American Airlines Flight 587 Crash Investigation: NASA Langley Research Center Participation and Perspective

Andrew E. Lovejoy

Senior Research Aerospace Engineer

Structural Mechanics and Concepts Branch

NASA Langley Research Center, Hampton, VA

Guest Lecture
Clarkson University: AE 466

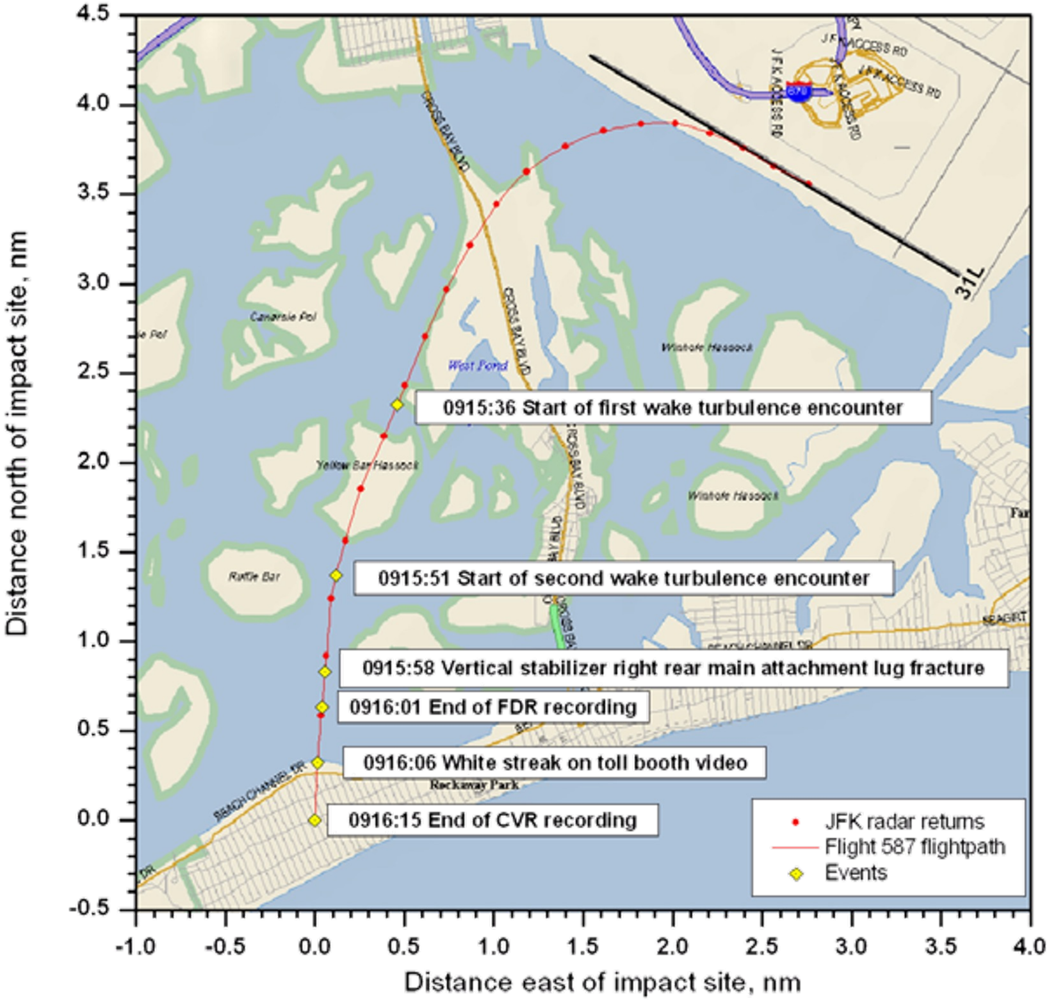
Outline

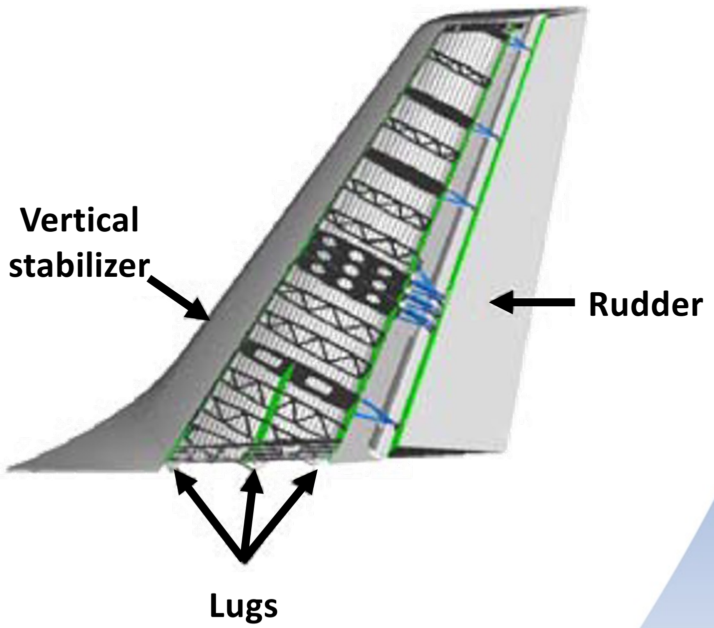
- **Introduction**
  - What Happened
  - National Aeronautics and Space Administration (NASA) Participation Request
  - References
- **NASA Activities**
  - Design and performance of the Vertical Tail Plane (VTP)
  - Physical evaluations of the VTP
  - Wake vortex investigation
- **Summary of NASA Findings**
- **Update: Title 14 / Chapter 1 / Subchapter C / Part 25**

Introduction: What Happened

- **On November 12, 2001, an Airbus 300-605R operated as American Airlines flight 587 (AA587) crashed soon after take-off from John F. Kennedy airport in New York City**
  - While accelerating to approximately 255 knots during initial climb, the aircraft twice experienced turbulence consistent with encountering wake vortices from a Boeing 747 operated as Japan Air Lines flight 47 (JAL47) that had departed ahead of them
  - JAL47 and AA587 were approximately 5 statute miles and 90 seconds apart at the time of the vortex encounters
  - The composite vertical stabilizer and rudder, or VTP, separated from the aircraft prior to the aircraft impacting the ground
  - 260 persons aboard and 5 on the ground were killed as a result of the crash
- **The National Transportation Safety Board (NTSB) summarized the results in Aircraft Accident Report NTSB/AAR-04/04**
  - “In-Flight Separation of Vertical Stabilizer, American Airlines Flight 587, Airbus Industrie A300-605R, N14053, Belle Harbor, New York, November 12, 2001”
  - Adopted October 26, 2004

AA587 Flight Path





Vertical Tail Plane (VTP)

Introduction: NASA Participation Request

- **The NTSB asked NASA to participate in the investigation**
  - The VTP failure was the first failure of primary composite structure on a commercial transport aircraft
- **NASA Langley Research Center (LaRC) participation in the investigation**
  - LaRC is the NASA Center of Excellence for composite materials
  - Dr. James H. Starnes, Jr. and Dr. Damodar Ambur directed LaRC participation in the investigation
  - The LaRC team investigated several aspects associated with the investigation
    - Design and performance of the VTP
    - Physical evaluations of the VTP
    - Wake vortex investigation
- **NASA Ames Research Center participation in the investigation**
  - Investigation of human performance
  - Used the vertical motion simulator to conduct tests and make observations

References: Special AIAA SDM Session

Starnes Memorial Session - Selected Studies Supporting the NTSB AA587 Accident Investigation*

- B. Murphy, J. O'Callaghan, and M. Fox, L. Ilcewicz, and J. H. Starnes, Jr., "Overview of the Structures Investigation for the American Airlines Flight 587 Investigation," **AIAA 2005-2251**
- M. R. Fox, C. R. Schultheisz, and J. R. Reeder, "Fractographic Examination of the Vertical Stabilizer and Rudder from American Airlines Flight 587," **AIAA 2005-2252**
- W. P. Winfree, E. I. Madaras, K. E. Cramer, P. A. Howell, K. L. Hodges, J. P. Seebo, and J. L. Grainger, "NASA Langley Inspection of Rudder and Composite Tail of American Airlines Flight 587," **AIAA 2005-2253**
- R. D. Young, A. E. Lovejoy, M. W. Hilburger, and D. F. Moore, "Structural Analysis for the American Airlines Flight 587 Accident Investigation – Global Analysis," **AIAA 2005-2254**
- I. S. Raju, E. H. Glaessgen, B. H. Mason, T. Krishnamurthy, and C. G. Dávila, "NASA Structural Analysis Report on the American Airlines Flight 587 Accident – Local Analysis of the Right Rear Lug," **AIAA 2005-2255**

***(46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference, Austin, Texas, April 18-21, 2005)**

References: Other

- "In-Flight Separation of Vertical Stabilizer, American Airlines Flight 587, Airbus Industrie A300-605R, N14053, Belle Harbor, New York, November 12, 2001," **NTSB/AAR-04/04,** Adopted October 26, 2004
- A. E. Lovejoy, "A Procedure for Modeling Structural Component/Attachment Failure Using Transient Finite Element Analysis," **NASA/CR-2007-214540,** January 2007
- L. S. Peterson, L. A. Haworth, R. C. Jones, R. L. Newman, R. J. McGuire, A. A. Lambregts, T. McCloy, and T. R. Chidester, "An International Survey of Transport Airplane Pilots' Experiences and Perspectives of Lateral/Directional Control Events and Rudder Issues in Transport Airplanes (Rudder Survey)," **DOT/FAA/AM-10/14,** October 2010

NASA Activities

Design and performance of the VTP

Physical evaluations of the VTP

Wake vortex investigation

Design and Performance of the VTP

- **Led by Dr. James H. Starnes**
- **Two analysis teams were formed**
  - Global analysis team
    - Review Airbus certification process: testing, analysis, and design procedures
    - Develop and interrogate failure scenarios
    - Provide loads to Local Analysis Team to perform strength analyses
    - Conduct failure sequence analyses for most likely failure scenario (and correlate predicted damage with physical evidence)
    - Provide evidence to assess whether the structure performed as it was intended
  - Local analysis team
    - Detailed progressive failure analysis (PFA) of local regions

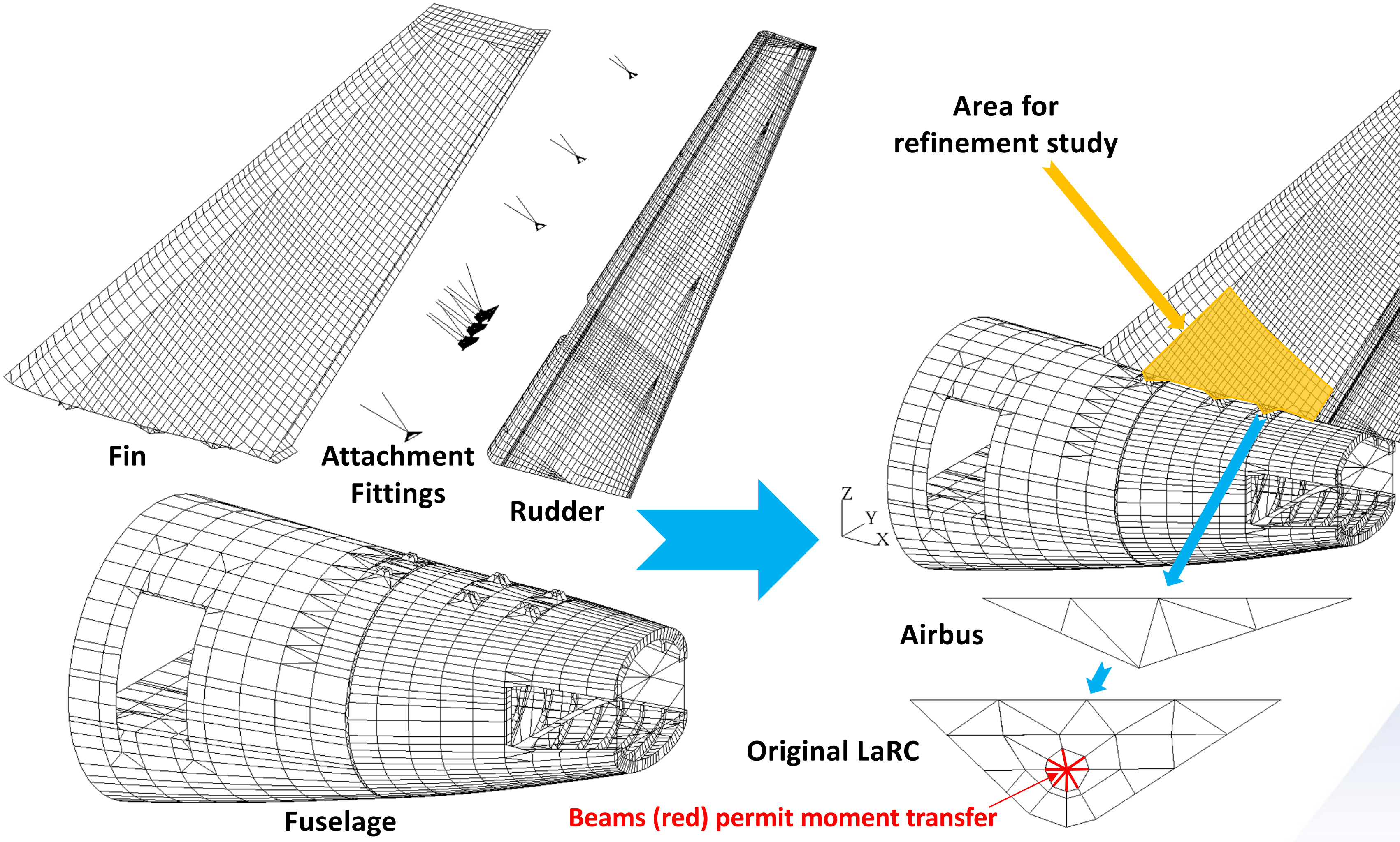
Review of Airbus Certification Process

- **Objectives:**
  - Review Airbus drawings and finite element models
  - Review Airbus finite element modeling assumptions
  - Review Airbus strength justification documents
  - Review Airbus finite element analysis and full-scale test correlation documents
- **Actions:**
  - Read documents, met with Airbus engineers, performed finite element analyses, and performed test and analysis correlation

Finite Element Model

- **Received fin and rudder finite element models from Airbus**
- **Modified finite element models to review certification and failure scenarios**
  - Main attachment fitting modification progression
    - Refined shell representation
    - Solid-shell local model with pin contact
    - Layered-shell local model with pin contact
    - Global shell model with stiffness tuned to simulate local solid-shell model
    - Global-local iterative procedure to effectively embed local solid-shell models
  - Mesh refinement demonstrated convergence of global-local models
  - Nonlinear capable global and local models
  - Compared linear and nonlinear results to assess nonlinear effects

VTP Finite Element Model



Fin

Attachment Fittings

Rudder

Fuselage

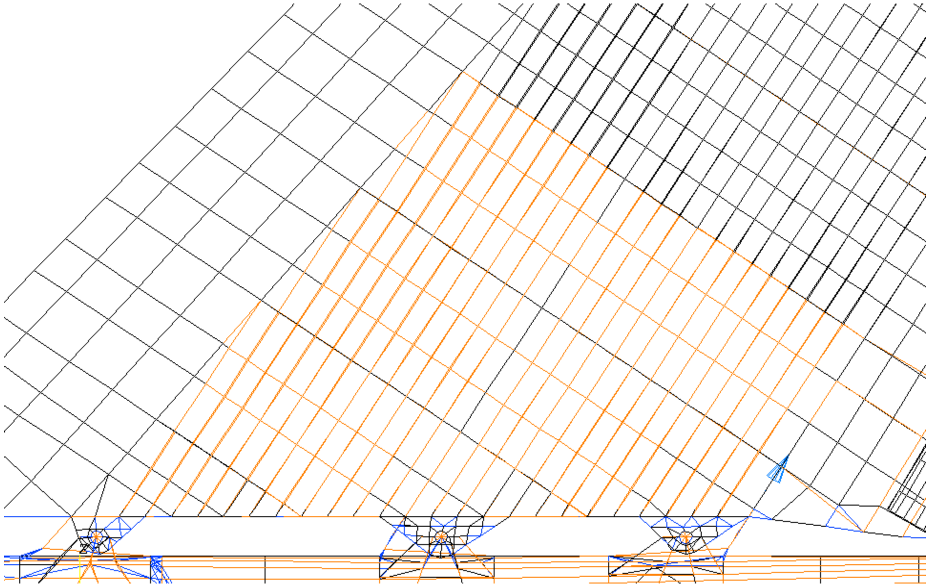
Area for refinement study

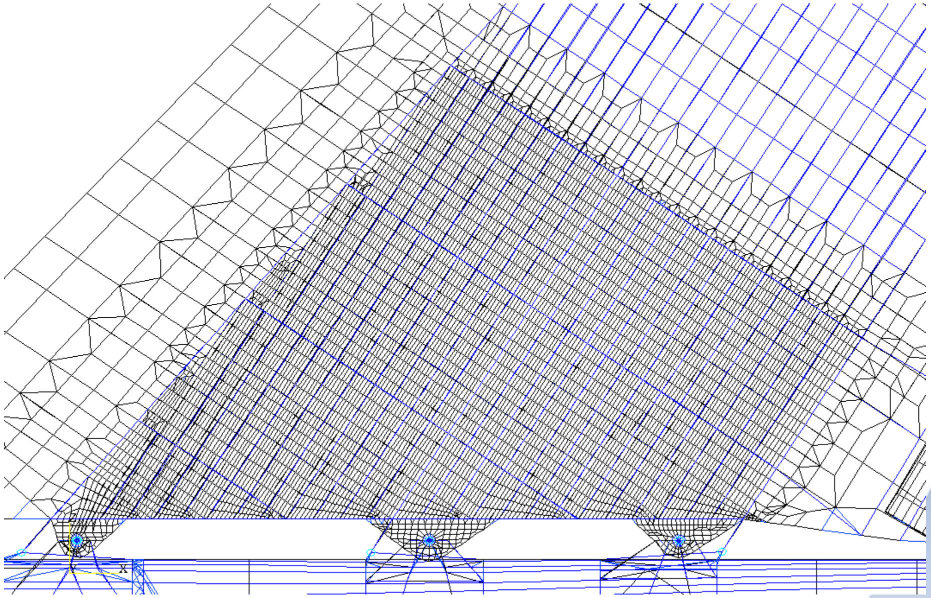
Airbus

Original LaRC

Beams (red) permit moment transfer

LaRC Original and Refinement Study Models

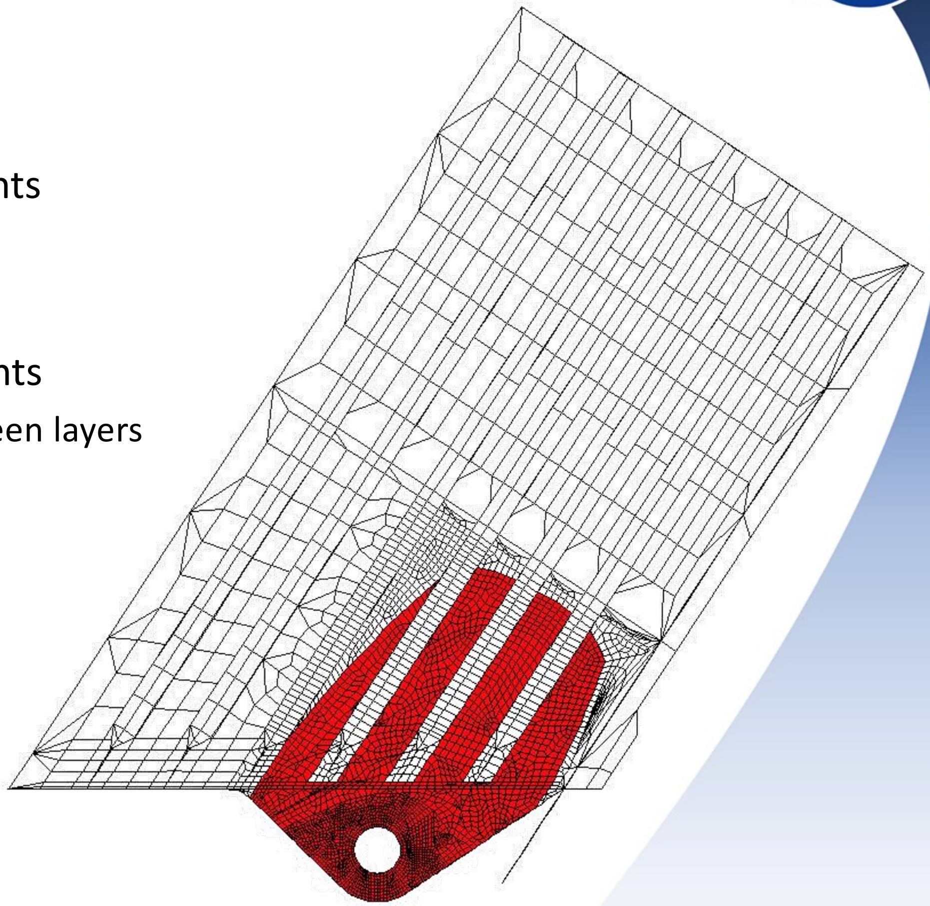




- **Original**
  - Nonlinear capable (e.g., remove offsets)
  - Lug refinement
  - Mass adjustment
- **Refinement (added to original)**
  - Mesh Refinement
  - Transverse load offsets
  - Tuned lug stiffness (from global-local)

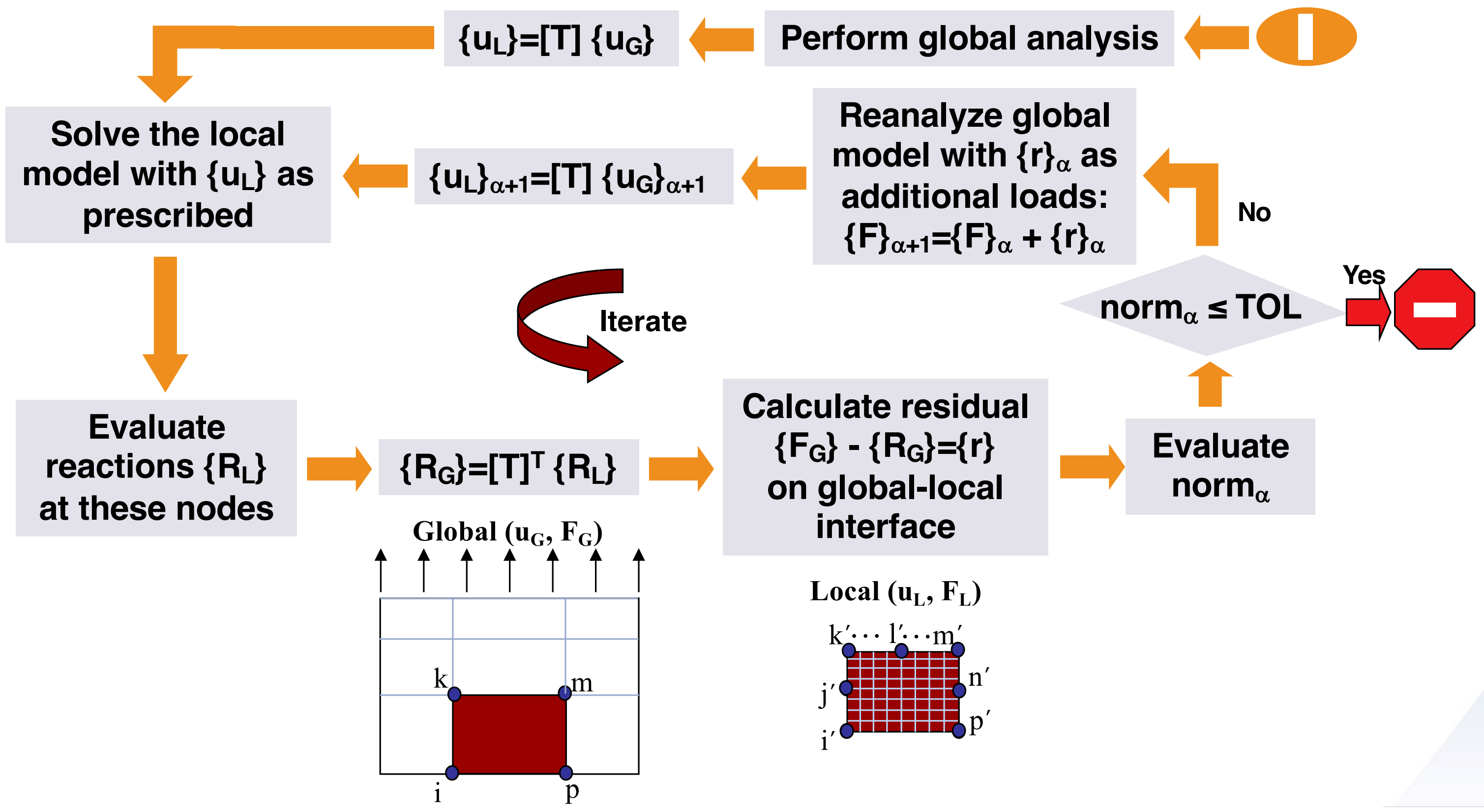
Local Lug Finite Element Model

- **Lug (red) modeled using two methods**
  - Solid-shell model
    - Lug fittings and skin modeled with solid elements
    - Remainder shell elements
  - Layered-shell model
    - Lug fittings modeled with layers of shell elements
      - Three-dimensional decohesion elements between layers
    - Remainder single layer of shell elements
- **Pin modeled as frictionless rigid surface**
- **Validated against test data**
  - Two 1985 tests, 2003 subcomponent test



Global-Local Analysis Process

- **Used to provide flight loads to the local models and more accurately represent local lug stiffness in the global model**



Perform global analysis

$\{u_L\}=[T]\{u_G\}$

Solve the local model with $\{u_L\}$ as prescribed

Evaluate reactions $\{R_L\}$ at these nodes

$\{R_G\}=[T]^T\{R_L\}$

Calculate residual $\{F_G\} - \{R_G\}=\{r\}$ on global-local interface

Evaluate norm_α

$\text{norm}_\alpha \leq \text{TOL}$

Yes

No

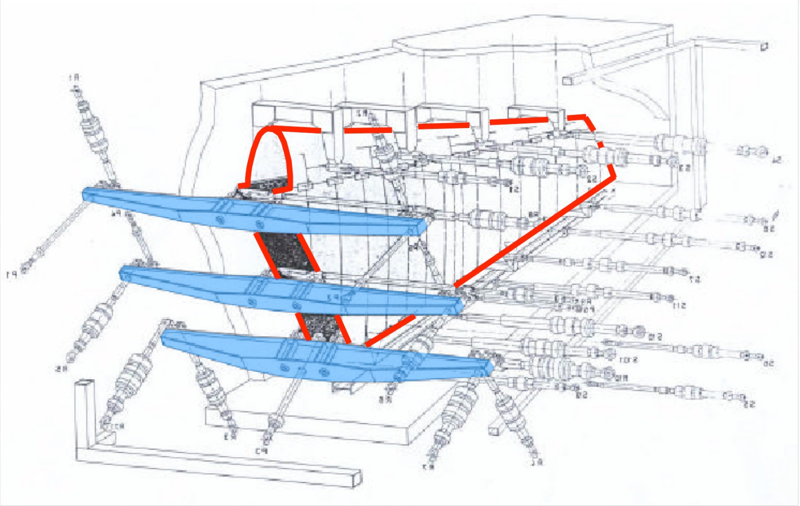
Reanalyze global model with $\{r\}_\alpha$ as additional loads: $\{F\}_{\alpha+1}=\{F\}_\alpha + \{r\}_\alpha$

$\{u_L\}_{\alpha+1}=[T]\{u_G\}_{\alpha+1}$

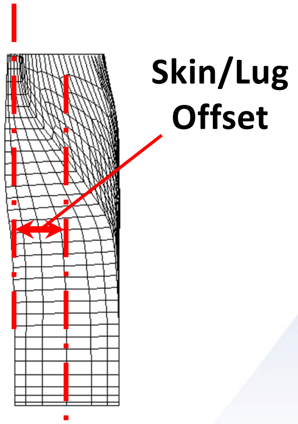
Iterate

Review Airbus Certification Process

- **Airbus lug certification process**
  - Allowable from lug only tests
  - Test a VTP with representative loading
  - Adjust allowable based on VTP test (approx. 13%)
    - Reduction due to bending moment within lug due to skin/lug offset
  - LaRC ran analyses to examine effect of lug stiffness on load distribution between lugs (varied each lug)
    - Loads in lugs insensitive to lug stiffnesses and dependent upon applied load and geometry



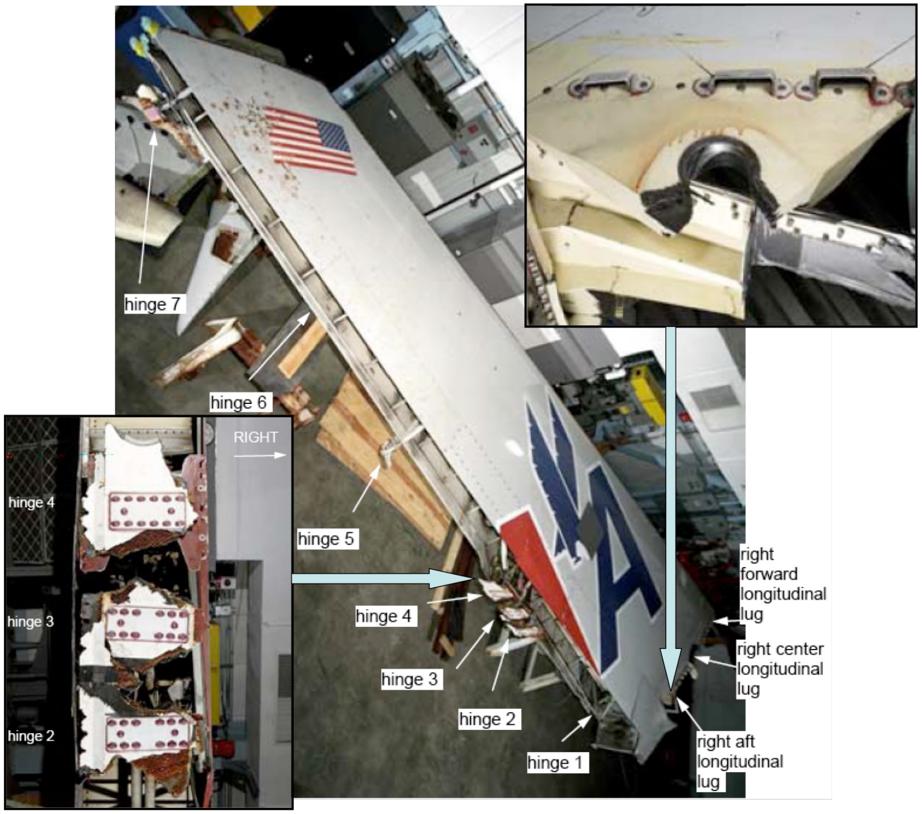
- **Findings:**
  - Airbus global finite element model adequate
    - Loads in lugs insensitive to lug stiffnesses
    - Loads in VTP test representative of aircraft loads
  - Reduced lug allowable represented true strength, so acceptable

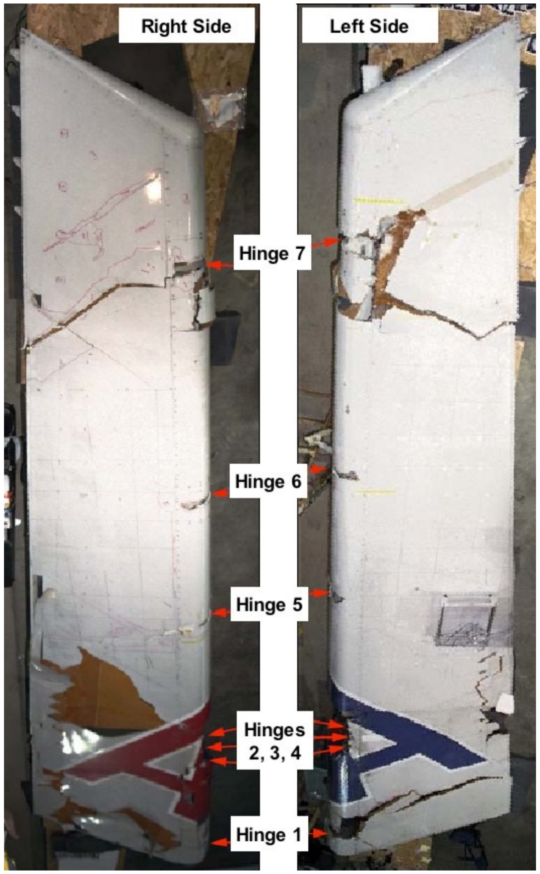


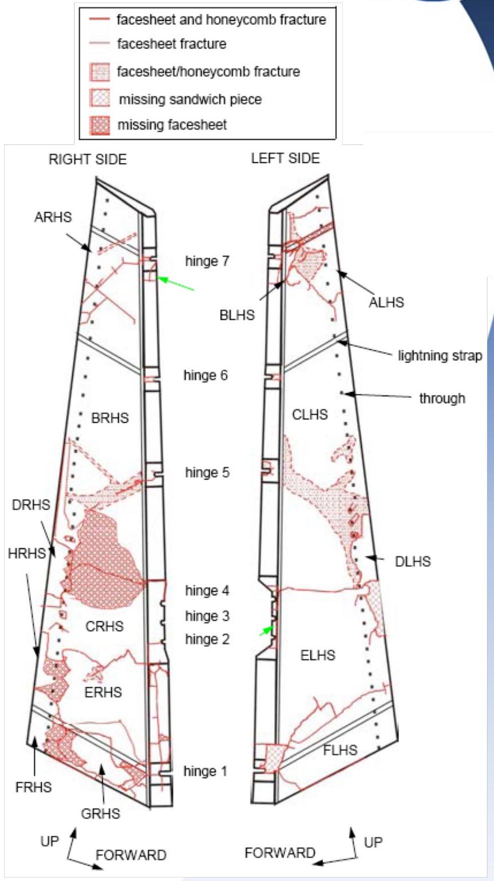
Develop and Interrogate Failure Scenarios

- Examine physical evidence
- Develop possible failure scenarios
- Develop/update models
- Run analyses
- Interpret analysis results

Failure Scenario Development: Physical Evidence







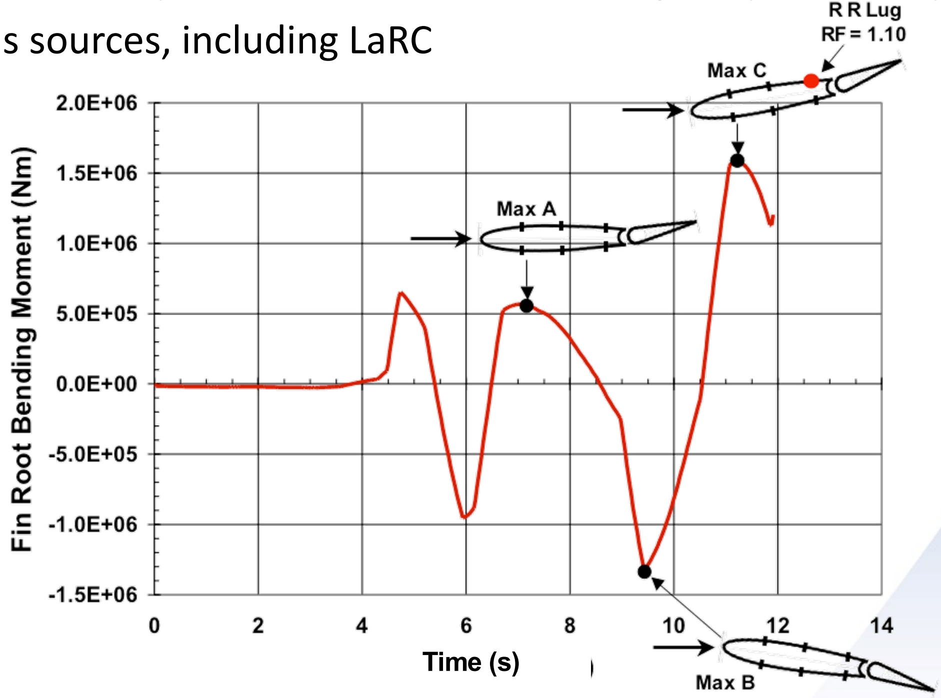
Develop Failure Scenarios

- **Main attachment fitting**
  - Pristine VTP
  - VTP with hypothetical pre-existing fitting failure
- **Buckling of fin causing failure elsewhere**
- **Rudder skin failure near ply drops**
- **Actuation of bent rudder**
- **Flutter of VTP from delamination of rudder skin**

Main Attachment Fitting Failure: Pristine VTP

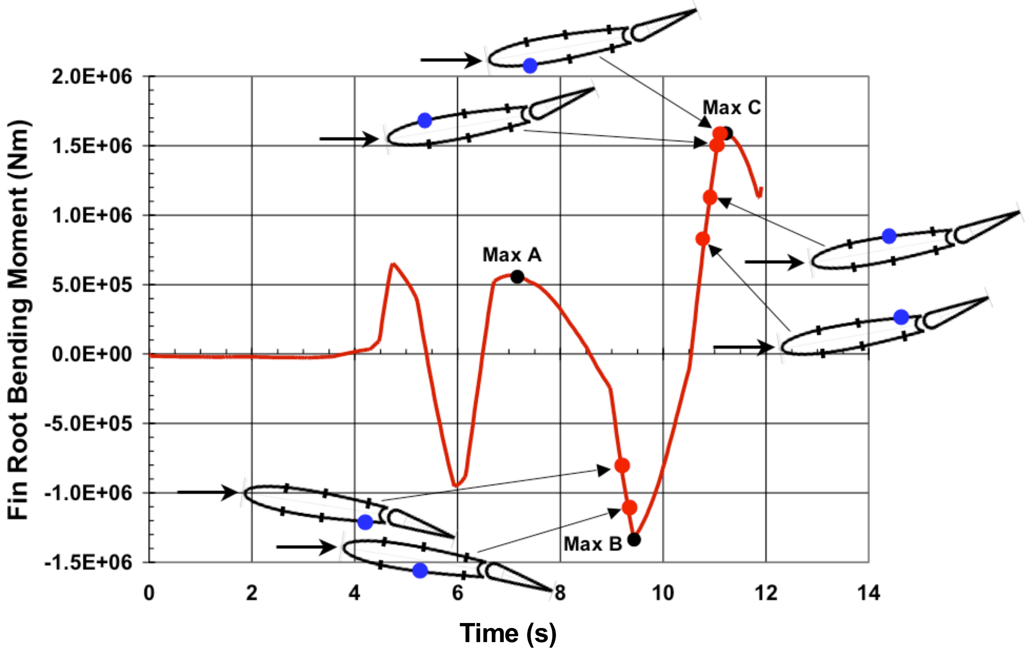
- **Used the LaRC original finite element model**
- **Flight simulation based on flight data recorder (FDR) data**
  - Time history of fin root bending moment, torsion and shear loads
    - Bending moment increased due to aerodynamic load reversal resulting in dynamic response
    - Loads were developed by various sources, including LaRC
  - Linear analyses conducted at maximum locations (A, B, C)
  - Lowest reserve factor (RF) at right rear lug at Max C
    - Minimum RF = 1.1
    - Most likely failure scenario

(Note: VTP cross-section icons viewed from above throughout presentation.)



Main Attachment Fitting Failure: Pre-Existing Lug Failure

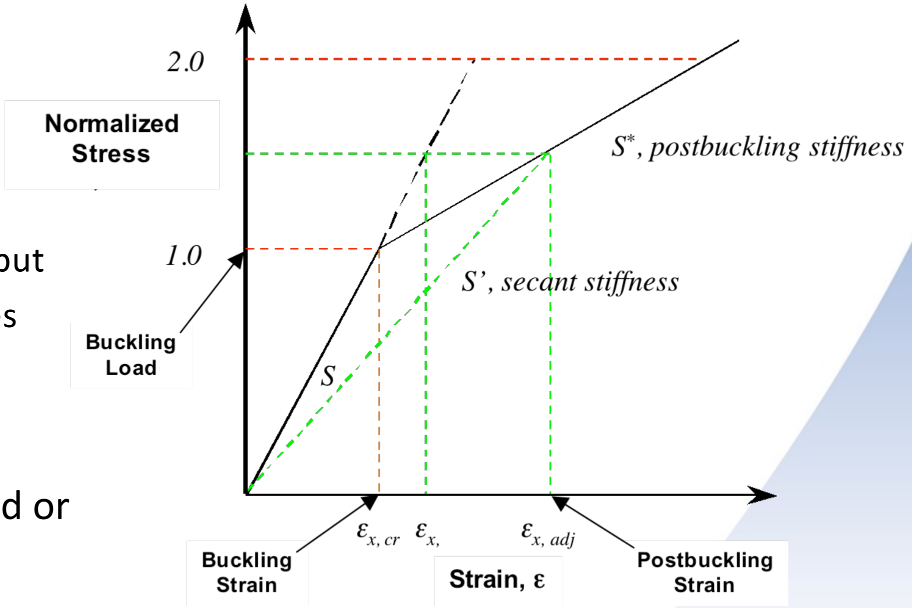
- **Conclusion the same for right front, center, and rear, and left center and rear lugs**
  - Finding: No pre-existing failure of lug could exist; predicted catastrophic progressive failure of attachment fittings
- **Left front lug**
  - Finding: No progressive failure of attachment fittings predicted
  - Physical evidence does not support pre-existing failure



- **Findings:**
  - Initial failure of right rear lug most likely failure scenario
  - Pre-existing lug failure would have initiated catastrophic failure prior to maximum experienced load, or not change right rear lug failure as first failure under flight loads

Buckling of Fin Causing Failure Elsewhere

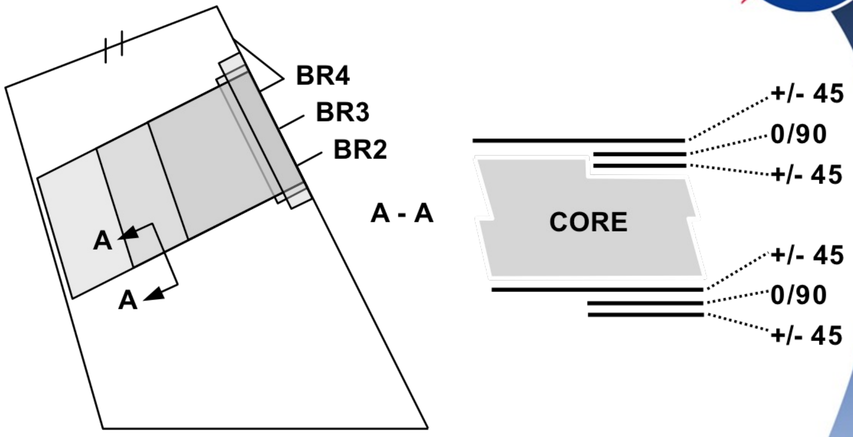
- **Preliminary analyses of the VTP indicated sections could exhibit buckling at accident loading conditions**
  - Not necessarily failure, but could cause detrimental load distribution
  - Due to reduction in stiffness, so approximated using secant stiffness
    - Applied to regions that might buckle
    - Used 50% of prebuckled stiffness
    - Skin strains increased around regions
      - Conservative allowables and large stiffness reduction indicate skin might have failure, but physical evidence did not show such failures
      - Load redistribution to lugs minimal effect

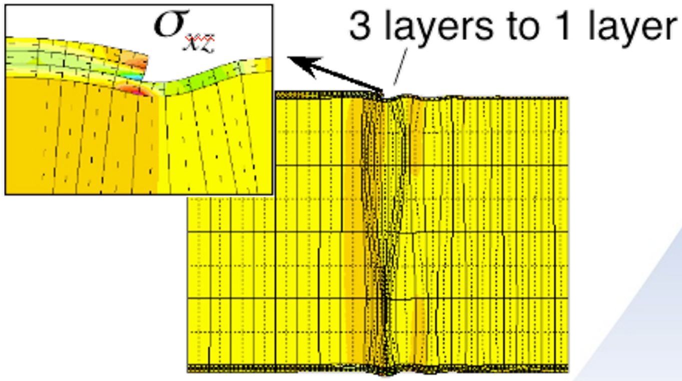


- **Finding:**
  - Buckling of fin skin did not affect the failure load or mode of the VTP

Rudder Skin Failure Near Ply-Drop

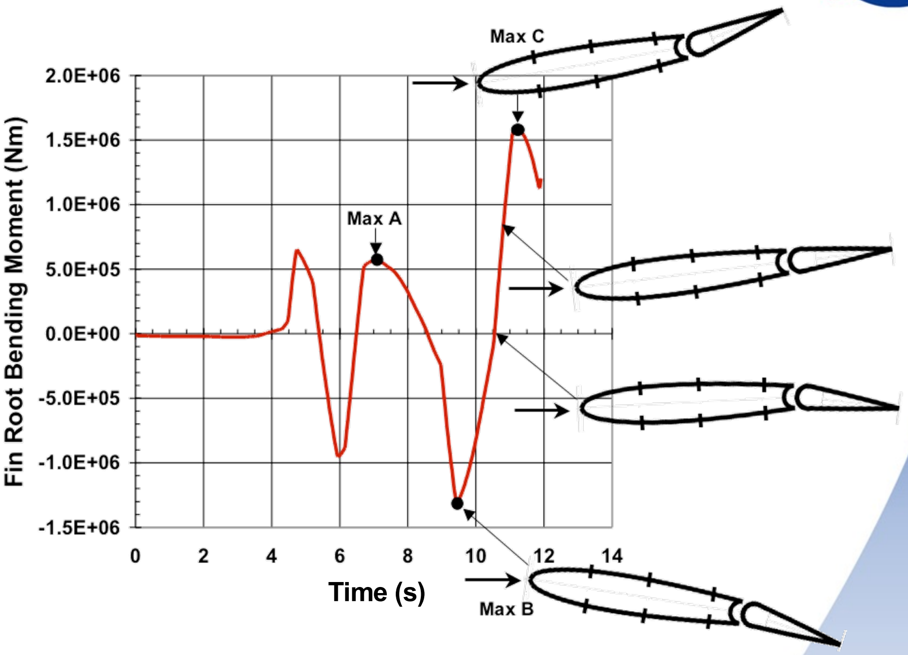
- **Physical evidence showed significant failures in rudder ply drop region near actuators**
  - Not explicitly addressed in documentation
  - Local model made to investigate this region
    - Solid elements for skin and core
      - Local model validated against global model response
    - Fiber failure most likely mode, not delamination
      - Strains during accident did not reach predicted allowables
- **Finding:**
  - Failure in ply-drop region of rudder not likely candidate for initiation of VTP failure

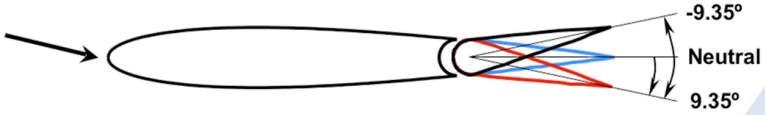




Actuation of Bent Rudder

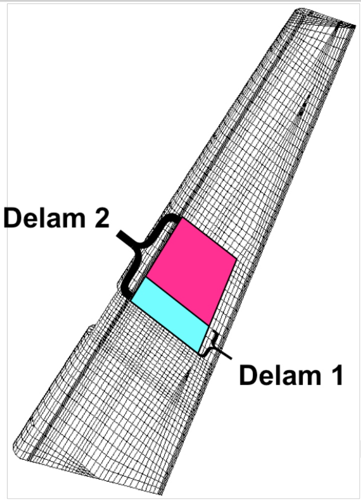
- **Examine if bent VTP could affect rudder motion**
  - LaRC original finite element model used
    - Maximum loading condition used
    - VTP only used, lugs restrained
    - Actuation by thermal load to actuator beam
    - Nonlinear analysis
  - Rudder stiff in torsion, low in bending
    - Conforms easily to bent condition
    - Required fitting forces are small
    - Effect negligible to response
- **Finding:**
  - Rudder binding did not affect the VTP response

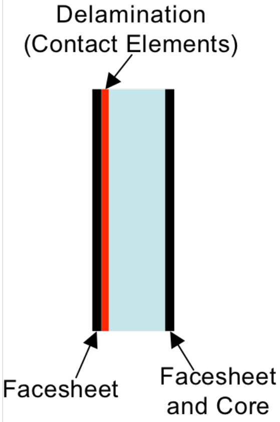


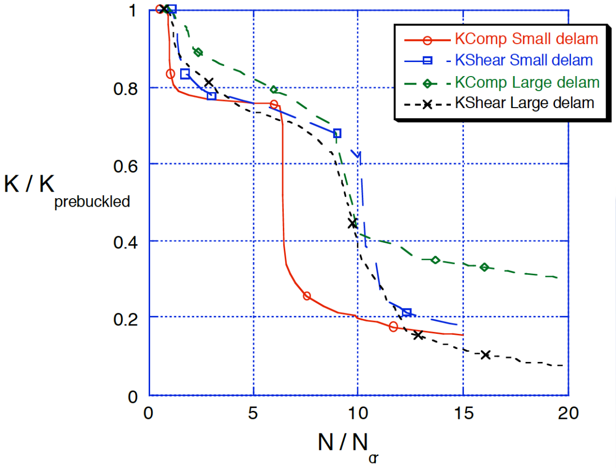


Flutter of VTP From Delamination of Rudder Skin

- **Skin delaminations could cause flutter and subsequent failure of VTP**
  - Two delamination sizes were studied
    - Approximate shear and compression stiffness reductions in global analysis
      - ○ Local model used to develop stiffnesses
        - Effective stiffness function of normalized load
      - ○ Skin stiffness reduced and core eliminated
      - ○ Modal results provided to aeroelasticity group
    - Little effect on overall flutter response of VTP
- **Finding:**
  - Flutter-induced failure not likely initiator of the VTP

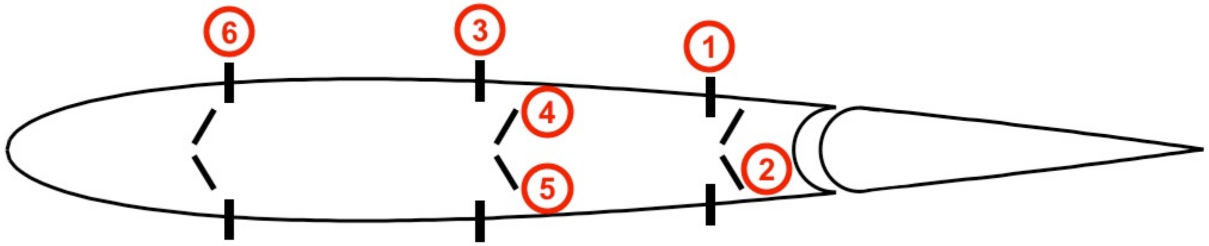






Most Likely Failure Scenario Sequence Development

- **Used LaRC refined finite element model**
- **Performed linear and nonlinear static analyses**
  - Each VTP connection was disconnected in order of predicted failure

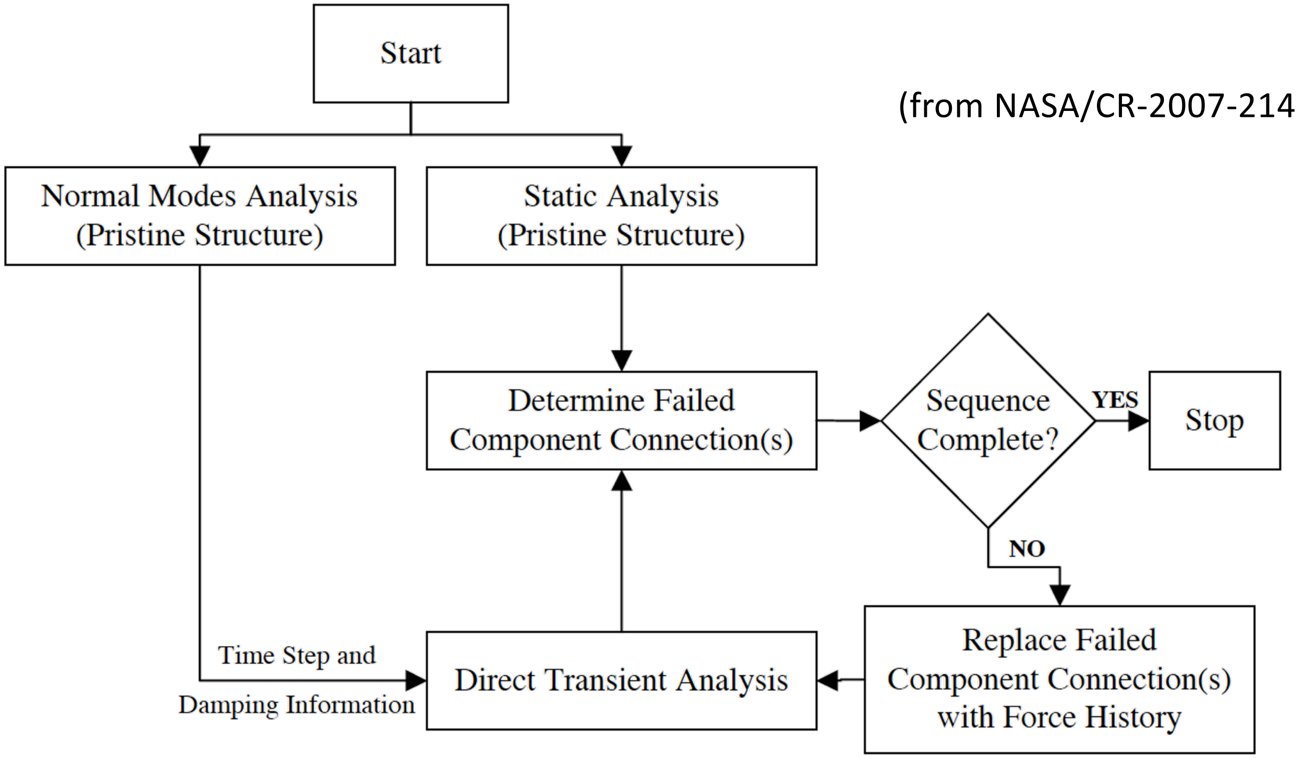


No.	Location
1	Right rear lug
2	Left rear yoke
3	Right center lug
4	Right center yoke
5	Left center yoke
6	Right front lug

  - Predicted failure of all VTP connections, but no damage in rudder
  - No rudder damage being predicted was not consistent with the physical evidence
- **Transient failure approach was developed and implemented**
  - This approach accounts for dynamic load amplification factors
  - Objective was to identify damage in rudder consistent with the physical evidence prior to complete separation of the VTP from the aircraft

Transient Failure Sequencing: Process

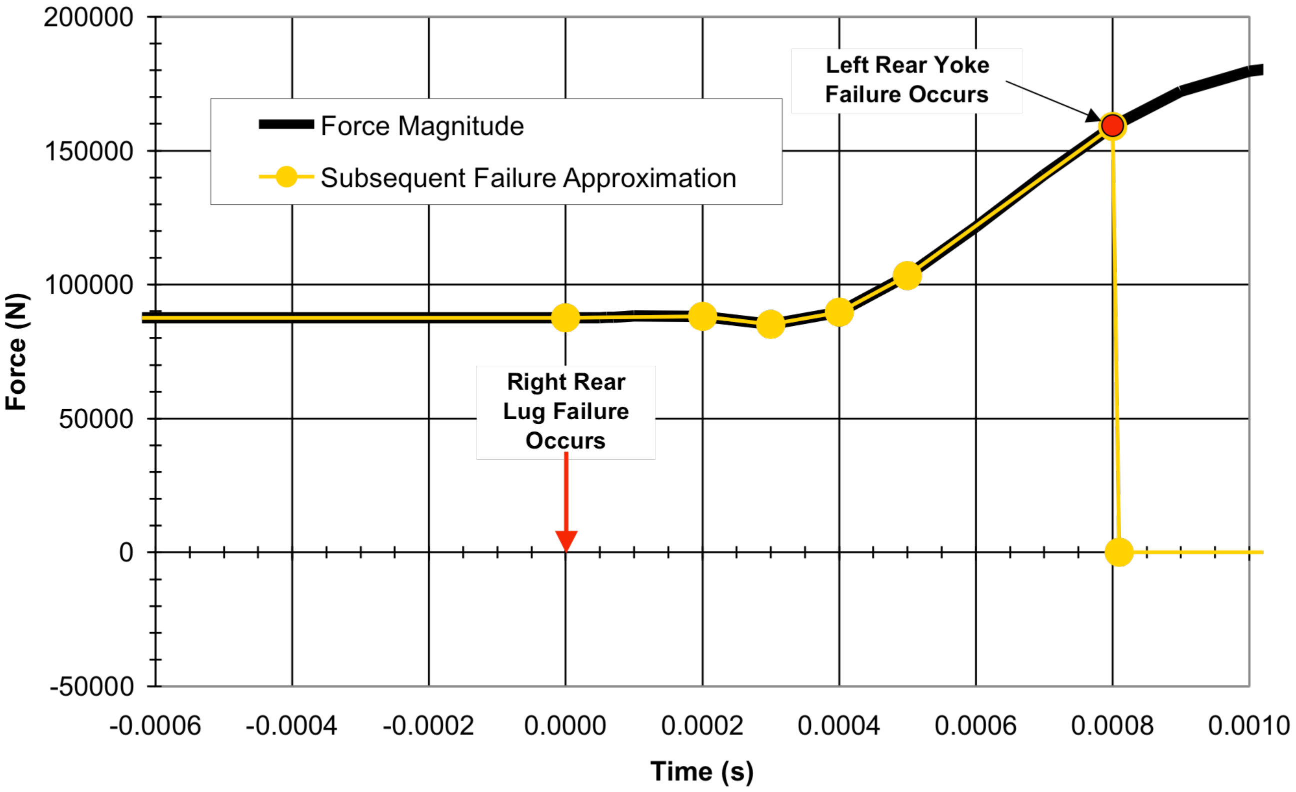
- **Modified the LaRC refined finite element model**
  - Multi-point constraints connect VTP to fuselage clevises
  - Failed component multi-point constraints replaced with force-time history in next analysis



(from NASA/CR-2007-214540)

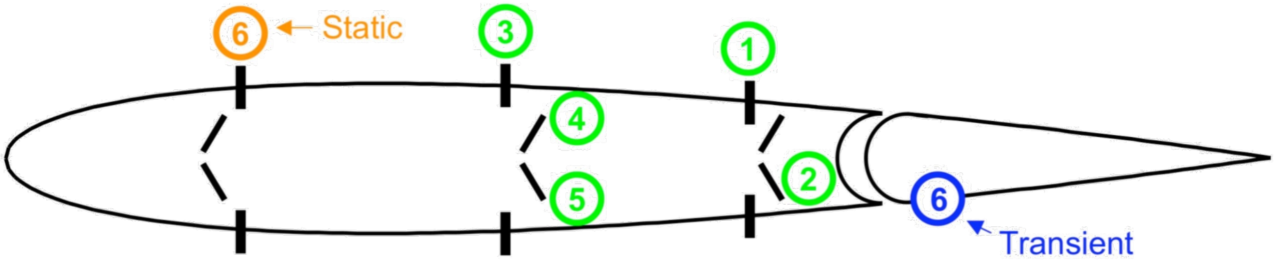
Transient Failure Sequencing: Analysis

- Conducted at Max. C load conditions (right rear lug failure)
- Example of force-time history approximation, left rear yoke



Transient Failure Sequencing: Results

- Many locations on rudder exhibited dynamic load variation
- Predicts failures in rudder prior to VTP separating from aircraft



No.	Location
1	Right rear lug
2	Left rear yoke
3	Right center lug
4	Right center yoke
5	Left center yoke
6 Static	Right front lug
6 Transient	Left rudder skin by lower fitting

- **Findings:**
  - Structure performed in manner consistent with its design and certification
  - Dynamic effects predict the most probable failure scenario sequence is consistent with the physical evidence, including on the rudder

NASA Activities

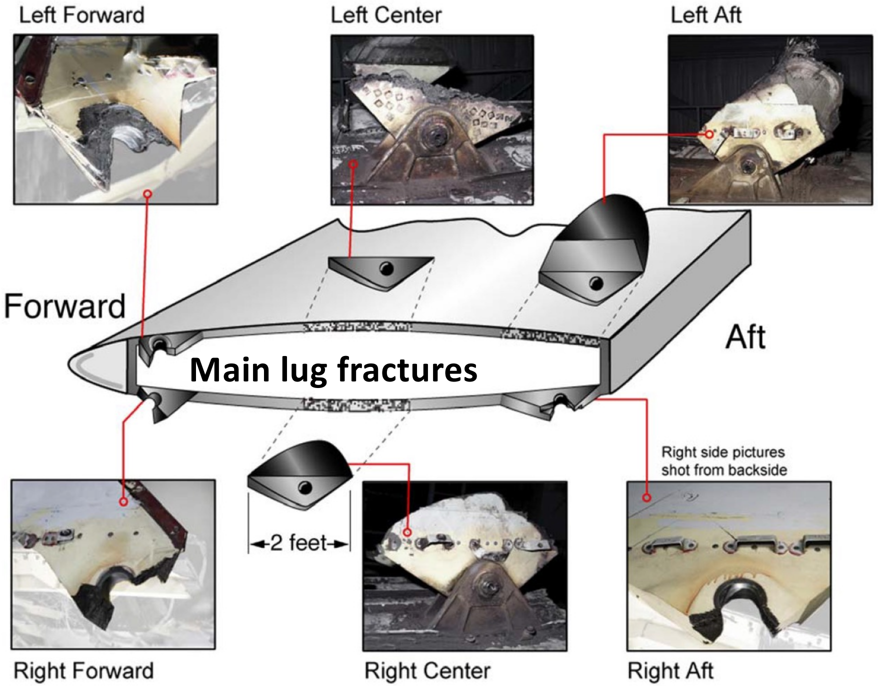
Design and performance of the VTP

Physical evaluations of the VTP

Wake vortex investigation

Physical Evaluations of the VTP

- **Performed visual and scanning electron microscope (SEM) examinations**
  - Over 300 SEM photographs taken of translaminar fractures
  - More than 150 square inches of delamination surface area examined
  - Challenges encountered due to the presence of woven fabric in the construction
- **Observations:**
  - Fracture patterns were consistent with lug failure on the right side resulting in fin bending to the left before failure of the left side
  - No evidence of fatigue cracks on the lugs
  - No evidence of significant pre-existing damage was observed on the rudder
- **Findings:**
  - No evidence of pre-existing damage or fatigue cracking in the VTP was revealed by the fractographic examination



NASA Activities

Design and performance of the VTP

Physical evaluations of the VTP

Wake vortex investigation

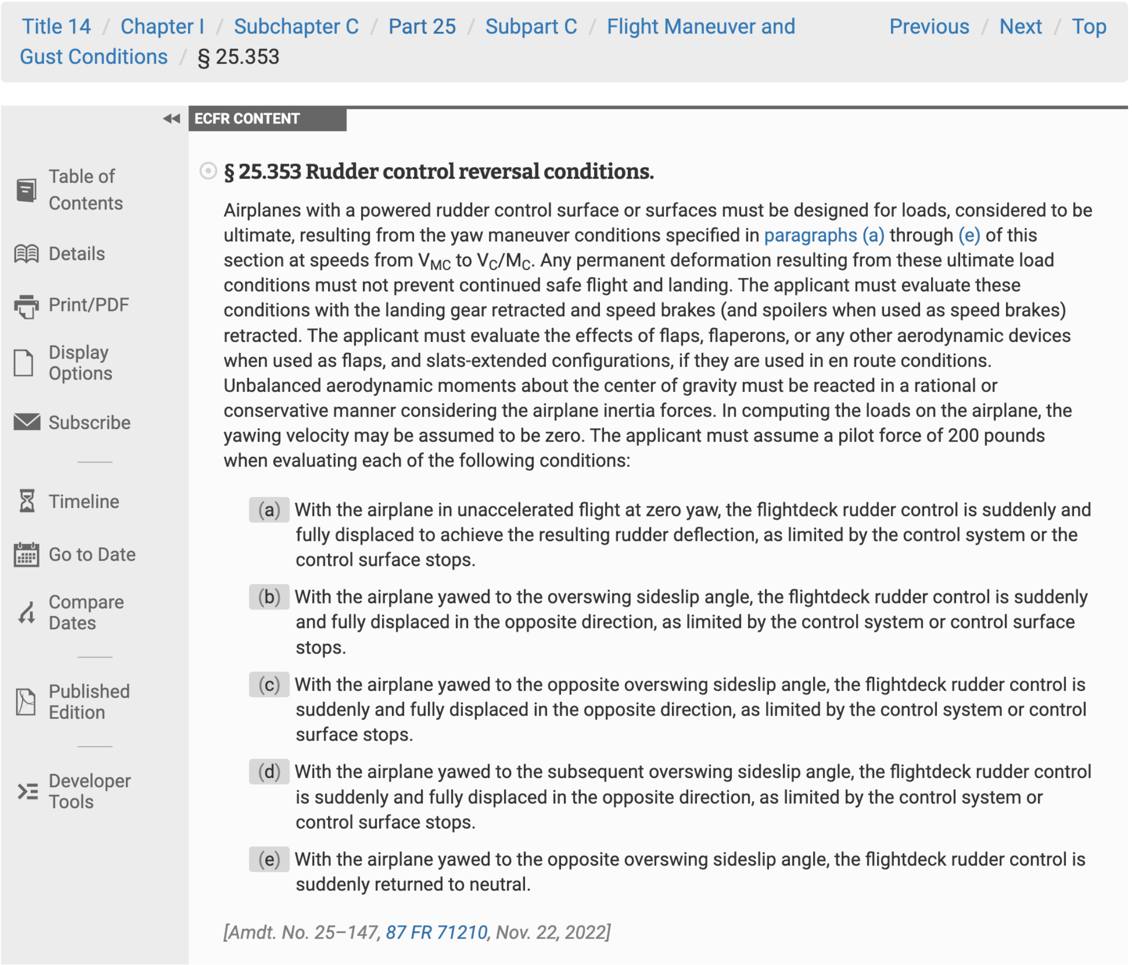
Wake Vortex Investigation

- **Researchers at LaRC investigated whether AA587 could have encountered the wake vortices from Japan Air Lines flight 47 (JAL47)**
  - Determining whether wake vortex interaction explained two sets of load factor excursions that were recorded by the FDR
  - Data and analysis
    - Used flightpath and wind information for the two flights
    - Used atmospheric data from the day of the accident
    - Input data into four wake prediction models (models and results described in appendix B of the “Aircraft Performance Group Chairman’s Aircraft Performance Study”)
  - AA587 would have encountered the wake vortices
    - Vortex strengths between 63% and 80% of the initial vortex strength
- **Finding: Verified that AA587 encountered wake vortices of JAL47**

Summary of NASA Findings

- **No significant or obvious deficiencies in Airbus certification and design methods**
- **VTP performed consistent with design and certification**
- **VTP failure attributed to loads greater than expected**
  - Loads at first failure at minimum 1.92 times limit load
- **Failure scenario interrogation**
  - Most likely failure scenario was failure initiation at right rear lug attachment fitting
    - Pre-existing lug failures would have initiated catastrophic failure prior to maximum experienced load, or not change right rear lug failure as first failure under flight loads
    - Dynamic effects predict failure sequence consistent with the physical evidence, including rudder
  - Buckling of fin skin did not affect the failure load or mode of the VTP
  - Failure in ply-drop region of rudder not likely candidate for initiation of VTP failure
  - Rudder binding did not affect the VTP response or failure
  - Flutter-induced failure not likely initiator of the VTP failure
- **No evidence of pre-existing damage or fatigue cracking in the VTP**
- **Verified that AA587 encountered wake vortices of JAL47**

Update: Title 14 / Chapter 1 / Subchapter C / Part 25



§ 25.353 Rudder control reversal conditions.

Airplanes with a powered rudder control surface or surfaces must be designed for loads, considered to be ultimate, resulting from the yaw maneuver conditions specified in paragraphs (a) through (e) of this section at speeds from V_{MC} to V_C/M_C. Any permanent deformation resulting from these ultimate load conditions must not prevent continued safe flight and landing. The applicant must evaluate these conditions with the landing gear retracted and speed brakes (and spoilers when used as speed brakes) retracted. The applicant must evaluate the effects of flaps, flaperons, or any other aerodynamic devices when used as flaps, and slats-extended configurations, if they are used in en route conditions. Unbalanced aerodynamic moments about the center of gravity must be reacted in a rational or conservative manner considering the airplane inertia forces. In computing the loads on the airplane, the yawing velocity may be assumed to be zero. The applicant must assume a pilot force of 200 pounds when evaluating each of the following conditions:

(a) With the airplane in unaccelerated flight at zero yaw, the flightdeck rudder control is suddenly and fully displaced to achieve the resulting rudder deflection, as limited by the control system or the control surface stops.

(b) With the airplane yawed to the overswing sideslip angle, the flightdeck rudder control is suddenly and fully displaced in the opposite direction, as limited by the control system or control surface stops.

(c) With the airplane yawed to the opposite overswing sideslip angle, the flightdeck rudder control is suddenly and fully displaced in the opposite direction, as limited by the control system or control surface stops.

(d) With the airplane yawed to the subsequent overswing sideslip angle, the flightdeck rudder control is suddenly and fully displaced in the opposite direction, as limited by the control system or control surface stops.

(e) With the airplane yawed to the opposite overswing sideslip angle, the flightdeck rudder control is suddenly returned to neutral.

[Amdt. No. 25–147, 87 FR 71210, Nov. 22, 2022]

https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-25/subpart-C/subject-group-ECFR3e855ea22ea15d0/section-25.353

QUESTIONS?