

# **The Effects of Damage and Uncertainty on the Aeroelastic / Aeroservoelastic Behavior and Safety of Composite Aircraft**

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## Contributors

- **Department of Aeronautics and Astronautics**
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  - **Dr. Mark Tuttle, co-PI, professor and chairman**
- **Boeing Commercial, Seattle**
  - **Dr. James Gordon, Associate Technical Fellow, Flutter Methods Development**
  - **Dr. Kumar Bhatia, Senior Technical Fellow, Aeroelasticity and Multidisciplinary Optimization**
- **FAA Technical Monitor**
  - **Curtis Davies, Program Manager of JAMS, FAA/Materials & Structures**
- **Other FAA Personnel Involved**
  - **Dr. Larry Ilcewicz, Chief Scientific and Technical Advisor for Advanced Composite Materials**
  - **Carl Niedermeyer, Airframe and Cabin Safety Branch (ANM-115), Standards Staff - Transport Airplane Directorate (previously: Boeing flutter manager for the 787 and 747 programs\_**

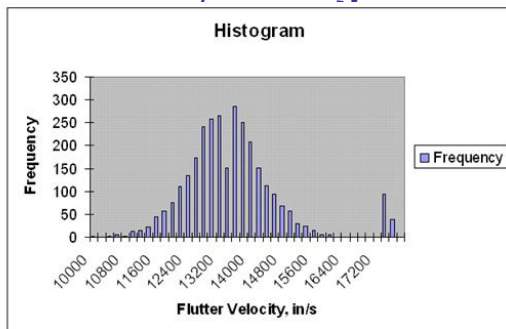
## Scope

- **Motivation & Key Issues – a Review of the complete project:**
- **1. Probabilistic aeroelastic reliability estimation**
- **2. Simulation of aeroelastic behavior with local structural nonlinearities**
- **3. Simulation of aeroelastic behavior with global distributed structural nonlinearities**
- **4. Experimental aeroelasticity**
- **2009 focus: Experimental aeroelastic capabilities for testing degraded, damaged, nonlinear composite airframes**
  - **Development**
  - **Status**

# 1. Probabilistic Reliability Assessment of Actively Controlled Composite Airframes Including Damage Statistics, Damage Effects, and Maintenance Procedures

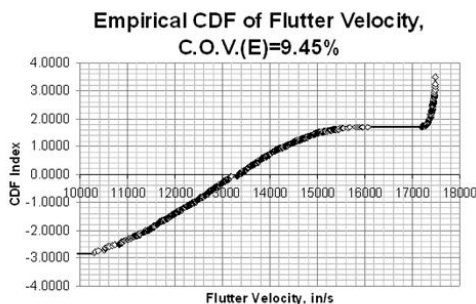
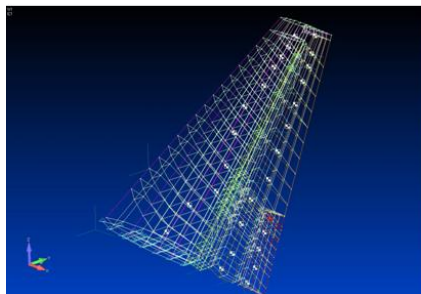
## FE Model of Composite Structure:

- Number of grid points = 1268
- Number of CBAR elements = 309
- Number of CBUSH elements = 45
- Number of CONM2 elements = 28
- Number of CQUAD4 elements = 1409
- Number of CROD elements = 1056
- Number of CSHEAR elements = 91
- Number of CTRIA3 elements = 187
- Number of RBE2 elements = 16
- Number of RBE3 elements = 28

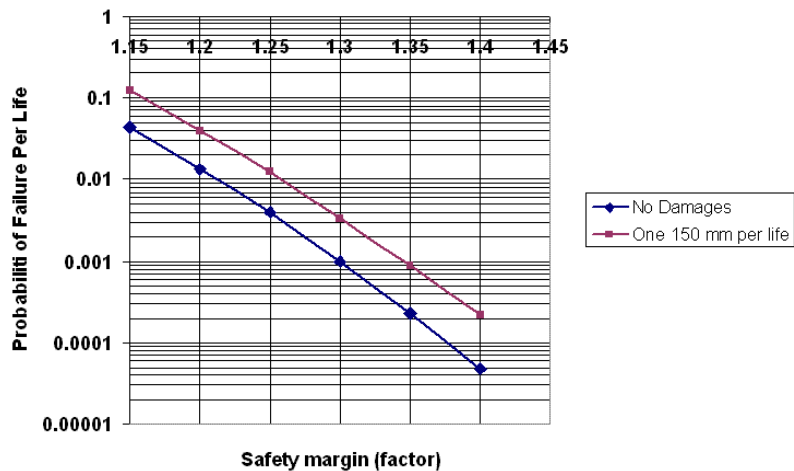


## Qualifications!

Not a real flying structure;  
 Flutter analysis carried out for a cantilevered tail and not for empennage/tail system;  
 Results – problem dependent



Flutter speeds uncertainty in a transport-type Composite vertical tail/rudder system.  
 Note the possible switch in flutter mechanisms  
 For certain combinations of system parameters.



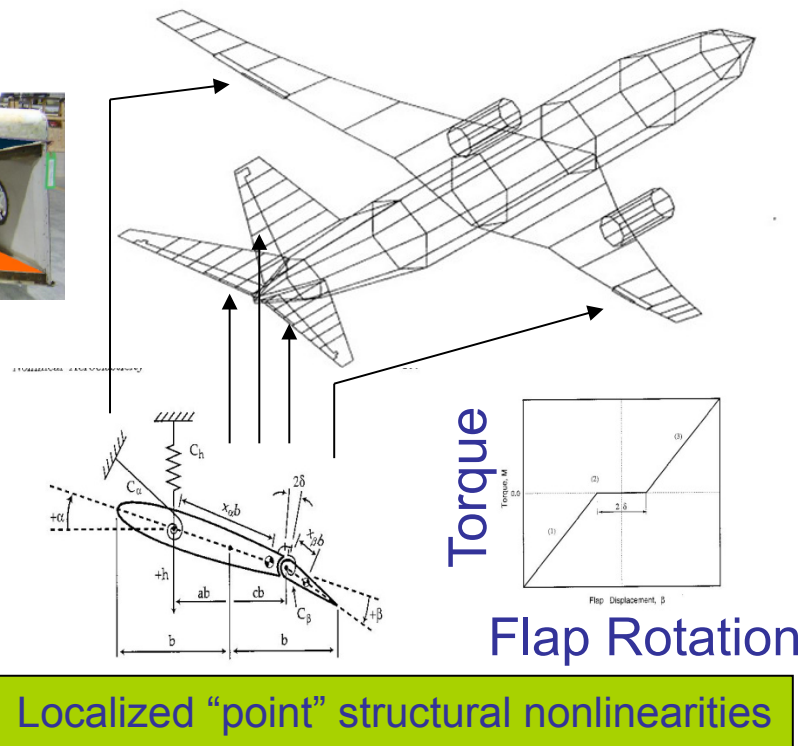
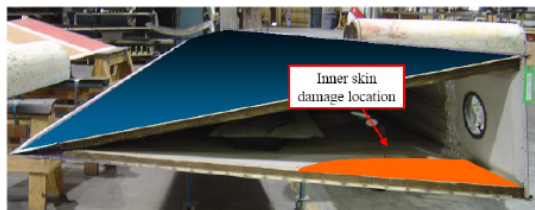
Accounting for damage statistics:  
 the effect on probability of flutter failure per life of the flutter design safety margin used

To obtain the same flutter reliability in the accounting-for-possible-damage case  
 Compared to no-damage case, the flutter design margin Has to increase from 1.15 to 1.2 (in the vertical tail case).



- 2. Local nonlinear structural behavior:
  - Delamination, changes in joints/attachments stiffness and damping, as well as actuator nonlinearities may lead to nonlinear aeroelastic behavior such as Limit Cycle Oscillations (LCO) of control surfaces with stability, vibrations, and fatigue consequences.

Airbus Rudder disbond detected during maintenance in November 2005



Localized "point" structural nonlinearities

- **3. Distributed nonlinear structural behavior:**
  - **Highly flexible, optimized composite structures (undamaged or damaged) may exhibit geometrically nonlinear structural behavior, with aeroelastic consequences.**

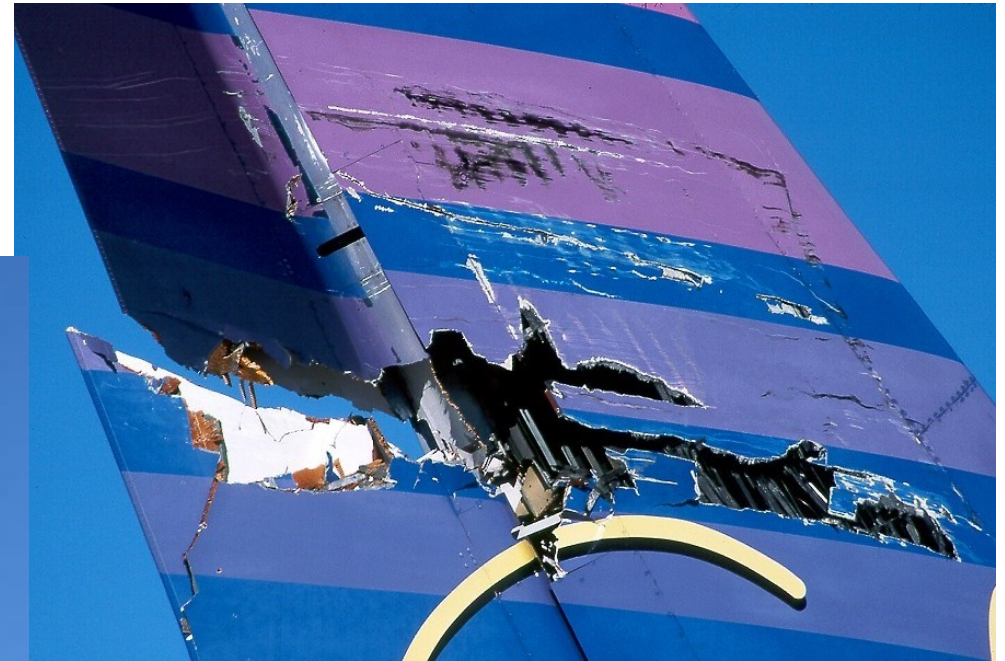


## Objectives – a Review of the Multi-Year Program

- Develop computational tools (**validated by experiments**) for automated local/global linear/nonlinear analysis of integrated structures/ aerodynamics / control systems subject to multiple local variations/ damage.
- Develop aeroservoelastic probabilistic / reliability analysis for composite actively-controlled aircraft.
- Link with design optimization tools to affect design and repair considerations.
- Develop a better understanding of effects of local structural and material variations in composites on overall Aeroservoelastic integrity.
- Establish a collaborative expertise base for future response to FAA, NTSB, and industry needs, R&D, training, and education.

# 2008-2009 Focus: Tail / Rudder Systems

Air Transat 2005



Damaged A310 in the hangar  
(picture found on the web)



# Experiments and experimental capabilities development

- Rudder hinge stiffness nonlinearities and hinge failure can be caused by actuator behavior or by failure of the composite structure locally and globally.
- Use tests to validate and calibrate numerical models – a UW / Boeing / FAA collaboration.
- Wind tunnel model designs and tests will start with simulated hinge nonlinearities using nonlinear springs and then proceed to composite rudder structure with actual composite failure mechanisms.

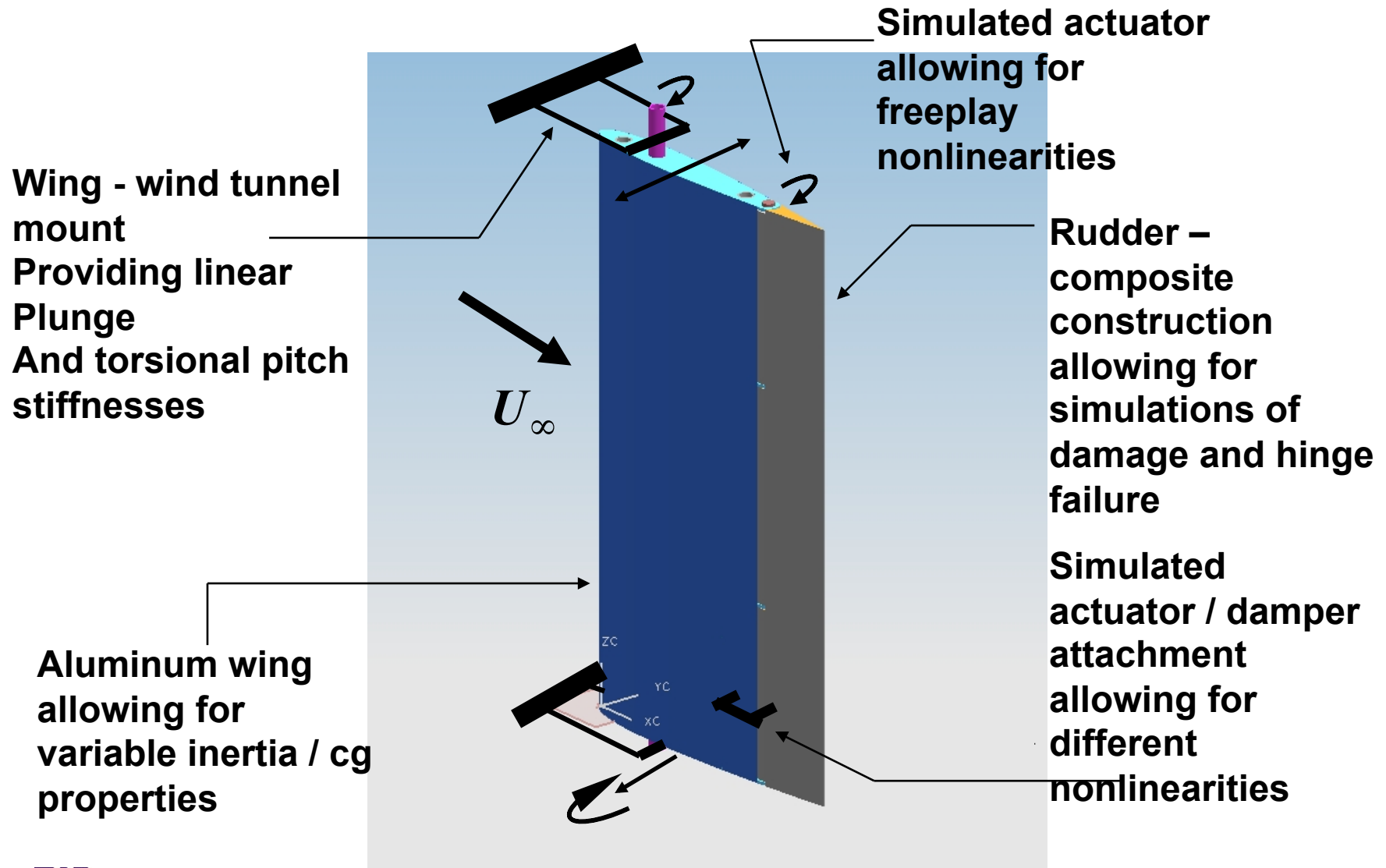
# Aeroelastic Experimental Capability and Flutter Experiments

## Experiments and experimental capabilities development

### General Approach:

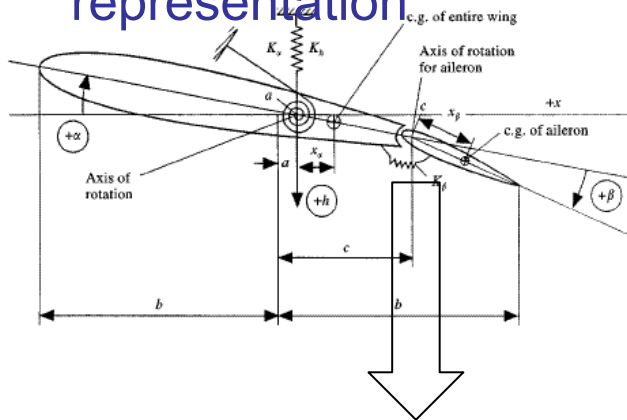
- **Start with simple models for which experimental and theoretical results already exist – the Duke U wing / control surface LCO model**
- **Expand and generalize by adding**
- **Develop the model design & construction and test conduction as well as data processing hardware and software tools**
- **Use as a foundation upon which to build aeroelastic experimental capabilities using more complex models**

# UW Flutter Test Wing / Control Surface Design mounted vertically in the UW A&A 3 x 3 wind tunnel

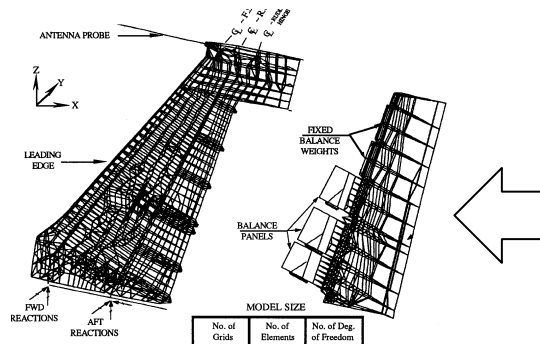


# Limit Cycle Oscillations and flutter due to control surface hinge stiffness nonlinearity

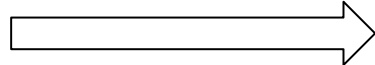
Basic aeroelastic model representation



Local degradation / damage

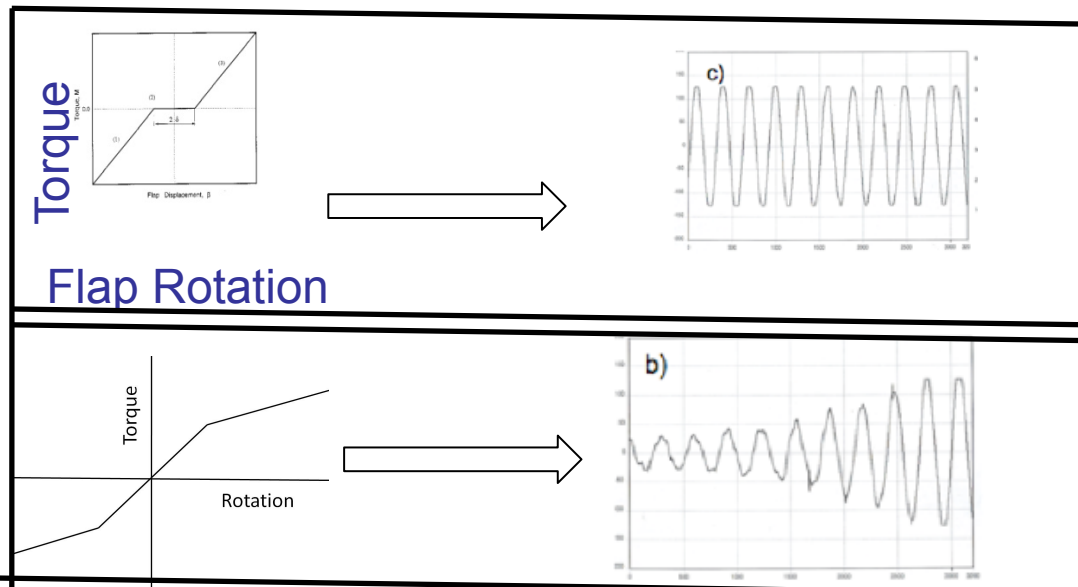
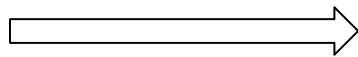


Hinge stiffness



Hardening

softening



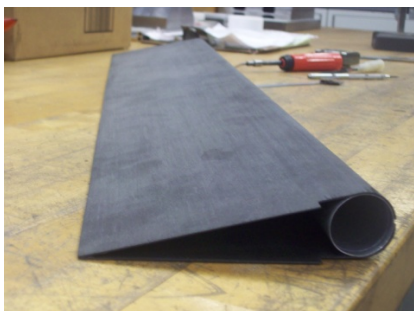
## The tail / rudder model at the UW's 3 x 3 wind tunnel 2008 - 2009



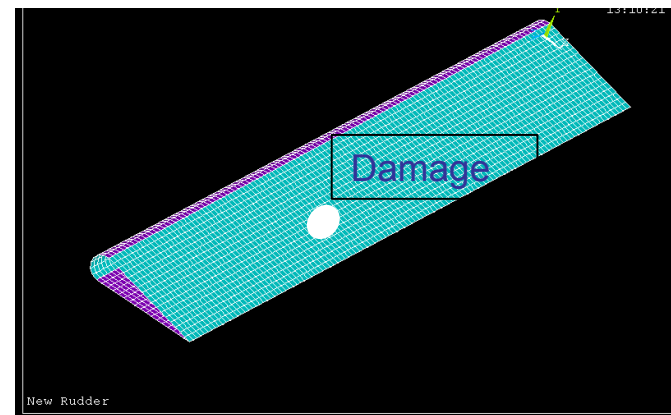
## LCO Tests Status

- Modification of model to allow tests with larger freeplay magnitudes
- Improvement of instrumentation and data processing equipment.
- Modification of model to allow rapid changes in system's characteristics
- Search for / design hinge dampers for tests involving complete loss of actuator stiffness (to allow validation of UW and Boeing computational tools)
- Testing of dampers & modification of model to accept hinge dampers

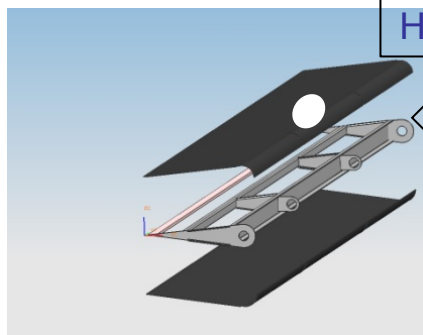
# Design / Construction of Composite Rudders for Flutter Simulations / Tests of Damaged Rudders Representing Realistic Rudder Designs: In Progress



Highly flexible rudder model for exploratory flutter / LCO studies of Pristine and damaged structures with more complex dynamics (including Rudder torsion and bending)



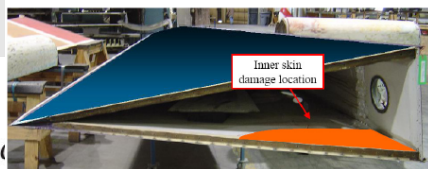
Detailed finite element / Unsteady aerodynamic modeling, including 3D and Local effects



Hinge Failure

Rudder models reflecting Actual composite rudder Designs with various internal Structural arrangements And damage mechanisms

▪ Rudder disbond detected during maintenance in November 2005





# Progress

- Progress in the development of the UW's aeroelastic wind tunnel capabilities.
- Linear flutter as well as Limit Cycle Oscillations (LC) tested in the UW's 3 x 3 wind tunnel and used to validate UW's numerical modeling capabilities.
- Correlation with Boeing flutter and LCO simulation runs – underway. Wind tunnel tests of tail / rudder systems with actuator failure and with nonlinear dampers – in development.
- Wind tunnel tests of representative tail / rudder systems with realistic rudder composite structures – in development.
- Results from this effort will provide valuable data for validation of simulation codes used by industry to certify composite airliners.

# Accomplishments

- Development of a comprehensive methodology and computational tools for the estimation of the probabilistic aeroelastic reliability of undamaged and damaged composite airframes.
- Development of a unique coupled nonlinear structural / linear unsteady aerodynamic capability for flutter analysis of geometrically nonlinear optimized composite airframes.
- Development of a wind tunnel aeroelastic testing capability and preparations for nonlinear aeroelastic tests that will provide data for validation of corresponding industry-used codes. Initial focus: the tail / rudder problem.