Design of a High-g Unmanned Aerial Vehicle Structure

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WIDE AREA SURVEILLANCE PROJECTILE

- WASP commenced in 1997

- Developed at Charles Stark Draper Laboratories

- Small autonomous flyer launched in an artillery shell, deployed over the battlefield

- Reduce the risk and time of obtaining crucial battlefield reconnaissance data

- Expendable vehicle, low manufacturing costs

Concept

WASP Over Target

PHASE I — INITIAL PROOF OF CONCEPT

- Meet geometric constraints of 5" naval shell

- Design vehicle components to survive 15,000 g's

- Largely Aluminum for fabrication & cost considerations
  - could not achieve flight because of weight
  - difficult to control because of cg location
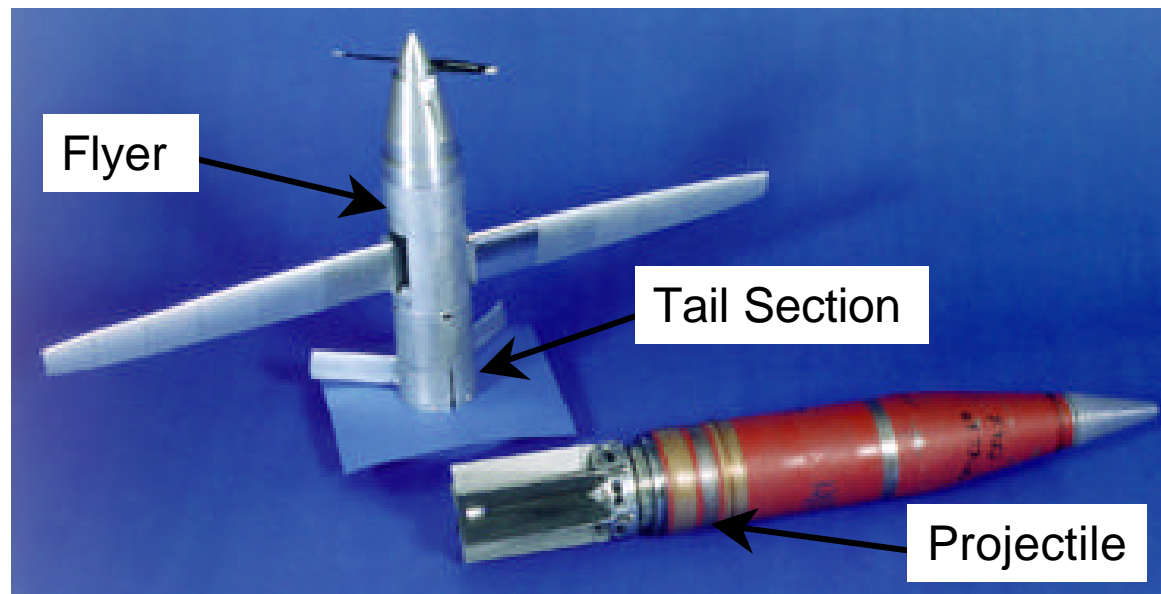
PHASE II — INTEGRATED VEHICLE DEMONSTRATION

- Functional test article demonstration with components

- 155 mm shell launched at 16,000 g's

- Need to reduce weight for endurance and control
  - introduction of composite to key components
 - move center of gravity further forward

→ Focus on tail section design
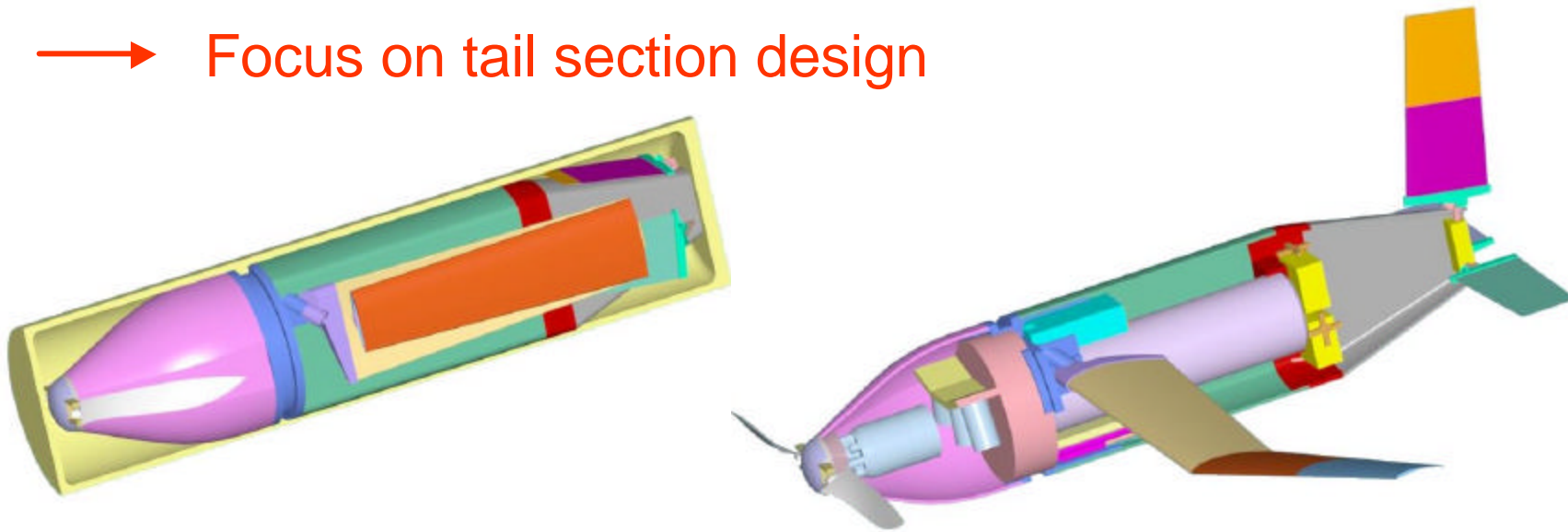
OBJECTIVES

- Design tool for high-g composite components
  - design and analysis of complex composite parts
  - high-g qualification with analysis and testing

- Manufacturing of WASP parts
  - fuselage sections, attachments
  - aerodynamic primary and secondary surfaces

PROTECTIVE SHROUD

Shroud
attachment
ring

Gap

Gap
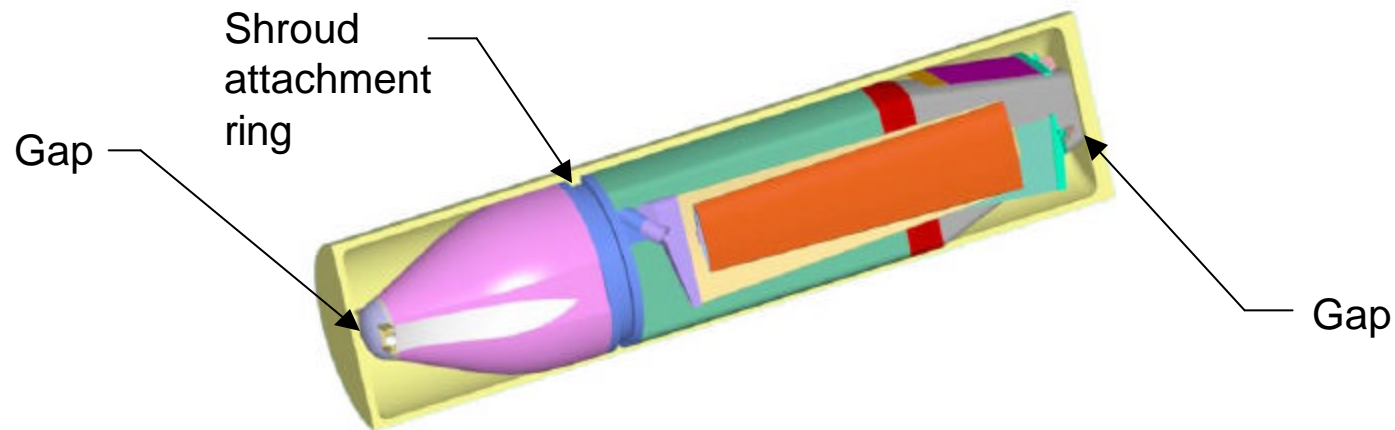
- Supports vehicle during gun launch
  - Provides load path for acceleration force
  - Most of vehicle in tension, prevents buckling
  - Relieves tail section requirements, improves cg

- Bears 60,000 lbs force of expulsion charge

- Protects vehicle during balloting

- Provide ballistic weight for ballistic trajectory

SHROUD DESIGN

Allowable g-Level for Shrouds of Different Metals
(16,000 required, thickness=0.2")

	Steel AISI 4140H	Tungsten W-25Re	Moly Mo-47.5Re	Titanium Ti 6211	AL AL 7075T6
Yield	24,000	8,000	9,000	16,000	12,000
Euler Column Buckling	583,000	643,000	725,000	443,000	331,000
Local Shell Buckling	145,000	160,000	180,000	110,000	82,000
Local Clamshell Buckling	30,000	33,000	37,000	23,000	17,000

- AISI 4140H Steel, 500?F temper selected
  - E = 30 msi, σ_y = 240 ksi, ρ = 0.283 lbs/in^3
  - K_{Ic} = 53 ksi*in$^{1/2}$ ($2a_{cr}$ = 0.070 in)
- Attachment ledge sized for bearing loads & shear
- FEA used to validate results
  - mass proportional load + weight of vehicle
  - max stress of 180 ksi at base and attachment ledge

LAMINATE SELECTION

- Classic Laminated Plate Theory code
  - given laminate, incrementally increase g-level until first ply failure and predicted ultimate strength using Tsai-Wu
  - showed sensitivity to different lay-ups, 90's cause early failure

- Quasi-isotropic lay-up of AS4/3501-6 at design load
  - 20 ply laminate $[0_2/+45/0_2/-45/0_2/90/0]_s$ for ultimate failure
  - 40 ply laminate $[0_2/+45/0_2/-45/0_2/90/0]_{2s}$ for first ply failure

- Illustrates advantages of composite sections over metal
  - large weight savings over original tail design (>85%)
  - improvement of cg location (tail = ¼ total vehicle weight)

⟶ More detailed analysis needed for composite design

HIGH-g DESIGN APPROACH

- Resonant frequency of system much greater than gun shot

- Strength of materials model
  - static finite element model with thin shell elements
  - equation solver using Tsai-Wu failure criteria

- Buckling model
  - FE structural model identical to strength of materials model
  - linear eigenvalue analysis

- Tests to validate model
  - compression tests on servo-hydraulic testing machine
  - air-gun tests at Picatinny Arsenal

- Sensitivity trade study to guide future configurations

FAILURE PREDICTION METHOD

- Maximum stress locations identified from FEA results

- Axial, circumferential, and shear stress recorded

- Laminate Tsai-Wu failure constants calculated

- Equation solver used to find failure load
  - stress scales linearly with load before buckling
  - FEA solution using nominal 1000 lbs load
 - solve Tsai-Wu equality using stress*X scaling factor

COMPRESSION TEST SETUP

Al Mass

Al Mount

Sample

Platens
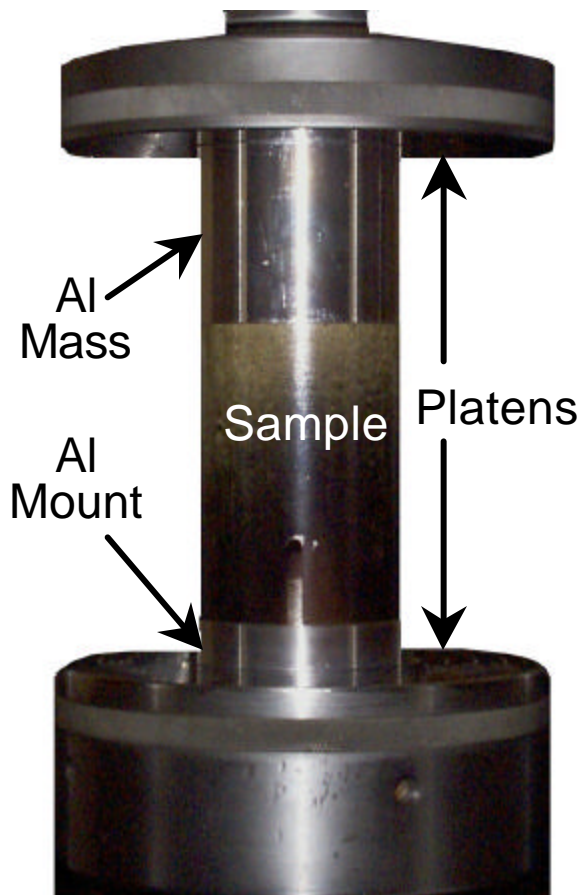
- Six samples loaded in axial compression

- Loaded to failure in displacement control

- Al 4 lbs weight on top
  - uniform loading
  - prevent circumferential strain

- Al bottom fixture
  - melted wax to hold firmly in place
  - simulates clamped boundary

COMPARISON OF FEM AND TESTS
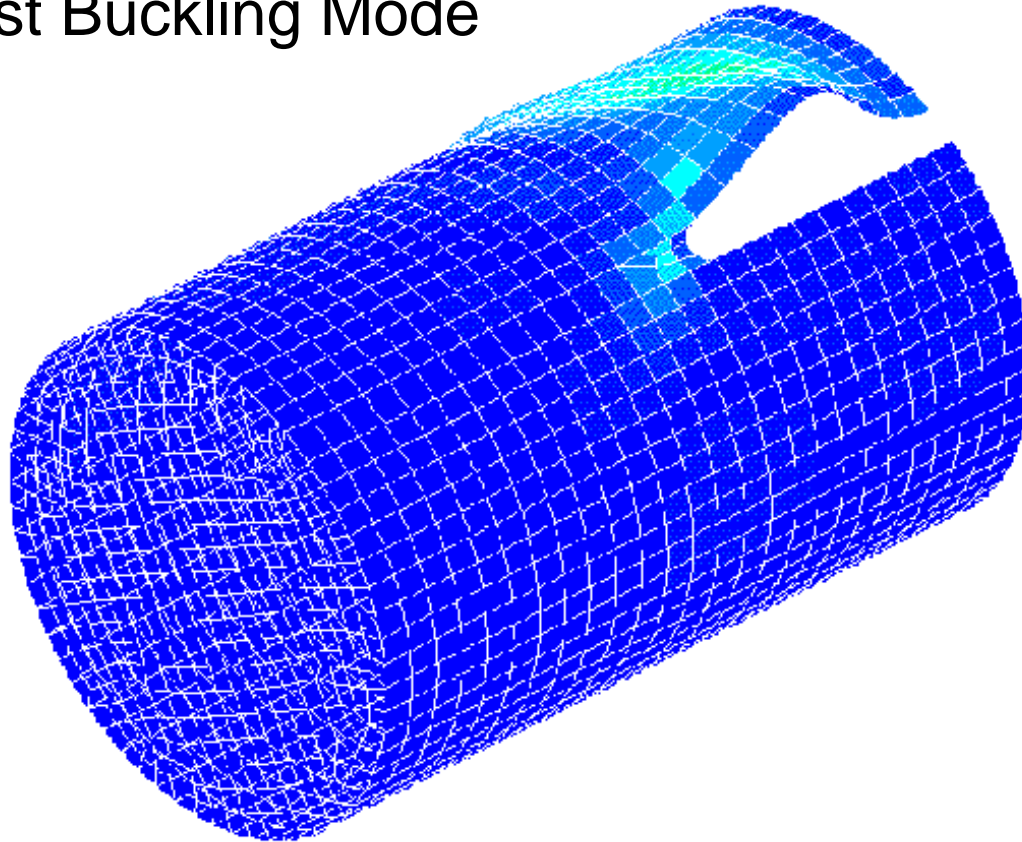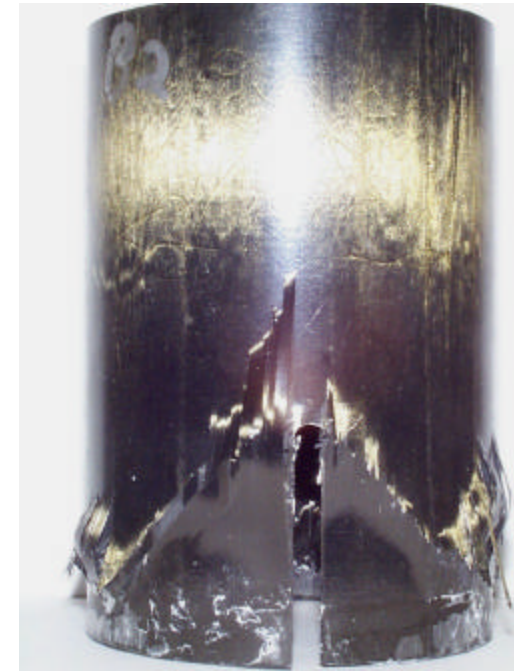
First Buckling Mode
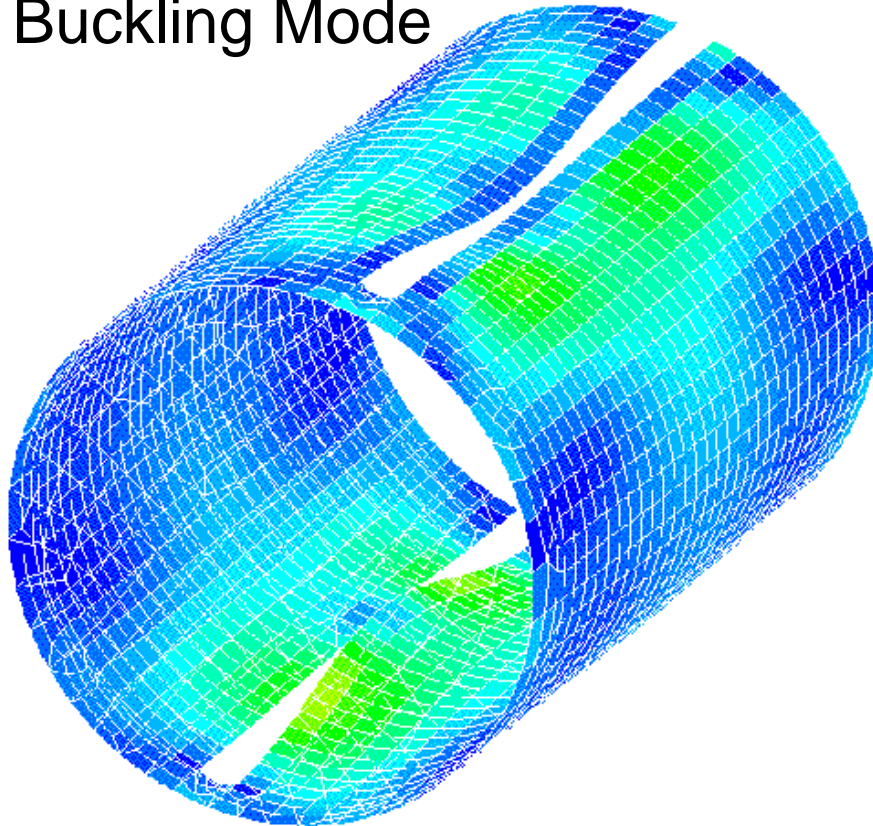
Tested Sample

45,000 lbs

- Predicted buckling load of 56,400 lbs
- Predicted fracture strength of 64,100 lbs

COMPARISON OF FEM AND TESTS

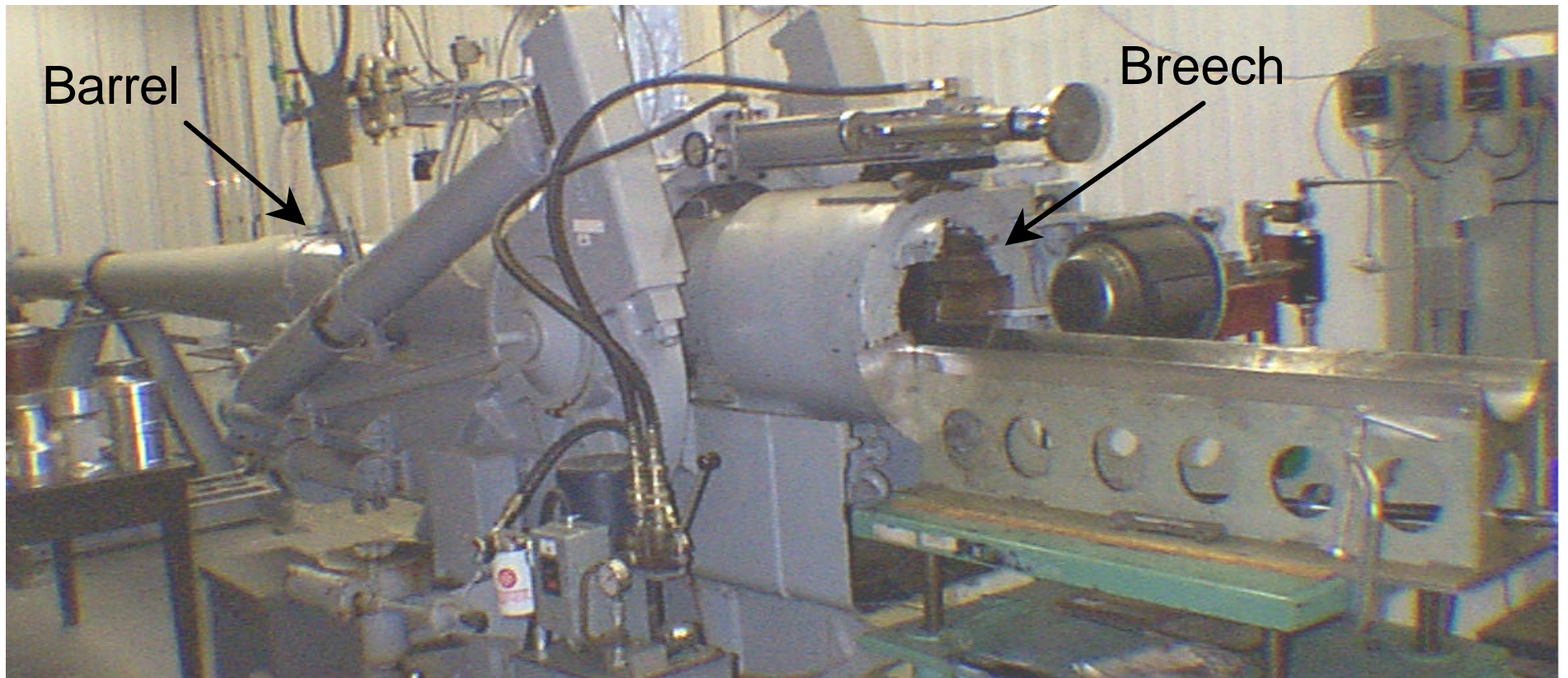First Buckling Mode

Tested Sample

56,000 lbs

- Predicted buckling load of 92,700 lbs
- Predicted fracture strength of 51,900 lbs

155-mm NAVY GUN

Barrel

Breech

AIR-GUN TESTING

- Six samples with same configuration as compression tests

- Both slot lengths survived 10,000 g's
  - equivalent to 40,000 lbs with 4 lbs block
  - below threshold measured for compressive tests

- Both failed catastrophically at 15,000 g's
  - equivalent to 60,000 lbs with 4 lbs block
  - exceeds both 45,000 and 55,000 lbs measured failure limits

- Results provide envelope consistent with quasi-static tests

BUCKLING TRADE STUDY

- Short slotted specimen
  - load factors were very high
  - will always fail in fracture according to model

- Long slotted specimen
  - buckling and fracture load factors of similar magnitude
  - load factor scales linearly with E
  - cylinder length has little effect; slot length is critical dimension
 - appears to scale linearly with tube diameter

CONCLUSIONS

- Modeling
  - weight can be saved using composites over Al design
  - finite element model accurate for predicting failure modes
  - failure load prediction has 10-20% error

- Testing
  - compression testing correlates well with air-gun
  - can potentially save much money and time

- Design
  - preliminary design criteria using static + dynamic FEA
  - knockdown factor of 1.25 for failure criteria obtained

COMPOSITE BODY

- 3 parts: Nose, Wing and Tail sections

- Compression molding by Quatro Composites[?]

  - graphite fibers, 33 msi

  - high temperature / high strength epoxy system

  - 0.1" wall thickness, 20 fiber layers

- Machined with diamond grit carbide tools

- Sections joined by Aluminum bulked

- Designed to be g-hardened from previous static and
 dynamic FEA, tests of composite cylinders

BODY MANUFACTURING

6"

4.5"
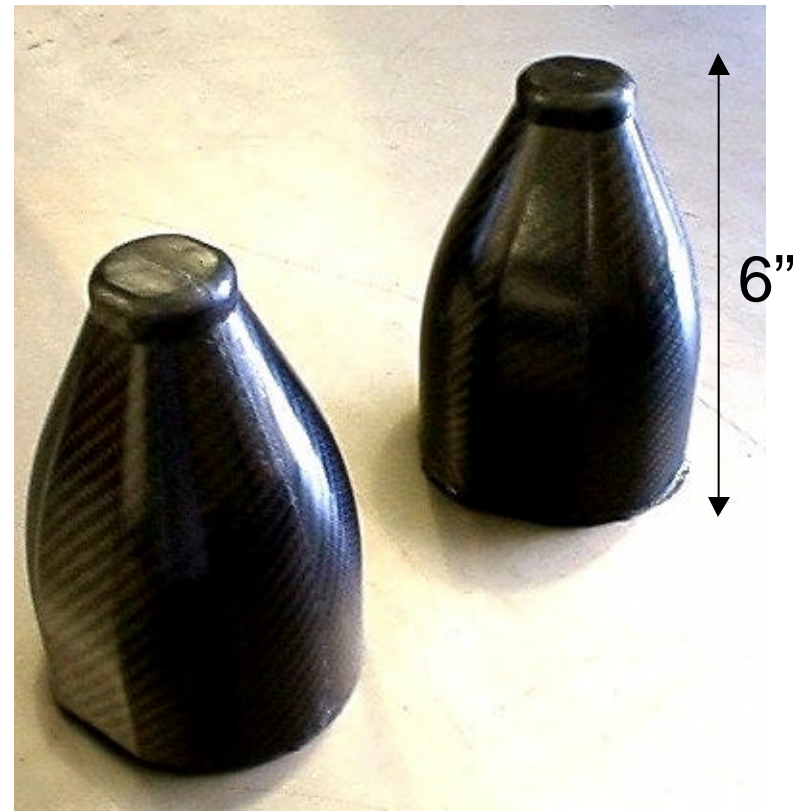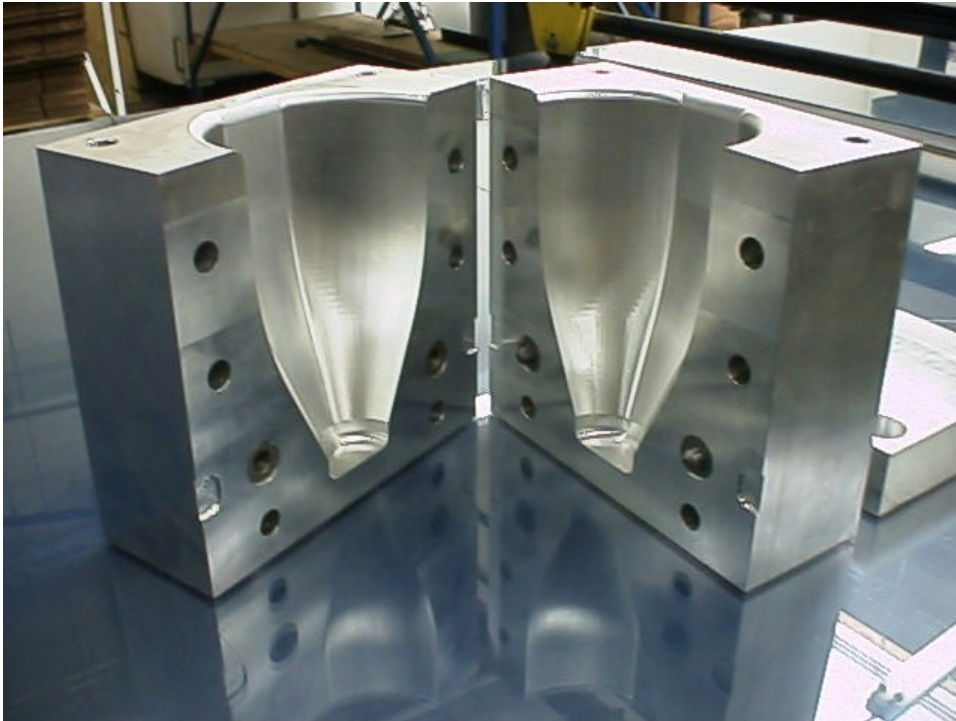
COMPOSITE WINGS

- All aero-surfaces made in composite
  - 3 part hinged wing sections, thin cambered airfoil
  - 1 vertical rudder, symmetric airfoil
  - 2 horizontal tail fins, unsymmetric airfoils
- Manufactured by hand "wet" lay-up at MIT
  - graphite woven ?45? fabric and unidirectional tape
  - taper of 28 layer leading to 12 layer trailing edge
  - model aircraft epoxy with colloidal silica thickener
  - single-sided female mold, vacuumed room temp cures
- Sized from original WASP work (Jenkins, Radcliffe)

WING MANUFACTURING

10"

9"

5"

3"
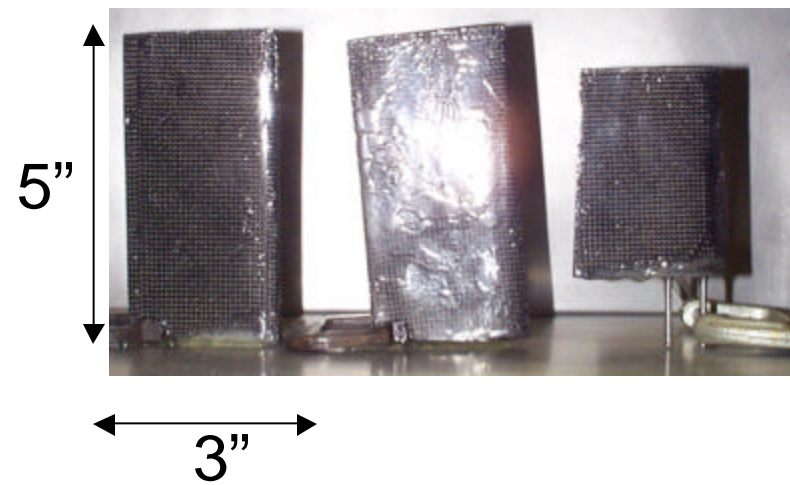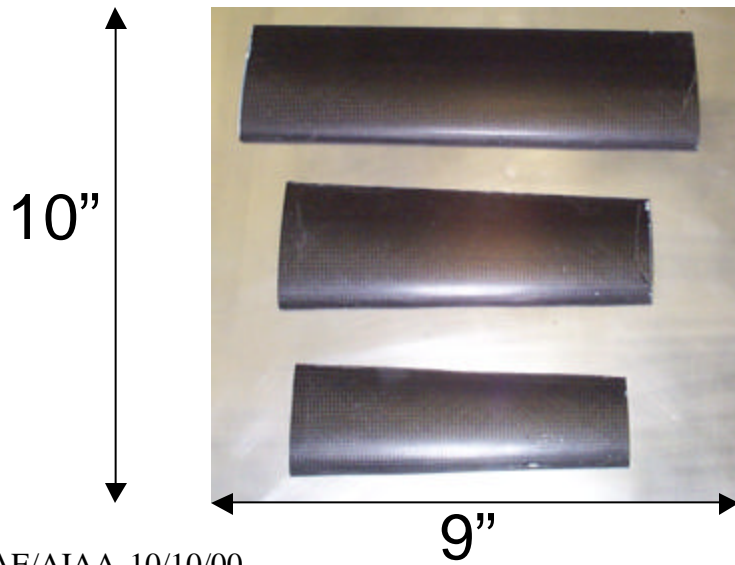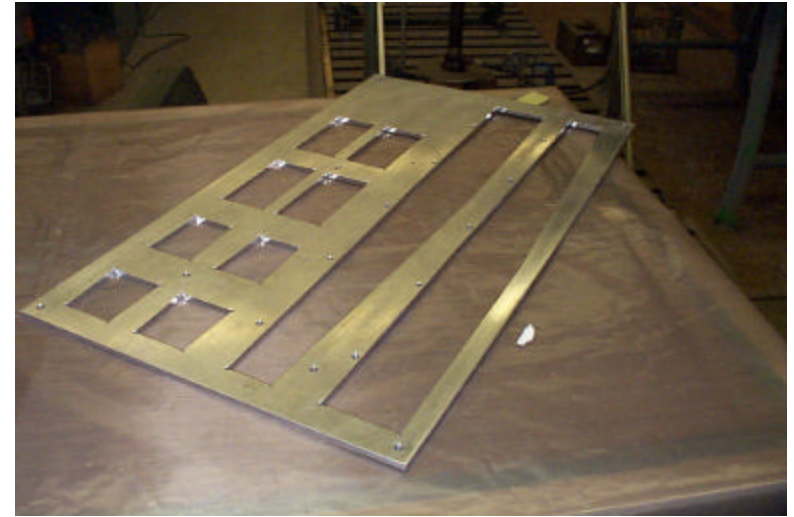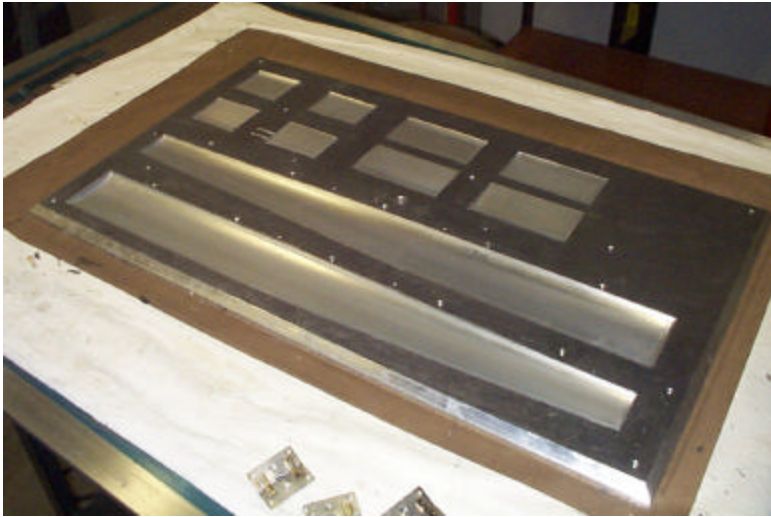
MANUFACTURING CONCLUSION

- Molds provide little flexibility and are expensive, think through carefully and prototype if possible

- Composite adds flexibility to the design, easy to increase stiffness with minimal impact if test results warrant

- Fabric wet-layup is a good alternative for manufacturing complicated shapes

- Use epoxy and bleeder bag generously for good parts

- Wet lay-up is as much of an art as a science

- Biggest challenge lies in joints and hinges

ONGOING DRAPER/MIT WASP WORK

- Manufacturing
  - wings are now foam filled and closed off for stiffness, 2 sections
  - need to develop g-hardened hinge and lock mechanism

- Testing
  - static tests on composite body parts, wings and hinges
  - air-gun tests of structure and on all components

- Analysis
  - integrate composite failure tool in ANSYS
  - analyze and optimization of all WASP composite parts

- Production
  - design of production scale vehicle, 1000/year for 10 years
  - proof test of flight ready, g-hard vehicle in 2002

WASP TEST FLIGHT VEHICLE