Development of a Biaxial Test Facility for Structural Evaluation of Aircraft Fuselage Panels

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Background - The number of commercial airframes exceeding twenty years of service continues to grow. An unavoidable by-product of aircraft use is that crack and corrosion flaws develop throughout the aircraft's skin and substructure elements. Economic barriers to the purchase of new aircraft have created an aging aircraft fleet and placed even greater demands on efficient and safe repair methods. Composite doublers, or repair patches, provide an innovative repair technique which can enhance the way aircraft are maintained. Instead of riveting multiple steel or aluminum plates to facilitate an aircraft repair, it is now possible to bond a single Boron-Epoxy composite doubler to the damaged structure. The composite doubler repair process produces both engineering and economic benefits. The FAA's Airworthiness Assurance Center at Sandia National Labs completed a project to introduce composite doubler repair technology to the commercial aircraft industry [1].

This paper focuses on a specialized structural test facility which was developed to evaluate the performance of composite doublers on actual aircraft structure. The facility can subject an aircraft fuselage section to a combined load environment of pressure (hoop stress) and axial, or longitudinal, stress. The tests simulate maximum cabin pressure loads and use a computerized feedback system to maintain the proper ratio between hoop and axial loads. Through the use of this full-scale test facility it was possible to: 1) assess general composite doubler response in representative flight load scenarios, and 2) verify the design and analysis approaches as applied to an L-1011 door corner repair.

L-1011 Fuselage Section - The aircraft test article was a door surround structure cut from an L-1011 aircraft retired by All Nippon Airways. It was approximately 141" H (151" arc length in the hoop direction) X 114.75" W and included all of the substructure elements. Figure 1 shows a photograph of the door surround structure section after being cut from the L-1011 fuselage. The specimen contained eight circumferential frames and six longitudinal stringers, as well as, the upper and lower longeron around the door cut-out. The Lockheed-designed composite doubler, also shown in Figure 1, was installed by Delta Air Lines technicians at Delta's Atlanta maintenance facility in accordance with references [2] and [3]. The perimeter of the door surround structure was reinforced with bonded and bolted doubler plates to accommodate the tension rams and clevises in the axial direction and the turnbuckle restraints in the hoop direction. During all structural tests, a door was mounted and sealed in the fuselage surround structure.

Test Facility Description - The door surround structure test article was subjected to a combined load environment of external vacuum (note: external vacuum is used to simulate the internal pressure which generates the primary hoop stresses in an airplane) and longitudinal, stress. The differential cabin pressure was generated using a custom vacuum chamber while the axial loads were applied by hydraulic rams. The applied biaxial tension loads approximated the stresses induced by normal flight pressure loads.
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Figure 2 shows a schematic of the door surround structure mounted in the biaxial test facility. It shows the vacuum chamber and the restraints in the hoop direction and the load trains in the axial direction. Turnbuckles in the hoop direction allowed adjustments to the boundary conditions in order to assure a uniform load across the width of the door surround structure. As the vacuum load was applied, hoop and axial loads were developed in the test article. In order to maintain proper control over the desired ratio between hoop and axial loads, twelve tension rams were used to supplement and or relieve axial loads during the tests. The loads applied by the hydraulic tension rams or restrained by the turnbuckle load trains were monitored by load cells.

Figure 2: Biaxial Test Facility Design Drawing Showing the Door Surround Structure Mounted in the Vacuum Chamber and the Hoop and Axial Load Application Hardware

Load Application Points - Figure 3 shows the series of reinforcing plates which were attached to the test article and the whiffle tree load train assemblies. The primary purpose of the reinforcing plates was to eliminate the possibility of local material failure at the load application points. In addition, the particular stack up of plates shown in the drawings was designed to apply the loads at approximately the location of the section's neutral axis and to transfer loads into the stringer and frame substructure elements. This, in turn, minimized the amount of bending imparted to the structure. Overall, the number of attachment points were selected to apply the desired far-field stresses to the structure such that a uniform stress field was produced in the area of interest around the composite doubler (i.e. eliminate test boundary condition effects).

The door surround structure tests were conducted on a large, multi-purpose mechanical test frame. The frame, which measures 10' W X 20' L, contained a continuous grid of threaded and through-holes in order to accommodate any system of load restraints (e.g. I-beams, plates) and mechanical load application linkages. Photographs of this multi-purpose test frame with the door surround structure mounted in place are shown in Figures 4 and 5. Figure 4 is a view inside the perimeter of the test frame. It shows one side of the hoop restraints and the longitudinal whiffle trees attached to the test article. Figure 5 provides a view from the outside of the frame. The test article is in the background while the load restraint beams, hydraulic rams and data acquisition system are in the foreground.

The vacuum, or pressure differential loads, were generated by vacuum pumps connected to the door surround structure. Figure 4 shows the flexible hose used to connect the vacuum pumps to the test article. One of the window cut-outs was fitted and sealed with an aluminum plate. The plate contained the vacuum port, the pressure transducer, and the overpressure relief valve. An air tight seal between the fuselage skin and the vacuum chamber was achieved using maleable strips of caulking putty.
mounted on the inside of the door surround structure at the same X,Y location. This allowed for an assessment of the bending strains at those locations.

Instrumentation - The entire strain field on and around the composite doubler was monitored using a series of biaxial and Rosette strain gages. Data was acquired to study the following issues: 1) load transfer through the doubler, 2) stresses in the doubler and parent structure, and 3) effect of the repair on the fuselage stresses adjacent to the doubler. The strain gage locations are shown in Figure 6. The locations shown correspond to high strain areas, potential crack initiation sites, and important load transition regions along the outer perimeter of the doubler. Several external gage locations had matching strain gages mounted on the inside of the door surround structure at the same X,Y location. This allowed for an assessment of the bending strains at those locations.

Sample Test Results - Reference [4] is a comprehensive report on the test series results. Some of the important results are highlighted here. The door surround structure was tested before and after the doubler was installed to evaluate strain field improvements.
The maximum principal stresses in the doubler-affected region are listed in Table 1. The largest stress in the aluminum skin was found at R-7 (inside skin) at the door corner radius. The magnitude was 10.6 KSI, reduced from the 15.3 KSI recorded at that same location before the doubler was installed. The largest Boron-Epoxy stress was 19.3 KSI at the R-8 Rosette gage. This is less than the 22.4 KSI measured at that same location before the doubler was installed. Similar comparisons of aluminum stresses before the doubler versus aluminum/boron stresses at the same locations after the doubler revealed the stress reductions summarized in Table 1. It can be seen that the stresses were reduced by as much as 53% through the application of the reinforcing doubler. Figure 7 plots the reduction in several principal stresses after the doubler was installed. Strain gage data from common locations on the inside and outside of the test article showed that, during cabin pressurization, out-of-plane bending accounts for up to 50% of the total strain induced in the fuselage structure. Thus, bending effects should be a prime consideration in composite doubler designs.

<table>
<thead>
<tr>
<th>Rosette Gage Number</th>
<th>Stress Before Doubler (KSI)</th>
<th>Stress After Doubler (KSI)</th>
<th>Percent Reduction in Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-2</td>
<td>12.7</td>
<td>6.9</td>
<td>45% *</td>
</tr>
<tr>
<td>R-4</td>
<td>9.6</td>
<td>6.2</td>
<td>35% *</td>
</tr>
<tr>
<td>R-5</td>
<td>7.5</td>
<td>4.9</td>
<td>35%</td>
</tr>
<tr>
<td>R-6</td>
<td>15.3</td>
<td>12.9</td>
<td>18% *</td>
</tr>
<tr>
<td>R-7</td>
<td>15.3</td>
<td>10.6</td>
<td>31%</td>
</tr>
<tr>
<td>R-8</td>
<td>22.4</td>
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<td>14% *</td>
</tr>
<tr>
<td>R-10</td>
<td>13.2</td>
<td>6.2</td>
<td>53% *</td>
</tr>
</tbody>
</table>

* Indicates aluminum stress before vs. boron stress in same location after doubler was installed

**Table 1: Principal Stress Reductions Observed Within the Doubler Footprint**

**Conclusions** - In this test series, a custom facility was used to evaluate the response of composite doublers on fuselage structure. The full-scale fuselage test series validated composite doubler technology using realistic structures and flight loads. It showed that a properly designed and installed composite doubler is able to enhance fatigue life, transfer load away from damaged structure, and avoid the introduction of new stress risers (i.e. eliminate global reduction in the fatigue life of the structure). The biaxial fuselage test facility was critical in certifying this advanced repair technique. As a result, FAA and industry approval has been received for the use of bonded composite doublers on the U.S. commercial aircraft fleet.

**Figure 7: Comparison of Principal Stresses Before and After Doubler Installation**

**References:**


