NASA’s Hypersonic Inflatable Aerodynamic Decelerator and Rusty Old Bridges

Bill Davids, PhD, PE
John C. Bridge Professor and Chair
Department of Civil and Environmental Engineering
Four Questions

1) What does NASA have to do with bridges?
2) What is a HIAD?
3) What is the point of this presentation?
4) Why does this matter for Maine?
Journey to Mars

Goal: send humans to Mars

Real engineering challenges remain:
• Exposure to radiation
• Long-term habitats
• Entry, Descent and Landing (EDL)
• Dome video of moon landing – selected 30 seconds or so that shows landing with retro-rockets
• I will explain why this is not necessary and would not work well for Mars landing, so low or no volume.
What is a HIAD?

Traditionally, decelerators have been rigid, limiting the size and drag that can be achieved.

HIAD is a blunt shaped aerodynamic decelerator constructed with a stack of inflatable, fabric tori that are strapped together.

HIAD achieves a large ballistic coefficient while maintaining a small packed volume and weight.
• HIAD video sent to you a few weeks ago – I will speak over this, so little or no volume.

• Please edit to run only from 13 secs to 1 min 03 secs (lift-off through deployment of parachute, when video goes black).
Big Picture HIAD Timeline

- Conceptualized by NASA about 50 years ago
- 2012: Successful re-entry flight test of 3m HIAD into Earth’s atmosphere
- 2011 – 2016: extensive ground-based experimental program for 6 meter HIAD
- Ongoing and future: develop larger (~12 meter) HIADs to further investigate scale effects, assess feasibility for manned Mars missions
Initial Testing and Simulation by NASA

Wind Tunnel Testing

Test of Individual Torus

“What we want is a structure that we love and understand. Right now we have neither.”

Pressure Tub Tests and Simulation

2013, Dr. Anthony Calomino, formerly HIAD Flexible Structures Principal Investigator, NASA LaRC
Critical Questions for NASA

• How does the HIAD deform under atmospheric loading?

• How is HIAD capacity affected by inflation pressure?

• What is the best way to strap the tori together to optimize performance?

• How can the HIAD concept be scaled up for a Mars mission and decelerate 20-40 metric tons?

• Why should NASA trust a civil engineer from Maine to help answer these questions?
UMaine’s Prior Work On Inflatables

Structural behavior of inflated fabric beams and arches (airbeams) 2004 – 2011, funded by US Army Natick Soldier Center

Source: [http://www.braider.com/?a=41](http://www.braider.com/?a=41) (A&P Technology)
UMaine’s Prior Work On Inflatables

- Novel material-level test methods
- Full-scale structural testing
- Development of advanced numerical analysis techniques
- Development of specialized analysis software

\[
\int M + P(r - \bar{y})\delta k dx + \int (GA_s + P)\gamma \delta \gamma dx = \int q \delta v dx
\]
UMaine HIAD Research Program

**Coupled experiments and simulations**

- Experimentally determine behavior of torus fabric and reinforcement
- Test full-scale beams and tori to assess response
- Develop computational models of beams, tori and HIAD device
Component-Level Testing: Cords

Cord stiffness drives stiffness and strength of a torus: a single cord is ~100 times stiffer than the braided shell and bladder.
Component-Level Testing: Shell

Shear Stress (N/mm)

Inflation Pressure (kPa)

Shear Modulus (N/mm)

Shear Microstrain
Straight Beam Bending Tests

[Image of a bending test setup with labeled components: Pressure transducer port, Stringpot (typ.), Air supply port, Saddle roller support (typ.), Electric screw jack.]
Straight Beam Bending Tests

$\beta = 65^\circ$

$\beta = 60^\circ$
Torus Testing
Torus Testing

Initial tests were performed at NASA Armstrong Flight Research Center, but many questions were left unanswered

**UMaine goals:**

1. Accurately quantify initial geometry and track 3D deformations
2. Build our own load application and control system (out of necessity)
3. Improve mechanical systems to reduce variability in load
4. Control based on loads measured near the torus
5. Quantify stiffness of mechanical systems
6. Investigate load vs. displacement control
**Electric Actuator Control System**

- Effective and relatively inexpensive, but a lot of work!
- Design, software development and fabrication done by students

![Diagram of Electric Actuator Control System]
Torus Testing

Displacement control results in a square-like shape

Load control results in a triangle-like shape
A 4x increase in inflation pressure yields ~60% capacity increase.
**Goal:** Develop experimentally-validated numerical modeling techniques and software that will allow strength and stiffness of HIAD device to be accurately predicted with minimal effort

- Models used by NASA can take hours or days of computer time
- Optimizing HIAD design will require thousands of analyses to answer important engineering questions
- Our approach captures 90% of the physics and achieves 90% of the answer in a few minutes instead of hours or days
Validation of Numerical Tool

Predict Beam Response

\[ \beta = 71^\circ \]

1 cord up

Displacement (mm)

Load (kN)

Test Model

Predict Torus Response

Displacement (mm)

\[ \Theta \] (deg)

Load (kN)

Test Model
Validation of Numerical Tool

Predict HIAD Response

![Graph showing vertical displacement and reaction](image-url)

**Graph Details:**
- **Vertical Displacement ($\Delta z$)** in millimeters
- **Vertical Reaction ($R_z$)** in kilonewtons (kN)
- **Test**
- **Nominal Model**
- **Model with bounding values of parameters**
Outcomes and Benefits

For NASA:
• Very high-quality set of data
• Validated numerical design and optimization tool
• Now closer to HIAD deployment

For Maine:
• Supported dozens of UMaine students
• Added to UMaine’s research infrastructure
• Cornerstone of what we intend to become a long-term relationship
Student Support

3 Graduate Students:
- Josh Clapp (PhD, 2017)
- Andy Young (PhD, 2017)
- Dan Whitney (MS, 2016)

23 Undergrad Students:
- Bill Barker
- Donald Bistri
- Alicia Bonney
- Nick Brown
- Erich Engelhart
- Ben Fairfield
- Charlie Gardner
- Eve George
- Ben Gottlieb
- Sam Heathcote
- Josh Kovach
- Joseph Manley
- Jess Murphy
- Zac Palmeter
- Chelsey Pelkey
- Daniele Pelkey
- Cam Poussard
- Dana Pride
- Nathan Roscoe
- Andrew Schanck
- Cody Sheltra
- Phoenix Throckmorton
- Alexandra Wirth

9 High School Interns:
- Sharon Audibert
- Spencer Campbell
- Ezra Frost
- Irja Hepler
- Angel Loredo
- Mark Muir
- Paul Rudnicki
- Abby Webber
- Alex Inman
• Video of HIAD students
• Use portion from 2:14 – 3:11 (students speaking)
Rusty Old Bridges
UMaine-MaineDOT Bridge Partnership

Development of advanced software
- Used by MaineDOT and consultants
- Gives better estimate of bridge capacity
- Typically predicts strength gain of 20%
- Allows bridges to be kept in service

Development of new bridge types
UMaine-MaineDOT Bridge Partnership
Development of novel concrete strengthening technologies

![Image of concrete strengthening technology](image_url)

Graph showing deflection in millimeters (mm) against load in kilonewtons (kN) for different reinforcement types:
- Steel and FRP reinforcing
- Steel reinforcing only

Load, kN
Steel and FRP reinforcing
45% strength increase

Deflection, mm
20 40 60 80 100 120

Steel reinforcing only

45% strength increase
28 bridges tested since late 2011
- Six concrete slab bridges
- Four truss bridges
- Nine concrete T-beam bridges
- One concrete box girder bridge
- Eight steel girder bridges

Why load test bridges?
- Maine has many older bridges
- Designed for low loads
- Calculations indicate under strength
- Bridges may be in good condition
- Load testing can give us a more accurate estimate of strength
- May allow bridge to be kept in service
Five Bridges Tested in Summer 2016

<table>
<thead>
<tr>
<th>Year Built</th>
<th>Span (feet)</th>
<th>Rating Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckfield</td>
<td>1951</td>
<td>42.50</td>
</tr>
<tr>
<td>Pembroke</td>
<td>1944</td>
<td>45.25</td>
</tr>
<tr>
<td>Steuben</td>
<td>1949</td>
<td>50.00</td>
</tr>
<tr>
<td>Waltham</td>
<td>1935</td>
<td>55.00</td>
</tr>
<tr>
<td>Windham</td>
<td>1950</td>
<td>46.00</td>
</tr>
</tbody>
</table>
Instrumentation

- **Gauge support mounted to girder flange**
- **Clip angle adhered to concrete slab**
- **Displacement transducer near beam end**
- **Span**

*Strain gauges at mid-span*
Loads Applied on Bridge

Four dump trucks ≈ 220,000 lbs
Every wheel is weighed, every truck measured
Trucks are positioned to produce worst-case effect
Then, Back in the Office…

$$DF_i = 2 \frac{\sum M_i}{5} = 2 \frac{\sum S_i \varepsilon_i}{5}$$

$$K = 1 + 0.5 K_b$$

$$K_b = \frac{\varepsilon_C}{\varepsilon_T} - 1$$

Data from Test + Many Calculations = ???
More Accurate Picture of Bridge Safety

<table>
<thead>
<tr>
<th>Year Built</th>
<th>Span (feet)</th>
<th>Original Rating Factor</th>
<th>New Rating Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buckfield</td>
<td>1951</td>
<td>42.50</td>
<td>0.96</td>
</tr>
<tr>
<td>Pembroke</td>
<td>1944</td>
<td>45.25</td>
<td>0.86</td>
</tr>
<tr>
<td>Steuben</td>
<td>1949</td>
<td>50.00</td>
<td>0.80</td>
</tr>
<tr>
<td>Waltham</td>
<td>1935</td>
<td>55.00</td>
<td>1.17</td>
</tr>
<tr>
<td>Windham</td>
<td>1950</td>
<td>46.00</td>
<td>0.81</td>
</tr>
</tbody>
</table>

These results are typical: of the 28 bridges we have tested, the data and analyses indicate that ~20 are structurally adequate.
Load Testing of Howland-Enfield Bridge
Load Testing of Howland-Enfield Bridge

- Five 183 ft span trusses over the Penobscot River on Route 155
- Only Penobscot crossing between Old Town and Lincoln, constructed in 1946
- Heavily used by logging and chip trucks as well as local traffic
- Bridge is generally in poor condition, and was scheduled for replacement in 2-3 years
- Given location and use, the structure had to remain in service
- Load rating indicated that the floor beam RF = 0.69, and that the stringers were also under capacity
Load Testing of Howland-Enfield Bridge

Critical members
Load Testing of Howland-Enfield Bridge

- Tests conducted on Dec 7, 2013
- Three engineers from UMaine on site for the day
Load Testing of Howland-Enfield Bridge

- Four loaded dump trucks weighing 55,000 – 58,000 lbs each
- Various configurations of 1, 2 and 4 truck load cases were used
- Likely the heaviest loads the floor beams have ever seen
Load Testing of Howland-Enfield Bridge

• Test results indicated partial composite action between deck slab and floor beams

• Ultimate rating factor increase justified due to LL test results was 18% (1.18)

• Embedment of top floor beam flange in slab eliminated lateral-torsional buckling failure increasing RF from 0.69 to 0.89

• Final RF = 1.18x0.89 = 1.05
Graduate Students Supported by Bridge-Related Research

- Chris Gamache (MS 2001; Cardno in Tampa, FL)
- Craig Weaver (MS 2002; Cianbro Corp in Pittsfield, ME)
- Matt Richie (MS 2003; SGH in Houston, TX)
- John DeLano (MS 2004; GZA in Norwood, MA)
- Sarah Ashley (MS 2005; Sash Engineering in Ft. Kent, ME)
- Harold Walton (MS 2011, PhD 2015; HNTB in Westbrook, ME)
- TJ Poulin (MS 2012; HNTB in Westbrook, ME)
- Heather Hayes (MS 2013; Louis Berger in Portland, ME)
- Hannah Loring (MS 2013; Gessner Engineering in College Station, TX)
- Leo Helderman (MS 2016; Hardesty and Hanover in Yarmouth, ME)
- Jason Burns (MS 2016; HNTB in Westbrook, ME)
- Two current MS students, one current PhD student
UMaine Civil and Environmental Engineering

- One of the oldest departments at UMaine
- The only civil engineering program in the state
- Cover five areas within the discipline
  - Water Resources Engineering
  - Structural Engineering
  - Environmental Engineering
  - Transportation Engineering
  - Geotechnical Engineering
- 15 full-time faculty members
- ~275 undergraduate majors, 45 graduate students
- Graduate ~60 students per year, >60% stay in Maine
- Highly research-active department
Thank You