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

Presented by Dr. Eli Livne
Department of Aeronautics and Astronautics
University of Washington

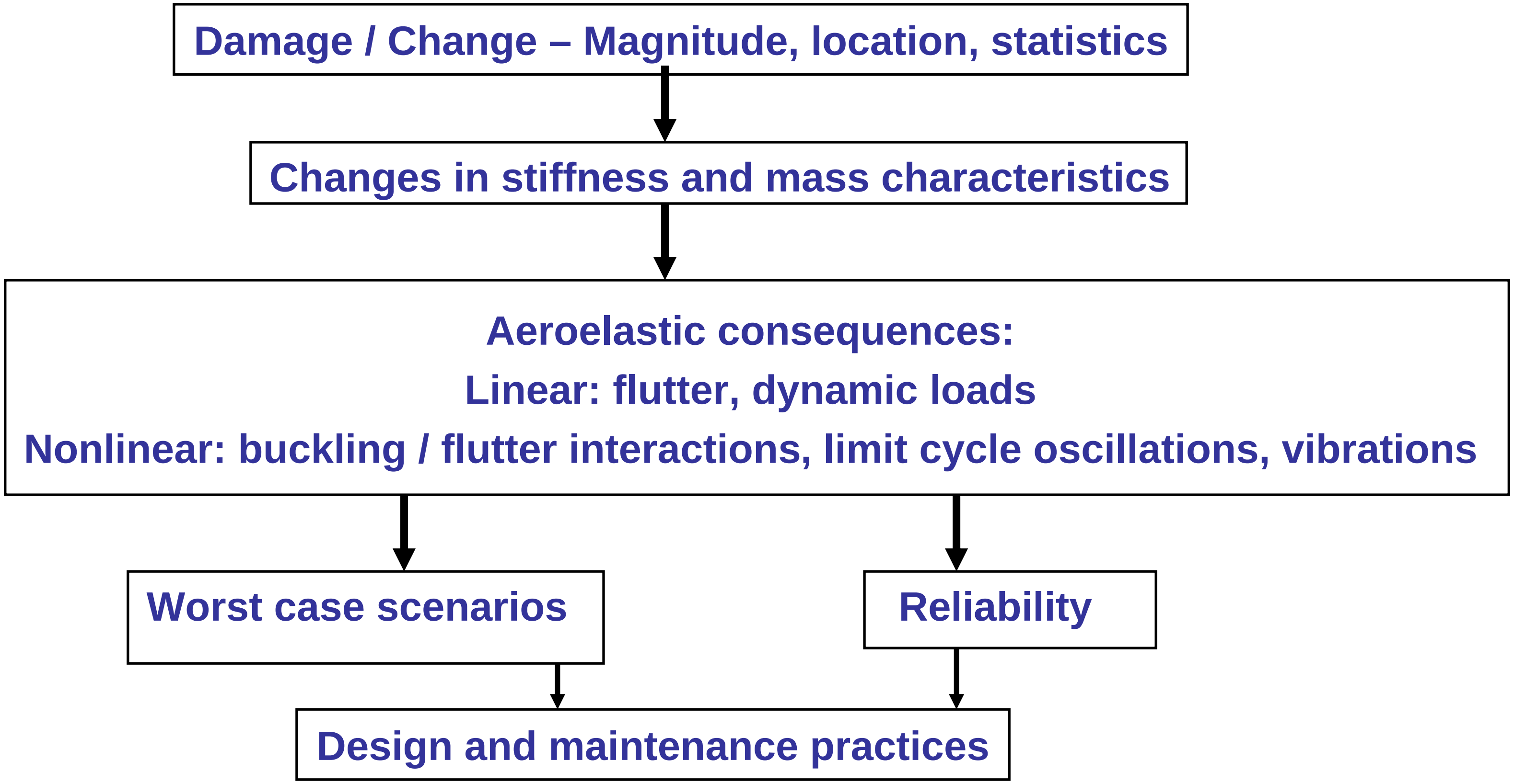
Contributors

- Department of Aeronautics and Astronautics
  - Luciano Demasi, post-doctoral research fellow
  - Andrey Styuart, research scientist, assistant professor temp.
  - Marat Mor, post doctoral research fellow
  - Eli Livne – PI, Professor
- Department of Mechanical Engineering
  - Francesca Paltera, graduate student
  - Mark Tuttle, professor
- Boeing Commercial, Seattle
  - James Gordon, Associate Technical Fellow, Flutter Methods Development
  - Carl Niedermeyer, Manager, 787/747 Flutter Engineering & Methods Development
  - Kumar Bhatia, Senior Technical Fellow, Aeroelasticity and Multidisciplinary Optimization
- FAA Technical Monitor
  - Curtis Davies, Program Manager of

Scope

- **Motivation & Key Issues**
- **Linear flutter of damaged and uncertain composite airframes**
- **Nonlinear flutter of damaged and uncertain composite airframes:**
  - **LCOs and explosive flutter cases**
- **Probabilistic approach to the aeroelastic reliability of damaged composite aircraft**
- **Automated simulation capabilities: linear and nonlinear**
- **Sensitivity analyses and worst-case scenario identification tools**
- **Monte Carlo simulations**
- **Experimental capabilities development**

The Problem



Damage / Change – Magnitude, location, statistics

Changes in stiffness and mass characteristics

Aeroelastic consequences:
Linear: flutter, dynamic loads
Nonlinear: buckling / flutter interactions, limit cycle oscillations, vibrations

Worst case scenarios

Reliability

Design and maintenance practices

Some sources of uncertainty in composite structures

Damage

Delamination

Joint/attachment changes

Debonding

Environmental effects, etc.

Objectives

- Develop computational tools (validated by experiments) for <u>automated</u> 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.

Linear Behavior – Classical Flutter

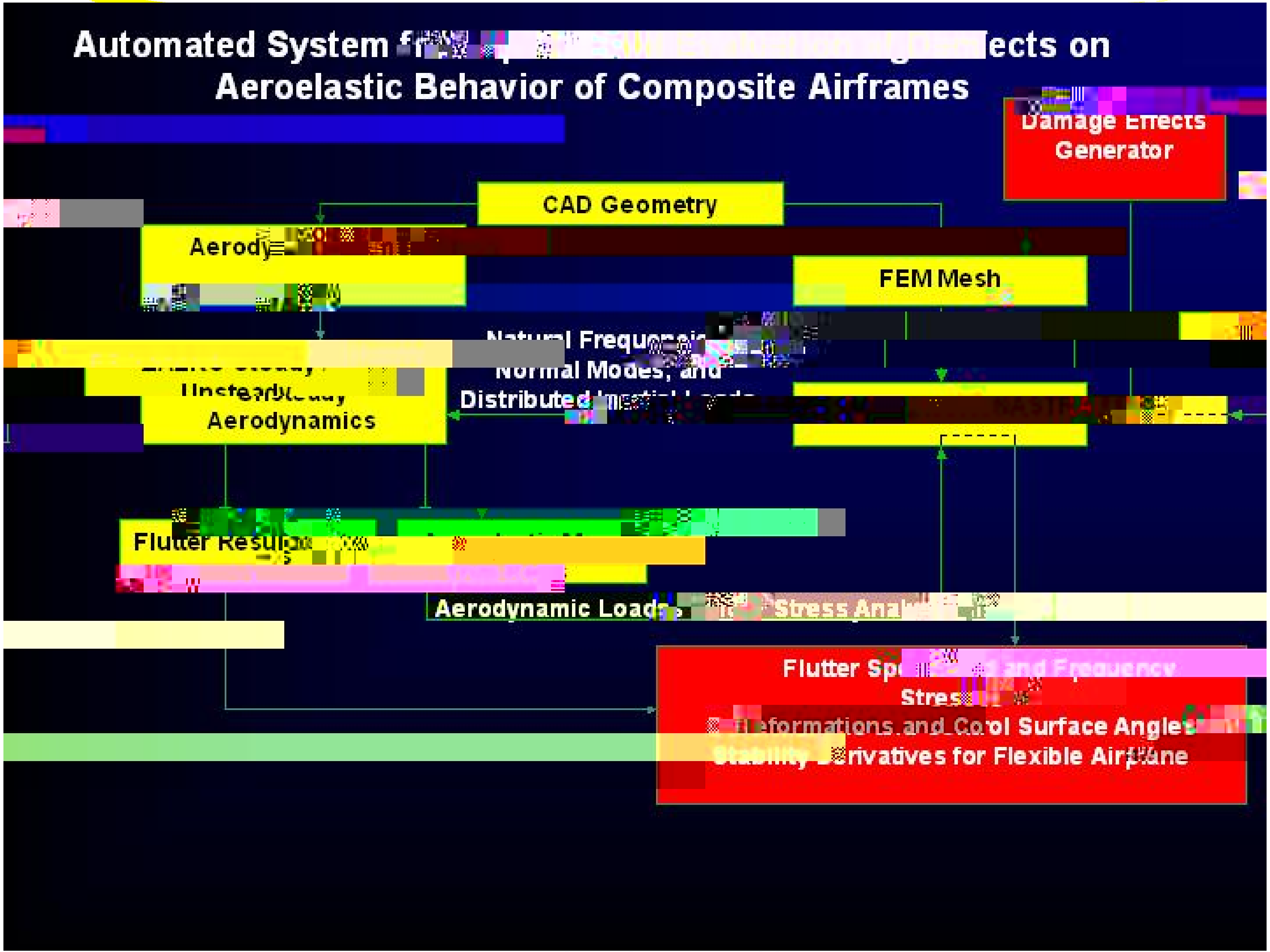
Automated simulations for carrying out fast repetitive analyses of large numbers of parameter variation cases

Goals:

Identify worst case damage and structural variation scenarios and critical areas

Provide flutter information for Monte Carlo (or other) statistical simulations

Automated System for Calculating Flutter Speeds of Large Numbers of Airframe Structural Variations



Automated System f[illegible]ects on
Aeroelastic Behavior of Composite Airframes

Damage Effects
Generator

CAD Geometry

Aerody[illegible]

FEM Mesh

Natural Frequencies,
Normal Modes, and
Distributed Inertial Loads

Unsteady
Aerodynamics

Flutter Results

Aerodynamic Loads

Stress Analysis

Flutter Sp[illegible] and Frequency
Stres[illegible]
Deformations and Control Surface Angles
Stability Derivatives for Flexible Airplane

Reduction in flutter speed on a TE flaperon due to loss of local panel stiffness due to damage (top covers)

- 🟥 ~10%
- 🟪 ~8%
- 🟨 ~4%
- 🟦 ~1-2%
- ⬛ <1%

Linear flutter of damaged and uncertain composite airframes

- Computational array of industry standard tools – ready and tested
- Used for flutter damage-sensitivity studies of fighter wing / flaperon system
- Used for flutter-failure reliability studies of fighter wing / flaperon system
- Ready for Boeing generic composite vertical tail / rudder system NASTRAN model
- Boeing NASTRAN model will be provided soon (in a way clear of proprietary and ITAR limitations), and used in flutter sensitivity-to-damage and reliability studies.

A typical passenger airplane Boeing vertical tail / rudder NASTRAN model

Automated nonlinear aeroelastic behavior simulations

<u>The control surface free-play problem</u>:

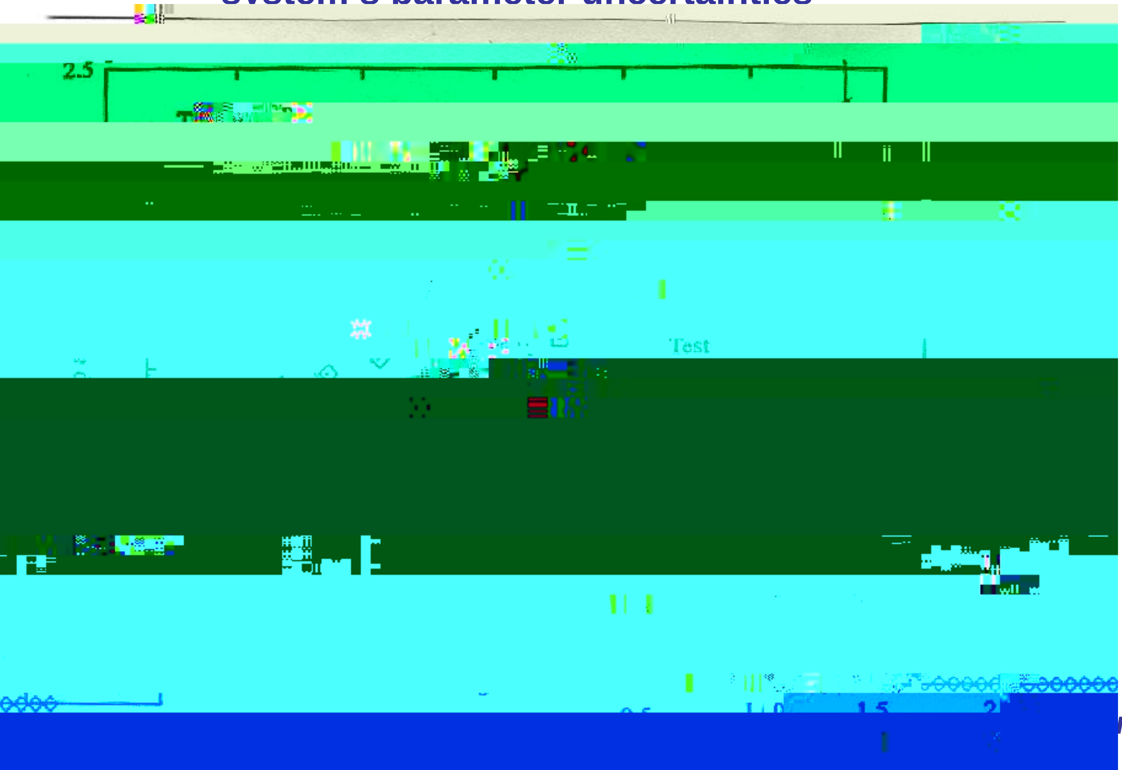
- Simulate wing / control surface systems with control system free-play over a range of parameter variations to capture LCO (limit cycle oscillations) behavior automatically
- Use in Monte Carlo simulations to obtain behavior statistics and reliability estimates
- Contribute to the aeroelastic design of currently emerging composite airframe passenger aircraft

<u>The Damaged airframe problem:</u>

- Simulate nonlinear aeroelastic behavior due to nonlinear local structural effects due to local damage or degradation
- Use to identify possible damage mechanisms that can lead to such behavior
- Use in Monte Carlo simulations and reliability studies

LCO simulation capabilities status

- Automated LCO simulation capabilities for 2D prototype airfoil / control surface systems –
  - completed
  - validated against experimental results
  - Used in Monte Carlo simulations to obtain response statistics due to a large number of system’s parameter uncertainties

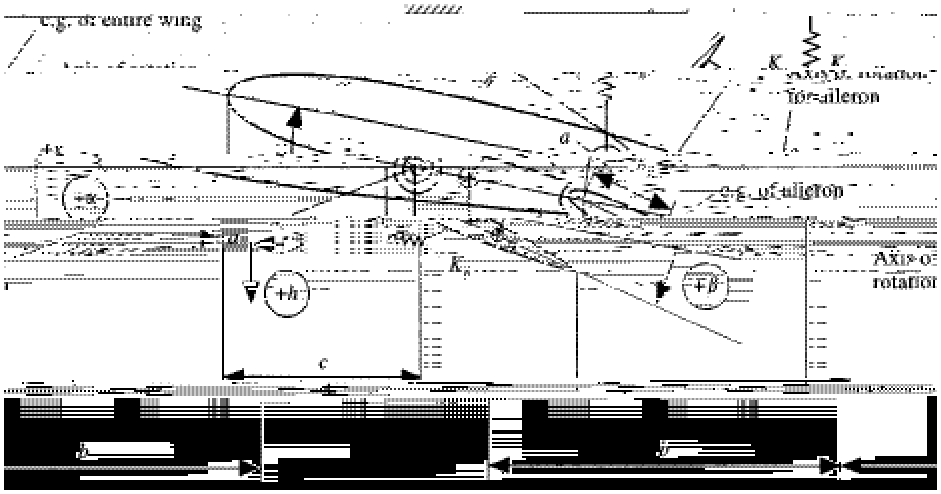


Boeing - UW

3DOF aeroelastic system

Damage may result in:

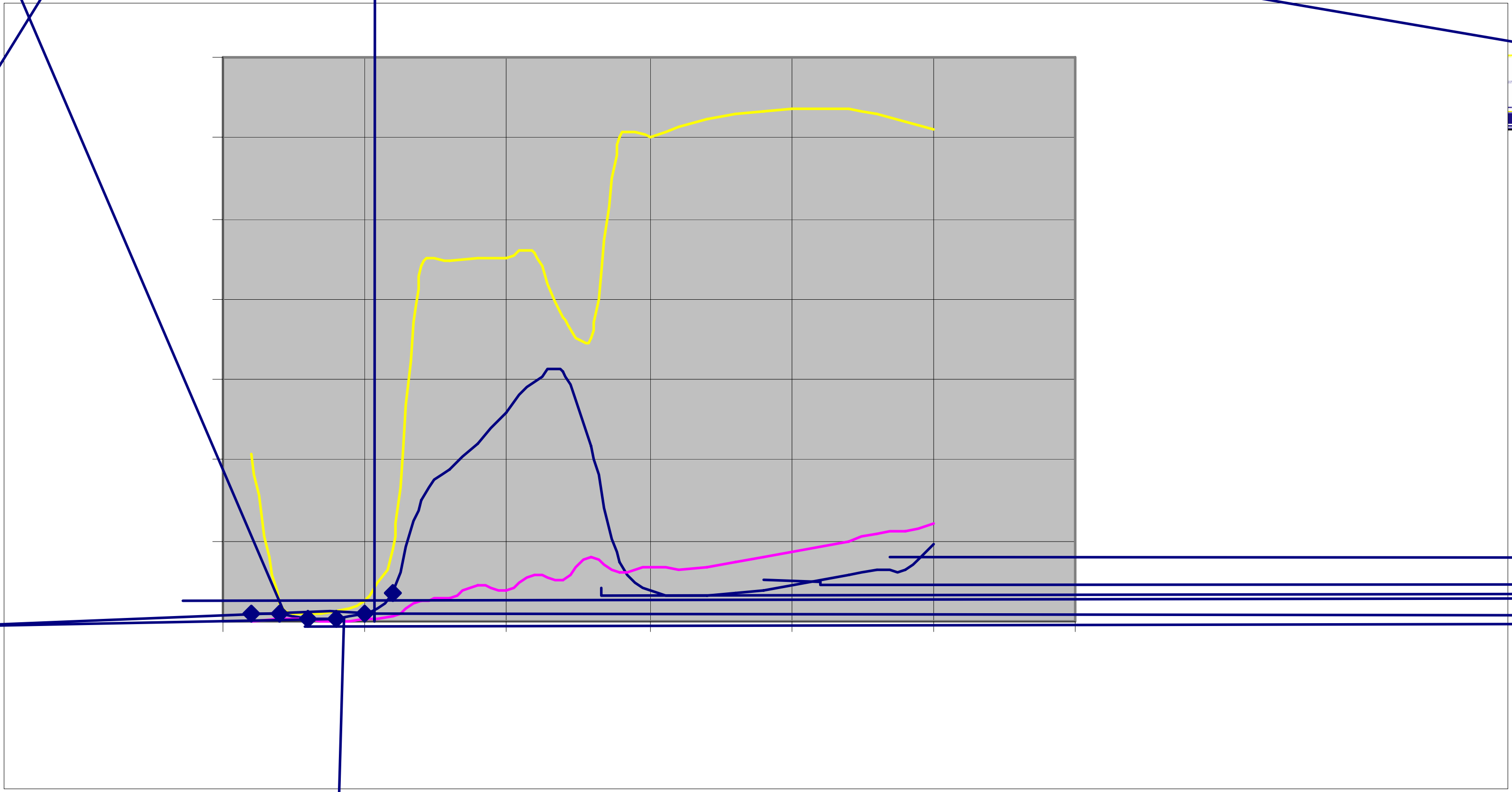
- **reduction of stiffness**
- **moisture absorption and possible changes in properties**
- **changes in stiffness and inertia properties after damage repair**
- **irreversible properties degradation due to aging**



Random Simulation

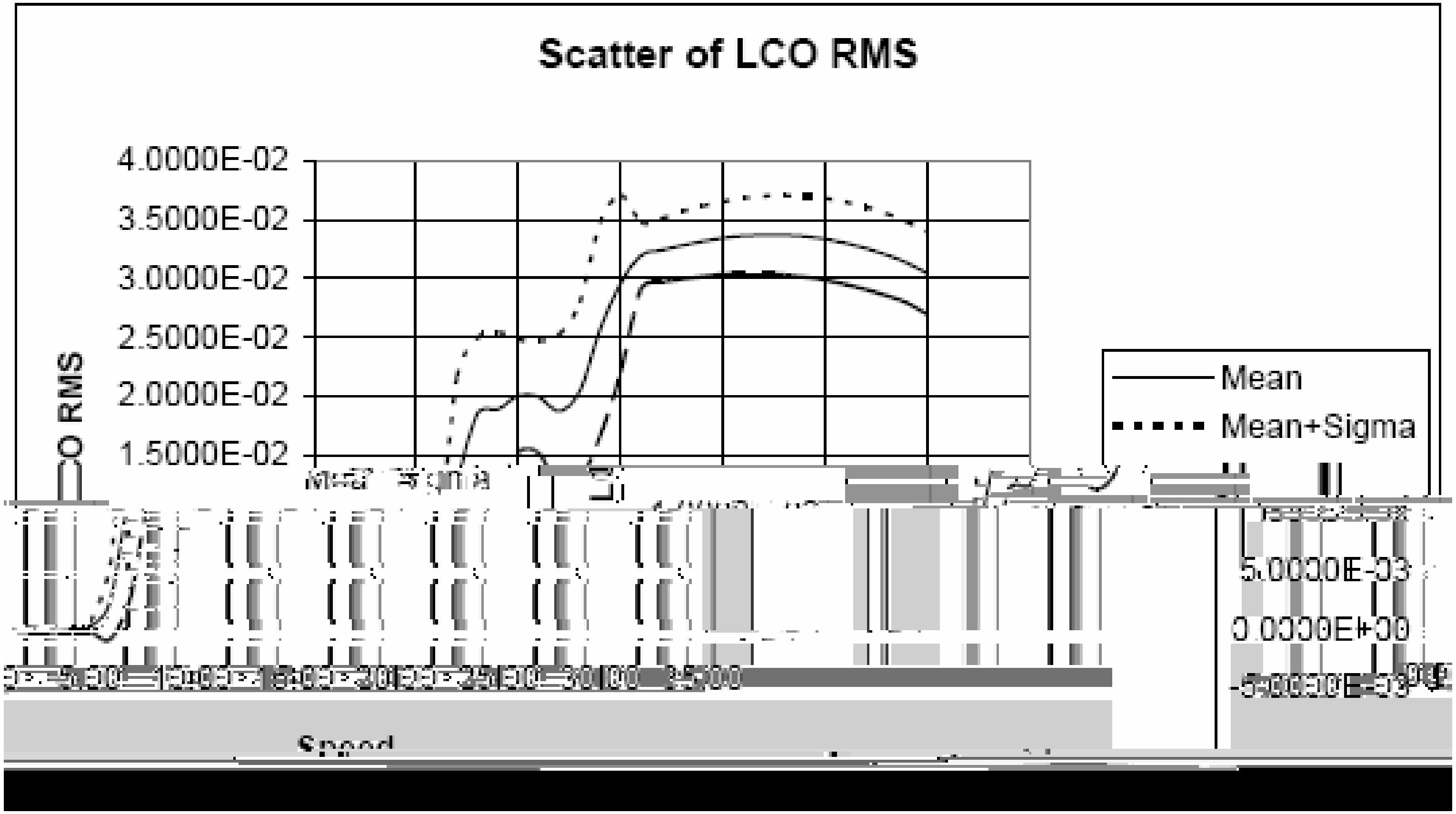
- **5 geometrical parameters**
- **6 inertia parameters**
- **4 stiffness parameters**
- **3 structural damping parameters**
- **2 free-play parameters**
- **air density, airspeed, discrete gust velocity**

LCO Study of wing / control surface 3dof system: nominal parameters



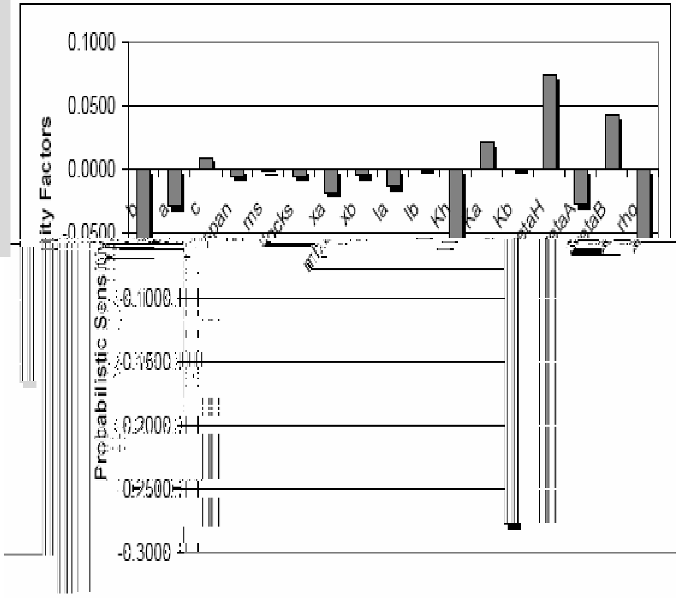
LCO study: Monte-Carlo results wing / control surface system

LCO study of wing / control surface system: scatter band



3DOF Problem: Flutter Speed Sensitivity Study

Variable	Description	PDF	mean	C_v
b	Semi-chord	Normal	0.127 m	0.2%
a_d	Elastic axis, m	Normal	-0.0635	1%
c_d	Hinge line, m	Normal	0.0635	1%
span	Span	Weibull	0.52 m	0.2%
x_a	c.g. of entire wing	Normal	0.0551 m	2%
x_b	c.g. of aileron	Normal	0.0025 m	2%
Ia	Moment of inertia of entire section	Normal	0.01347 kg m^2	4%
Ib	Moment of inertia of aileron-tab	Weibull	0.0003264 kg m^2	4%
ms	Mass of section	Normal	1.558 kg	0.2%
m_{blocks}	Mass of support blocks	Normal	0.9497 kg	0.2%
Kh				



Simulation of structurally nonlinear aeroelastic behavior due to distributed large deformations and damage in composite airframes

- **Status:**
  - Development complete
  - Major theoretical issues resolved
  - Validation using experimental and computational results for a simple geometrically nonlinear test wing model – complete

Possible large deformation

Possible nonlinear local behavior due to damage or degradation

Numerical simulation capabilities for structurally nonlinear aeroelstic problems using detailed industry-standard

Numerical simulation capabilities for structurally nonlinear aeroelstic problems using detailed industry-standard modeling techniques – localized nonlinearities

- Local structural nonlinearity due to local damage mechanisms
- Develop efficient Finite Element (NASTRAN-like) modeling for geometrically nonlinear thin-walled composite airframes
- Couple with industry-standard linear unsteady aerodynamics (Doublet Lattice, ZAERO, etc.) and industry standard aeroelasticity / controls integration practices
- Major parts completed. In progress.

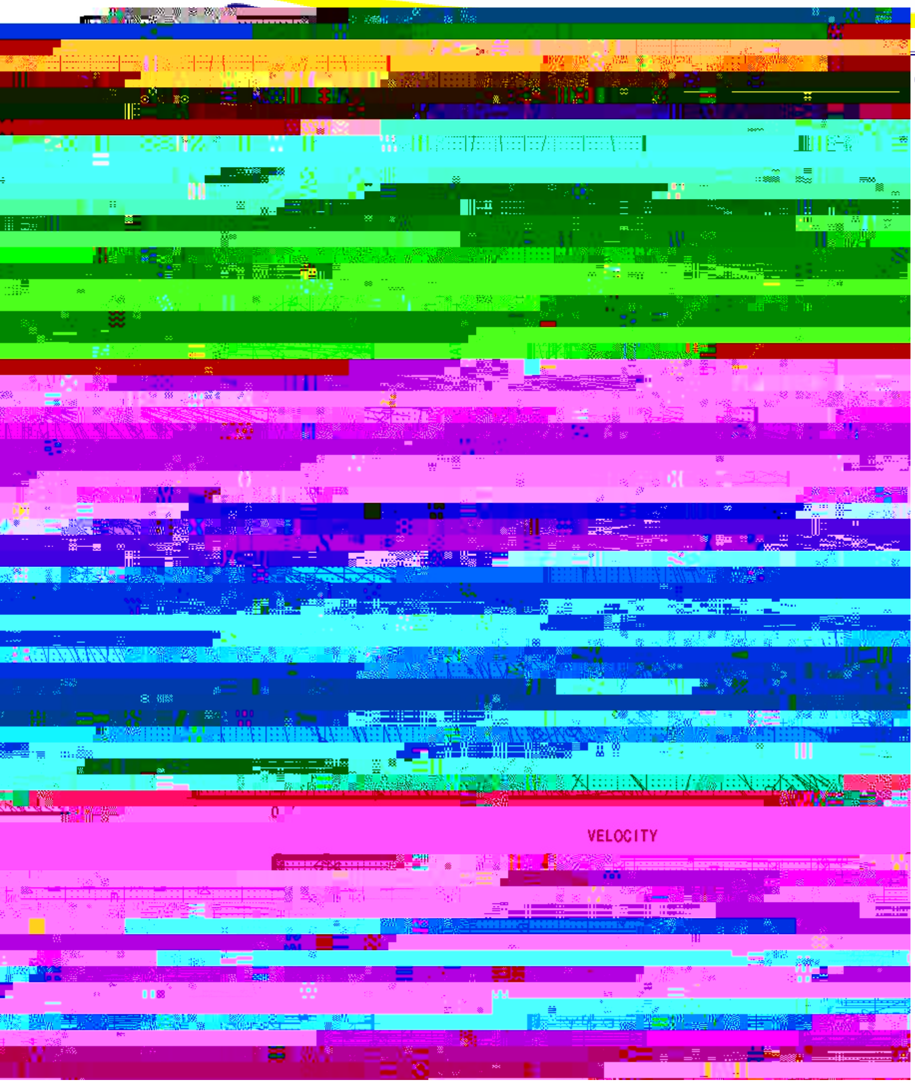
The Boeing LCO Test Case Study

- Test case uses representative airplane model with associated real-world complexity
- Test case does not reflect any service configuration / flight conditions
- Test case used freeplay values far in excess of any maximum in-service limits

The Boeing Development of Describing Function Tools for MDOF Aircraft

- Full size non-symmetric test-case passenger aircraft study
- 153 modes used
- Free-play allowed in one trim tab (only one side of the aircraft)
- Unsteady aerodynamics adjusted by wind tunnel data
- Algorithms and tools for automated determination of flutter speeds /

The challenging case of many degrees of freedom and closely-spaced Frequencies



Growth Rate

vs

Velocity

Effective tab rigid rotation stiffness = 0

Note the many closely-spaced modes, and the difficulty in tracking them

Frequency

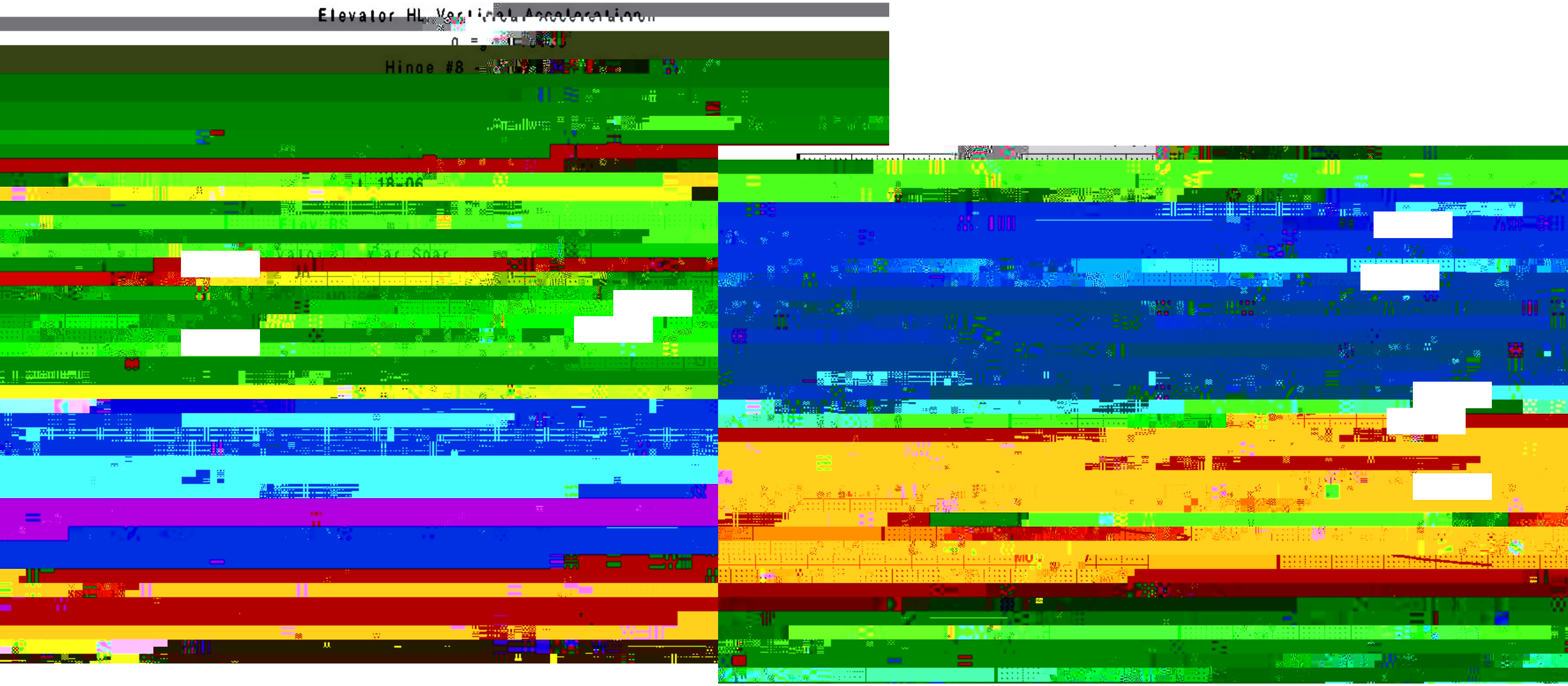
vs

Velocity

Representative Describing Function Limit Cycle Predictions and Flight Test Results

$_{fp} = \pm 1.71$ deg

g = +0.03



A Probabilistic Approach to Aeroservoelastic Reliability Estimation

Details:

Styuart, A., Mor, M., Livne, E., and Lin, K.,

“Risk Assessment of Aeroelastic Failure Phenomena in Damage Tolerant Composite Structures”,

AIAA Paper 2007-1981, 48th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics,

and Materials Conference, Honolulu, Hawaii, Apr. 23-26, 2007

Considerations

Failure types:

Flutter: airspeed exceeds the flutter speed of damaged structure

Post-static-failure flutter failure: airspeed exceeds flutter speed of buckled / failed structure

High amplitude limit cycle oscillations: the acceptable level of vibrations is exceeded

Uncertainties:

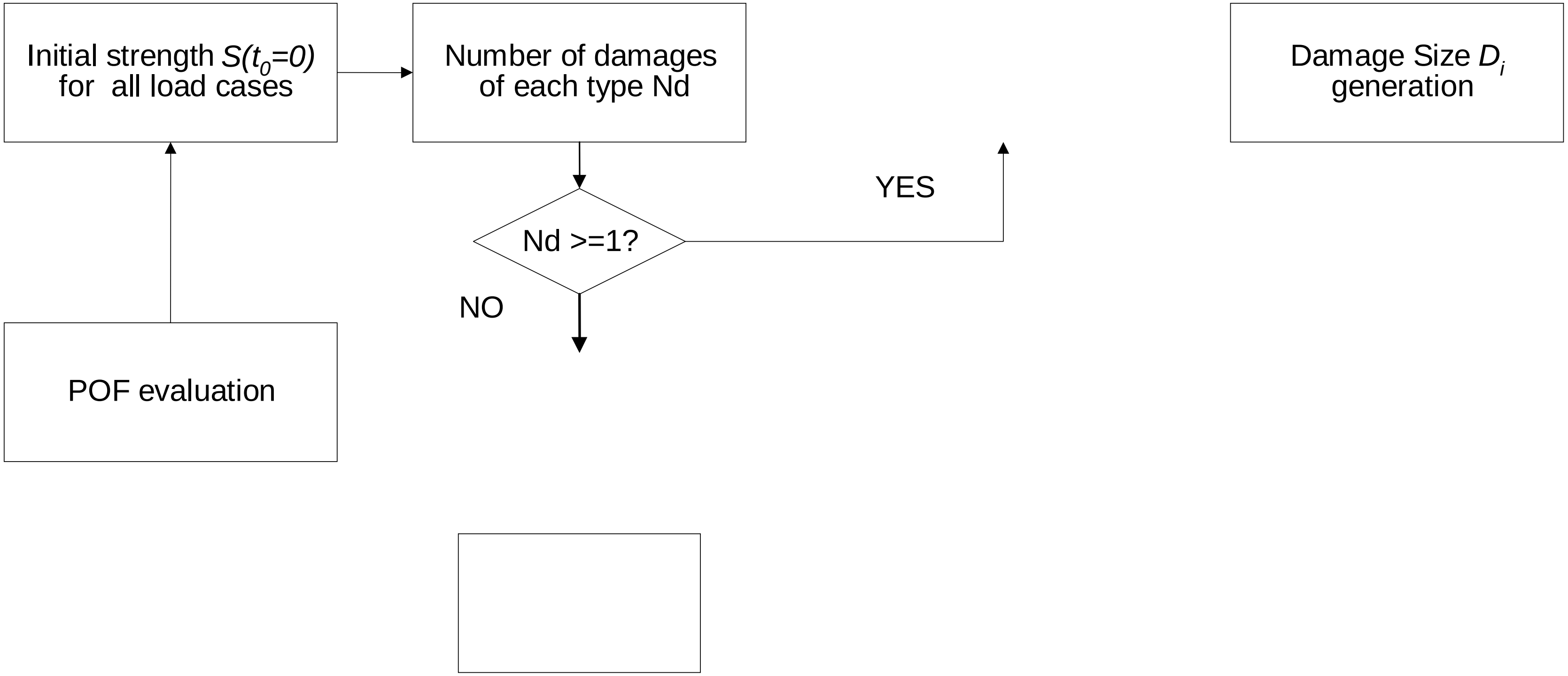
Flutter speed prediction: systemic (accuracy of simulation technology)

Flutter speed prediction: individual (variation of properties)

Fleet variability

Flight tests of one specimen (and possible modifications, if required)

Add damage statistics (size, location, type)



Initial strength $S(t_0=0)$ for all load cases

Number of damages of each type Nd

Nd >=1?

YES

NO

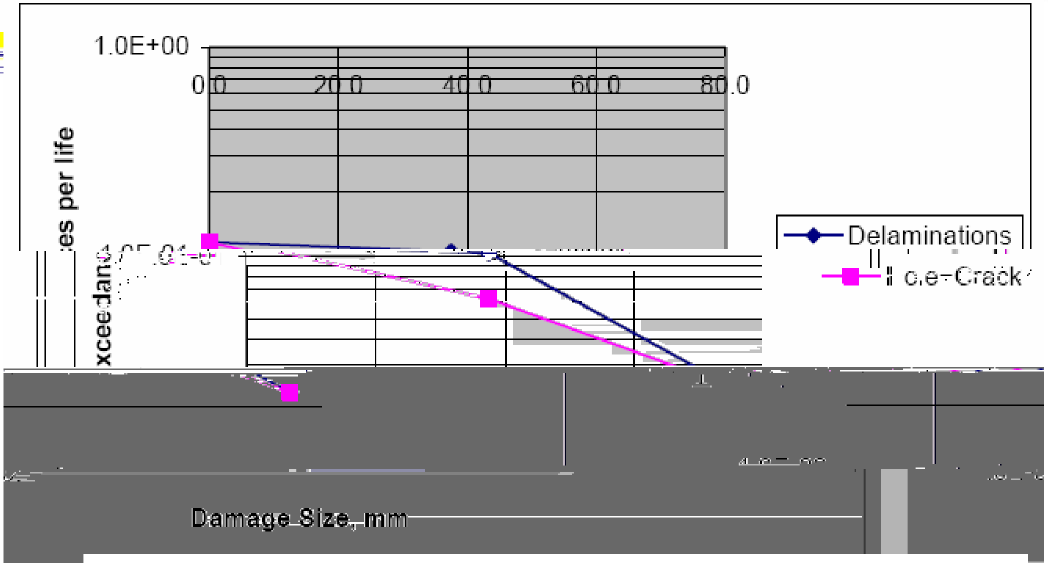
Damage Size D_i generation

POF evaluation

3D example problem – slide 2

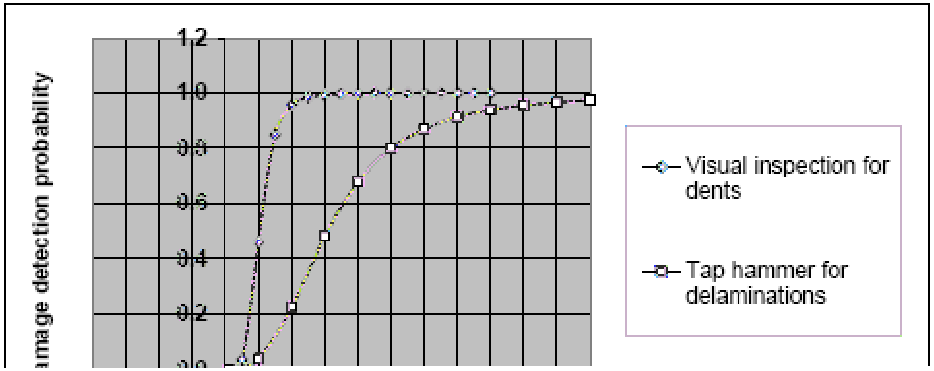
Damage Exceedance Data:

Delaminations; Holes and Cracks



Probability of Damage Detection per inspection:

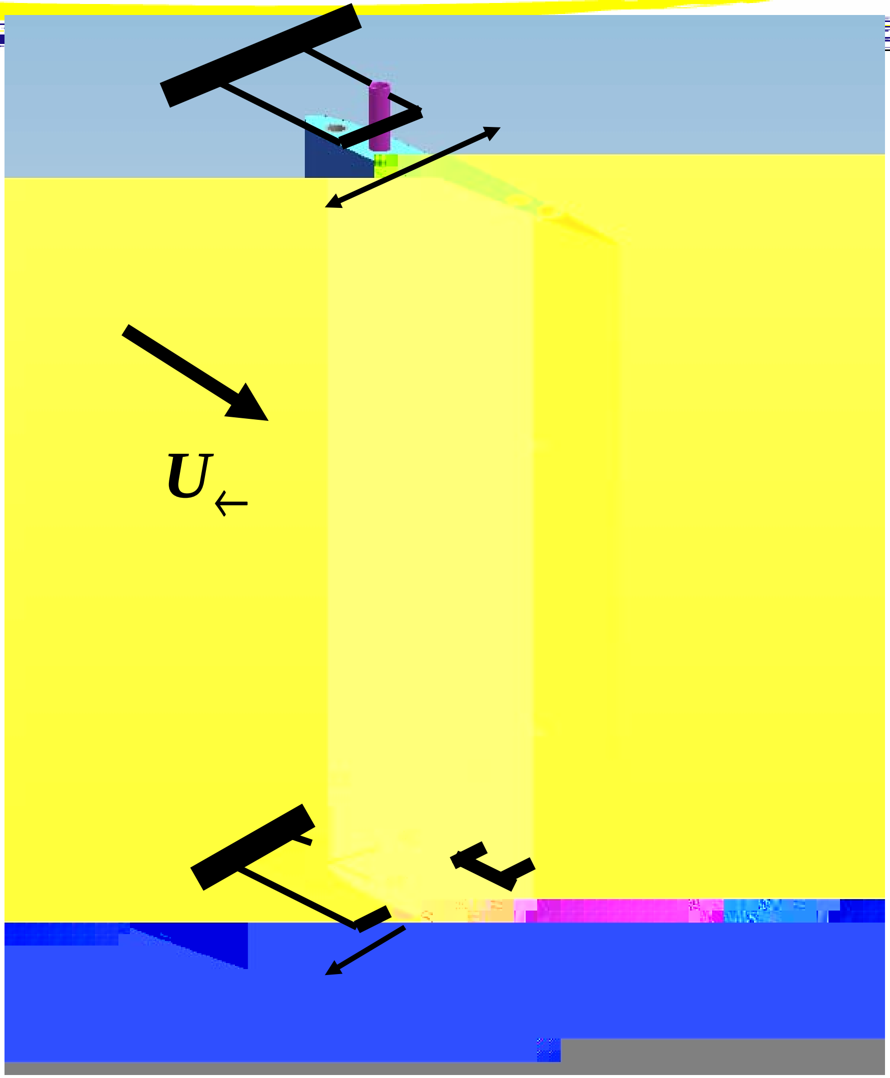
Visual inspection; tap hammer inspection

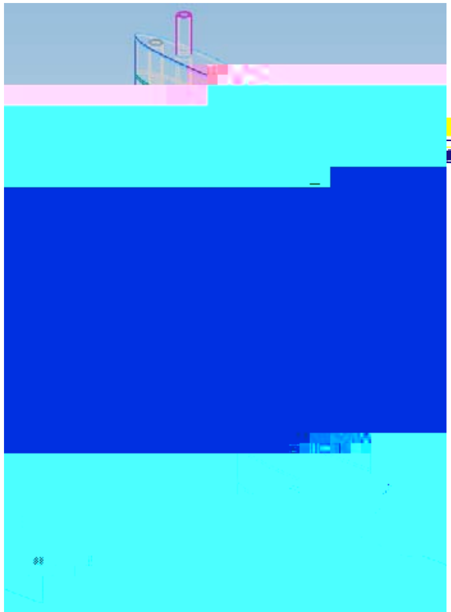


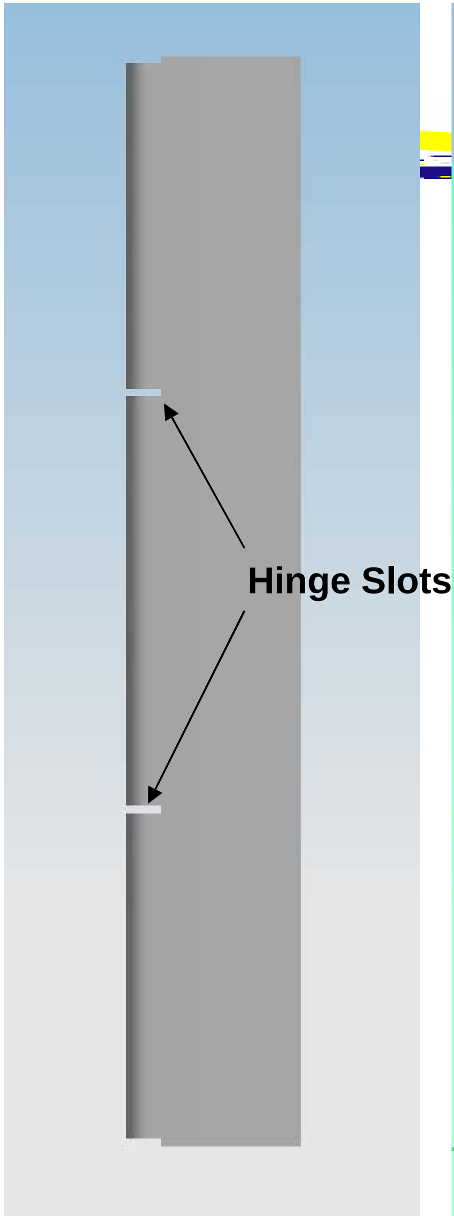
3D example problem – slide 4

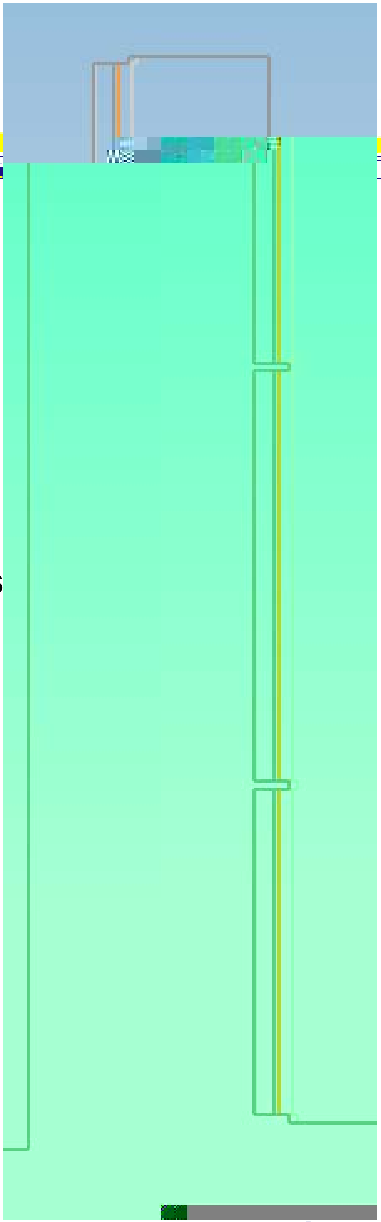
Probability of Failure due to Panel 15 vs.

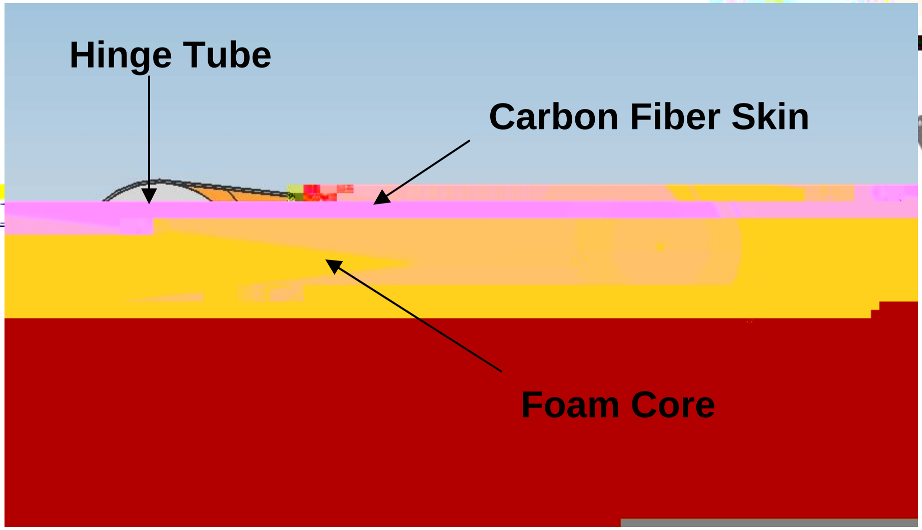
UW Flutter Test Wing / Control Surface Design mounted vertically in the UW A&A 3 x 3 wind tunnel



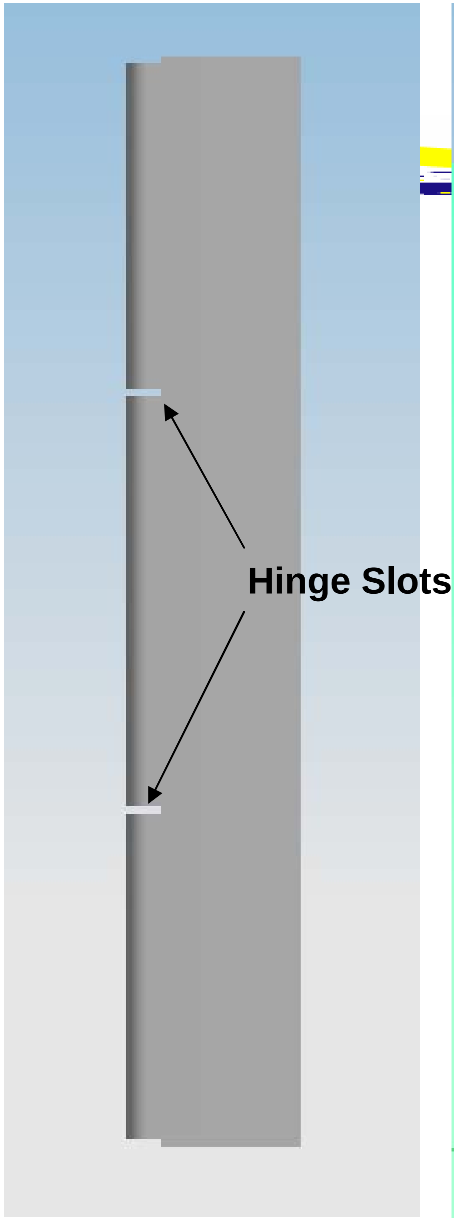


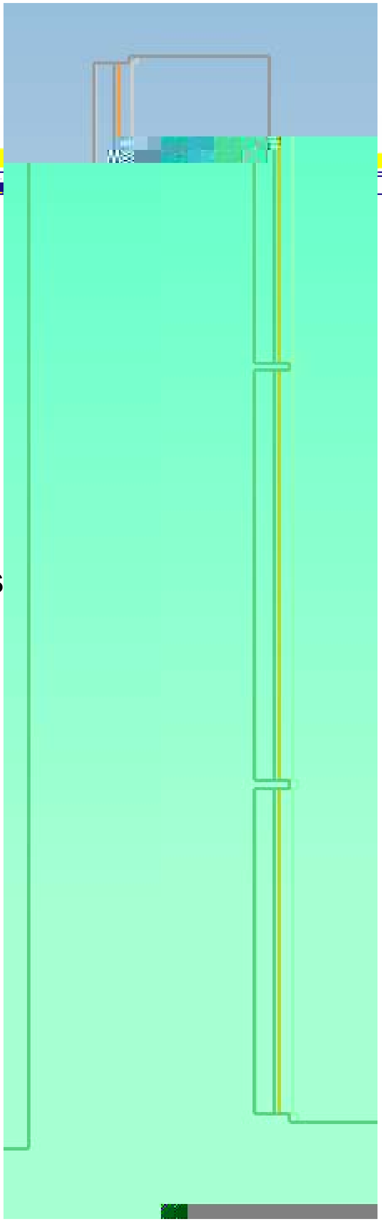


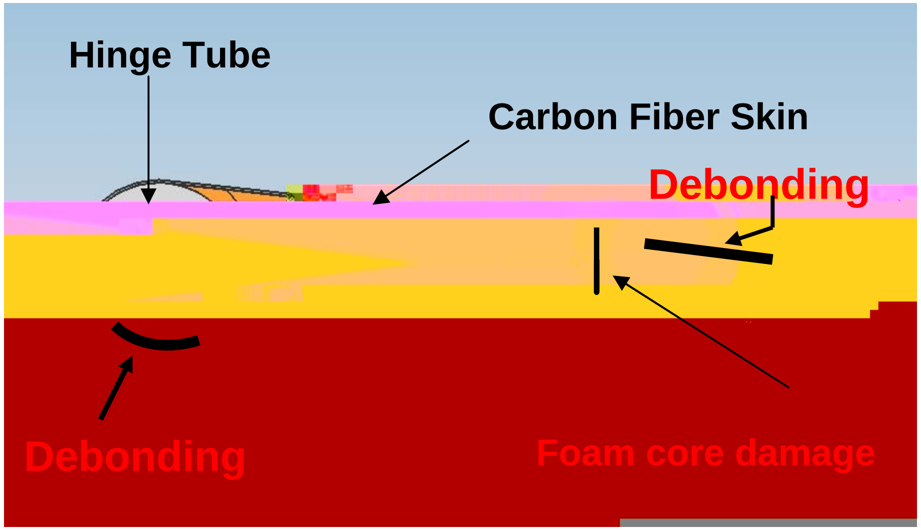




- Rudder Assembly
  - Foam core is CNC machined.
  - The aluminum hinge tube is epoxy bonded to the foam core.
  - Carbon fiber is layed up around the aluminum/foam assembly and cured.
  - Slots are machined to accommodate the hinge ribs.







- Damage modes
  - Debonding.
  - Delamination
  - Core cracking
  - Hinge failure

Benefits to Aviation

- Formulation of a comprehensive approach to the inclusion of aeroelastic failures in the reliability assessment of composite aircraft, and resulting benefits to both maintenance and design practices, covering:
    - Different damage types in composite airframes and their statistics;
    - Aeroelastic stability due to linear and nonlinear mechanisms;
    - Aeroelastic response levels (vibration levels and fatigue due to gust response and response to other dynamic excitations);
    - Theoretical, computational, and experimental work with aeroelastic systems ranging from basic to complex full-size airplanes, to serve as benchmark for industry methods development and for understanding basic physics as well as design & maintenance tradeoffs.

Plans

- Apply linear simulation tools to a representative (generic) Boeing-supplied vertical tail / rudder model.

– Extend the UW time-domain LCO simulation capability to complete