THE CORRECTIONS BELOW ARE INCLUDED
IN THIS VERSION OF THE FACTUAL REPORT

ADDENDUM NUMBER 8A (REV A) TO THE STRUCTURES GROUP CHAIRMAN'S FACTUAL REPORT

DCA02MA001

ACCIDENT

Location: Belle Harbor, NY
Date: November 12, 2001
Time: 09:16:14 EST
Aircraft: American Airlines Flight 587, Airbus Model A300-605R, N14053
Manufactures Serial Number (MSN) 420

- Pages 1 thru 9 have been updated to clarify NASA LaRC's Charter & Summary of the Findings for American Airlines Flight 587. (17 March 2004)

NATIONAL TRANSPORTATION SAFETY BOARD

Office of Aviation Safety
Aviation Engineering Division
Washington, DC 20594

March 17, 2004

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B. STRUCTURES GROUP

Chairman: Brian K Murphy
National Transportation Safety Board
Washington, DC

C. NASA REPORT

1. ***NASA/TMX-2003-0000, "Structural Analysis Report on the American Airlines Flight 587 Accident Investigation – Part 1 Summary of the Findings" Revision 1***

NASA/TMX—2003–000000

NASA Structural Analysis Report for the American Airlines Flight 587 Accident Investigation: Part 1 – Summary of Findings

NASA Langley Research Center, Hampton, VA

December 2003

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NASA/TMX—2003–000000

NASA Structural Analysis Report for the American Airlines Flight 587 Accident Investigation: Part 1 – Summary of Findings

NASA Langley Research Center, Hampton, VA

National Aeronautics and
Space Administration

Langley Research Center
Hampton, VA 23681

Dedication

This report is dedicated to the memory of **Dr. James H. Starnes, Jr.** Dr. Starnes was our friend and colleague, who led the NASA Langley AA587 investigation team and passed away before the completion of this report.

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Charter

At the request of the NTSB, the charter for the NASA structural analysis team for the American Airlines Flight 587 accident investigation was:

A team from NASA Langley Research Center (LaRC) shall apply their technical expertise with analysis and testing of composite structures to support the NTSB accident investigation. The team shall address the following objectives:

I. Review the Airbus certification analysis results.

II. Develop failure scenarios based on physical evidence and assess reserve factors by performing global analysis of the vertical tail plane (VTP) subjected to the accident loading conditions.

III. Develop failure analysis of the critical region(s) identified by the global analyses and predict the mode, load, and location of failure in the local region(s).

NASA Structural Analysis Team

To address the above charter, the NASA structural analysis team formed two sub-teams, the AA587 Global Analysis Team responsible for assessing the global response of the vertical tail plane (VTP), and the AA587 Local Analysis Team responsible for conducting detailed strength analysis of the most likely failure initiation site, the right rear attachment lug. The Global Analysis and Local Analysis team members are listed below.

<table>
<tr><td colspan="2">NASA AA587 Structural Analysis Team
James H. Starnes, Jr. – Lead</td></tr>
<tr><td>Global Analysis Team</td><td>Local Analysis Team</td></tr>
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The statements and conclusions in the following report represent the views of the NASA structural analysis team based upon analyses conducted by NASA.

Executive Summary

Introduction

On November 12, 2001, an Airbus 300-600R being operated as American Airlines Flight 587 crashed soon after take-off from John F. Kennedy airport in New York City, killing all 260 persons aboard and 5 on the ground. The plane's vertical stabilizer and rudder and both engines separated from the aircraft before it impacted the ground. This accident was the first commercial aircraft crash that involved failure of primary structure made from composite materials. NASA Langley Research Center (LaRC) was asked by the National Transportation Safety Board (NTSB) to support the accident investigation because of LaRC's expertise in composite structures and materials, structural analyses and tests, and expertise in all of the other disciplines necessary to examine the most likely failure scenarios. Personnel at NASA developed in-depth photographic records, performed non-destructive evaluations and chemical analysis, conducted aeroelastic and computational fluid dynamics analyses, and conducted fractographic analyses of failed metallic and composite parts to determine if fatigue was a contributor. In addition, a NASA Structural Analysis Team, consisting of a Global Analysis Team and a Local Analysis Team, was formed to review the manufacturer's design and certification procedures, conduct structural and failure analyses, and participate jointly with the NTSB and Airbus in lug subcomponent tests conducted at Airbus. The present document is the NASA Structural Analysis Team's report to the NTSB. An executive summary is presented here and detailed results from the Global Analysis and Local Analysis Teams are presented in the report in Part 2 and Part 3, respectively.

Throughout the investigation, the team from NASA worked closely with the investigation teams at NTSB and Airbus, and this report reflects many aspects of that collaboration. Often, the analysis efforts at NASA paralleled similar analyses conducted by Airbus. In these cases, NASA results have been used to independently verify Airbus results. In addition, NASA made unique contributions to the investigation by performing progressive failure analyses of the composite structure, and by developing analysis procedures and local models to assess alternative failure scenarios.

The following text summarizes the findings of the Structural Analysis Team. First, the findings of the Global Analysis Team are presented, followed by the findings of the Local Analysis Team. Then, a summary of the conclusions drawn is presented.

Global Analysis Team

Findings from the Global Analysis Team are presented below for the following activities:

- review of Airbus design and certification documents
- review of Airbus fin and rudder models
- model modifications to improve fidelity and assess alternative failure scenarios
- validation of the global finite-element model
- development of local detail models
- failure scenario interrogation
- failure sequence analyses

The NASA Global Analysis Team conducted a review of Airbus design and certification documents. The Airbus design methods, based on a building-block approach for coupon, subcomponent, and full-scale testing, were assessed as being comprehensive. Review of certification documents did not reveal any faulty methods or invalid assumptions, although there were two points of concern that came up during the investigation. These certification concerns and the findings related to them are:

1) <u>The validity of the full-scale fin certification test was questioned.</u>

   In the full-scale test, the fin was tested off the aircraft and there was concern that the loading applied at the main attachment fittings may not have been representative of the fin-on-aircraft condition. The fitting loads applied in the fin test were prescribed exactly from analysis of the fin-on-aircraft condition, and thus the validity of the test loading was dependent on the validity of the global finite-element model. The NASA team has demonstrated validity of the global finite-element model through a combination of test/analysis correlation and sensitivity studies, and determined that the applied forces in the full-scale test were representative of the aircraft condition. The insensitivity of attachment fitting forces to stiffness variations suggests that the attachment fitting forces are primarily dictated by the aerodynamic load distribution and the overall geometry of the structure, more than by the local stiffness representation. Another concern was that the load introduction structure did not produce attachment fitting moments that were representative of the fin-on-aircraft condition. The NASA team does not feel that this concern is substantiated, since the bending moments at the attachment fittings are predominantly due to stiffness eccentricity in the fin structure, and to lateral load on the fittings, both of which are represented in the full-scale fin test. Therefore, the applied forces and moments are judged to be representative of the aircraft condition and the NASA team concludes that the full-scale fin certification test was a valid test.

2) <u>Airbus lug strength allowables for design and certification were in terms of resultant forces, and did not explicitly include moment effects.</u>

   In the course of the investigation, the NASA and Airbus analysis teams recognized that non-trivial moments are reacted at the attachment fittings, and that the magnitude of the moments computed are sensitive to the finite-element idealization of the attachment region. In addition, the NASA team conducted detailed strength analysis of subcomponent models and has shown that the magnitude of the bending moment applied to the attachment fitting influences the failure strength of the fitting.

The lug strength allowables applied by Airbus during design and certification were expressed in terms of a resultant force, and did not represent explicitly the effect of bending moments on the strength of the fittings. The fact that Airbus did not express the strength allowables in terms of force and moment values does not indicate fault in their certification procedure for two reasons.

a. The bending moment at the lug is directly related to the force on the lug, and is not an independent quantity.

b. The Airbus strength (force) allowable for the lug attachment was based on a building-block test sequence that ultimately incorporated bending moment effects. The full-scale fin test article generated internally a representative moment in response to applied fitting forces, and the observed fitting strength was reduced, compared to previous fitting coupon and subcomponent tests. When Airbus reduced the lug force strength allowable for certification based on the full-scale test result, the effect of a representative bending moment on the lug strength was captured, even though the magnitude of the bending moment was never computed or measured.

The NASA team conducted a review of Airbus fin and rudder models that were delivered to NASA at the start of NASA's analysis efforts. Comparison of models to design drawings and physical hardware indicated that the models were generally representative of the actual structure.

A number of model modifications were implemented in a general attempt to improve model fidelity and to interrogate alternative failure scenarios. A listing of model modifications that was applied to the global model of the vertical tail plane (VTP) structure are listed below. Further information regarding these models changes is included in Part 2 of the report.

- Progression of NASA modifications to the model of the main attachment fitting
  - Refined shell representation
  - 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 to demonstrate convergence of global models
- Nonlinear capable global models
- Compared linear and nonlinear results to assess nonlinear effects

Significant findings from model modification efforts are:

- The original coarse mesh discretization in the stiffened fin skin panels used by Airbus was sufficient to represent the structural stiffness.
- Force resultants at main attachment fittings were insensitive to mesh discretization. Conversely, numerous modifications to the finite element idealization in the main attachment fitting region were required to converge on moment results. Ultimately, a global/local iterative method was adopted to effectively embed local detail models for the rear attachment fittings into the global VTP model.
- Linear analysis was deemed sufficient to examine the general response of the VTP structure. In pursuing the investigation, nonlinear analyses were executed occasionally to interrogate specific response phenomena, or to confirm that subsequent model changes did not create a geometrically nonlinear response.

Validation of the global finite-element model of the VTP was demonstrated through a combination of test/analysis correlation for the full-scale test, and sensitivity studies for stiffness variations in the main attachment fitting region and fuselage.

The NASA Global Analysis Team also developed local detail models and specialized procedures to examine alternative failure modes in the global shell model as follows:

- Ply-drop in rudder sandwich panel

  Nonlinear analyses were conducted with a three-dimensional finite element model of the ply-drop detail to determine allowables associated with facesheet buckling, and strain increase and peel stresses at the facesheet-to-core interface due to local bending.
- Delaminated rudder sandwich panel

  Postbuckling analyses were conducted for a three-dimensional finite element model of a sandwich panel with a delaminated facesheet to assess effect of delamination on membrane stiffness. The reduced effective stiffness of the panel was simulated in the global rudder model.
- Simulation of postbuckling stiffness

  Several regions of the VTP are indicated to be buckling critical for the accident loading conditions. Buckling of thin sections can produce significant stiffness reduction, and load redistribution, without causing damage to the buckled structure.

  To simulate buckling effects in the global model, regions that are buckling critical are assigned an aggressive 50% reduction in stiffness, and the analyses are repeated to assess the effect of these local stiffness changes.
- Actuated rudder

  Thermal expansion of the beam ‘actuator’ elements was used to simulate rudder actuation with the VTP subjected to bending loads.

Failure scenarios were developed based upon the physical evidence and an initial assessment of the critical reserve factors computed from global analysis of the VTP subjected to accident load conditions. Five failure scenarios were identified and interrogated.

Scenario #	Scenario Description
1	Main attachment fitting failure a. Pristine Structure b. Pre-existing failure of VTP main attachment fitting
2	Buckling of portions of the fin box, resulting in main attachment fitting failure, rudder hinge line failure, or rudder fracture
3	Rudder skin fracture at the ply-drop near the reinforced actuator region
4	Actuation of a bent rudder hinge line resulting in rudder fracture or rudder hinge line failure
5	Flutter of the VTP resulting from delamination of the rudder skin sandwich panel

Failure scenario interrogation has shown that Scenarios #3, #4, and #5 are unlikely. Scenarios #1b and #2 were shown to be inconsequential, in that they are unlikely, or revert to be equivalent to Scenario #1a. Thus, the most likely failure scenario is Scenario #1a, failure of the right rear main attachment fitting due to loads greater than expected.

The most likely failure scenario was validated by conducting a subcomponent test on a right rear attachment fitting, with loading based on analysis of the aircraft configuration at the final observed maximum fin loading condition. Preliminary strength analyses conducted by the NASA's Local Analysis Team had indicated that subcomponent strength was a function of the resultant force and lateral bending moment applied at the lug pin. To increase the fidelity of the computed pin loading, global and local models were coupled to tune the global model, and a global/local iterative procedure was applied to effectively embed a refined 3-D lug ABAQUS model into the global model for both rear main attachment fitting regions. The computed pin loading from the global/local analysis for the aircraft model and accident condition was used by the Local Analysis Team to prescribe loading conditions for the subcomponent test conducted at the Airbus facility in Hamburg. The Local Analysis Team then conducted strength analyses for the subcomponent test and the aircraft configuration. The strength analyses and test results for the subcomponent test produced failure loads and a mode of failure that were consistent with the predicted accident loading and the physical evidence of the right rear main attachment fitting from the accident.

Analyses were conducted to assess the final failure sequence associated with the most-likely failure scenario. The first series of failure sequence analyses conducted considered the static failure response of the VTP. The analysis results indicate that, after the rear main attachment fitting ruptures, all the remaining attachment fittings will fail sequentially, with no increase in external loading. Thus, initial failure of the rear main attachment fitting would initiate nearly instantaneous separation of the VTP from the aircraft. When the failure sequence is conducted using static analysis, the predicted modes of failure in the lower portion of the fin box appear to be consistent with the physical evidence. However, the loads predicted in the rudder hinge line and rudder skin are not high enough to indicate damage in these regions, which is inconsistent with the physical evidence. Subsequent analyses considering dynamic effects in the final failure sequence are TBD. The primary goal of pursuing the dynamic analysis is to determine if dynamic effects can contribute to rudder skin and rudder hinge line loads that could cause failure of the rudder structure consistent with the physical evidence.

Local Analysis Team

The failure of the right rear lug was evaluated using global models of the vertical tail, local models near the right rear lug, and a global-local analysis procedure. The NASA Local Analysis Team analyzed the right rear lug, including the neighboring fin region between ribs 1 and 5 and near the rear spar using two modeling approaches. The NASA analyses assumed that the pin was rigid. In the first approach, solid-shell type modeling is used, and in the second approach, layered-shell type modeling is used. The solid-shell and the layered-shell modeling approaches were used in progressive failure analyses (PFA) to determine the load, mode and location of failure in the right rear lug under loading representative of the lug subcomponent certification test conducted by Airbus in 1985 (1985 test). Both analyses are in excellent agreement with each other and the 1985 test on the predicted failure loads, failure mode, and location of failure. The solid-shell type modeling was then used to analyze another lug subcomponent test conducted by Airbus in 2003 (2003 subcomponent test) and the accident condition. Excellent agreement is observed between the analyses and the 2003 subcomponent test, which simulated the accident condition. From the analyses conducted and presented in this report, assuming a rigid pin, the following conclusions were drawn:

- The moment, M_x (moment about the fuselage longitudinal axis) has significant effect on the failure load of the lugs. Higher absolute values of M_x give lower failure loads. For example, results from strength analyses predict that the increase in M_x of 79 percent from the 1985 test to the 2003 subcomponent test would produce a 16 percent decrease in the failure load. The analysis is verified by noting that the observed decrease in the experimental strength between these two subcomponent tests was 13 percent. Therefore, accurate evaluation of the value of the moment, M_x, to be applied in a subcomponent test is important. Note that the quoted values are with the rigid pin assumption.

- The predicted load, mode and location of the failure of the 1985 test, 2003 subcomponent test and the accident condition are in very good agreement. This suggests that the 1985 and 2003 subcomponent tests represent the accident condition accurately.

- The failure mode of the right rear lug for the 1985 test, 2003 subcomponent test, and the accident load case is identified as a cleavage-type failure.

- For the accident case, the predicted failure load for the right rear lug from the PFA is greater than 1.98 times the limit load of the lugs.

Summary

Based upon analyses conducted by NASA to date, the NASA structural analysis team has formed several conclusions. The most-likely failure scenario is failure initiation at the right rear main attachment fitting, followed by an unstable progression of failure of all fin-to-fuselage attachments and separation of the VTP from the aircraft. The outcome of all analysis results indicates that failure initiates at the final observed maximum fin loading condition in the accident, when the VTP was subjected to a global root bending moment of 2.13 times the design limit load condition for certification. Relative to the BI17 (gust) certification limit load, the resultant lug force from linear global static analysis and progressive failure strength analysis correspond to load factors of 2.03 and 1.98 times limit load, respectively. For certification, the VTP is only required to only support loads of 1.5 times design limit load without catastrophic failure. The maximum loading during the accident was shown to significantly exceed the certification requirement. Thus, failure is attributed to VTP loads greater than expected. The load level and mode of failure in the accident are consistent with lug subcomponent tests. Thus, the structure did not fail prematurely and appeared to perform in a manner consistent with its design and certification.