structural Design and Analysis Considerations

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Outline

• **Part One**
  – Mechanical Design Considerations
  – Structural Assessment: Analysis and Test

• Break

• **Part Two**
  – Shell buckling research at NASA
    • Background
    • Test-article design example
    • Large-scale testing
Mechanical Design Considerations
Launch, Test
Typical Launch Vehicle

Wet structure

Dry structure

Payload fairing

Payload

Payload Adapter

Interstage

Skirts

Intertanks

Solid rocket motors

Engine section

Cryotanks

Payload Adapter
Structural Design Considerations

- Primary Function
- Loads and Environments
- Material Selection
- Structural Configuration
- Fabrication and Assembly
- Geometric Constraints and Interfaces
- Structural Integrity
Structural Design Considerations: Primary Function

- **Determine primary function**
  - Primary structure
  - Secondary structure
  - Propellant tank
  - Mechanism
  - Aerodynamic surface
  - Insulation
  - Etc.
Structural Design Considerations: Loads and Environments

• Aerodynamic loads
• Aeroheating
• Shock and vibration
• In-space environments
• Cryogenic storage
• Transportation and lifting

Shuttle

Saturn V, Dynamic Test Stand
Structural Design Considerations: Material Selection

- Metallic Propellant Tank
- Composite Payload Adapter
- Cork Thermal Protection System
- 3D Printed Plastic
Structural Design Considerations: Structural Configuration

- Monocoque/solid laminate
- Truss
- Stiffened skin
- Skin stringer
- Sandwich

Payload fairing

Second stage

Hat stiffened stringer

Metallic orthogrid

Composite isogrid
Structural Design Considerations: Fabrication and Assembly

- Precision-machined pieces
- Post-machined assembly
- Joint design
  - Rivet/Bolt/Weld/Bond
- Filament wound or composite layup
Structural Design Considerations: Fabrication and Assembly

Fabrication was performed at Marshall Space Flight Center (MSFC)
Structural Design Considerations: Fabrication and Assembly

Fabrication was performed at MSFC
Structural Design Considerations: Geometric Constraints and Interfaces

Solid Rocket Boosters (SRB)

External Tanks (ET) Thrust Beam

NASA Shuttle, Intertank/SRB Attachment
Structural Design Considerations:
Geometric Constraints and Interfaces

Apollo Era Lunar Rover

Lunar Rover Stowed

Lunar Rover Deployed
Structural Design Considerations: Geometric Constraints and Interfaces

NASA/DLR Deployable Composite Booms (DCB)

2,000-m²-class solar sail
Structural Design Considerations: Structural Integrity
Structural Design Considerations: Structural Integrity

- Strength
- Stability
- Frequency
- Fracture and fatigue
- Damage Tolerance

Each material and structural system has different failure modes.

NASA Space Launch System (SLS) Hydrogen Tank after test to failure at MSFC
Structural Design Considerations: Structural Integrity

Local buckling

Material failure

Global Buckling
Structural Design Considerations: Structural Integrity

Local buckling (facesheet dimpling)  Global buckling

Delamination  Core damage  Core damage

Material failures
Structural Assessment
Structural Assessment

• **Analysis**
  – Classical analytical methods
    • Hand calculations
    • Closed-form solutions
  – Numerical methods
    • Finite element analyses (FEA)

• **Testing**
  – Building block
Some Common Simplifications in Structural Analysis

- Continuum assumption
- Boundary conditions
- Uniformity/lack of design details
- Perfect or nominal
- “Smeared” shell or plate
- Linear material properties
- Geometrically linear response
- Assumed form of displacements, stresses, strains, etc.
- Transverse shear response: nondeformable, first- or second-order, etc.
Honeycomb-Core Sandwich Composite

Anders, et al., 2019

Centea, et al., 2018
Honeycomb-Core Sandwich Composite: Ply Drop

Redistribution of plies around ply drop

Little evidence of draping

~10 mm

Core cell wall
Integrally Stiffened Metallic Shell

Weld land

Attachment rings

Fail-safe bolt (typical)

Garcia, et al., 2019
“All models are wrong, but some are useful.”
– George E. P. Box
Short Break
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  – Structural Assessment: Analysis and Test

• Break

• Part Two
  – Shell buckling research at NASA
    • Background
    • Test-article design example
    • Large-scale testing
Shell Buckling Research at NASA

Background
Traditionally, metals have been used for most launch-vehicle primary shell structure
- Tanks
  - Integrally stiffened orthogrid or isogrid, etc.
- Dry structure
  - Fastened hat stiffeners, etc.

More recently, composites have been gaining wider acceptance for primary structure
- Potential gains (mass, thermal, cost, etc.)
- Most commonly have sandwich construction
- Most often considered for dry structures
• **Cylindrical shells**
  – Significant portion of launch-vehicle structure

• **Buckling**
  – Often a controlling failure mode during design
  – Empirical buckling loads are often significantly less than theoretical predictions
Empirical Shell Buckling Design Approach

- Standard practice is to predict the buckling load of an idealized perfect cylinder and apply an empirical buckling knockdown factor (KDF) to account for differences between test and analysis.

- Differences between test and analysis primarily attributed to initial geometric imperfections in the shell wall (i.e., out-of-roundness).

\[
\begin{align*}
P_{\text{cr}} & \quad \text{perfect} \\
\delta & \quad \text{knockdown} \\
P_{\text{lim}} & \quad \text{imperfect}
\end{align*}
\]
Most commonly used source of empirical buckling knockdown factors for cylindrical shells

Pedigree of test articles and test data (1920s-1960s) used to develop the knockdown factors is difficult to assess

Most test-article designs not relevant to modern launch-vehicle constructions and material systems
- Limited data for stiffened cylinders
- No data for composite cylinders

Generally thought to be overly conservative—this can lead to a large weight penalty
Shell Buckling Knockdown Factor Project: Composite Structures

• **Objective:** Develop new analysis-based buckling knockdown factors (KDFs) for composite launch-vehicle structures

• **Scope**
  – Sandwich-composite cylinders
  – Acreage designs
  – Axial compression

• **Approach**
  – **Analysis-based** knockdown factor development and validation
    • Develop and assess various knockdown factor prediction methodologies
  – Targeted **validation testing** at coupon, panel, and cylinder levels
    • Relevant subscale test-article designs that span the launch-vehicle design space
    • State-of-the-art manufacturing, testing, and measurement techniques
  – Implementation of new knockdown factors
    • Engage the user community to review and refine a technology development and implementation plan
    • **Domestic and International collaborations**
Validation Testing Levels

• **Coupon**
  – Shell property testing
  – Transverse shear stiffness

• **Panel**
  – Out-of-plane deformations
  – Effects of joints
  – Effects of damage
  – Scaling

• **Subscale cylinders**
  – 2.4-m diameter
  – Validate analysis approach
For subscale cylinder testing

- **Test articles**
  - 2.4-m diameter
  - Lengths up to 3 m

- **Loading**
  - Uniform compression up to 7000 kN
  - Combined compression and bending
Shell Buckling Research at NASA

Test-Article Design Example
Test-Article Design Example: Design Requirements

- **Test-article first failure mode under axial compression should be global buckling**
  - Desire to have *factor of 1.4 (Failure Index* below 0.71) between global buckling and all other failure modes
  - Buckling should occur within facility load limits (1.5x10⁶ lbf)

- **Test-article shell design should be in desired design space ("thin," axially stiff, etc.)**

- **Design should follow best practices for aerospace composite design and fabrication**

- **Test article to be fabricated at MSFC using automated fiber placement**

\[ *\text{Failure Index} = \frac{p_{cr}^{\text{FEA Perfect}}}{P_{fail}} \]
Test-Article Design Example: Analyses

- Closed-form “hand” calculations
- Finite element analysis: shell models
- Finite element analysis: axisymmetric models
- Finite element analysis: global-local models
Test Article Design

Closed-Form Calculations
Closed-Form Calculations for Preliminary Design

- **Global buckling load,** $P_{cr}$
  \[ P_{cr} = 4\pi R t_f \phi \sigma_{cr}^r \left(1 - \frac{1}{2} \frac{\phi \sigma_{cr}^f t_f t_c}{G_x z h^2}\right) \]

- **Axial strain at buckling,** $\varepsilon_{cr}$
  \[ \varepsilon_{cr} = \frac{P_{cr}}{4\pi R t_f \bar{E}_x} \]

- **Sandwich failures**
  - Facesheet wrinkling, $P_{FW}$
    \[ P_{FW} = 4\pi R t_f \sqrt{\frac{2 t_f E_C}{3 t_c 1 - \bar{v}_{xy} \bar{v}_{yx}}} \frac{E_x E_y}{\sqrt{E_x E_y}} \]
  - Facesheet dimpling, $P_{FD}$
    \[ P_{FD} = 4\pi R t_f \frac{2 \sqrt{E_x E_y}}{1 - \bar{v}_{xy} \bar{v}_{yx}} \left(\frac{t_f}{d}\right)^2 \]
  - Core shear instability, $P_{CS}$
    \[ P_{CS} = 4\pi R t_f \frac{G_{xz} t_c}{2 t_f} \]

Sullins, et al., 1969
Subscale Cylinder Testing
(2.4-m diameter)

Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

- Calculate design-space parameters for launch-vehicle components
Subscale Cylinder Testing
(2.4-m diameter)

Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

– Calculate design-space parameters for launch-vehicle components
– Generate possible 2.4-m-diameter subscale designs
  • Variables: number of plies, ply angle, core thickness
Subscale Cylinder Testing
(2.4-m diameter)

Challenge is to design buckling-critical subscale test articles in relevant areas of the design space

- Calculate design-space parameters for launch-vehicle components
- Select subscale designs
  - Criteria: buckling critical, failure load, design space, etc.
  - Five test-article designs selected as minimum number to validate analysis methods
Selected Design

• **Faces**
  – 5-ply axially stiff facesheets: $[\pm 30/90]_s$
  – Padups: four interleaved ±45 plies/face dropped at 35 cm, 40 cm, 46 cm, and 51 cm

• **Core**
  – Acreage: 50 kg/m$^3$ aluminum honeycomb
  – End 25 cm: 130 kg/m$^3$ aluminum honeycomb
  – Thickness: 5 mm

• **To be tested in axial compression to failure**
Test Article Design

Finite Element Analysis: Shell Model
• **Model**
  - Approximately 154,000 shell elements (S4R)
  - Element size: 13 mm in the axial direction by 0.5-degree (approximately 10 mm) in the circumferential direction
  - Problem size: approximately 932,000 degrees-of-freedom

• **Analyses**
  - Linear buckling
  - Nonlinear transient buckling (perfect and imperfect geometries)
Characteristic Loads and Linear Buckling

Load versus end shortening

Perfect Linear Buckling 2467 kN
Perfect Nonlinear Results at 2397 kN
Nonlinear w/ Radial Imp. Results at 529.6 kips

Radial displacement, fundamental mode, 2467 kN
Nonlinear Analysis at 2397 kN
Perfect Geometry

Radial Displacement, mm

Axial Strain, με
Additional Sandwich Composite Failure Modes

Core crushing

Core-to-facesheet separation

Core tensile failure

Sullins, et al., 1969
Test Article Design

Finite Element Analysis: Axisymmetric Model
Axisymmetric FEA Analysis: Model

- **Half-cylinder-height model**
  - Applied displacement at midlength
  - Midlength constrained from rotating

- **Abaqus CAX4 elements**
  - Fully integrated
  - Axisymmetric continuum formulation

- **Individual plies modeled**
  - Ply drops modeled as wedges
  - Wedges have same properties as terminating ply

- **Model metrics**
  - 220,000 elements
  - 685,000 DOFs

- **Static solver**
  - Geometrically nonlinear
  - Linear-elastic material
**Axisymmetric Analysis**

**Comparison with perfect-geometry shell model**

Radial displacement at 1779 ± 22 kN

End of potting
Test Article Design

Finite Element Analysis: Global-Local Model
Finite Element Analysis: Global-Local Analysis

Solid elements in core, continuum shell elements in facesheets

Two Global Models
• Perfect mesh model
• Radial imperfection mesh model
Finite Element Analysis Results: Global-Local Analysis

Global Shell Model

Local Solid Model

Radial displacement (mm)

27.4

Perfect, 2144 kN

28.7

With radial imperfection, 2135 kN
<table>
<thead>
<tr>
<th>Analysis</th>
<th>Failures interrogated</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
</table>
| Closed-form (hand calculations) | • Linear global buckling (for initial down select)  
• Facesheet wrinkling  
• Facesheet dimpling  
• Shear crimping | • Quickly assess many designs  
• Calculate otherwise difficult-to-predict failure loads | • Linear only  
• Perfect geometry only  
• Simple, uniform shell only |
| FEA shell                | • Global buckling  
• Facesheet strength failures | • Linear/nonlinear analyses  
• Can easily include measured radial and thickness imperfections  
• Pretest buckling predictions | • Cannot capture core crush or shear failures  
• Cannot capture end conditions in great detail |
| FEA axisymmetric        | • Global buckling  
• Smeared-core strength failures (crush, shear)  
• Core-to-facesheet interface stresses  
• Facesheet strength failures | • Linear or nonlinear analyses  
• Interrogate facesheet and core response in detail (high mesh density) for low computational cost  
• Investigate effects of various end conditions  
•Captures closed-cylinder response | • May not capture minimum buckling mode  
• Cannot include realistic geometric imperfections  
• Composite layup approximated  
• Smeared-core assumption |
| FEA global-local        | • Global buckling  
• Smeared-core strength failures (crush, shear)  
• Core-to-facesheet interface stresses  
• Facesheet strength failures | • Interrogate the effects of nonaxisymmetric deformations on core stresses/strength failures  
• Can properly model composite layup  
• Computationally efficient  
• Can include nonaxisymmetric imperfections | • Difficult to model end conditions in detail  
• Smeared-core assumption  
• Results may not be accurate near edges of local model  
• Difficult to capture thickness imperfections |
Shell Buckling Research at NASA

Test and Analysis Correlation
First Large-Scale Test Article

• Construction
  – 2.4-m-dia. honeycomb-core sandwich composite cylinder
  – Single piece (unsegmented)
    • Core: 6.4-mm Korex honeycomb
    • Facesheets: 7-ply [±45/0/90]s

• Fabrication
  – Built by Northrop Grumman under collaborative agreement
  – Manufacturing development unit
  – Out-of-autoclave
    • Material properties not well known
Structured Light Scanning Geometry Measurement

- **Photogrammetric technique to measure 3-D shapes**
  - Inside and outside

- **Radial variation**

- **Thickness variation**
Testing and Instrumentation

• **Test conditions**
  – Subcritical axial compression and combined loading cases
  – **Axial compression** to failure

• **Instrumentation**
  – 300 electrical strain and displacement sensors
  – Digital image correlation (DIC)
    • Low speed and high speed
  – 16,000 fiber-optic strain sensors
Test Setup

- Load introduction
- Test article
- Lights
- Load lines
- DIC cameras
Analysis Approach

• Test article and testing hardware
  – Abaqus shell and beam elements
  – 156,960 elements

• Geometrically nonlinear transient analysis
  – Radial and thickness variations included
Subcritical Compression

- **Significant difference in axial stiffness**
  - Measured at end rings
  - Manufacturing demo—uncertain material properties
  - Ply extensional stiffnesses increased by 8.7%
Test and Analysis Correlation: End Shortening

Predicted radial deformation (variable scale)

Axial Load (kN)

Average End Shortening (mm)

LS7 pretest FEA
LS7 test
Test and Analysis Correlation: End Shortening

Slipping in end rings occurred

Axial Load (kN)

Average End Shortening (mm)

Test article
Epoxy potting
End ring

LS7 pretest FEA
LS7 test
Test and Analysis Correlation: Test-Section End Shortening
Material Testing

• Material nonlinearity
  – Though often ignored in analysis, it is known that fiber-reinforced composites can show material nonlinearity

• Measured stiffness
  – Sectioned barrel and performed edgewise compression testing
  – Ply thickness 9.2% greater than assumed
  – Nonlinear ply stiffnesses calculated
Test and Analysis Correlation: Test-Section End Shortening
Test and Analysis Correlation: Radial Deformation, 2038 kN

Pretest prediction

Test (digital image correlation)
Test and Analysis Correlation: Radial Deformation, at Failure

Pretest prediction

Test (digital image correlation)
Test and Analysis Correlation: Radial Displacement
Failure Event:
Standard-Rate Video

Load_Total: 856.125 kips
Failure Event:
High-Speed Video (~10,000 fps)
Failure Event:
High-Speed Digital Image Correlation

Radial deformation (~10,000 fps)
Concluding Remarks

• **Structural design considerations**
  – Numerous and potentially conflicting
  – Need to work with other groups, i.e., loads, aerodynamics, guidance and navigation, etc.

• **Structural assessment**
  – Analysis
  – Test

• **Design**
  – May require different analysis methods at different stages of design or to interrogate different potential failure modes

• **Test and analysis correlation**
  – High-fidelity models can represent physical response very well, but need good understanding of test article and test conditions
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- Clint Cragg, NESC
- Shell Buckling Knockdown Factor Project Team
Questions?
Backup
Structural Design Considerations: Finite Element Modeling

- Finite element models are idealizations and assumptions
- Majority of analyses are not designed to predict failure, but to ensure the part will not fail

Test article in test stand

FEM of test article in test stand
Structural Design Considerations: Finite Element Modeling

- Shell Buckling Knockdown Factor test article, TA07
  - 2.4-m diameter
  - 2-m length
- 3-panel construction
  - Axial friction stir welds
Structural Design Considerations: Finite Element Modeling

2.4-ft-Diameter Cylinder Buckling Test Facility

- Load spider
- Load strut
- Load-introduction cylinder
- Test article
- Load line

Attachment ring detail:

- Test article
- Bolt
- Potting material
- Attachment ring
Mechanical Design Considerations: Finite Element Modeling

- **Modeled using Abaqus finite-element software**
  - *Shell* and *beam* elements
  - *Nominal geometry* and material properties
  - Measured shell-wall geometric imperfections included

- **Buckling response predicted using geometrically nonlinear transient analysis**
Structural Design Considerations: Finite Element Modeling

Measured Geometric Radial Imperfection

\[ x = 34.4 \text{ in.} \]
\[ x = 0.0 \text{ in.} \]
\[ x = -34.4 \text{ in.} \]

Weld land

\[ \theta = 0^\circ \]
\[ 180^\circ \]

Panel C  Panel B  Panel A

\[ x, \text{ in.} \]

\[ \theta, \text{ degrees} \]
Structural Design Considerations: Finite Element Modeling

- **Hand Calculations: 1483 kN**
  - Smeared stiffness
  - Perfect geometry
  - SP-8007 knockdown factor (0.495)

- **Pretest Predictions (FEM): 2424 kN**
  - Stiffeners and weldlands
  - Geometric radial imperfections

- **Test: 2869 kN**
  - Unknown unknowns

48% difference between hand calculations and test
15% difference between pretest predictions (FEM) and test
Structural Design Considerations: Finite Element Modeling

- Post test model refinement predicted buckling load to within 1% of measured
- Effects of individual refinements
  - Material stiffnesses (1.3%)
  - Skin and stiffener dimensions (7.8%)
  - Stiffener fillet representation (4.2%)
  - Geometric imperfection (4.5%)
  - Attachment ring modeling (< 1%)
  - Loading imperfection (-1.8%)
Structural Design Considerations: Finite Element Modeling

- Cracks in the STS-133 Intertank stringers of the External Tank
- Crack suspected to occur during filling the tank with cryogenic propellant
Structural Design Considerations: Finite Element Modeling
Structural Design Considerations: Finite Element Modeling

- Forward Chord
- Skin Panel
- Doubler Panel
- Extruded Shim
- Stringer
- Installed GP Lockbolt
Structural Design Considerations: Finite Element Modeling

Test

Finite Element Model
Structural Design Considerations: Finite Element Modeling

- Boundary conditions lead to difference in test and analysis.
- Large test fixtures were not as rigid as they appeared.
IDEAL PLANES
OR WHAT CAN HAPPEN IF ONE OF
THE TEAM GETS ALL THEIR OWN WAY!
Design Considerations

1. Functionality
2. Strength/stress
3. Distortion/deflection/stiffness
4. Wear
5. Corrosion
6. Safety
7. Reliability
8. Manufacturability
9. Utility
10. Cost
11. Friction
12. Weight
13. Life
14. Noise
15. Styling
16. Shape
17. Size
18. Control
19. Thermal properties
20. Surface
21. Lubrication
22. Marketability
23. Maintenance
24. Volume
25. Liability
26. Remanufacturing/resource recovery

Ref: Shigley’ Mechanical Engineering Design, 9th ed.
Mechanical Design Considerations

• **Functionality**
  – Designing for ease of assembly, testing, and installation
    • Assembly, what will you need access to prior to launch, does a welded joint need to be a bolted one?
    • Cutout sizes determined by Human Factors
NASA’s SLS LH2 Buckling Test
Program Considerations

- **Capability vs. “requirement” negotiations**
  - Trades among all subsystems to get best/cheapest system
  - Risk/cost/performance trades with customer

- **Margin management of design resources**
  - Packaging volume, Dynamic/static clearances, structural strength, mass, mechanism force/torque, motor and pyro control circuit quantities

- **Larger structure margin vs. more structural test; subsystem vs. system testing**
  - Risk/cost/schedule/mass trade offs

- **Trade-offs of simplicity vs. performance**
  - Manufacturing and assembly
Mechanical Design Considerations

- **Mechanisms**
  - Electric vs. Spring Motors, Linear vs. Rotating Action, Articulation Geometry
  - Latches, Pyro Devices, Wet vs. Dry Lube, Rolling vs. Sliding Interfaces
Closed-Form Failure Predictions

FEA buckling load from shell analysis for perfect cylinder, \( P_{cr}^{\text{FEA Perfect}} = 2467 \text{ kN} \)

<table>
<thead>
<tr>
<th>Critical closed-form calculated loads</th>
<th>Facesheet Wrinkling</th>
<th>Facesheet Dimpling</th>
<th>Shear Crimping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load (kN)</td>
<td>4849</td>
<td>21,396</td>
<td>12,055</td>
</tr>
<tr>
<td>Failure Index</td>
<td>0.51</td>
<td>0.12</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Failure Index = \( \frac{P_{cr}^{\text{FEA Perfect}}}{P_{fail}} \)
Shell FEA Analysis: Facesheet Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Perfect, 2397 kN (before plateau)</th>
<th>Radial Imperfection, 2356 kN</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Axial Strain (με)</td>
<td>Hoop Strain (με)</td>
</tr>
<tr>
<td>Value</td>
<td>-4503</td>
<td>2652</td>
</tr>
<tr>
<td>Failure Index</td>
<td>0.57‡</td>
<td>0.15^</td>
</tr>
</tbody>
</table>

Observation

- Reasonable axial strains and Tsai-Hill index that satisfy design requirements

‡Axial-strain failure index = $\varepsilon_{FEA_{axial}}/-7926$ με

^Hoop-strain failure index = $\varepsilon_{FEA_{hoop}}/17,400$ με

**Co-cure failure index = (Tsai-Hill Index)/0.71
Axisymmetric FEA Analysis: Core-Splice Detail

- Core splice section
- End ring section

49.5 kg/m³

130 kg/m³ + Hysol

130 kg/m³

pcf

IML – inner old line
OML – outer mold line

38 mm

25 cm
Axisymmetric FEA Analysis: Core-to-Facesheet Interface Stresses

Axisymmetric model: sliding, no fillet, 2381 kN

(127 cm)

IML Interface

(6.90 MPa)

Shear stress, psi

(-6.90 MPa)

Position from End Ring, (in)

Core to scale 6.4 mm

Core to scale 6.4 mm
Finite Element Analysis Results: Global-Local Analysis

With radial imperfection, 2358 kN*

Normal stress

L-direction shear stress

*the peak load