**EXPERIMENTAL AND ANALYTICAL PROGRAM TO DETERMINE STRAINS IN
737 LAP SPLICE JOINTS SUBJECTED TO NORMAL FUSELAGE PRESSURIZATION LOADS**

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ABSTRACT

The Federal Aviation Administration Technical Center (FAATC) has initiated several research projects to assess the structural integrity of the aging commercial aircraft fleet. One area of research involves the understanding of a phenomenon known as "Widespread Fatigue Damage" or WFD, which refers to a type of multiple element cracking that degrades the damage tolerance capability of an aircraft structure. Research on WFD has been performed both experimentally and analytically including finite element modeling of fuselage lap splice joints by the Volpe Center. Fuselage pressurization tests have also been conducted at the FAA's Airworthiness Assurance NDI Validation Center (AANC) to obtain strain gage data from select locations on the FAA/AANC 737 Transport Aircraft Test Bed. One-hundred strain channels were used to monitor five different lap splice bays including the fuselage skin and substructure elements. These test results have been used to evaluate the accuracy of the analytical models and to support general aircraft analysis efforts. This paper documents the strain fields measured during the AANC tests and successfully correlates the results with analytical predictions.

INTRODUCTION

Over the past decade, the commercial aviation industry has experienced a substantial growth in its aging aircraft fleet due to increasing airlift demands coupled with the high cost of aircraft replacement. In 1989, the average age of the commercial fleet was 12.7 years with 25 percent of the fleet exceeding the estimated economical design life of 20 years. If this trend continues, 60 percent of the current commercial aircraft fleet will exceed their economic design life by the year 2000. Chronological age alone is not an effective measure of aircraft condition. The most important indicator is the number of flights while other factors include flight time, environmental exposure and usage patterns.

It is clear that the total usage of the commercial fleet is increasing to unprecedented levels in every aspect: age, number of flights, and flight hours.

In 1978, fail-safe design requirements gave way to the damage tolerance approach. Damage tolerance requires that the structure be capable of sustaining small cracks without failure, and an inspection program be instituted to detect such cracks before they grow to a critical length. This damage tolerance philosophy recognizes the impossibility of establishing complete structural redundancy (the fail-safe premise) and places greater emphasis on inspection. The FAA issued Advisory Circular (AC) 91-56 in 1981 which provided a means for aircraft maintenance and inspection procedures to meet damage tolerance criteria. It required the evaluation of structures using fracture mechanics analysis to develop supplemental structural inspections. Through the resulting Supplemental Structural Inspection Document (SSID) program, fail-safe designed aircraft were brought into conformance with the damage tolerance approach by means of an updated inspection program. The 737 strain field mapping produced in this study contributes essential information to these fracture mechanics and damage tolerance analyses.

One focus area for the Federal Aviation Administration (FAA) research initiatives involves the understanding of a phenomenon known as "Widespread Fatigue Damage" or WFD, which refers to multiple cracks that erode the damage tolerance capability of an aircraft structure. The terms "Multiple Site Damage" and "Multiple Element Damage" have been used to refer to specific types of WFD characterized by the simultaneous presence of fatigue cracks in the same structural element (MSD) and in similar adjacent structural elements (MED). The formation and growth of multiple cracks along a longitudinal lap splice in the fuselage is believed to have contributed to the structural failure of Aloha Airlines Flight 243 in April 1988 [1].

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This paper describes the results from a series of tests to measure strain fields in Boeing 737 aircraft subjected to ground pressurization. The strain gage tests were conducted at the FAA's Airworthiness Assurance NDI Validation Center located at Sandia National Laboratories. The objectives of these tests were: 1) to characterize the strain field at the probable location of failure in the Aloha Airlines aircraft, 2) to verify the accuracy of empirical results from laboratory aircraft panel tests, and 3) to validate the results from the finite element models of curved stiffened panels containing lap splice joints. The AANC Test Bed is a Boeing 737-200 aircraft (line number 49, manufactured in 1968) which was retired in 1988. During its service lifetime, the airplane accumulated 48,358 cycles in 38,342 flight hours.

737 FUSELAGE PRESSURE TEST

The cabin of the AANC aircraft was pressurized to simulate in-flight loads experienced by the fuselage skin and its supporting structure. Sections of the aircraft above and below the windows, and forward and aft of the wing were instrumented to study structural uniformity, effects of fuselage bending and effects of different frame

configurations. The selection of strain gage locations accommodated the following issues: 1) instrumentation of several key lap splice joint bays, inside and out, with strain gages, 2) instrumentation of similar bays forward and aft of the wing to assess variations due to bending, and 3) determination of strain levels in high gradient areas on the skin as well as on substructure elements such as tear straps, stringers, and frames. For reference during the following discussion, a schematic of the entire test set-up is shown in Figure 1.

Five (5) fuselage stringers with lap splice joints can be found on both the left and right side of the Boeing 737 airplane. These stringers are designated as S-4, S-10, S-14, S-19, and S-25. Stringers are numbered sequentially from the crown (S-1) to the keel (S-28). The National Transportation Safety Board (NTSB) report [1] on the Aloha accident concluded that the most likely point of failure initiation was the fuselage lap splice at stringer S-10L, located just above the windows in the fuselage, in Section 43. Therefore, bays at the S-10L stringer locations were chosen as areas for strain gage instrumentation. The lap joints at the S-4 stringers are located closer to the aircraft crown, and are more isolated from the structural effects of windows. The lap joints at the S-14 stringer are located between the

Figure 1: AANC 737 Strain Monitoring Test Set-Up

windows and the floor line. Both structural features have the potential to affect the strain field and were selected for instrumentation. Figure 1 shows the location of the lap splice bays where strain gages were installed. The longitudinal strain gage locations - at Body Stations (BS) 480 and 780 - were chosen to minimize interactions from major structural features such as wings, doors, vertical and horizontal stabilizers, repairs, and tapers in the fuselage radius.

Lap Splice Bay Design and Location of Strain Gages

A lap splice joint consists of two overlapping fuselage skin sections with a reinforcing longitudinal stringer. Figure 2 shows the three inch skin overlap which accommodates three rows of rivets. The "hat section" stringer is fastened along the middle rivet row. Each lap splice bay is approximately 20" wide with a circumferential frame member at each end. Thin, reinforcing plates, called tear straps, are bonded to the fuselage skin at the midpoint of each lap splice bay.

Specific strain gage locations were selected within a given lap splice bay. Figure 2 and the description below summarize these gage locations.

- (1) the stringer above the lap joint,
- (2) a "midbay" location: halfway between the lap joint stringer and the one above it,
- (3) a position just above the upper boundary of the lap joint, two inches above the lap joint stringer,
- (4) the upper row of rivets in the lap joint,
- (5) the middle row of rivets along the lap joint stringer,
- (6) the lower row of rivets, and
- (7) the position just below the lower boundary of the lap joint, two inches below the lap joint stringer.

Four longitudinal gage positions can be identified as (see Figure 2):

- (A) along the frame,
- (B) along a "midline" location: halfway between the tear strap and the frame, halfway between the two central rivets,
- (C) along the tear strap, and
- (D) one inch from the midline location, but closer to the tear strap than the frame.

Figure 2: Guide to Strain Gage Locations Within Selected Lap Splice Bays

Characterization of the strain gradient across the lap splice was considered in the selection of strain gage locations. The effects of local bending were examined by installing gages on both the inside and outside surfaces of the fuselage skins at coincident locations. Substructure elements such as tear straps, stringers, and frames were also instrumented to assess load transfer into the fuselage structure.

Some of the strain gages were arranged in rosette configurations to provide principal strain data. It is not possible to present the strain gage data from all 100 channels acquired in this paper. For the purpose of this publication, one of the instrumented lap splice bays has been selected as the means to present the test results. Figure 3 shows the exact locations (and assigned channel numbers) of the uniaxial, biaxial, and rosette gages in the S-10L (BS 470-480) lap splice bay.

Aircraft Ground Pressurization

The AANC airplane was pressurized using an Engine Airstart Unit. The maximum differential pressure applied to the aircraft

was dictated by flow restrictions and aircraft leakage. Leaks in the fuselage were sealed to minimize loss of pressure. These areas included door seals, drain hole seals, lavatory and galley vents, seals on dump valves, air inlet valves, and check valves. The Airstart Unit was connected to the aircraft packs so that the turbines could maximize the volume flow into the aircraft. The aircraft was equipped with pressure relief valves that were calibrated to prevent inadvertent pressurization beyond 8.5 psi. The maximum differential pressure in the AANC tests was 6.5 psi. This value, while less than the maximum pressure difference of 8.5 psi experienced in flight, was sufficient to allow for accurate extrapolation of the strain data. Cabin pressure levels were regulated using the pressurization controls in the cockpit of the Boeing 737. The pressurization rates were chosen to closely match those associated with normal aircraft climb rates.

Figure 3: Strain Gage Numbers for Lap Joint at Stringer S-10L, Body Stations 470-480

Experimental Strain Data

Load Transfer Through the Lap Splice Joint

In each of the five (5) instrumented lap splice bays, gages were installed to monitor strain levels at locations above and below the joint

as well as in the upper, middle, and lower rivet rows of the lap itself. Figure 4 shows plots of hoop strains in the external skin as a function of pressure.

Figure 4: External Skin Hoop Strains Along Midline at S-10L, BS475

The following observations can be made from these plots:

- (1) Most of the load in the skin above the lap splice joints is transferred into the skin around the upper rivet row. Strain levels above the lap joint (e.g., Channels 48 and 50) are approximately equal to those in the first row of rivets (e.g., Channel 54).
- (2) Strain levels in the upper skin of the lap decrease drastically in the circumferential direction across the lap joint, from above the upper rivet row to the lower rivet row. The Figure 4 plots show that the skin around the middle rivet row of the S-10L lap joint experienced only 56% of the total strain; the same area of the S-4L lap joint experienced 17% of the total strain. A possible cause for this difference in load transfer between the S-4L and S-10L lap splice bays is a difference in the bond quality (i.e. effectiveness of adhesive which joins the two aluminum sheets) between these two joints.

- (3) Even though internal pressurization of the fuselage generally produces positive hoop strains, strains in the skin around the lower rivet rows in all bays (Channel 58) are negative. Reverse or compression type bending in the lower rivet row develops as the lap joint deforms. Deformation of the lap joint shifts the neutral axis of the structure which, in turn, induces a bending load into the lap skins.
- (4) Strain levels below the lap joint on the lower skin are approximately equal to the strain levels above the joint. As shown in Figure 4, the strain measured in Channel 60 (lower skin below lap joint) is $906 \mu\epsilon$ compared to the strain measured in Channel 48 (upper skin above lap joint) which is $907 \mu\epsilon$.

Hoop Strains Along the Lap Splice Joint

Figure 5 is a plot of hoop strains in the external skin along the lap splice joint in the longitudinal direction at stringer S-10L (between Body Stations 470 and 480). Three longitudinal locations on the fuselage were monitored above and below stringer S-10L: (1) over the tear strap, (2) at the midline location or center of the bay where there is no circumferential reinforcement, and (3) over the frame.

Figure 5: External Skin Hoop Strains One Inch Below Lower Rivet Row at S-10L Lap Splice Bay Between BS470 and BS480

In general, the strain levels are both uniform and consistent as the longitudinal position changes from the tear strap, through midbay, and over to the fuselage frame. Therefore, at the S-10L bay the reinforcing substructure elements do not affect the strain levels around the skin and rivets to which they are attached.

Strain variations were observed along the middle rivet row of stringer 4L where the strain at the center of the bay was only half as large as the strain over the tear strap. This may be due to the effect of load transfer into the inner/lower lap skin. This variation in middle row strain levels also indicates a difference in the bond integrity between the S-4L and S-10L joints. Table 1 summarizes the strain variations across the stringer 10L lap splice bay between body stations 470 and 480. Maximum strain values measured at the peak pressure load of 6.5 psi are listed versus their location in the bay.

Load Transfer Into Lower/Inner Skin Of Lap Splice Joint

Another way to analyze the load transfer from the upper/outer lap skin into the lower/inner skin is to examine the strain values on both skins of the riveted assembly. Figure 6 compares strains measured on the inner and outer skins at the lower rivet row of S-10L. The hoop strains on the outer skin are less than $200 \mu\epsilon$ and compressive. Most of the load at the lower rivet row is transferred into the inner skin where the strain values are equal in magnitude to those observed in the external, upper rivet row. The maximum strains are approximately $950 \mu\epsilon$ in the hoop direction and $250 \mu\epsilon$ in the longitudinal direction. These results show that the lower rivet row of the inner skin experiences the same peak strains as the upper rivet row of the outer skin. Thus, these two areas should receive similar emphasis in fatigue and damage tolerance analyses.

Strains In Substructure Elements

Gages were installed on the frames and stringers directly beneath the S-4L and S-10L lap joints between Body Stations 470 and 480 to study the strains in fuselage substructure elements. The maximum hoop strains measured in the frame are between $600 \mu\epsilon$ and $700 \mu\epsilon$ which are approximately 30 to 40% lower than the maximum strains in the skin directly above the frame. The strains

measured in stringers S-4L and S-10L (BS475) are slightly lower than those measured on the attached skin (maximum strains in the stringer vary between 200 $\mu\epsilon$ and 350 $\mu\epsilon$; in the skin between 250 $\mu\epsilon$ and 400 $\mu\epsilon$).

Figure 6: Hoop Strains in Lower Rivet Row on Inner and Outer Lap Skins at S-10L, BS475

Stress Fields In Lap Splice Bays

Strain data collected from the biaxial and rosette gages were used to calculate stresses in the aircraft. Membrane stresses were calculated from the following equations:

$$\sigma_{\theta} = E(\epsilon_{\theta} + \nu\epsilon_z) / (1 - \nu^2) \quad (1)$$

and,

$$\sigma_z = E(\epsilon_z + \nu\epsilon_{\theta}) / (1 - \nu^2) \quad (2)$$

where E is the modulus of elasticity, ν is Poisson's ratio, σ_{θ} is the hoop stress in the skin or the frame, σ_z is the longitudinal stress in the skin or the stringer, ϵ_{θ} is the hoop strain, and ϵ_z is the longitudinal strain.

Table 2 lists hoop and longitudinal strains measured at the midbay and midline location in each of the five lap splice test sections in the AANC airplane. The corresponding hoop and longitudinal stresses, calculated from equations (1) and (2), are also listed in the table. Numbers in parentheses are ratios of measured quantities to theoretical values based on thin-walled cylinder approximation.

Strain Channel	Body Station	Circumferential Position	Strain at Max Pressure
31 37 48	470 (over tear strap) 475 (mid bay) 480 (above frame)	4.75" above upper rivet row 4.75" above upper rivet row 4.75" above upper rivet row	933 $\mu\epsilon$ 935 907
32 43 38 45 50	470 (over tear strap) 471 475 (mid bay) 479 480 (above frame)	1" above upper rivet row 1" above upper rivet row 1" above upper rivet row 1" above upper rivet row 1" above upper rivet row	709 $\mu\epsilon$ 641 915 707 715
33 36 39	470 (over tear strap) 475 (mid bay) 480 (above frame)	Along middle rivet row over S-10L Along middle rivet row over S-10L Along middle rivet row over S-10L	506 $\mu\epsilon$ 506 526
34 40 60	470 (over tear strap) 475 (mid bay) 480 (above frame)	1" below lower rivet row 1" below lower rivet row 1" below lower rivet row	882 $\mu\epsilon$ 884 906

Table 1: Peak External Skin Hoop Strains Across S-10L Lap Splice Bay at Maximum Fuselage Pressure of 6.5 PSI

For comparison, the hoop and longitudinal stresses in a closed-end, thin-walled cylinder subjected to internal pressure can be calculated from:

$$\sigma_{\theta} = pR/t \quad (3)$$

$$\sigma_z = pR/2t \quad (4)$$

where p is the differential pressure, R is the radius of the cylinder, and t is the skin thickness. From equations (1) and (2), the theoretical strains are:

$$\epsilon_{\theta} = \frac{1}{E}(\sigma_{\theta} - \nu\sigma_z) = \frac{pR}{2Et}(2 - \nu) \quad (5)$$

$$\epsilon_z = \frac{1}{E}(\sigma_z - \nu\sigma_{\theta}) = \frac{pR}{2Et}(1 - 2\nu) \quad (6)$$

From Mil-Handbook 5, the modulus of elasticity and Poisson's ratio for 2024-T3 aluminum are: $E = 10.5$ msi and $\nu = 0.33$, respectively. Also, for the AANC Boeing 737 airplane, $R = 74$ inches, $t = 0.036$ inch. Therefore, for an internal pressure of 6.5 psi, the thin-walled cylinder approximation yields the following values for strains and stresses: $\epsilon_{\theta} = 1135 \mu\epsilon$, $\epsilon_z = 267 \mu\epsilon$, $\sigma_{\theta} = 13.4$ ksi, and $\sigma_z = 6.7$ ksi. These theoretical values are compared to the actual strains and stresses at the midline and midbay location in Table 2. The measured stresses and strains vary by 10% to 30% of the thin-walled cylinder estimates. This result is reasonable since an

actual airplane fuselage contains stiffening elements that carry load and generally reduce strain.

From the thin-walled cylinder approximation, the ratio of longitudinal stress to hoop stress is 0.5. Table 1 shows that the stress ratio determined from measured strain values compare well with this theoretical ratio. The ratio of the longitudinal strain to hoop strain is

$$\epsilon_z / \epsilon_{\theta} = (1 - 2\nu) / (2 - \nu). \quad (7)$$

For $\nu = 0.33$, this ratio is 0.204. Table 2 shows that the measured strain ratios vary from 0.205 to 0.281. Again, because of stiffening elements, the actual ratio of longitudinal strain to hoop strain should be slightly different from the value given by equation (7).

Correlations With Results From Finite Element Models

Description of Finite Element Models

Finite element models (FEMs) of fuselage lap joint structures were developed at the Volpe Center using the commercial finite element code ANSYS [2,3]. The FEMs included structural details such as tear straps, stringers, structural fillers, frames, stringer ties, and rivets. Two models were developed for direct comparisons with the AANC data. The first model assumed that the skins, tear straps, and structural fillers are attached by

Test Section Location	Measured Strain ($\mu\text{inch/inch}$)			Calculated Stress (ksi)		
	ϵ_{θ}	ϵ_z	$\epsilon_z / \epsilon_{\theta}$	σ_{θ}	σ_z	$\sigma_z / \sigma_{\theta}$
S-4L, BS475 (Channels 17 and 18)	825 (0.776)	189 (0.875)	0.229	9.7 (0.724)	4.8 (0.716)	0.495
S-10L, BS475 (Channels 47 and 48)	931 (0.876)	222 (1.028)	0.238	11.0 (0.821)	5.5 (0.821)	0.503
S-14L, BS475 (Channels 61 and 62)	929 (0.874)	190 (0.880)	0.205	10.8 (0.806)	5.2 (0.776)	0.475
S-4L, BS785 (Channels 83 and 84)	948 (0.892)	266 (1.231)	0.281	11.3 (0.843)	6.0 (0.896)	0.536
S-10L, BS785 (Channels 91 and 92)	961 (0.904)	225 (1.042)	0.234	11.3 (0.843)	5.6 (0.836)	0.499

Table 2: Comparisons of Strains and Stresses at Midline/Midbay Location in Various Test Sections at 6.5 PSI

an adhesive bond, and all other components are attached by rivets. In this paper, this model is referred to as the adhesive lap splice model. The second model, referred to as the riveted lap splice model, assumed no adhesive, and all structural components are attached by rivets only. Thus, the two models effectively bound the possible conditions of bonding in the lap joint between entirely bonded and completely debonded.

Both finite element models employ four-noded shell elements to represent the skins, tear straps, structural fillers, frames, and stringer ties of the aircraft fuselage. In the riveted lap splice model, three-dimensional beam elements represent the rivets at the individual rivet locations throughout the model. The flexibility of these rivets was estimated using the empirical formula derived by Swift [4]. The riveted lap splice model consists of 13,382 nodes and 12,740 elements which result in a total of 76,737 active degrees of freedom. The adhesive lap splice model uses 6,684 nodes and 7,042 elements which combine for 37,739 active degrees of freedom. Figure 7 shows the finite element mesh pattern used to model a section of the aircraft fuselage containing a riveted lap joint.

Body Station 475, stringer S-4L, with results from the riveted lap splice model. The solid, dotted, and dashed lines in the figure represent results from the finite element models; the symbols indicate the measured strain gage data. Similarly, Figure 9 shows the same comparison for the adhesive lap splice model. Clearly, the strain data are characterized more accurately by the lap splice model containing rivets only (no bond), especially in the upper rivet row, suggesting

Figure 7: Finite Element Mesh Pattern for Pressurized Aircraft Section

Results of Correlations Between Finite Element Models and AANC Data

Figure 8 compares measured hoop strains at various locations across the lap splice at

Figure 8: Comparison of Strains Across Lap Splice at S-4L, BS475 (Riveted Lap Splice Model)

that the cold-bond adhesive has degraded at that location in the AANC airplane. This result was supported when subsequent nondestructive inspections detected some corrosion and debonds in the lap joints.

The hoop strains in the inner and outer skins along the lower rivet row are shown in Figure 10 as functions of pressure for each finite

element model. The strain gage data for these plots correspond to BS475, stringer S-4L on the AANC 737 airplane. For this particular area of interest, the riveted and adhesively bonded lap splice models predict similar strains. These results show that the integrity of the lap splice bond has minimal effect on the strain field in the area of the lower rivet row.

Figure 9: Comparison of Strains Across Lap Splice at S-4L, BS475 (Adhesively Bonded Lap Splice Joint)

Figure 10: Comparison of Strains in Inner and Outer Skin at S-4L, BS475 (Riveted Lap Splice Joint)

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CONCLUSIONS

One of the concerns facing the civil aviation community is ensuring the continued integrity and safety of airframes and engines as these flight systems age. The extended usage of aircraft means that the occurrence of fatigue cracks and other flaws can be expected to increase. Fatigue cracks occur in aircraft structures from cyclic loading caused by repeated pressurization. Research is being conducted to ensure that the continued structural airworthiness of airplanes operated beyond their original design life is not compromised due to structural degradation caused by aging. The results presented in this report provide detailed information regarding strain fields in the lap splices of an early Boeing 737-200 series aircraft. In particular, the strains in both the skin and the substructure elements were measured experimentally on the retired 737 aircraft and predicted analytically by finite element analysis.

The strain data collected from the AANC airplane were analyzed to characterize the state of strain in the fuselage structure. Particular attention was given to the strains near the lap splices and to the load transfer through the joints. The results of the strain characterization and correlations with FEMs are summarized as follows:

- 1) In each test section of the AANC airplane, most of the load in the skin above the lap joint was transferred into the skin around the upper rivet row. Strain levels in the upper skin of the lap decrease drastically in the circumferential direction across the joint. The skin around the middle rivet row exhibited only a fraction of the strain measured at the upper rivet row; the lower rivet row experienced even less strain. Differences in load transfer among the different test sections appear to be related to differences in bond quality.
- 2) The lower rivet row of the inner skin experiences the same peak strains as the upper rivet row of the outer skin. Therefore, these two areas should be given similar emphasis in fatigue and damage tolerance analyses.

- 3) The maximum hoop strains in the fuselage frames were measured between 600 $\mu\epsilon$ and 700 $\mu\epsilon$. These values are approximately 30% to 40% lower than the maximum strains measured on the skin directly above the frame. The longitudinal strains measured in the stringers were slightly lower than those on the attached skin (maximum strains in the stringer were between 200 $\mu\epsilon$ and 350 $\mu\epsilon$; in the skin between 250 $\mu\epsilon$ and 400 $\mu\epsilon$).
- 4) The maximum hoop stresses measured in the skins of the lap joint were in the range of 9 to 13 ksi. The combined effect of the load transfer and reverse bending produced a large difference in hoop stresses between the internal and external skins near the lower rivet row. The stresses in the outer skin at the lower rivet row were negligible, but the stresses in the inner skin at the lower rivet row reached a peak value of 11 ksi. The longitudinal stresses were approximately one-half of the hoop stresses.
- 5) Agreement between results from finite element models developed by the Volpe Center and strain gage data was reasonable. The AANC 737 data agreed better with results from the riveted lap splice model than those from the adhesive lap splice model. This correlation suggests that the adhesive bond in the tested lap splices of the AANC aircraft may have degraded. Comparisons between the computational models and actual aircraft strain data revealed a number of critical design considerations and provided insight into the WFD phenomenon.

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