Composite Torsion Catapult Research: A Fun Use for Modern Engineering

David Mollenhauer[1], Bryan Langley[2], Chase Nessler[3], John Camping[4], Charlie Johnson[5], Josh "Bob" Briggs[6], 2nd Lt. Gabe Jacobson[1], Jennifer Chase-Fielding[1], Bob Oakes[7], Tara Storage[1], Garry Ware[10], Brian Owens[8], Capt. Ron Roberts[9], Art Safriet[4]

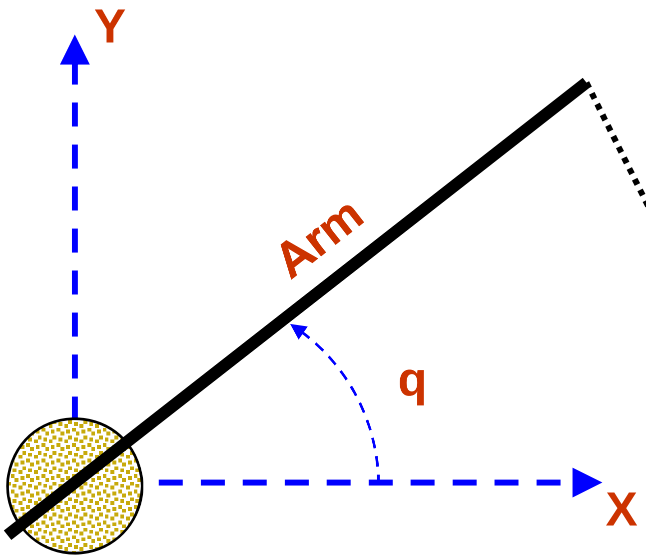
(1) Air Force Research Laboratory
(2) YUSA Corporation
(3) Wright State University
(4) University of Dayton Research Institute
(5) Northrop Grumman Mission Systems
(6) The job of the month
(7) Vibrodyne Systems
(8) Texas A&M University
(9) Air Force Institute of Technology
(10) University of Dayton

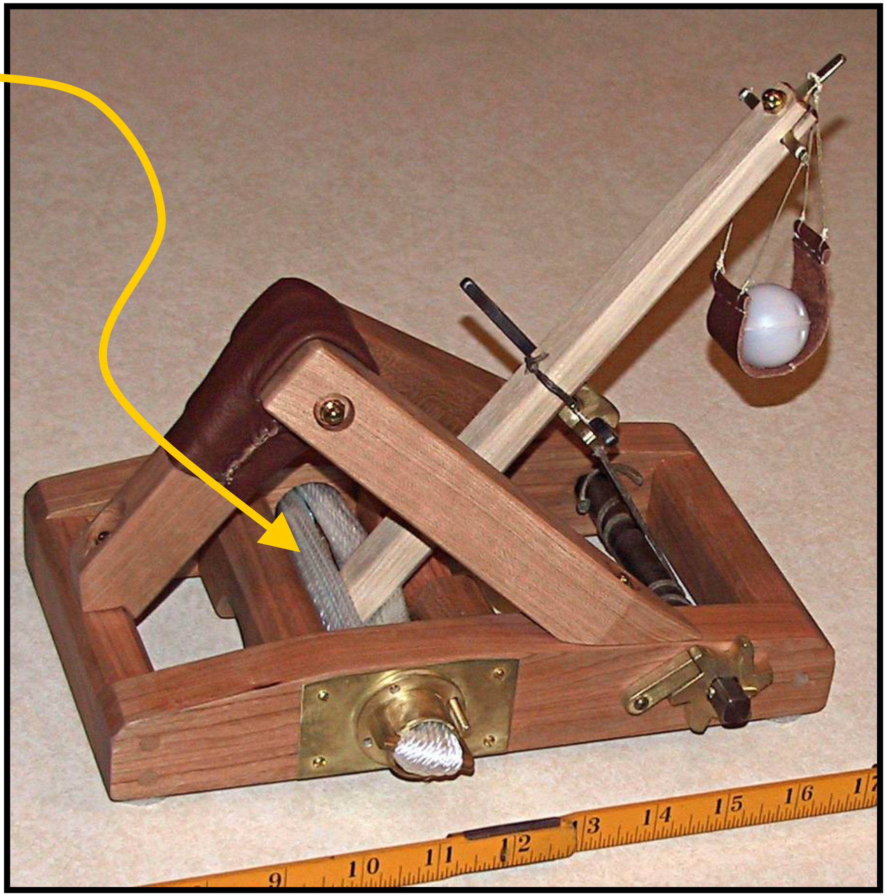
937-255-9728
david.mollenhauer@wpafb.af.mil

Background

an Onager is...

- a one armed catapult
- powered by torsion rope bundle
  - sinew or hair (women's or horse)
- usually with a sling

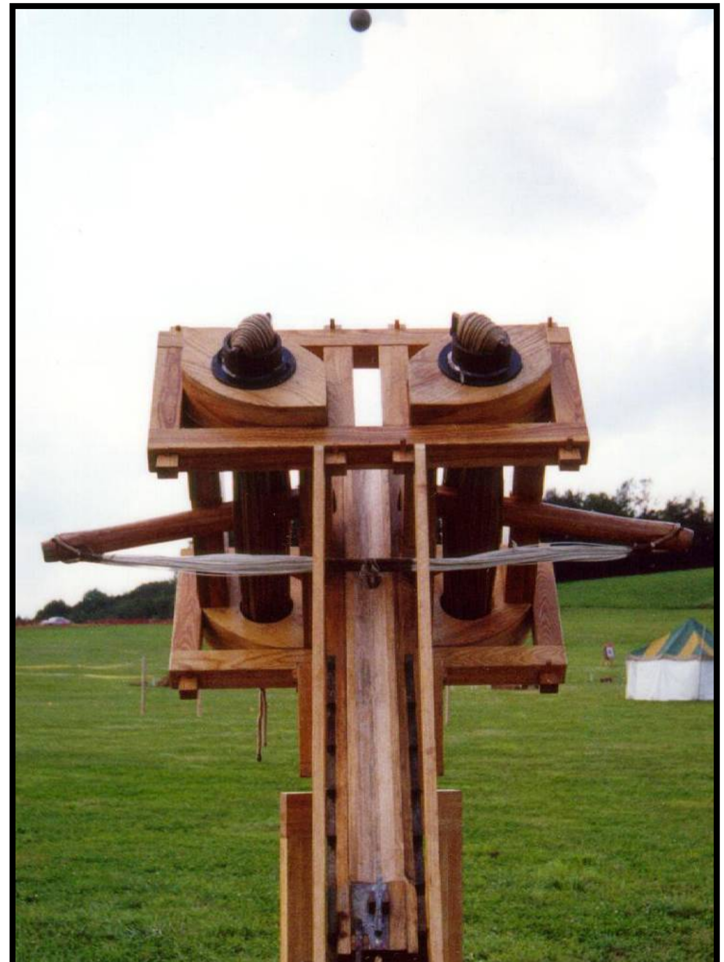




Background

an Onager is not...

a ballista



machine built by Kurt Suleski and team

a trébuchet

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Warwick Castle trebuchet

Background

(Historical Perspective)

- **torsion catapults were first mentioned *c.* 399 BC**
  - **invented in Syracuse**
    - **world's first big dollar military R&D program**
  - **2-armed torsion catapults were first to be developed**
- **inefficiencies in horn/sinew bows**
  - **horn on compression side**
  - **sinew on tension side**
  - **wood core is dead mass**
- **Greeks developed written guidelines for construction**

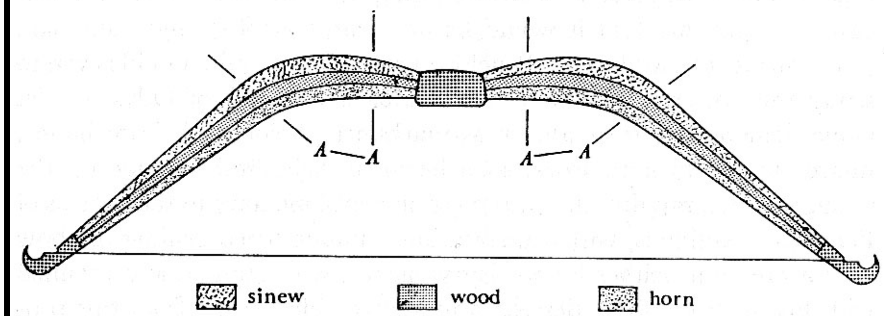


FIG. 2. The composite bow

ΤΑ ΦΙΛΩΝΟΣ ΒΕΛΟΠΟΙΙΚΑ

Φίλων Ἀρίστωνι χαίρειν· τὸ μὲν ἀνώτερον ἀποσταλὲν πρὸς σὲ βιβλίον περιεῖχεν ἡμῖν τὰ λιμενοποιικά· νῦν δὲ καθήκει λέγειν, καθότι τὴν ἐξ ἀρχῆς διάταξιν ἐποιησάμεθα πρὸς σέ, περὶ τῶν βελοποιικῶν, ὑπὸ δέ τινων ὀργανοποιικῶν καλουμένων. εἰ μὲν οὖν συνέβαινεν ὁμοίᾳ μεθόδῳ κεχρῆσθαι πάντας τοὺς πρότερον πε…
προσεδεόμ…
ἐπεὶ δὲ δ…
ἀναλογίαις…
τόνον μέλ…
παρεῖναι, …
ἔργων τὰ …

PHILON'S *BELOPOEICA*

Philon to Ariston, greetings.[1] The book we sent you before comprised our 'Making of Harbours'. Now is the time to explain (in accordance with the original programme we laid out for you) the subject of artillery-construction, called engine-construction by some people.[2] Had it been the case that all who previously dealt with this section [sc. of mechanics] used the same method, we should have required nothing else, perhaps, except a description of the artillery designs which were standard. But, since we see that they [sc. previous writers] differ not only in the proportions of interrelated parts, but also in the prime, guiding factor, I mean the hole that is to receive the spring, it is only right to ignore old authors and to explain those methods of later exponents that can achieve the requisite effect in practice.

Background

(Historical Perspective)

- the onager was first mentioned by Philon *c*. 200BC
  - λιθοβολοι μοναγκωνεζ (Lithobolos Monagon) “one arm”
- widespread use *c.* 300AD discussed by the Roman Ammianus
  - various names: scorpio, catapulta, & onager
- continued use into the Middle ages: known as a mangonel.
- supplanted by the Trébuchet in 12th century
  - gravity powered system easier to build in large sizes
- written design guidelines for onagers <u>absent</u> in the Literature

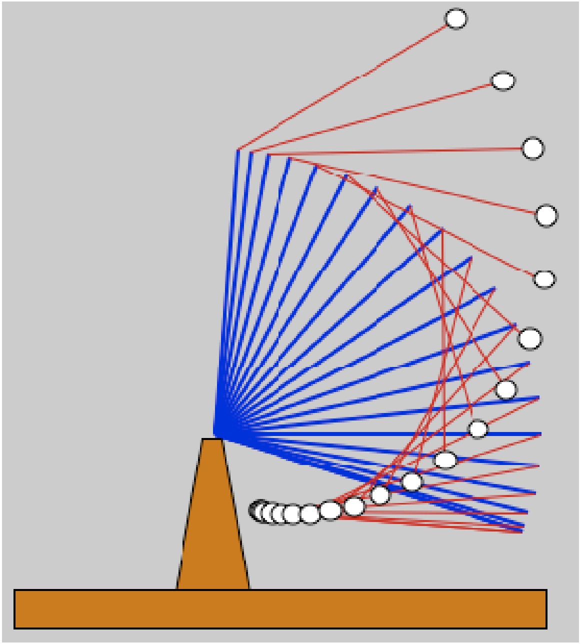
Project Objectives

- design and build:
  - use modern materials and design methodology
- research:
  - quantify behavior:
    - machine Range - traditional and modern
    - torsion bundle Response Surface
  - historical perspective:
    - tie Research to Greek Optimized Torsion Catapults
  - journal article:
    - peer reviewed and/or trade magazine
- pumpkin throwing competition:
  - local Kettering & Air Force competition – max. range 330m
  - nationals in Delaware - maximum class range 615m
  - our estimated maximum range should approach 1000m!
    - our demonstrated range 260m

Design

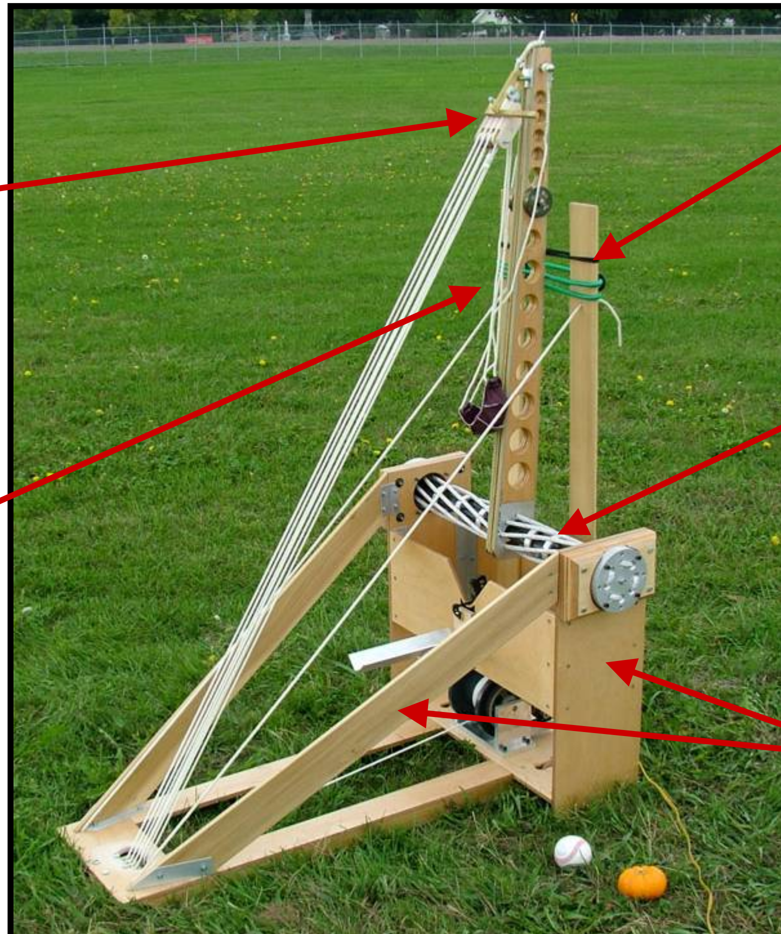
- **Our design is different...**

a traditional “onager”



the “high-angle” onager

Quarter Scale Design



trigger (brass)

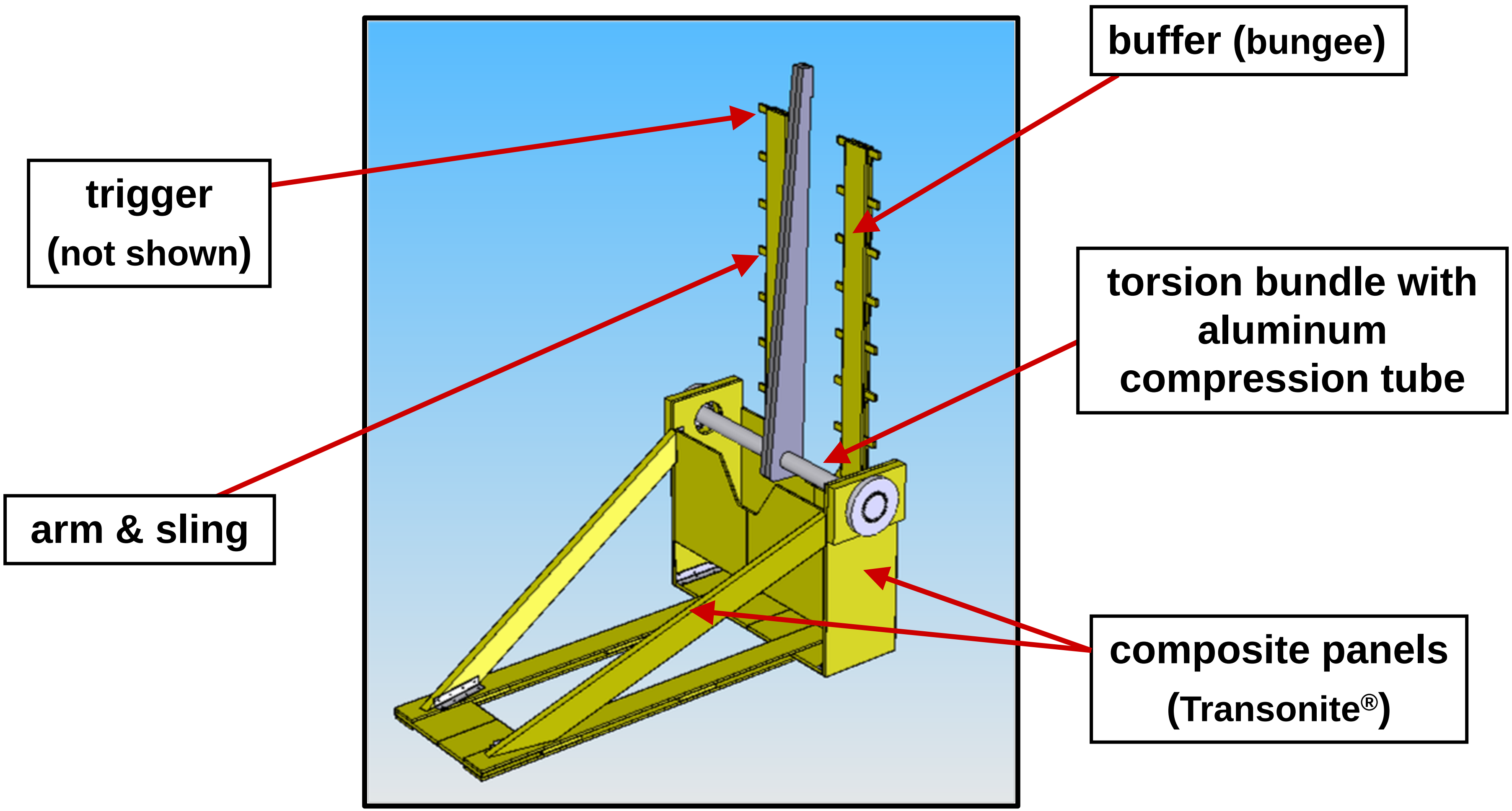
arm & sling

buffer (bungee)

torsion bundle with composite compression tube

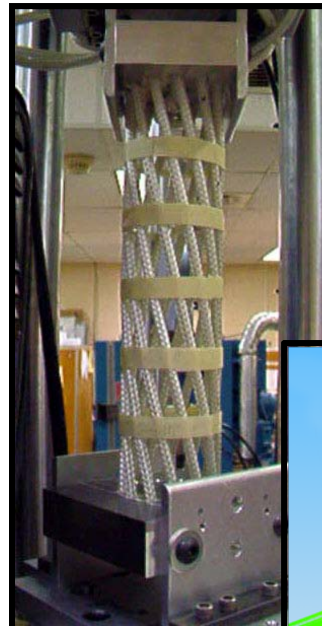
composite panels (birch ply wood)

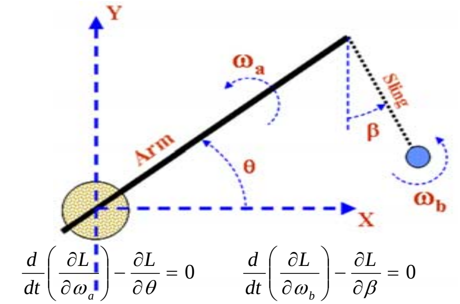
Design
(3D Solid Model)

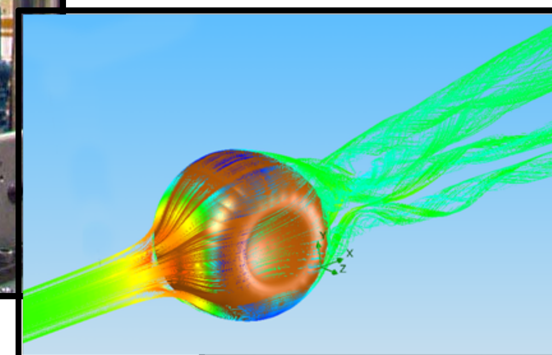


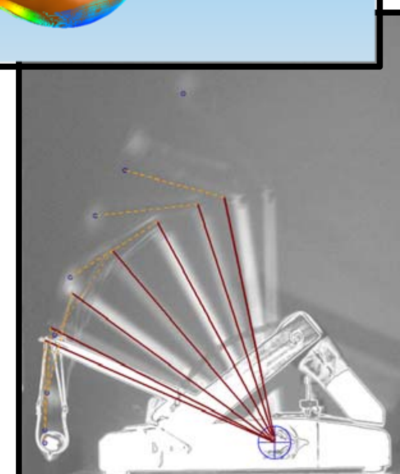
Modeling & Testing

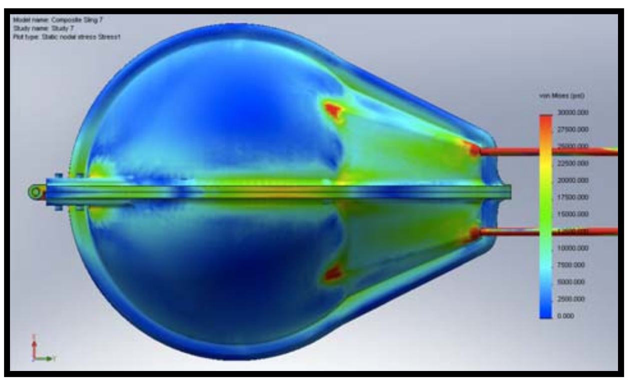
- extensive modeling:
  - dynamics behavior
  - structural
  - torsion bundle
- extensive testing as well
  - three 1/10th scale models
    - stop motion photography
    - high speed photography
  - one 1/4 scale model
  - two extensive torsion bundle testing programs

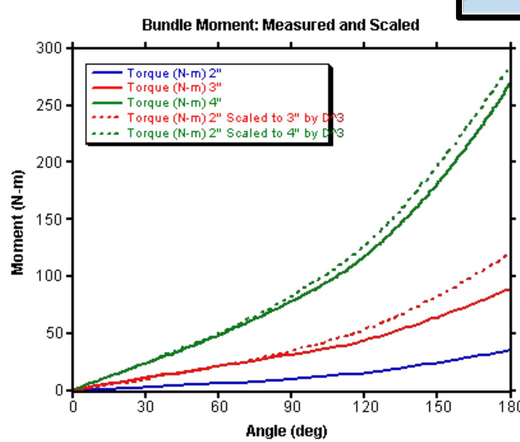






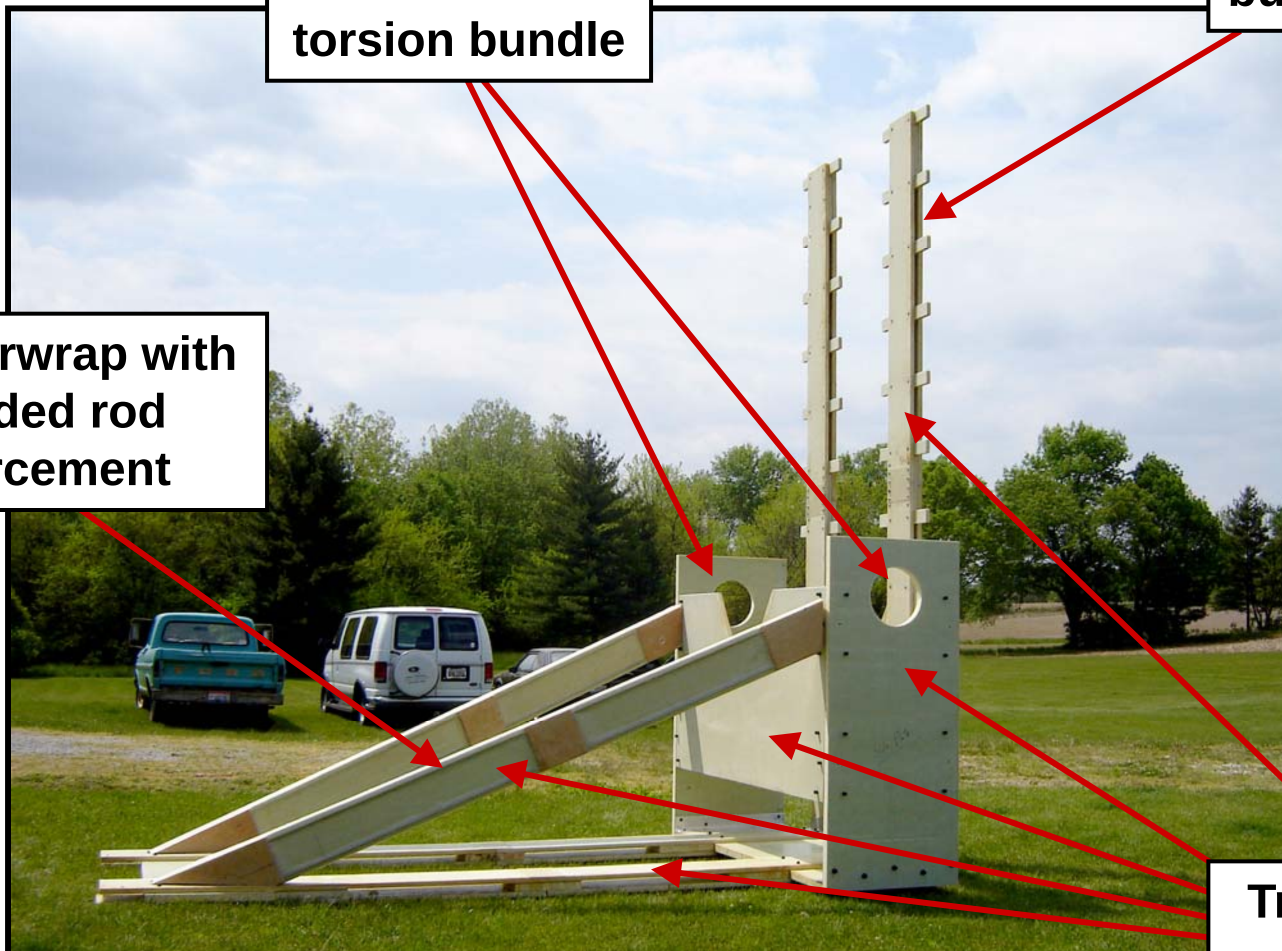






Construction Progress 2007

(photos)

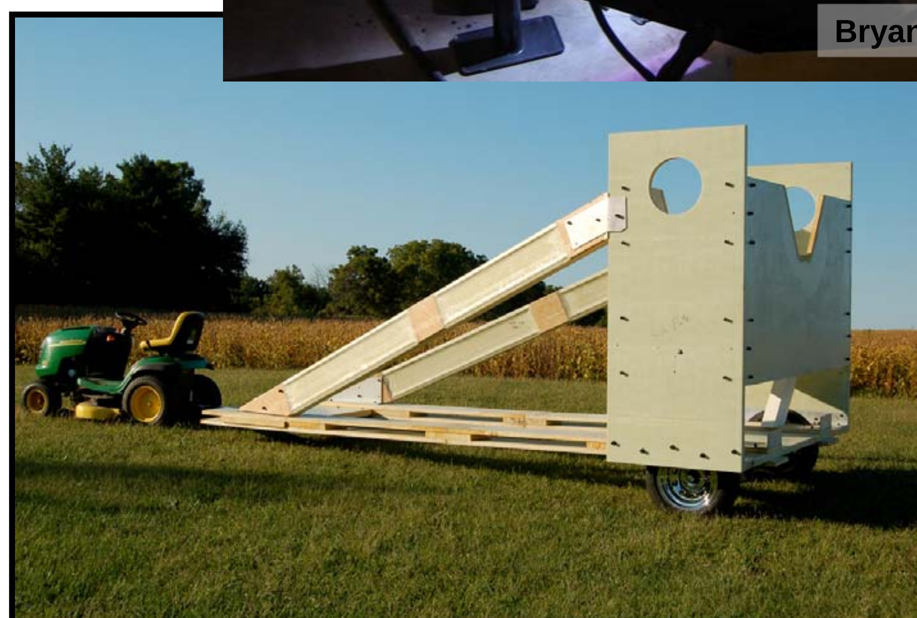


Construction Progress 2007
(Frame)


Bryan, David, & Chase

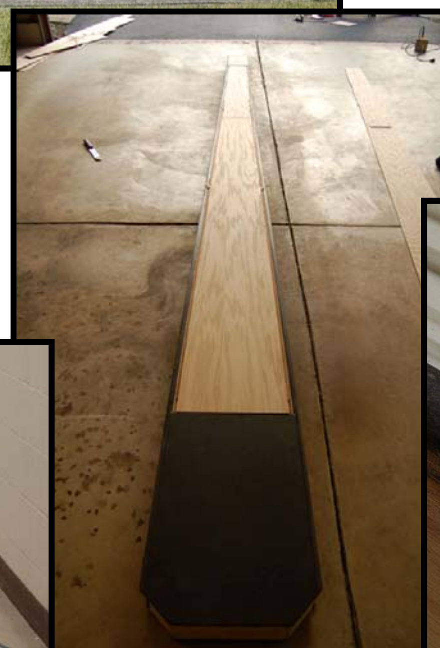

Bryan


Charlie, David, Chase, & Bryan



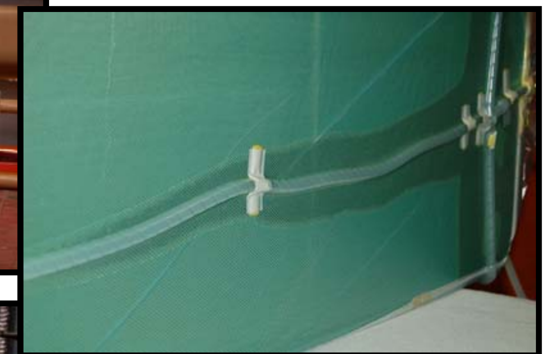
Construction Progress 2007

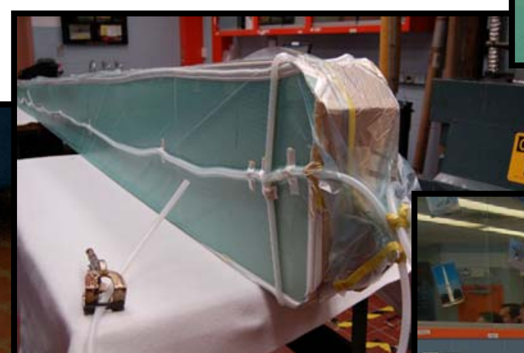
(Arm Core, Arm Root, and Pultruded Rods)

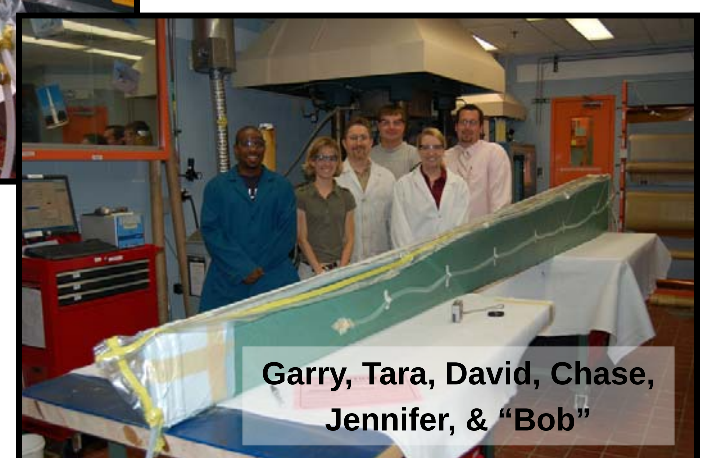


Construction Progress 2007

(Arm with Braid Overwrap being VARTMed)



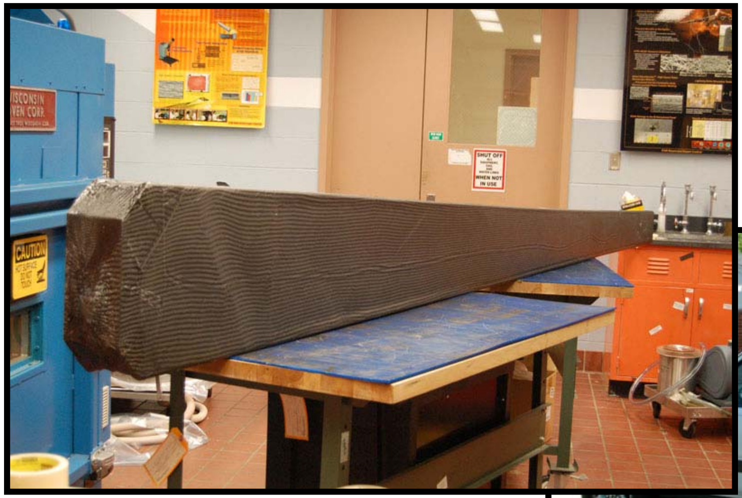




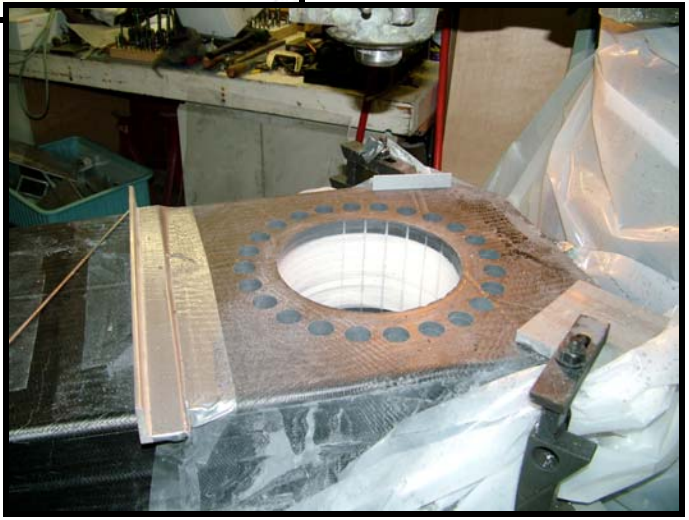
Garry, Tara, David, Chase, Jennifer, & “Bob”

Construction Progress 2007

(Arm Finished and Being Machined)

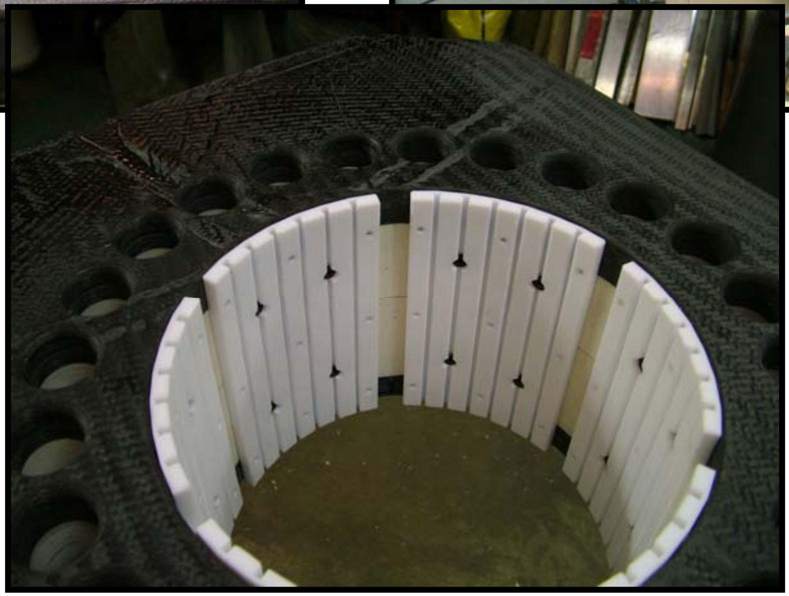


Too much machining!



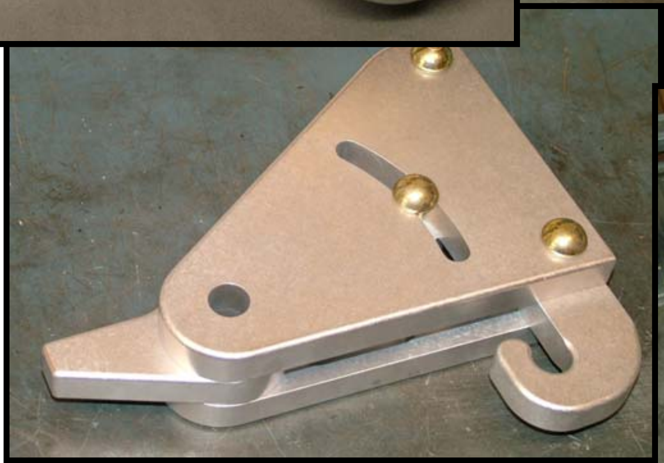
Construction Progress 2007

(photos)



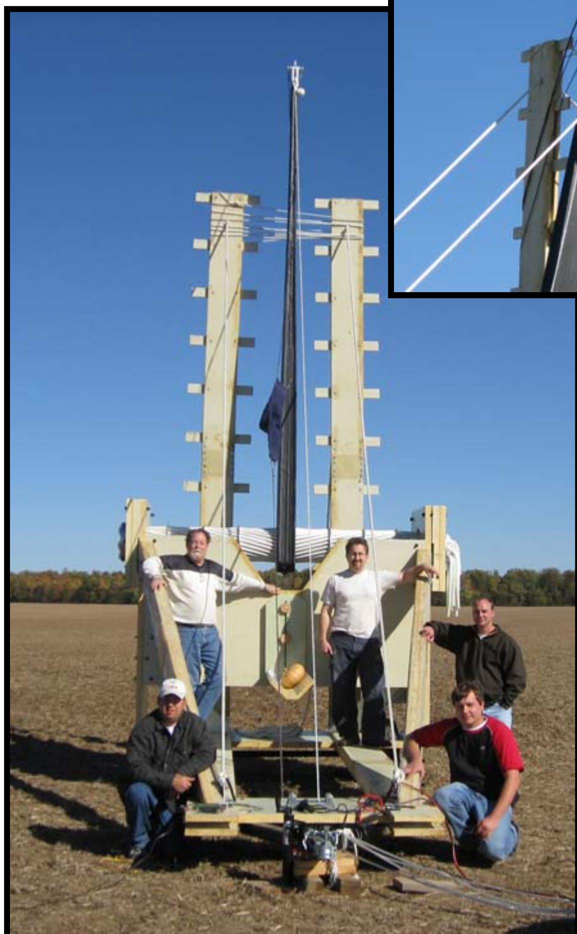
Construction Progress 2007

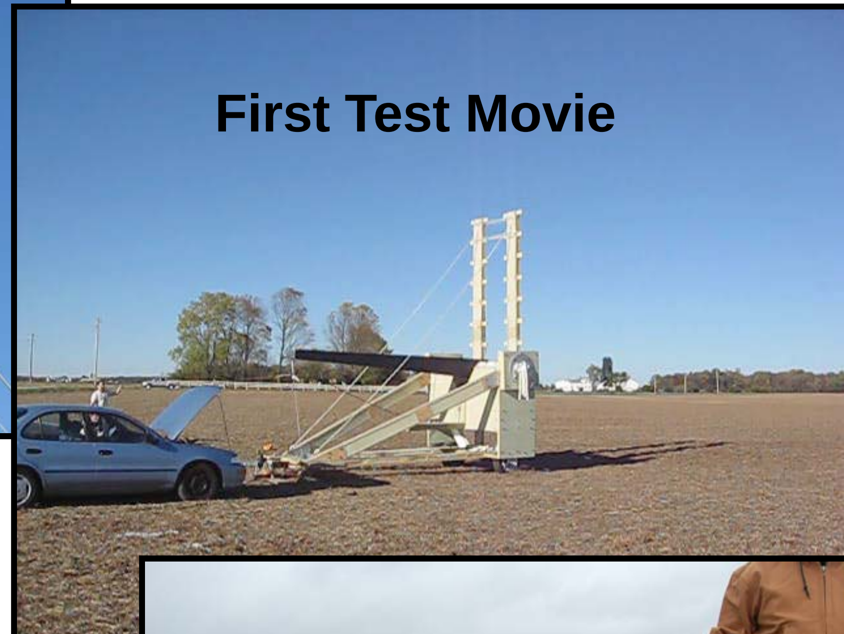
(Amazing Machining)



Full-Scale Testing 2007

(First & Second Test)



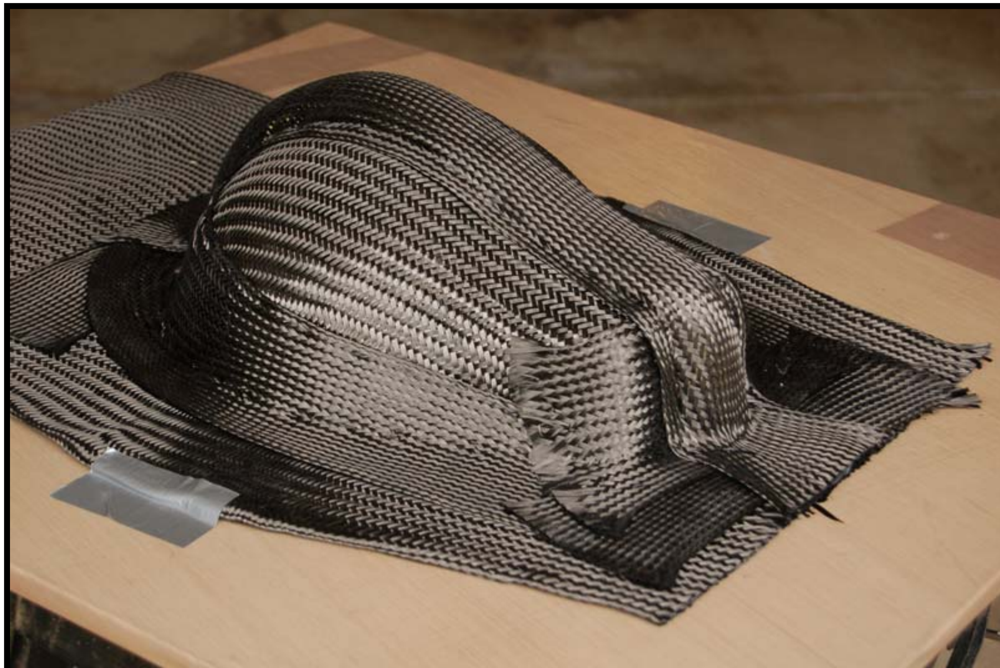


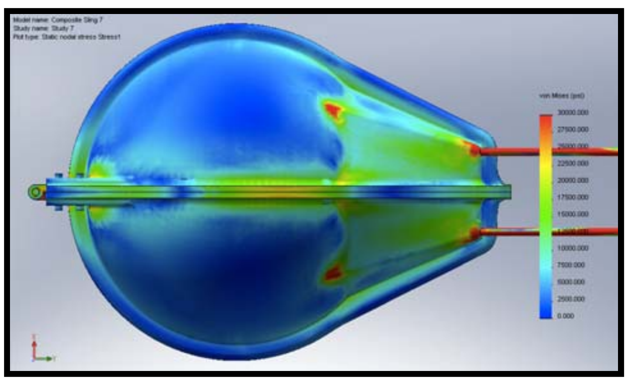
First Test Movie

Air Force Contest 2007

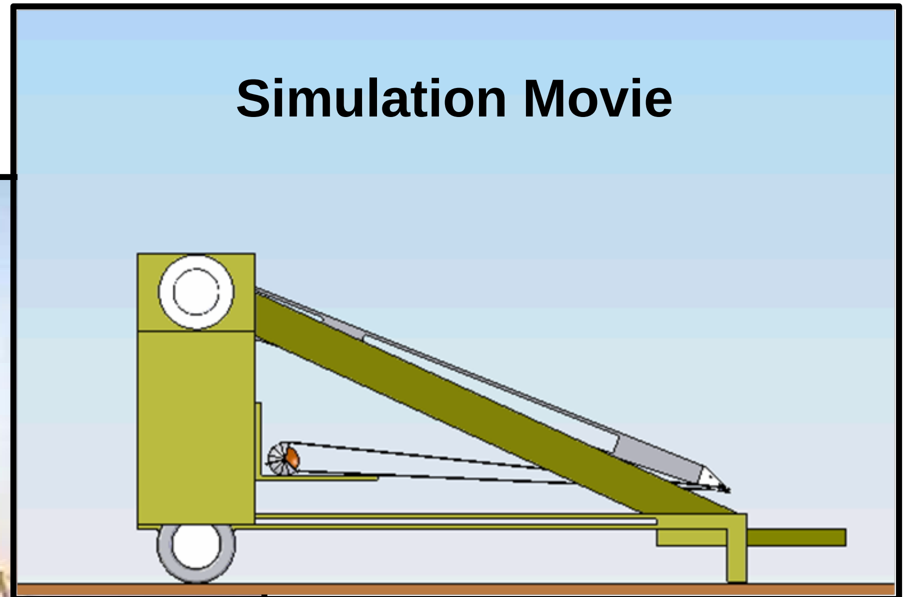
Construction Progress 2008

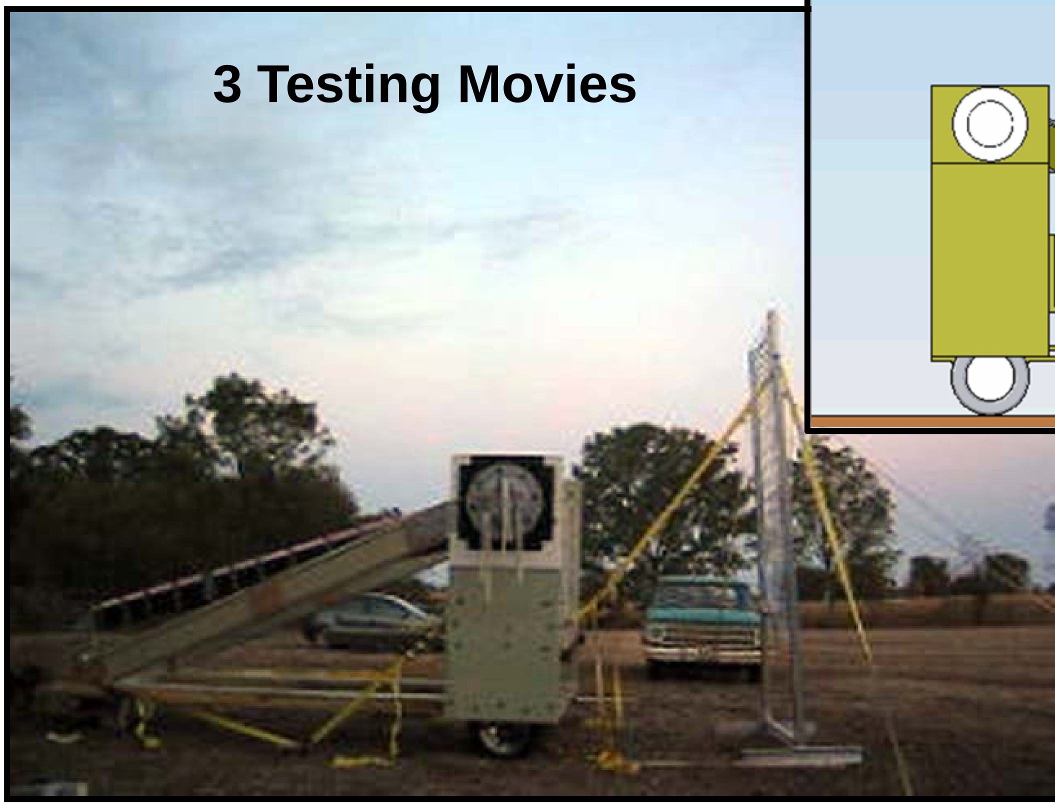
(clam-shell composite sling)





Testing & Modeling Progress 2008





Project Donors & Cost Estimate

NCC

CRG

ThyssenKrupp

Martin Marietta Materials

VIBRODYNE/TSI

ALCOA

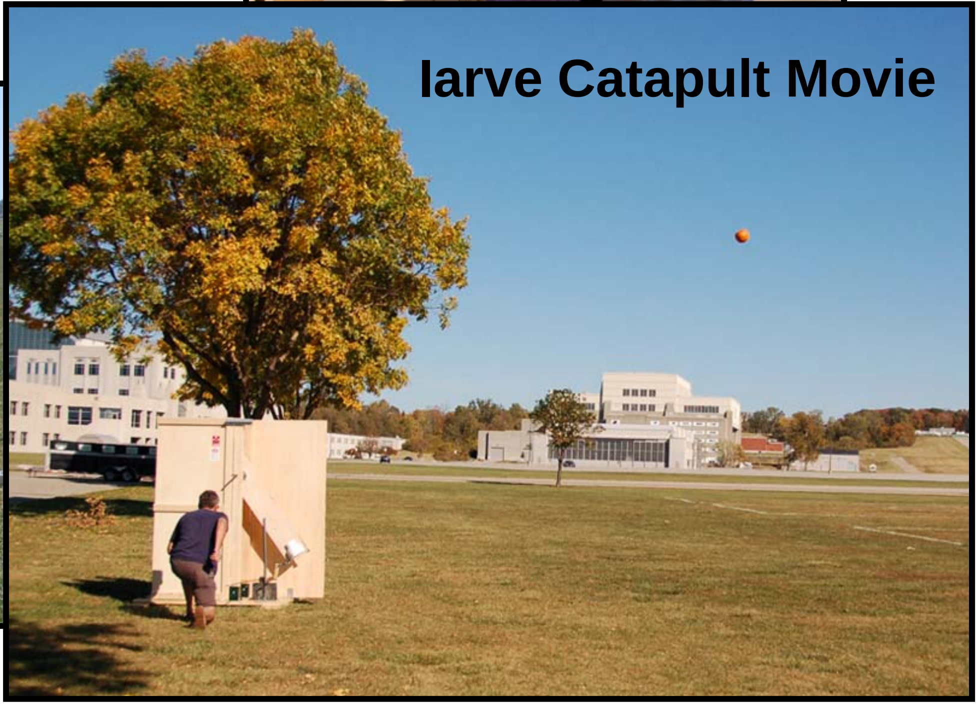
A&P Technology

Cortland. PUGET SOUND ROPE

Diversified Composites

Donations	**$57,800**
Purchased	**$5,783**
Total	**$63,583**

The Infection Spreads to Others

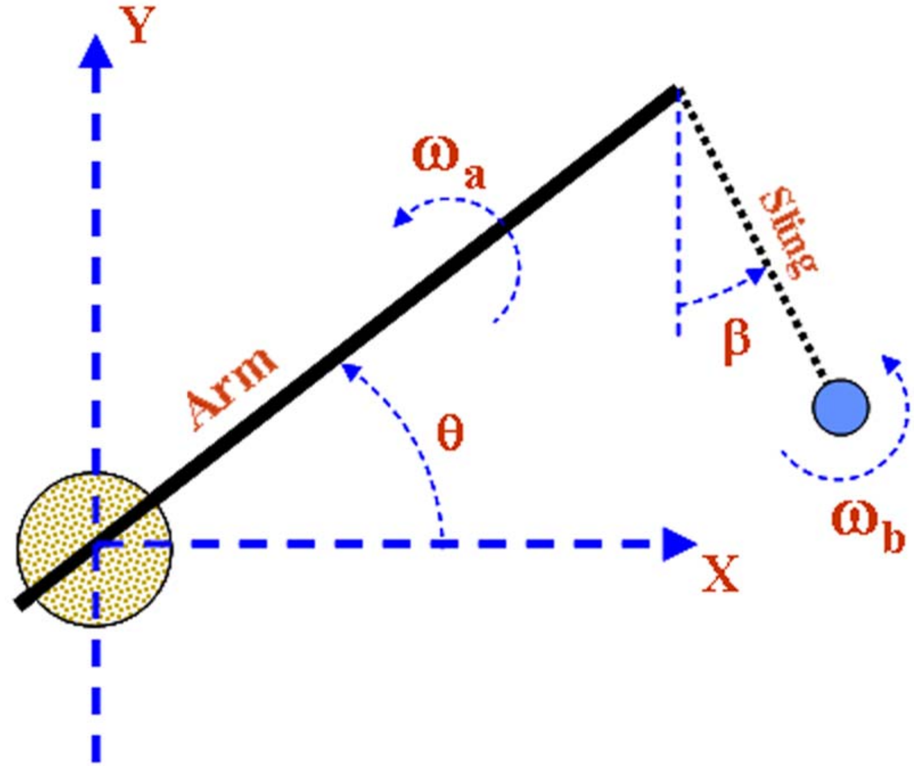


Questions?

Modeling

(Dynamics)

- define coordinate system
- make assumptions
  - sling & arm are rigid
  - sling is massless
- Lagrangian Method



$$L = T - V$$

potential energy

kinetic energy

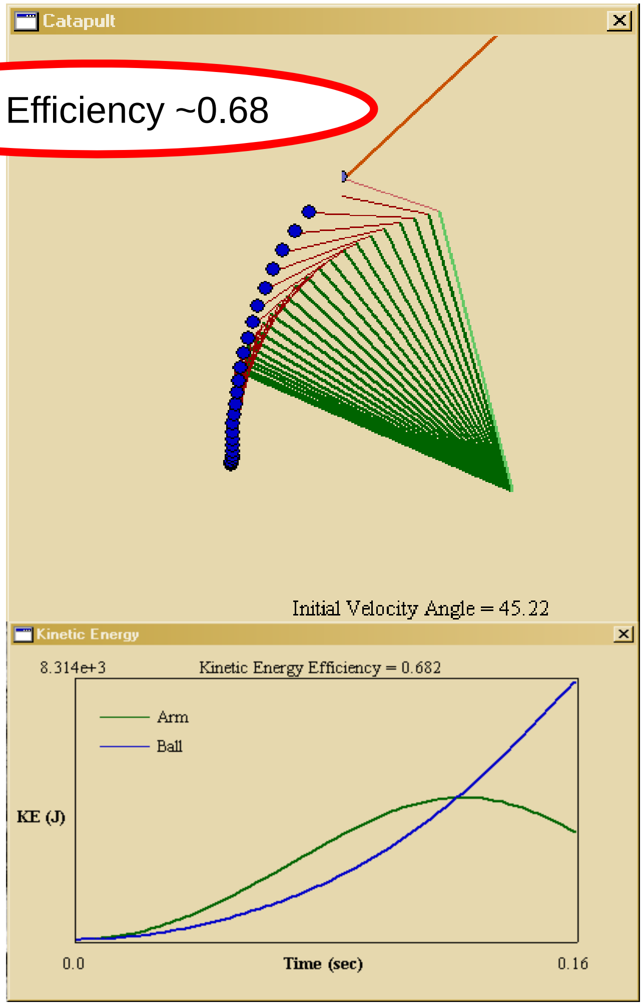
$$\frac{d}{dt}\left(\frac{\partial L}{\partial \omega_a}\right) - \frac{\partial L}{\partial \theta} = 0 \qquad \frac{d}{dt}\left(\frac{\partial L}{\partial \omega_b}\right) - \frac{\partial L}{\partial \beta} = 0$$

Modeling

(Efficiency – Traditional vs. High Angle)

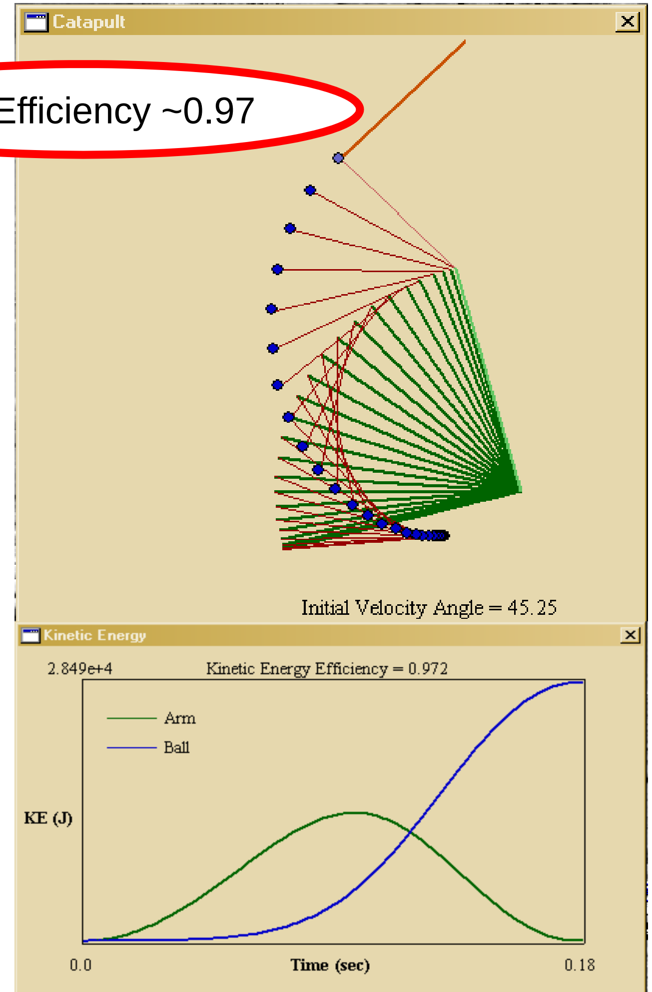
Traditional Onager

K.E. Efficiency ~0.68



High-Angle Onager

K.E. Efficiency ~0.97

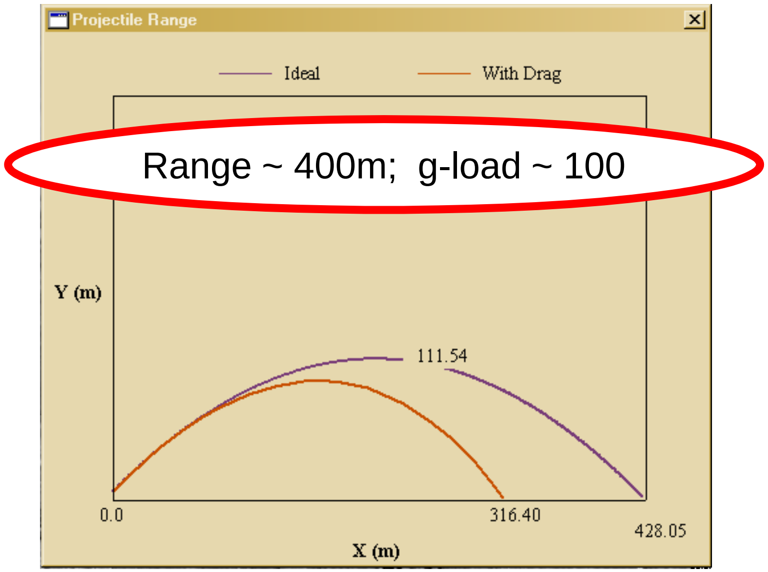


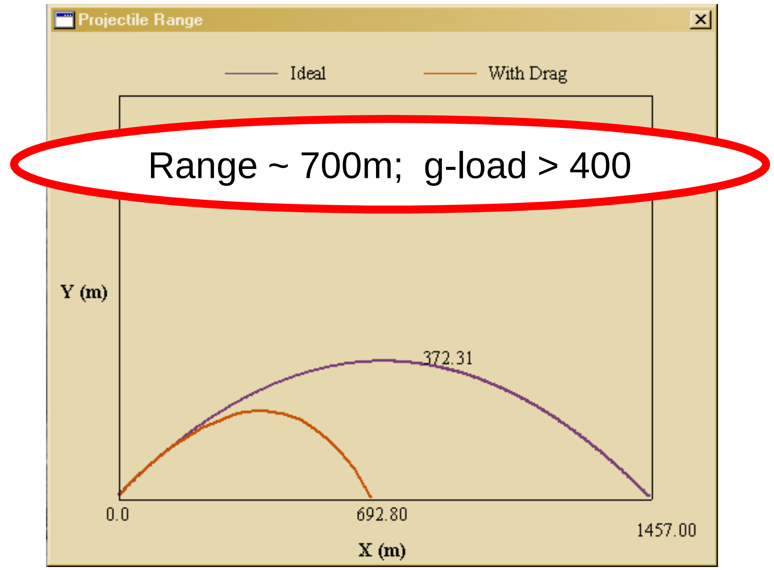
Modeling

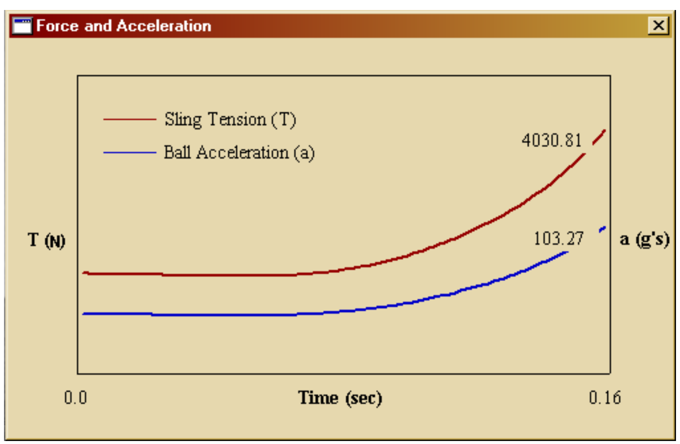
(Range & g-Load – Traditional vs. High Angle)

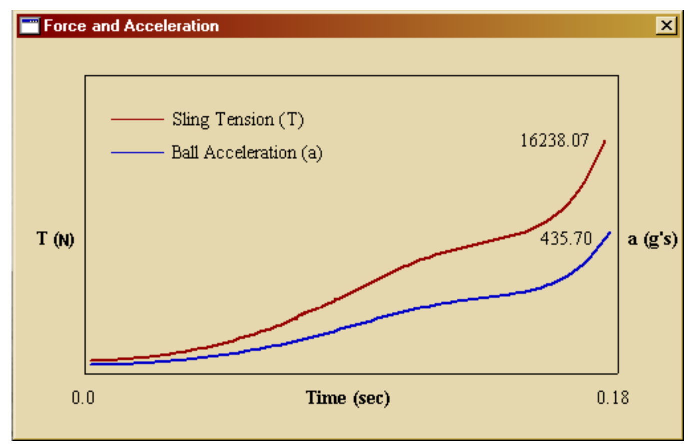
Traditional Onager

High-Angle Onager

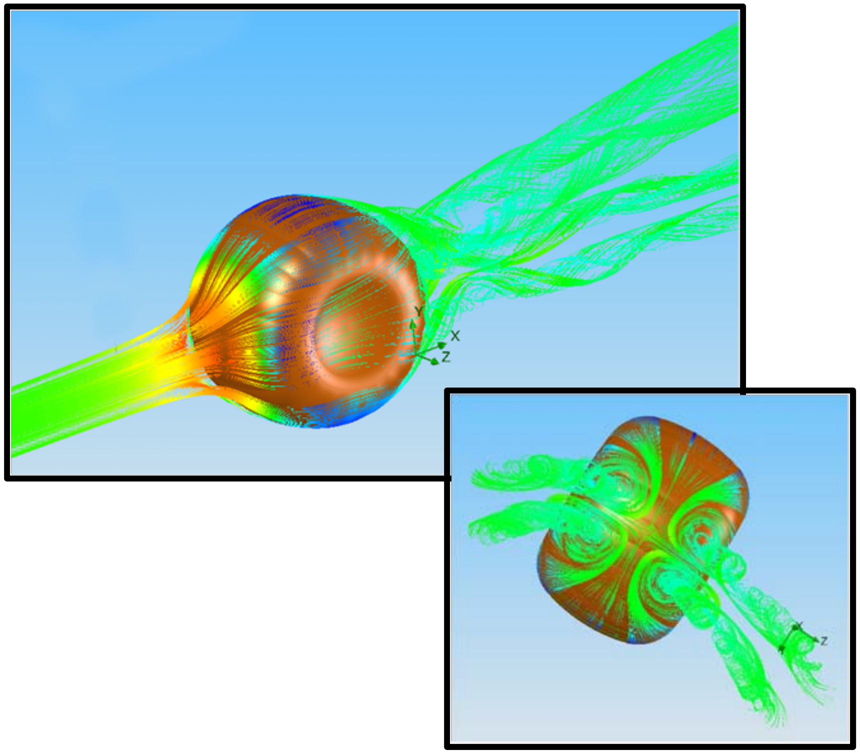




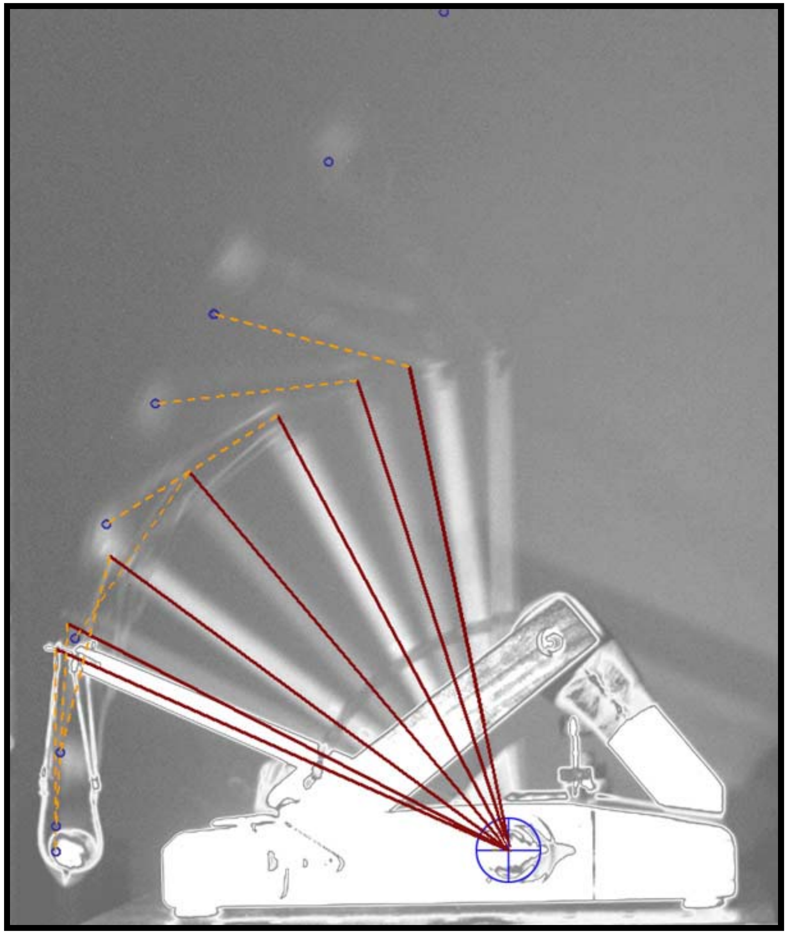




Modeling



CFD of 340 mile per hour
spinning pumpkin

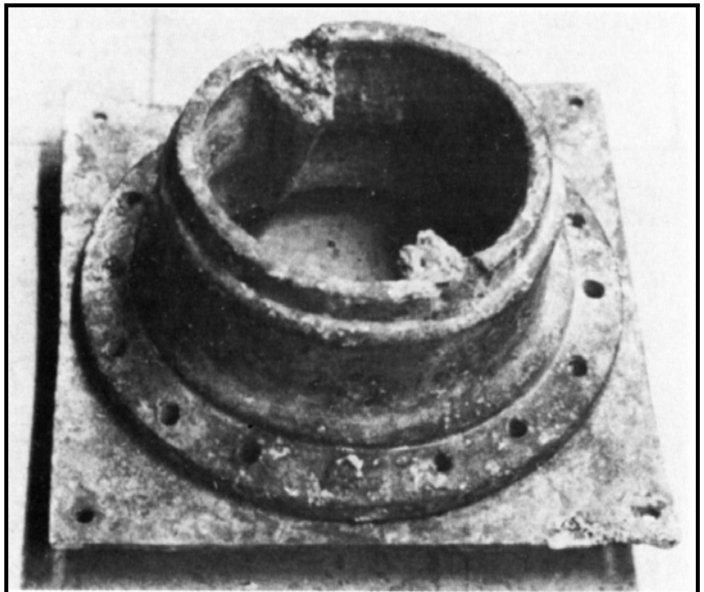


Stop Motion Photo
With Predicted Behavior

Torsion Testing

(Part 1: Details)

- **establish a reasonable understanding of torsion bundle performance as a function of …**
    - **bundle diameter**
    - **bundle length**
    - **rope pre-tension**
    - **rope material and architecture**
- **Greek formula (at right below) used as base-line for length to diameter ratio.**
- **inter-diameter pre-tension variations adjusted to match axial strain**
- **fixture design based on ease of test parameter variation, not Greek "washer" design shown at right above**



(Photo: D. Baatz)

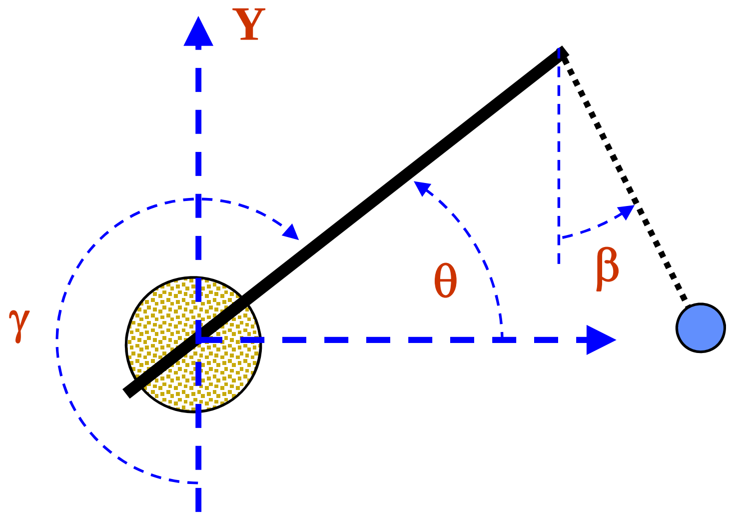
$$D = 1.1\sqrt[3]{100m}$$

where D is the bundle diameter in "dactyls" (~0.76 inches) and m is the mass of the shot in "Minae" (~0.96 Lbm)

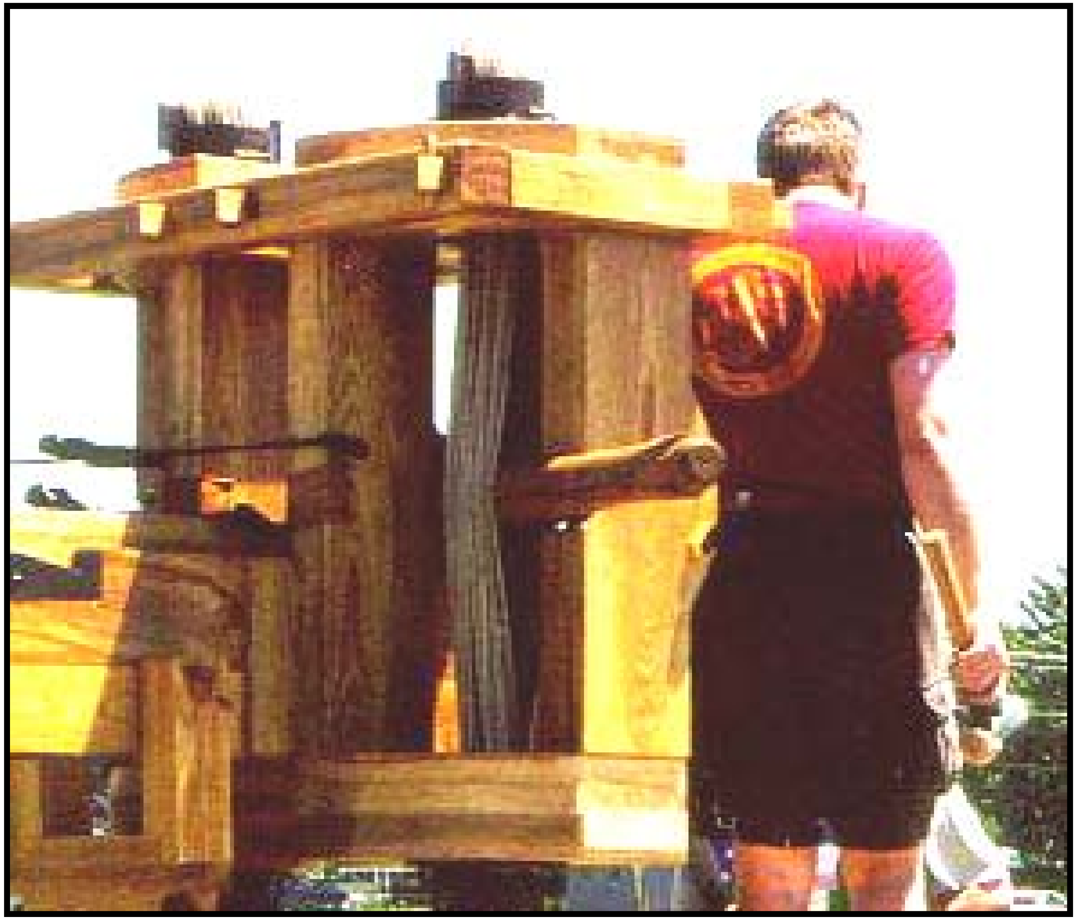
$$l = 9.4D$$ according to Philon

Torsion Testing

(Part 1: Details)



- professional MTS tension-torsion machine
- half-length bundle tested
- traditional design hard to wrap
- coordinate system based on γ in above diagram

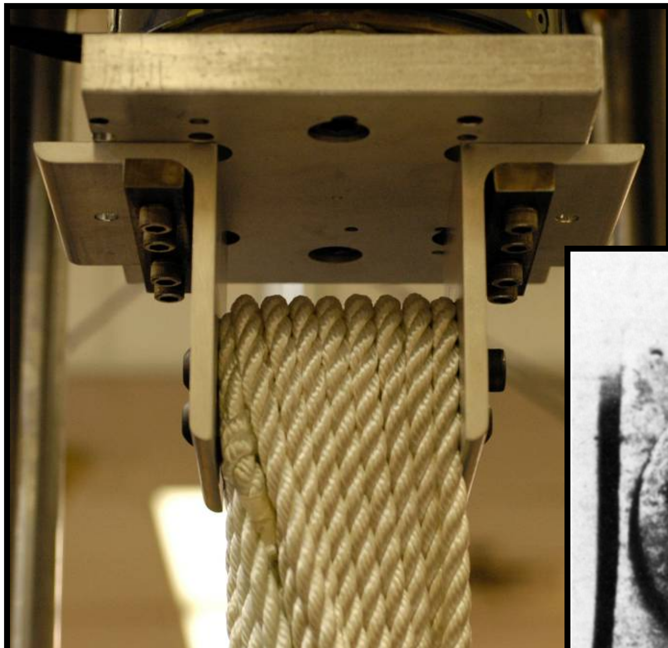


machine built by Kurt Suleski and team

Torsion Testing

(Part 1: Fixture)

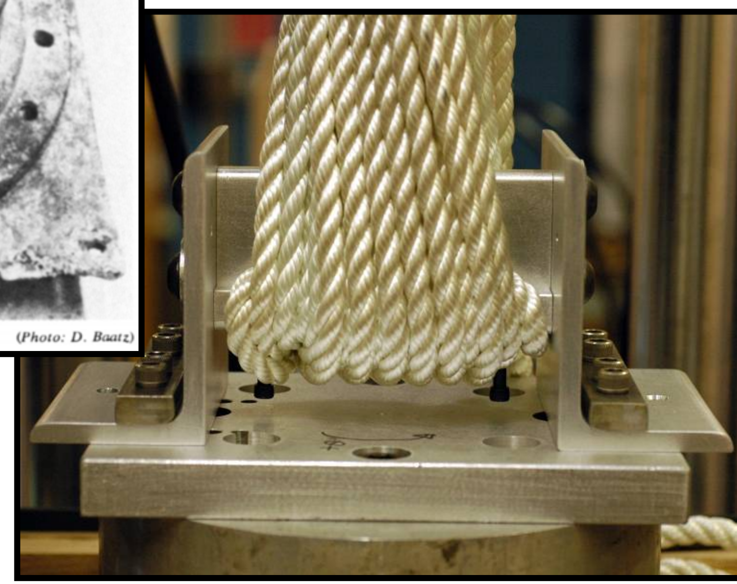
“Lever” side



Traditional washer

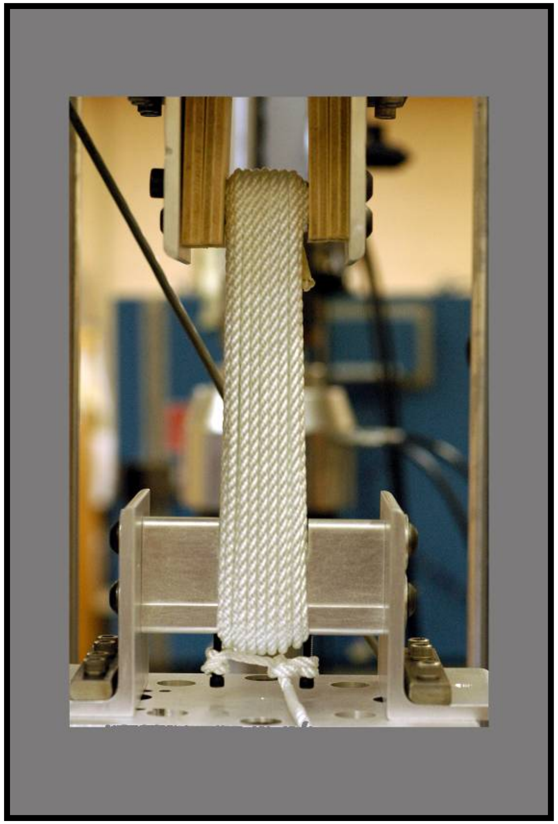
(Photo: D. Baatz)

“Arm” side

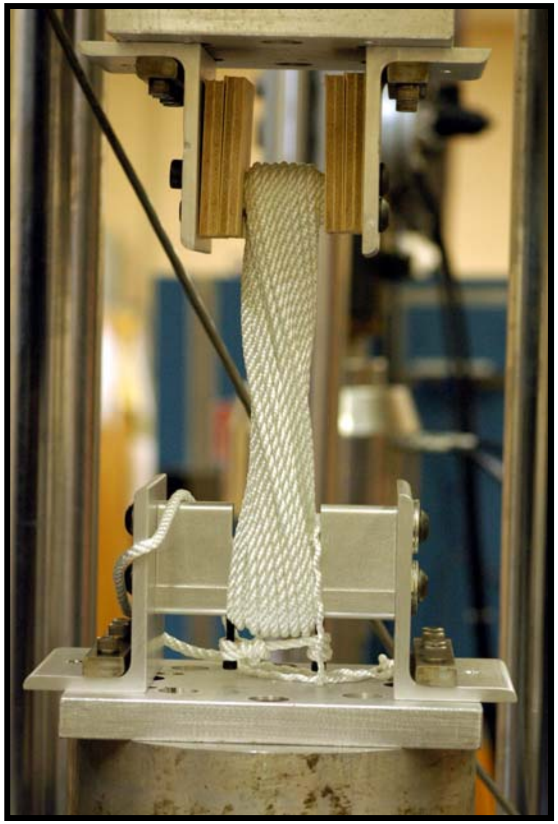


Torsion Testing

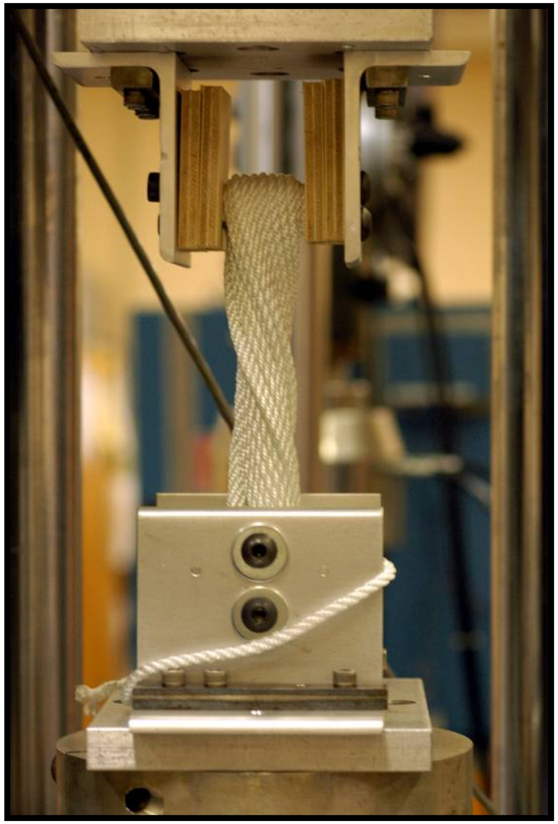
(Part 1: 2 Inch Diameter Bundle)



0° rotation



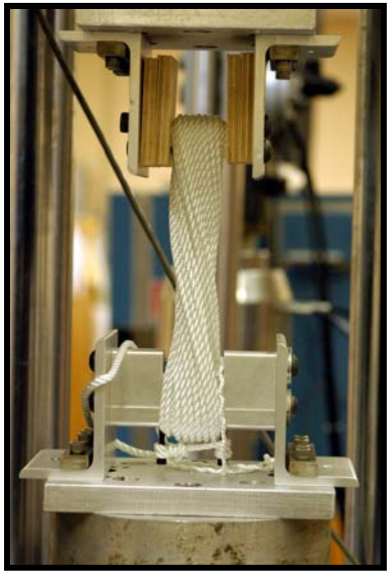
180° rotation



270° rotation

Torsion Testing

(Part 1: 2 Inch vs. 4 Inch Bundle)

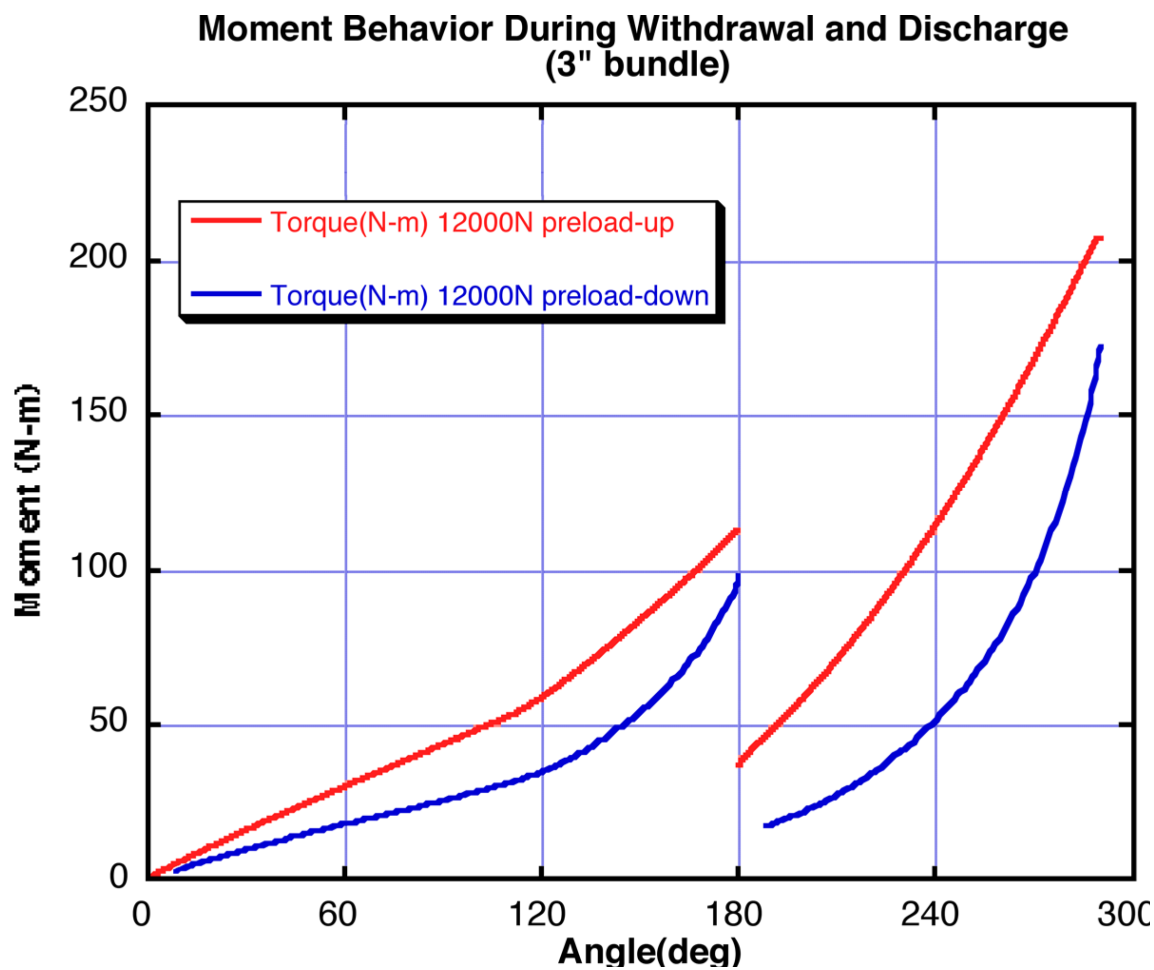


2 inch bundle

4 inch bundle

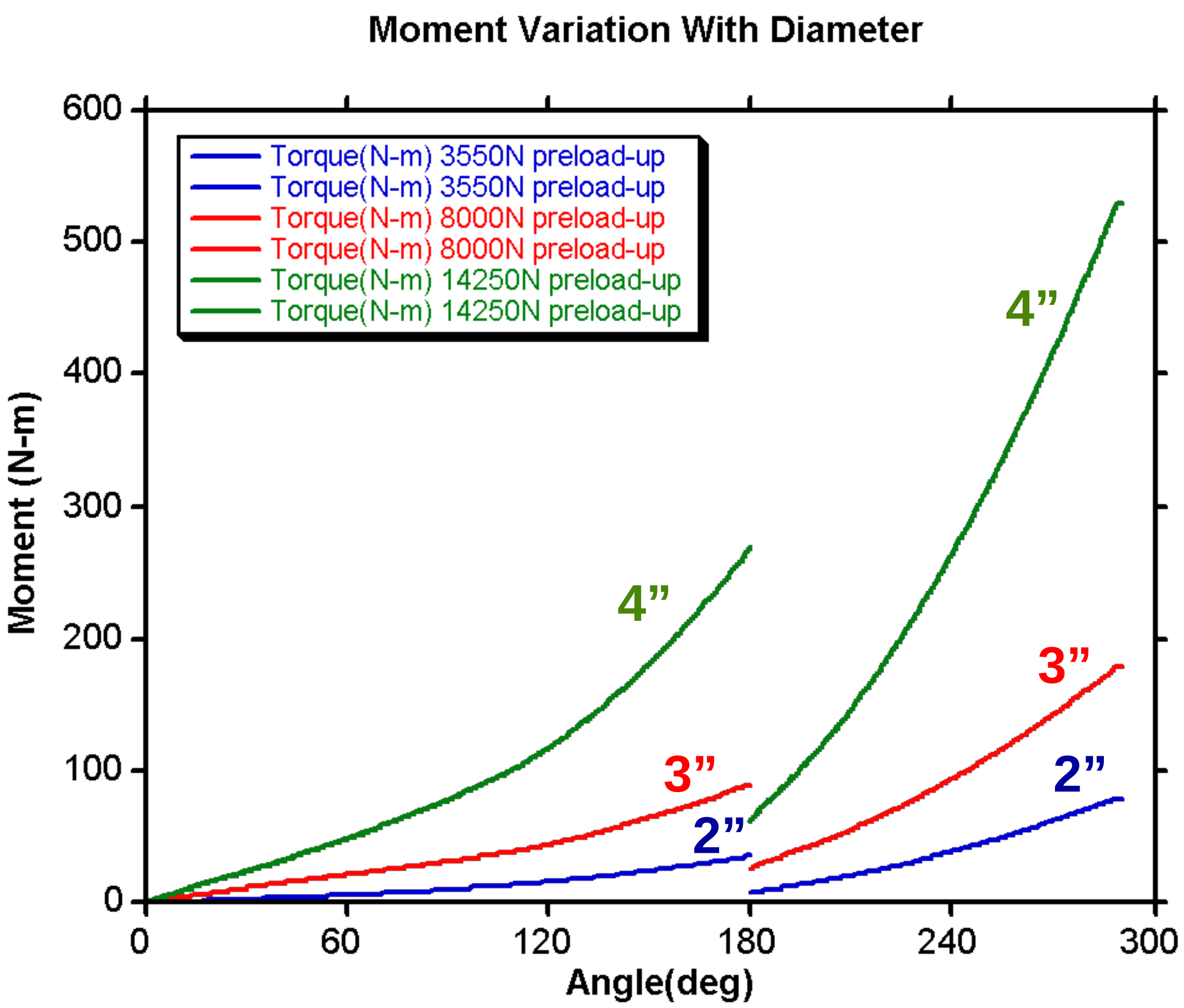
Torsion Testing

(Part 1: 3 Inch Moment Behavior)



Torsion Testing

(Part 1: 2, 3, & 4 Inch Moment Behavior)



Torsion Testing

(Part 1: Historical Hypothesis)

- **Greek formula ($D = 1.1\sqrt[3]{100m}$) scaled the bundle diameter to produce acceptable range for all shot masses (set of dimensions to go with diameter).**
- **exit velocity of the shot should be relatively constant for any given mass.**

$$V_1 + T_1 = V_2 + T_2 \quad \Longrightarrow \quad V_1 = T_2 \quad \Longrightarrow \quad V = \frac{1}{2}mv^2$$

$$D = A\sqrt[3]{Bm} \quad \Longrightarrow \quad m = \frac{D^3}{A^3 B} \quad \Longrightarrow \quad V = \frac{v^2}{2A^3 B}D^3$$

$V \equiv potential\ energy$

$T \equiv kinetic\ energy$

$$\boxed{V \propto D^3}$$

<u>Hypothesis:</u> The stored energy of various torsion bundle diameters should be related to the cube of the bundle diameter.

Torsion Testing

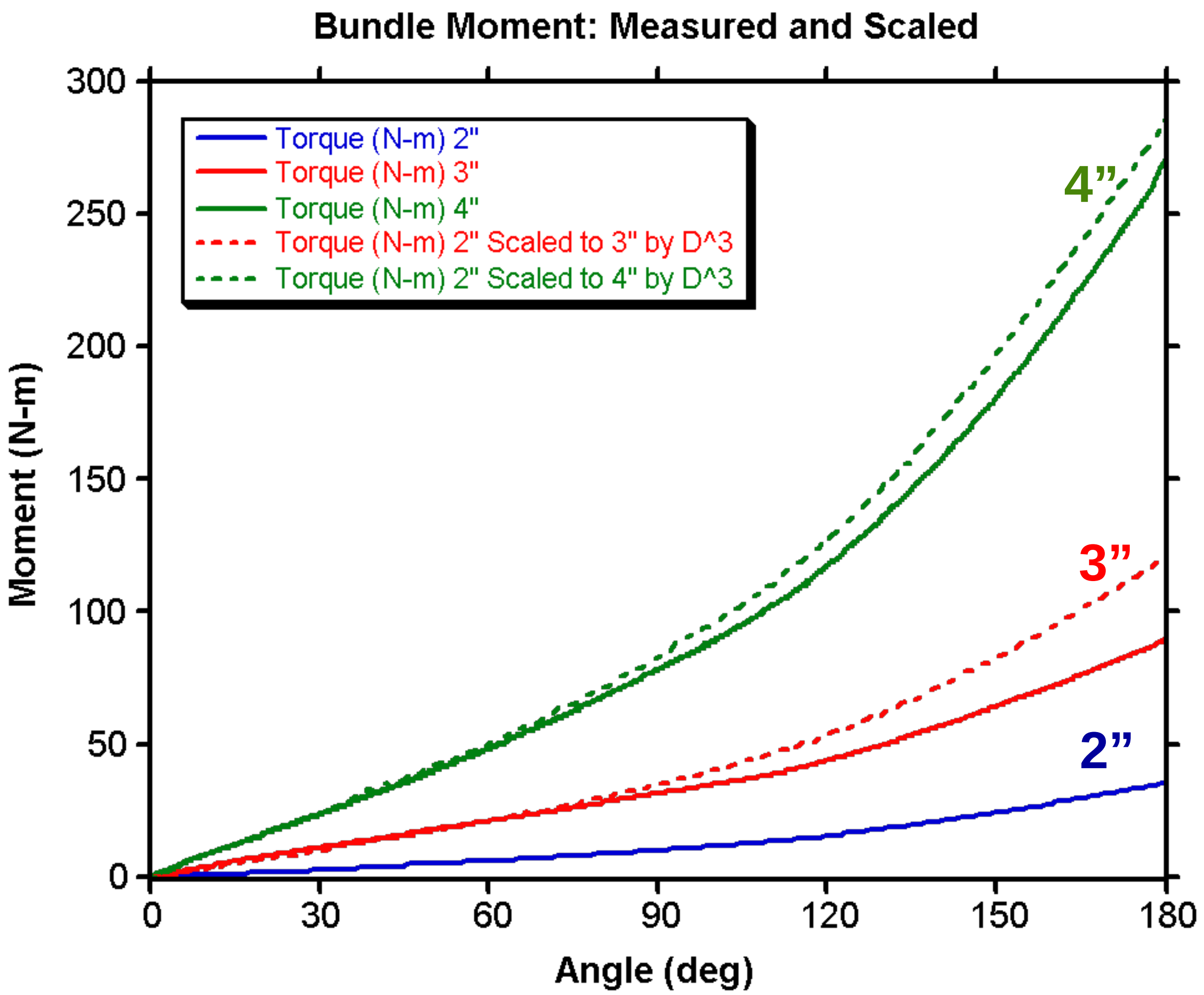
(Part 1: Hypothesis Test)

Formula	**Experiment**
Scaling 2” to 3” = 3.375	Scaling 2” to 3” = 2.80 (-17.0%)
Scaling 2” to 4” = 8.000	Scaling 2” to 4” = 7.47 (-6.6%)
Scaling 3” to 4” = 2.370	Scaling 3” to 4” = 2.67 (+12.7%)

$$\boxed{V \propto D^3}$$

Torsion Testing

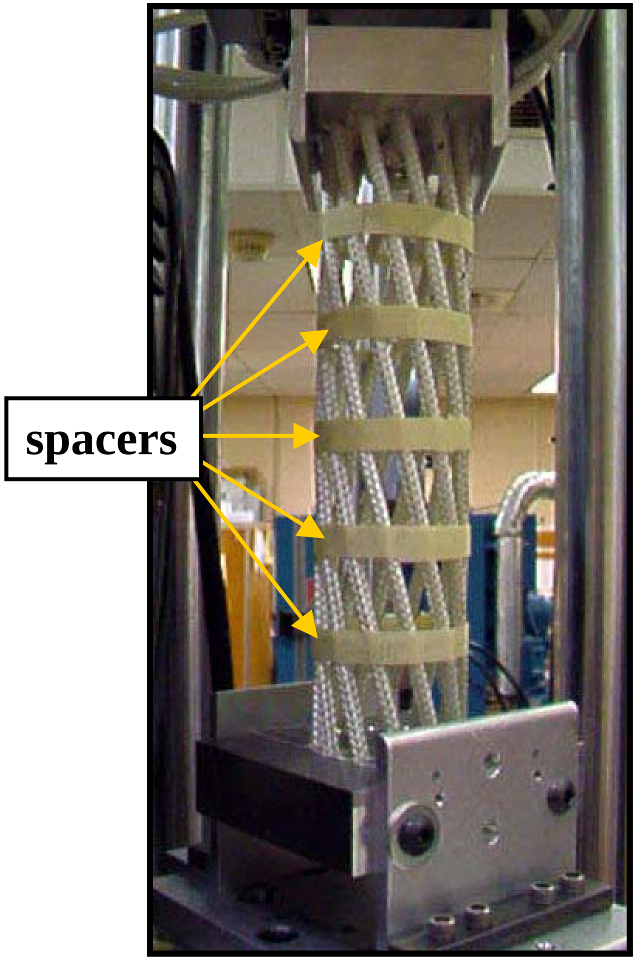
(Part 1: Hypothesis Test)



Torsion Testing

(Part 2: Details)

- establish a quantitative understanding of a segmented/helix torsion bundle (shown at right) as a function of …
  - number of spacers
  - bundle length
  - rope pre-tension
  - rope material and architecture
- as before, Greek formula used as base-line for length to diameter ratio.
- fixture design based on new concept designed to facilitate approximate straight line segment or helix behavior



Torsion Testing

(Part 2: Measured vs. Predicted Helix)

- polyester double braid with 30 second hold