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FATIGUE AND PROOF TESTING OF AN AIRCRAFT AUXILIARY FUEL TANK

In this study the structural performance of an aircraft auxiliary fuel tank was examined through an experimental program comprised of monotonic and fatigue loads. The study was conducted to insure compliance with the Federal Aviation Regulations (FAR)s and to assess the tank's reliability in terms of its resistance to fatigue damage and over-pressurization failure. In the past, the tank's fatigue design was based on a safe-life concept. The primary goal of this experimental investigation was to demonstrate that the current tank design meets the performance requirements outlined by the FARs for an unlimited service life. To achieve certification for an "unlimited service life" the tank's life must exceed the expected life of the aircraft.

INTRODUCTION

The flight range of commercial aircraft is limited by the onboard fuel capacity. For example, the Boeing Business Jet (BBJ) 737 has an onboard fuel capacity of approximately 5,300 gallons. Based on an average fuel consumption rate of 2 gallons/mile, the safe transport range of a BBJ is 2,650 nautical miles. With the ongoing rise in air traffic, flight stopovers for refueling represent a significant component of the operating costs. Recent national events have made the advantages of direct flights and fewer stopovers even more apparent. One way to reduce the frequency of refueling and extend the flight range is by increasing the onboard fuel capacity.

Auxiliary fuel tanks can be installed in the aircraft cargo bay to supplement the onboard fuel capacity contained within the wing and fuselage tanks. The auxiliary tanks are subjected to the same stringent design and performance standards as the primary aircraft. The airworthiness standards are defined by the Federal Aviation Regulations (FAR)s. Although there are many standards that apply to auxiliary fuel tanks, one of the most important pertains to the fatigue behavior.[1] Compliance with the FARs requires a thorough design analysis that is supported by an experimental evaluation and confirmation of the fatigue damage resistance.

EXPERIMENTAL METHODS

The test structure is a specially modified auxiliary fuel tank (PN 42441-201) which is similar to the units designed for placement in the cargo bay of a Boeing Business Jet (BBJ) 737 aircraft (Figure 1). Each tank has a capacity of 500 gallons and is generally installed in a series of units to extend the total onboard fuel capacity by up to 3,200 gallons. The tank has a double wall construction that consists of an aluminum honeycomb that is sandwiched between two aluminum face sheets; both the skin and core are Al 2024-T3. The interior face sheet serves as the primary fuel enclosure while the exterior sheet serves as a redundant fuel enclosure. The cavity located between the two face sheets is occupied by the aluminum honeycomb and termed the tank core. An open cell construction allows fuel to drain through the honeycomb between the two skins. If fuel penetrates the primary skin from the tank interior, a drain outside the exterior skin allows identification of the leak. Internal aluminum tubular stiffeners reinforce the top, bottom, aft and forward panels (Figure 1). The largest unsupported panel dimension is less than an 18 inch square.

A pressure fatigue test, a rocking fatigue test, and a proof (over-pressure) test were performed in accordance with FAR 25.965.[2] A steel test fixture was constructed to duplicate the aircraft mounting system and facilitate the experimental investigation. The auxiliary tank is shown mounted within the test fixture in Figure 2(a).

Pressure Fatigue Test

The pressure fatigue test was conducted to simulate changes in the internal tank pressure that occur with altitude profiles of a standard flight. The fatigue cycle consisted of a maximum pressure of +3.80 psig and minimum pressure (vacuum) of −1.50 psig. Variations in pressure were achieved by pumping water between the tank and an adjoining reservoir. The hydraulic system (Figure 2(b)) consisted of a centrifugal pump, four solenoid valves to change the direction of water flow, two limit switches (pressure and vacuum) to monitor the tank pressure, and a surge tank to dampen pressure spikes. All pressure gauges and switches were calibrated against a commercial pressure gauge†. The fatigue cycle was controlled by a closed loop computer system†† that monitored the internal tank pressure. Limit switch feedback was used to initiate valve actuation and control the direction of water flow between the tank and reservoir. With the tank filled near full capacity, a pressure cycle (full reversal from −1.50 to +3.80 psig) could be completed within 10 seconds. The pressure variation was achieved through a transfer volume of approximately 5 gallons of water, indicating an average flow rate of 60 gallons/minute.

Strain gages were mounted within the tank to monitor incipient changes in structural behavior with fatigue loading. Commercial waterproof uniaxial and triaxial rosettes were used with integral lead wires†††. Nine sites were monitored during the fatigue test and consisted of locations identified as sensitive to fatigue damage from an analytical structural evaluation. Each individual gage element was incorporated into a Wheatstone bridge in a quarter bridge arrangement;

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†PTE-1 Pressure Gauge, Heise, Dresser Industries, Stratford, CT.

††SCXI-1000 4-Slot Chassis, SCXI-1121 4-Channel Isolation Amplifier, SCXI-1321 Offset-null and shunt calibration terminal block, National Instruments, Austin, TX.

†††WFLA-6-23-5LT and WFRA-6-23-5LT, Tokyo Sokki Kenkyujo, Tokyo, Japan.

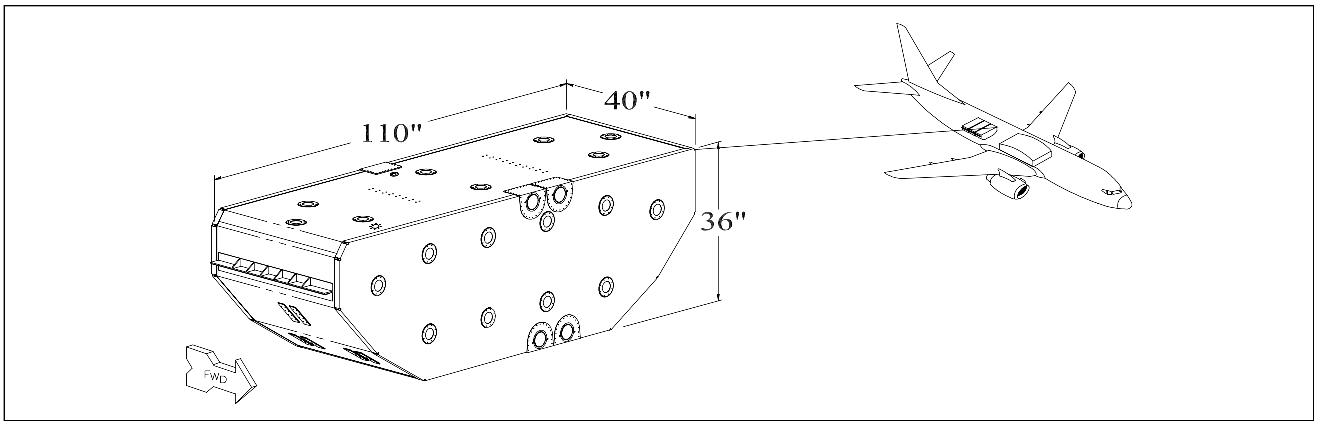
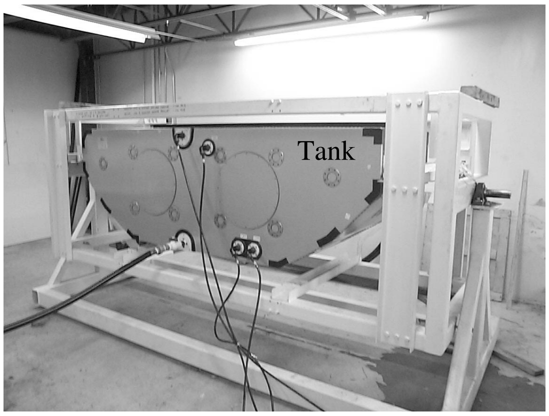


Fig. 1: **Schematic diagram of an auxiliary fuel tank and its placement within an aircraft cargo bay. The tank is typically installed as part of a series of tanks to increase the total onboard fuel capacity by up to 3,200 gallons.**



a) tank mounted within the rocking test frame (looking forward at the aft panel)

b) dedicated hydraulic system for the pressure fatigue test

Fig. 2: **Auxiliary fuel tank, load frame, and pump used for the fatigue test**

the gage response was calibrated using a commercial strain indicator† prior to testing. The strain at each gage site was recorded at the extreme pressures (high and low) of each cycle using a computer controlled data acquisition system with commercial software. The data acquisition system monitored 16 independent channels of strain and the internal pressure, while simultaneously controlling the pump and valves for pressurizing the tank. The control software also counted the pressure cycles and stopped the test at inspection intervals. Thermal compensation for the measured strains was available from the strain response of specific strain elements within the tank. These elements served as the standard “dummy gage” in which the apparent strain was due to thermal strains only. Compensation was then achieved through subtraction.

From an expected aircraft life of 75,000 cycles (flights) and a scatter factor of 4, the experimental evaluation required that the tank undergo more than 300,000 cycles to achieve certification for unlimited service life. Thus, the tank was subjected to $N = 325{,}000$ pressure cycles. The strain difference ($\Delta\varepsilon$) at each gage site was monitored throughout the test and was calculated from the range in strain over each pressure reversal ($\Delta\varepsilon = \varepsilon(P = +3.8 \text{ psig}) - \varepsilon(P = -1.5 \text{ psig})$). In addition, the strain history in each gage was recorded continuously for approximately 2 minutes at the beginning ($N = 0$) and completion of fatigue testing to analyze changes in the structural response resulting from fatigue loading. Visual internal inspections and a core vacuum test were performed after specified intervals of fatigue loading (typically every 50,000 cycles). At the completion of each fatigue cycle increment the tank was drained and subjected to a leak test by subjecting the tank core to a pressure of −18.0 inHg, holding the core pressure for 10 minutes, and monitoring changes. The tank was also inspected after each increment for structural damage resulting from fatigue.

Rocking Fatigue Test

After completion of the pressure fatigue test the tank was subjected to cyclic rocking fatigue between +15° and −15° within a specially designed fixture (Figure 2(a)). The rocking frame enabled rotation about the pitch axis to simulate excitation resulting from gust loads that occur during flight and routine take-off/landing. According to the FAR,[2] the auxiliary tank must be subjected to rocking fatigue (approximately 2/3 full of water; 330 gallons) at a rate 16 to 20

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†Model P 3500, Measurements Group, Raleigh, NC.

cycles/minute for a period no less than 25 hours; these conditions require a minimum of 20 × 60 × 25 = 30,000 cycles. The tank was subjected to a total of 36,920 rocking cycles at a frequency of 0.32 Hz. Eight sites were monitored with strain gages including 4 gages mounted along the largest unsupported interior panels and 4 gages located on the tank's exterior rail mounts. A continuous strain history was obtained every 1,500 cycles over a period of 10 rocking cycles at 30 Hz sampling rate. After completion of the rocking fatigue test a visual inspection of the tank's interior and exterior was performed and a core leak test was conducted at a pressure of −18.0 inHg for 10 minutes.

Proof Pressure Test

A proof test was performed on the tank after fatigue testing to examine the structural response to high-pressure loads that could occur during refueling. A preliminary study of the tank displacement was performed first on the four primary panels (top, aft, forward and bottom) using a digital indicator† at an internal pressure of +3.8 psig. The external displacement of each panel was mapped over the length and used to locate the position of maximum displacement. The tank was then subjected to a series of 4 monotonically increasing pressure cycles from 0 to 10 psig and the external tank displacement along the four primary panels (top, forward, aft, and bottom) were recorded at the location of maximum displacement as identified earlier. In addition, the strain distribution within the tank interior was recorded at sites that experienced large strains during the pressure and/or rocking fatigue tests. The final proof test involved pressurizing the tank from 0 to 20 psig and holding for a period of 5 minutes. Both strain and displacement measurements were recorded using the data acquisition system throughout the pressure cycle. The tank exterior and interior were inspected for damage after releasing the pressure. A leak test was also performed on the tank core at a pressure of −18.0 inHg to identify functional changes resulting from the proof test.

RESULTS AND ANALYSIS

The strain difference ($\Delta\varepsilon$) was determined at all gage sites during the pressure fatigue test from the difference in strain at the maximum (+3.8 psig) and minimum internal pressure (−1.5 psig) of a fatigue cycle. A typical raw strain difference history recorded over the duration of the study is shown in Figure 3. Evident in this figure are the daily and weekly variations in strain due to temperature changes of the testing environment with air conditioning and inspection intervals. In general, there were limited variations in $\Delta\varepsilon$ resulting from the pressure fatigue test; the average change in maximum strain over the 325,000 pressure cycles was 13.7%. However, a 70% decrease in strain occurred within the first 10,000 cycles at site G (Figure 4(a)) which corresponded to the strain within a vertical tube reinforcement spanning the top and bottom interior panels. The tube and interior skins were joined through right angle gussets that were riveted to each member. Fretting fatigue was found evident on the gusset along the riveted joints between the gusset and vertical tube stiffeners (Figure 4(b)) during the first interior inspection at 36,300 cycles. Although fretting was noted at the riveted joints of other structural members as the pressure fatigue testing progressed, there was no significant change to the tank's structural response.

In comparison to the strain distribution resulting from cyclic internal pressure, the strains resulting from the rocking test were much smaller in magnitude, indicating that this activity was less severe. The maximum strain occurred within the exterior tank rail and was found to be 300 μin/in; the maximum $\Delta\varepsilon$ occurred on the interior skin of an unsupported panel and was found to be 34 μin/in. An example of a typical strain history record resulting from rocking is shown in Figure 5. The repetition in strain evident in this figure occurs due to the redistribution in water with rocking between the forward and aft panels.

Displacement of the exterior panels resulting from an internal tank pressure of +3.8 psig was examined to identify the location of maximum displacement. An external displacement map of the top panel along the forward/aft centerline is shown in Figure 6(a). The location of maximum deflection of each panel was then monitored during the monotonic pressure tests from 0 to 10 psig. A comparison of the displacement records obtained for all four panels during proof testing from 0 to 20 psig is shown in Figure 6(b). Displacement of the forward panel was 0.324 inches at 20 psig and was the

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†Model 575-123, Mitutoyo.

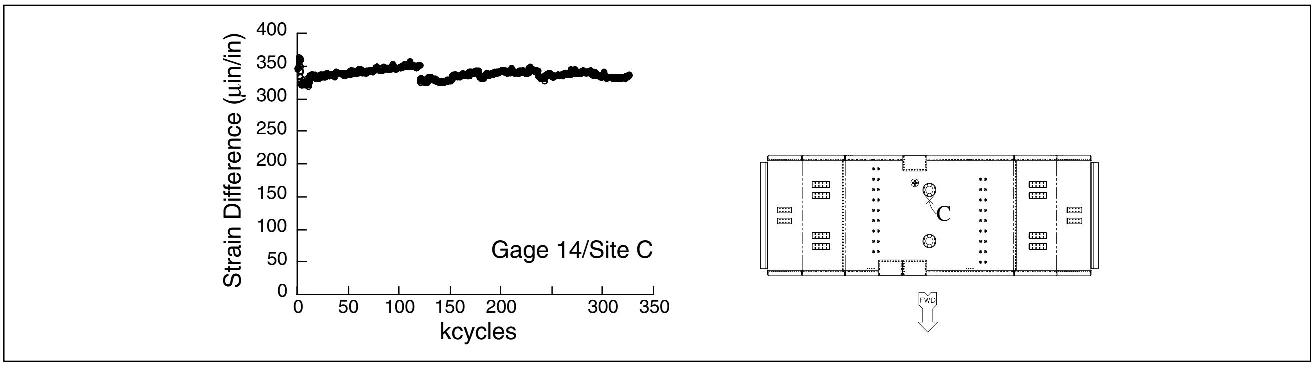
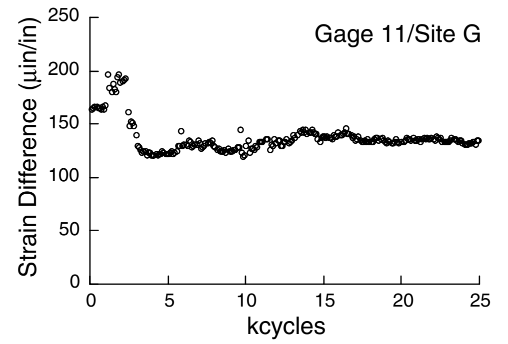
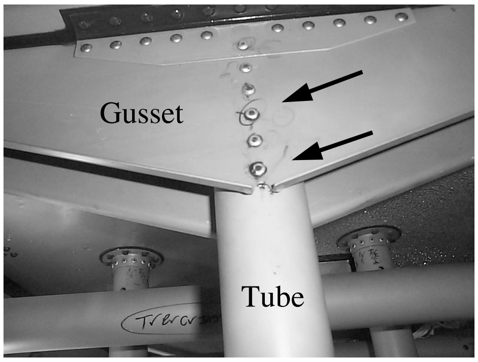


Fig. 3: **Maximum strain difference history ($\Delta\varepsilon$) obtained from the raw strain measurements at site C located on the interior surface of the bottom panel. This section view shows the gage location on the interior bottom panel (looking from the top panel) and gage 14 is oriented perpendicular to the forward direction.**



a) decrease in strain difference (Δε) at gage site G with pressure fatigue loading



b) evidence of fretting corrosion after the first inspection (Note the dark ring around the two highlighted rivet heads corresponding to fretting debris)

Fig. 4: Change in strain difference with fatigue loading and evidence of fretting fatigue at a integral joint between a vertical tube reinforcement and gusset

largest of all four panels. The strain distribution within the tank was also recorded during proof testing at nine sites, corresponding to locations that experienced the large strains during the pressure and rocking tests. Redistribution in strain initiating at 14 psig was evident from the strain records and corresponded with the nonlinearity in the forward panel displacement in Figure 6(b). The onset of nonlinear response in strain and displacement with pressure resulted from debonding or loosening of horizontal stiffeners from the aft and forward panels.

The maximum principal stress resulting from the proof pressure test was nearly 19 ksi and occurred at 20 psig in an internal tube stiffener reinforcing the top and bottom panels. Despite the onset of nonlinearity in strain and displacement of the forward panel at 14 psig, there was no change in the tank functionality during the proof pressure test. No leaks occurred during the proof test and the tank passed a core vacuum test of 18.0 inHg for 10 minutes. Therefore, results from the proof pressure test indicated that the tank performed successfully up to a pressure of 14 psig following both the pressure and rocking fatigue test (no evidence of changes in structural integrity) and maintained function up to a pressure of 20 psig.

FUTURE PLANS

Results from the fatigue tests were used to identify the strain distribution that resulted from operational loads at all monitored locations within the tank. The corresponding stress distribution at these locations was determined using generalized Hookes Law for plane stress and the locations of maximum stress were identified from a comparison of the stress state at all monitored sites. This information provides the necessary foundation for a damage tolerance analysis (DTA), which is used to establish an inspection program for the tank to insure that fatigue crack growth will not enable fracture of the interior skin and consequent failure.

A DTA of the auxiliary fuel tank requires that critical locations of the structure are identified, the stress spectrum at these locations is known, and that the crack growth rate is determined. The principal stresses, their orientation, and stress ratio ($R = \sigma_{min}/\sigma_{max}$) can be determined from the in-plane stress distribution. These quantities are then used with the minimum detectable flaw length (a), which is the smallest flaw on the tank's interior skin that can be detected using the selected (or available) method of inspection. The flaw is assumed to be oriented perpendicular to the largest opening mode stress such that it will experience the largest crack growth rate. Knowledge of the stress state and flaw dimensions enables calculation of the stress intensity range according to linear elastic fracture mechanics. The fatigue

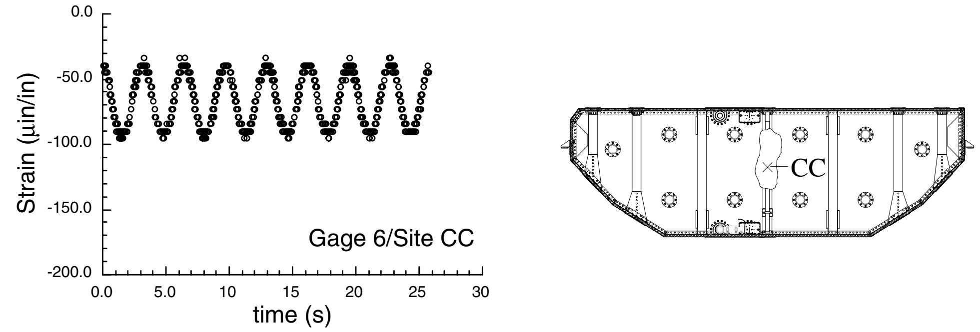
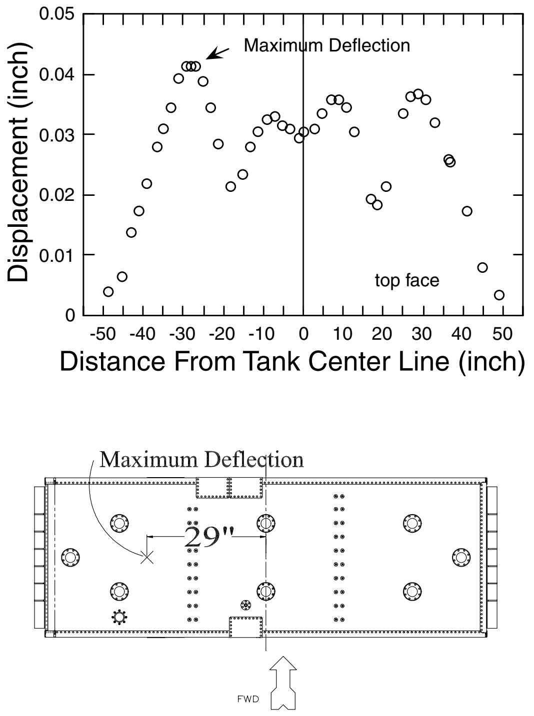
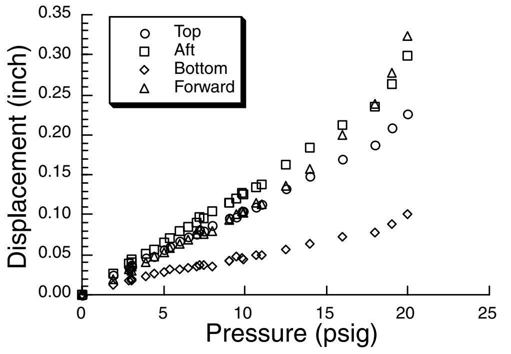


Fig. 5: Strain history from raw measurements recorded during the rocking test at site CC located on the interior surface of the largest section of unsupported forward panel. This section view shows the gage location looking forward and gage 6 is oriented parallel to the horizontal plane.



a) displacement map of the top exterior panel (P=+ 3.8 psig)



b) external displacement of the primary exterior panels (top, bottom, forward and aft) during the proof test

Fig. 6: External displacement of the auxiliary tank panels resulting from internal pressures.

crack growth rate resulting from cyclic pressure loading of the tank can then be estimated in terms of Walker's equation[3] or the Forman equation.[4] The growth rate and expected flight schedule are then used to establish an inspection interval that insures that a flaw can be detected and repaired prior to reaching a critical length that enables fracture. These activities are currently underway and are being used to establish service requirements for the new tank design.

REFERENCES

1. Federal Aviation Regulation, Section 25.571, "Damage Tolerance and Fatigue Evaluation of Structure," Title 14 Code of Federal Regulations (CFR), Federal Register, December 19, 2000.

2. Federal Aviation Regulation, Section 25.965, "Fuel Tank Tests," sub-section b)(2), Title 14 Code of Federal Regulations (CFR), Federal Register, December 19, 2000.

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4. Forman, R. G., Kearney, V. E., and Engle, R. M., "Numerical Analysis of Crack Propagation in a Cyclic-Loaded Structure," *Transactions ASME J Basic Eng*., Vol. D89 (3), 1967, pp. 459–464.

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