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Development of a novel test rig for the evaluation of aircraft fuel tank sealant.

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Abstract

A key concept for the future evaluation of sealant materials for commercial aircraft is to expose realistic sealed joint systems to typical dynamic and environmental parameters representative of actual flight conditions. The development of a mechanism to undertake the full range of test parameters for the evaluation of sealants for current and future aircraft is described in this paper. This mechanism, or Model Sealed System (MSS), consists of an axial stress machine into which vibrational fatigue, high and low temperatures and pressures can be programmed for automatic operation. The test coupons, within the MSS, can be stressed to simulate flight conditions along with the flight pressures and temperatures. The MSS is described and the results of sealant evaluation to date are presented.

1 Introduction

Aircraft fuel tanks represent a constant source of problems for aircraft designers and users. The integrity of sealed joints in the integral fuel tanks of civil and military aircraft has important operational, cost, safety and ecological implications. Integral fuel tanks within aircraft structures are typically located within the wings.

Traditionally, aircraft integral fuel tanks are designed from a structural point of view first and as a fuel tank second. The skin of the wing is attached to the internal structure of the wing and the joints between the internal structure and the skin have to be sealed to prevent leakage of fuel. The highly loaded structures on a modern aircraft are designed and built with the use of machined parts that, if sealed correctly, perform both as a load bearing structural member and as an integral fuel tank. Unfortunately, within the wings of a modern aircraft there exist innumerable potential leak paths for the fuel ranging from those between interfaying surfaces, those from skin joints, those from conduits housing electric cables, fuel, hydraulic and de-icing fluids, and those from the fasteners themselves. To these may be added the effects of flight stress fatigue, temperature, contaminants (water, de-icer fluid and microbiological attack), the fuel itself, and practical application failures on initial assembly and at subsequent repairs (AGARD (1989)). It can therefore be appreciated that the potential for leaks is enormous. The life of an aircraft can be 30 + years with no significant operational leaks, so to promote a leak that is reproducible, and accurately simulate the real world dynamics of an aircraft integral tank, is a challenge.

In a single typical wing of a commercial aircraft it is likely that there is about 100kg of sealant material. This is applied, and has to stick, to primed, coated, etched and anodised aluminium in current aircraft. In some military aircraft, and future civil aircraft, the relevant surfaces will be epoxy-matrix fibre-reinforced plastics. A sealed joint system, therefore, comprises the sealant, primer coating(s) and the parent skin material.

A review of recommendations from the Advisory Group for Aerospace Research and Development report (AGARD-R-771, 1989) illustrated that there were a couple of key concepts for the future evaluation of sealant materials for commercial aircraft that need to be addressed. Firstly, expose realistic sealed joint systems to typical dynamic and environmental parameters representative of actual flight conditions (Richardson, (1989) and Keller, 2004)). Secondly, the ageing of the sealant systems as a result of chemical interaction with hydrocarbon fuels must be duplicated during testing to provide valid performance information during the expected service life of the fuel tank. This ageing can only be accomplished by combining environmental exposures with the use of actual fuel in the test structure (Richardson (1989)).

Several studies have been carried out to establish test procedures for testing the sealants used in the fuel tanks. A couple of examples are; Clark carried out tests on several aerospace sealants (PR-1422 A and B along with PR-1440 A and B) using the H-type test configuration using various surface treatments (Clark (2001)). Secondly, Giannis carried out research work under Airbus sponsorship that focused on the peel performance of aircraft fuel tank sealants with an aim to optimizing industry testing specifications (Giannis et al (2008)). However, the primary objective of this research was the development of a mechanism to undertake the full range of test parameters for the evaluation of sealants, representative of actual flight conditions, utilising realistic sealed joint systems.

Several test rigs have been developed over the years to help in the development and/or test various sealants and gaskets. To mention a few, a test rig was developed at Oxford Brookes University to evaluate weatherproofing joint seals in building façades. These joints are exposed to frequent cyclic movements caused by the effects of temperature (Jones et al (1999)). A test rig to test the reliability of formed in place gaskets under fatigue loading, was also developed by Henkel (Kreuzer R and Romanos G, (2004)). However, test rigs that can combine the dynamic test, the environmental conditioning and the ageing of all of the various components involved in a joint system without actually fabricating a “Puffer Box” or a full scale wing in one test (both of which are very expensive options) are not available at the present time.

In 1977 the United States Air Force Wright-Patterson Aeronautical Laboratories (AFWAL) supervised a programme of research to evaluate experimental sealant materials against dynamic and environmental criteria. This led to Mallory and Elmer (1978) developing the Wright-Patterson Bench "Dynamic" Apparatus. The programme led to the assigned investigators testing sealant materials (but not a combination of all the components in the joint, for example, the sealant, the aluminium substrate and/or the fasteners) under integrated conditions of dynamic loading and environmental parameters of fuel, pressure and temperature that were representative of a typical aircraft flight spectrum. A key issue explored was the durability of a fillet seal on a joint subjected to cyclic loading.

The first two-year period of the research programme was terminated prematurely due to the poor reliability of the bench facility and heat distortion of the cup and disc test coupons. However, regardless of the shortcomings of the experimental facility, the feasibility of dynamic testing in conjunction with environmental parameters had been demonstrated.

A mechanism, known as a Model Sealed System (MSS), was developed under contract to Airbus UK to undertake the full range of test parameters for the evaluation of sealants for current and future aircraft. The MSS can be programmed to simulate aircraft flight cycles over a wide range of dynamic and environmental parameters (temperatures ranging from -55°C to 30°C), as well as wet and dry cycles where the sealant is exposed to fuel vapour or allowed to dry out completely.

2 Concept

A mechanism was developed that subjects a circular lap joint to cyclic axial stresses whilst simultaneously imposing a range of experimental parameters. The circular lap joint is assembled using aerospace fasteners and sealed, and it simulates a wing skin butt-strap joint in a real aircraft. However, by making it circular the complications of corners and joint ends are eliminated. The joint (test coupon set) is located in a pressure pot (**Fig.1)** that provides containment for the fuel on one side of the joint and access to different environmental parameters on the other side. The circular joint is subjected to cyclic axial loads that induce realistic magnitudes of stress in the aluminium that correspond to spanwise and chordwise wing skin stresses **(Fig.2)**. Depending on the orientation of applied load, the joint can be either opened or closed. The whole mechanism is operated by a programmable control system, enabling different parameters of stress level, frequency, temperature, etc to be varied. The control system also incorporates safety valves.

The MSS is fitted with a leak detection system that records the number of cycles to fuel leakage.

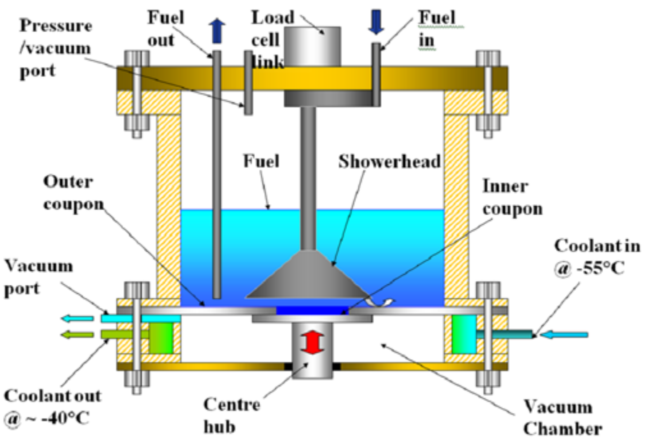

Figure 1. Cross-section through the Pressure Pot (PP).

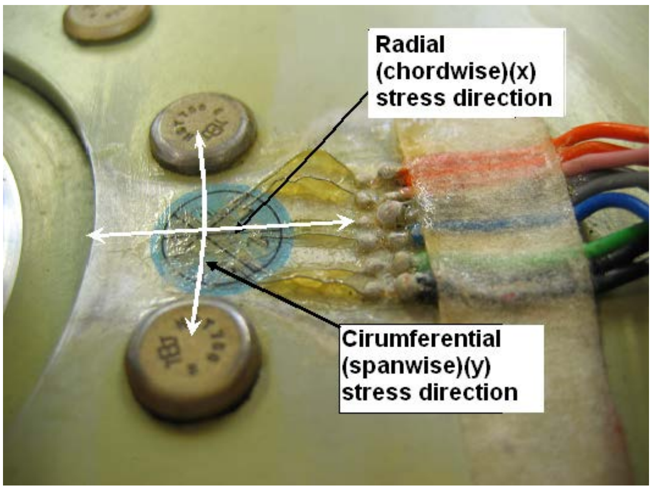

Figure 2. Test coupon strain gauge showing circumferential and radial stress

3 Principal components

3.1. Coupon set

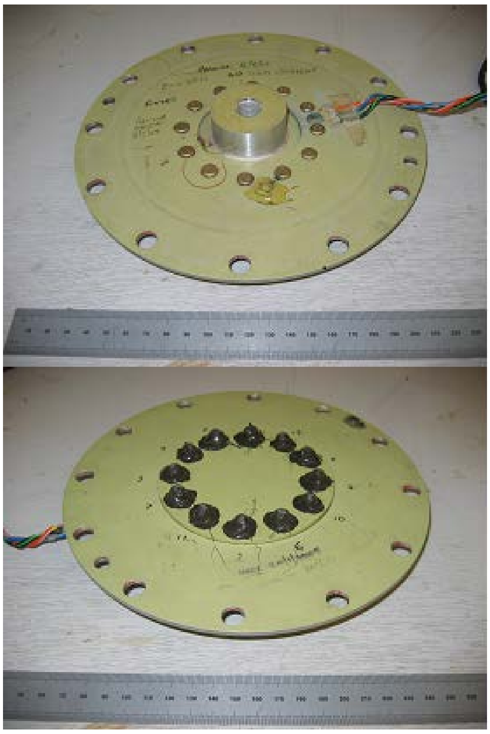

Figure 3. Coupon set underside (top) and fuel side (bottom). Note: the strain gauge location.

The test coupon set shown in **Figure 3** comprises two circular plates that are fastened and sealed. The details of the fastening and sealing (interfay, fillet, and overcoat) represent variables that can be changed to suit any particular test. The outer circular coupon is 216 mm diameter, with a central circular hole of 64 mm diameter, and is fabricated from aircraft quality 3.18 mm thick aluminium sheet (2024-T3 clad). The inner coupon of 104 mm diameter is formed from a billet of aluminium so that an integral threaded centre hub can be machined into it. A stainless steel threaded centre hub is then attached to this. The coupons are prepared in exactly the same way as an aircraft wing; they are degreased, pickled, anodised and finally painted to the relevant aircraft manufacturer's standards.

The test sealant is sandwiched between the two bolted aluminium circular coupons of dissimilar size **(Fig. 3)** mounted concentrically. In the research reported herein the two discs were attached to each other utilising twelve, 3/16” Titanium fasteners (ASNA 2027HK3-4) and nuts (NSA 5474-3K7). The sealant used was Chemetall MC238B2. Sealant may be used in the test joint as required, for example, interfay plus overcoat with no fillet or only fillet and no interfay, etc.

3.2. Pressure pot

The test coupon set is mounted as the base of a “Fuel Tank” or Pressure Pot (PP) that is structurally stiff and filled with jet fuel **(Fig.1).** The pressure pot has a bolted flange at either end for the top plate and the coupon set (and the lower clamp plate /cooling manifold). The two flanges have a machined groove to accommodate a large fluorosilicone “O” ring at each end. The top of the tank is an aluminium plate that houses the three ports (one for pressure/vacuum and the two inlet/outlet ports for the test fluid). From beneath the top plate the “Showerhead” and the pickup pipe are fastened **(Fig.1).** The concept of the “Showerhead” is to “crash” cool the joint and fill the MSS rapidly. The “Showerhead” is a small, flat, circular vessel that looks like a showerhead, with the outlet (the base) for the test fluid being the same dimensions as a small coupon and rotated by 15°. This will bring the drilled holes directly over the area (land) between the fasteners.

The top plate and the coupon set sandwich the pressure pot and is secured by two sets of 12 x 10mm nuts and bolts and sealed by the two fluorosilicone “O” rings. The whole assembly is then mounted in a fatigue test machine. One end of the test rig is supported rigidly to the test frame end plate (load cell) via the thick steel top plate and pushrod, whilst the other end is free to deflect (the actuating ram). The loads are applied to the test coupon via the stainless steel centre hub. One end of the hub is attached to the fatigue machine actuating ram, whilst the other end is screwed into the hub of the smaller inner coupon.

3.3. Cooling system

To impose the different temperature regimes upon the test coupons a refrigerated circulator is used. It is necessary to enable the coolant from the circulator to be in direct contact with the test coupon to maximise the heat transfer capabilities. This was achieved by manufacturing a lower clamp plate/cooling manifold. (**Fig.1**)

The manifold was machined from one piece of aluminium. Aluminium was chosen for two reasons. Firstly, to ensure that the materials used in the pressure pot assembly (including the coupons) were made only from materials used in the full size wing, reducing the effects of galvanic corrosion and any other related problems. Secondly, aluminium exhibits a high factor of thermal conductivity (approximately 120W/m °K); this means that heat from the MSS, and in particular the coupon set, can be conducted away quickly. The manifold consists of a square section, doughnut shaped ring with a deep groove machined into the top side. The top of the groove is sealed by the outer coupon itself. The coolant is introduced to the groove via an insulated hose through a drilling in the outer wall. The coolant has to travel around the groove, because of a machined plug in the groove, and flows back out of another drilling and back to the circulator via the coolant flow control solenoids and another insulated hose. The coolant flow control solenoids divert the coolant, either back to the circulator directly or through the coolant/fuel heat exchanger. The lower end of the lower clamp plate/cooling manifold is sealed by an aluminium plate with a vacuum hose attachment and a boss attached to the centre with two “O” ring seals through which the stainless steel centre hub is located. The two “O” rings seal the chamber, allowing it to serve as the vacuum chamber beneath the test coupon set.

3.4. Fuel circulation

The system allows approximately 1.5litres of JP8 jet fuel to be circulated. The top plate of the pressure pot has ports for fuel inlet and outlet plus a port for air pressure or vacuum. The outlet port has a pick-up pipe attached that is situated just above the coupon set whilst the inlet port has a "showerhead" that is situated over the coupon test seal **(Fig.1).** The fuel circulation system consists of the fuel flow control solenoids that divert the fuel to either the external fuel tank or via the magnetic coupling fuel pump and "Rotorflow" visual/digital flow meter, through the coolant/fuel heat exchanger where the temperature of the fuel is logged with a PT100 temperature sensor and back into the pressure pot via the showerhead. For safety reasons, the fuel hoses used are Teflon-lined stainless steel braided hose with threaded aluminium hose ends.

3.5. Vacuum system

The vacuum system consists of the pump, a reservoir and a heat exchanger. There are various ports from where the vacuum is drawn and used, via the control solenoids, to empty/fill the pressure pot and the external fuel tank. Air is also drawn from beneath the coupon set. The two "O" rings that seal the lower chamber allow a certain amount of airflow through the hydrocarbon (HC) detector whilst still maintaining a pressure differential across the joint. There is also a one-way valve fitted in the vacuum hose between the vacuum reservoir and the HC detector to stop it registering a high HC reading every time the external fuel tank or the pressure pot is subjected to vacuum. This causes some of the residual fumes from the fuel in the pressure pot or external tank to be drawn through the HC detector and these fumes register a leak, thereby stopping the test.

3.6. Leak detection

The hydrocarbon (HC) detector is a solid state device. The HC detector module is enclosed in an aluminium housing which is in turn situated in the vacuum hose that leads from the vacuum chamber below the test coupon. Attached to this housing is a K-type thermo-couple to log the temperature of the HC detector. The HC detector does not work below -10°C, so it has to be situated in such a manner that the through flow of air has a chance to warm up. To achieve this, the air drawn from below the test coupon has to be warmed. A heat exchanger was fabricated and attached to the hot air outlet vent of the refrigerated circulator. This utilises the hot air discharged from the circulator and warms the air flow from below the test coupon to room temperature (approx. 23°C). The controller uses the reference voltage and an output voltage from the detector to establish if there is a rise in the HC content of the sampled air. A 5V DC voltage is applied to the detector. Within the detector there is a heated gas sensor. The reference voltage (V_{ref}) is about 2.5 V whilst the output voltage (V_{out}) is around 0.75V. When the gas sensor module is exposed to a higher than normal concentration of hydrocarbons in the airflow the value of V_{out} will reach or exceed the value of V_{ref}. When the value of V_{out} exceeds the value of V_{ref}, a safety trip on the controller stops the test.

3.7. Data acquisition and control

An Si-Plan Electronics control and data acquisition system was used. This consists of a 1 x 879 32-bit digital servo-controller and data acquisition unit, configured for single axis operation. The operating software is the standard package, with bespoke software writing designed by Si-Plan, by its in-house software engineers. The MSS has several temperature and pressure sensors in the system. These are there to:

- Log data
- Act as sensors for alarms that enable the controller's adjustable trips to stop the test if certain parameters are exceeded.

The function of these sensors is described in the appropriate section of text.

4 Capabilities

4.1. Pressure

The test apparatus has two chambers which simulate the inside and outside an aircraft fuel tank. The test coupon forms a boundary between these two chambers. Fuel inertia and tank pressures can be simulated by introducing a pressurised gas (inert, for safety reasons) into the pressure pot. This acts on the test fluid stressing the sealant slightly. The more important factor that can be combined with the above is to introduce a slight vacuum into the lower cooling manifold centre chamber, below the test coupons, to simulate the pressure differential experienced by the wing during flight. This would, in effect, pull the fuel through the interfay joint and possibly causing an advancement of a leak path tip.

Health and Safety issues have been addressed. As well as an automatic safety relief valve, there is a manual release valve and a pressure transducer attached to the Pressure Pot (PP). The pressure transducer enables the control system to:

- Monitor and record the pressure within the PP
- Enable a shut down procedure should there be a sudden rise in pressure. This shouldn't happen because of the spring relief valve, but it could ice-up and seize closed
- Enable a comparison to be made between the readings from the pressure transducer and the hydrocarbon (HC) detector. For example, if a leak is detected with the HC detector and, simultaneously, there is a drop in pressure in the PP, it may be possible to dispense with the HC detector system altogether and only use a pressure drop system for leak detection.

The pressures can range from 12.3 psi (0.85 bar) to 35 psi (2.4 bar) (gauge pressure). Pressures above 1 bar are set using a Norgren pressure regulator, whilst the pressures below 1 bar are controlled by turning the vacuum pump on/off using a vacuum switch connected to the Si-Plan controller.

4.2. Temperature

The temperature of the test coupon set is controllable from approx. -60°C to 50°C (for health and safety reasons the maximum temperature is set at 30°C). Different temperatures can be generated at different times in the test cycle. The coolant from the refrigerated circulator flows through a heavily insulated hose into the lower clamp plate/cooling manifold **(Fig 1).** To maximise the heat transfer capabilities, the coolant from the circulator is in direct contact with the test coupon. The modified lower clamp plate/cooling manifold acts as a large heat sink because of its high rate of thermal conductivity, and this helps to reduce the temperature of the pressure pot and test fluid quickly. To speed this up, returning coolant is diverted through a heat exchanger. This in turn lowers the temperature of the test fluid (JP8), which when pumped back into the pressure pot (via the showerhead attachment that directs the cold test fluid directly onto the test joint), helps to reduce the temperature of the test joint quickly (thermal shock) and generally lower the temperature of the MSS (down to approximately -40°C).

The temperature of the sealed joint is taken from a PT100 temperature sensor attached to the coupon at the test joint. The temperatures are recorded on the data logging facility of the Si-Plan controller.

4.3. Mechanical loading

When a test coupon set is fitted into the test rig, a loading condition that provides similar movement (within the joint) to that experienced on the aircraft must be applied. The loading for the coupon test is based on a lower wing skin butt-strap joint for a typical Airbus (A318) single aisle aircraft. The primary purpose of the butt-strap is to join the skin panels. This part of the structure has had in-service fuel leak problems and has reasonably straightforward loading conditions.

The loading on the aircraft wing skin butt-strap joints consists of:

- **Spanwise** loads carried longitudinally by the butt-strap and stringer due to wing bending. Tension stresses are associated with wing-up bending.
- **Chordwise** loads carried transversely across the butt-strap joint. These loads are typically smaller than the spanwise loads.
- **Shear load transfer** due to wing bending and torsion.

The maximum fatigue stress is calculated from superposition of two load cases. These are the 1g level flight and 30 foot per second (fps) gust loads. The following stresses for the spanwise skin stresses in a particular rib bay are given by Buller (2001(a)):

- 1g Flight Stress: **46.4 MPa**
- 10fps Gust Stress: **23.2 MPa**

A maximum gust of 30fps leads to a Gust Stress of **69.6 MPa**. The maximum (spanwise) fatigue stress for this element is then:

46.4 MPa + 69.6 MPa = 116.0 MPa.

The Chordwise and Shear stresses derived in a similar way are shown in **Table 1**.

Spanwise stresses (MPa)	Chordwise stresses(MPa)	Shear stresses(MPa)
116.0	**41.7**	**53.5**

Table 1. Direct and shear fatigue stress for skin joint configurations (Buller(2002(a)).

It was felt that these stresses may be too high to achieve, realistically, on the test rig in the laboratory. However, it is possible to replicate the relative proportions between the various stresses, i.e. the ratios between the stresses, because it was felt that this would certainly load the joint higher than in normal flight and, consequently, could shorten the time required to test the joint configuration and sealant adequately (or until failure) whilst keeping the stresses within the linear elastic region (Buller, 2002(b)). The corresponding maximum applied loads and the stresses from these loads in the MSS can be seen in **Table 2.**

Configuration	**Radial(σ_r) (MPa)**	**Hoop(σ_θ) (MPa)**	**Shear(τ) (MPa)**	**Ratio ($\sigma r/\sigma r$)**	**Ratio ($\sigma\theta/\sigma r$)**	**Ratio ($\tau/\sigma r$)**
Theoretical stresses (Buller, 2002(a))						
Fatigue stress skin	**41.7**	**116**	**53.5**	**1**	**2.78**	**1.28**
Fatigue stress butt strap	**52.1**	**112.3**	**66.9**	**1**	**2.15**	**1.28**
Experimental static load check						
Single coupon, joint in tension, Max load 4kN	**-19.2**	**-49.85**	**-15.32**	**1**	**2.59**	**0.80**
Single coupon, joint in compression, Max load 4.5kN	**11.4**	**56.9**	**22.75**	**1**	**4.99**	**1.99**

Table 2. Stress comparison with Buller (2002(a)).

For the initial fatigue test a 1g flight stress (46.4MPa) ± 10fps flight gusts (23.2MPa) was decided upon at the required frequency of 5 Hz by Airbus (UK). The loads are applied using a sinusoidal waveform with the following maximum and minimum stresses seen at the joint:

Min. = 23.2MPa

Mean = 46.4MPa

Max. = 69.6MPa

A static load test was carried out using strain gauges **(Fig. 3)** to check that the stresses obtained were within the test parameters. The results showed that with the sealant in tension, the proportions of the stresses achieved were close to the proportions of the stresses referred to by Buller (2002(a)) **(Table 2).** The loads can be applied to the joint to either open (tension) or close (compression) the sealant joint. The maximum load that could be applied to the coupons before permanent deformation (damage) was detected was between 6.5kN and 7kN.

From static and dynamic testing, the loads imposed on the coupons by the fatigue machine were modified to keep the proportions correct (**Table 3**). However, the fatigue loads had to be increased to achieve the desired stresses **(Figs. 4 and 5).**

Joint load mode	Load (kN)	Equivalent stress (MPa)
Tension	-1.5	-21.3
	-3.0	-39.2
	-4.5	-55*
Compression	1.5	18.1
	3	37.1
	4.5	56.9

Table 3. Loads and equivalent stresses *** Projected stress, see Figure 4**

Figure 5 shows the magnitudes of measured coupon stresses for one load/unload cycle (that is, 0.2s or 5Hz).

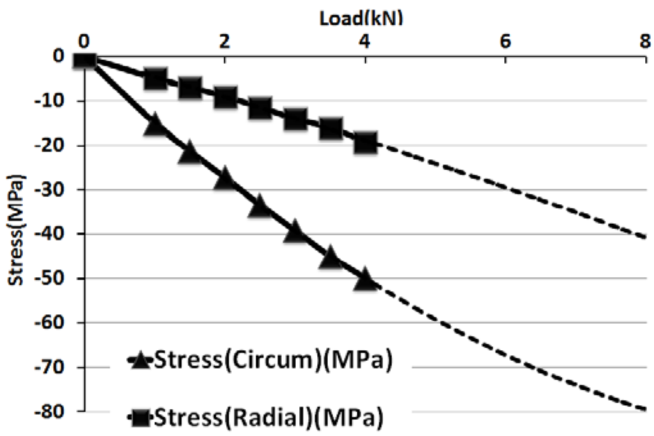

Figure 4. Static stress against load with a trendline showing the predicted stresses at higher loads (joint in tension).

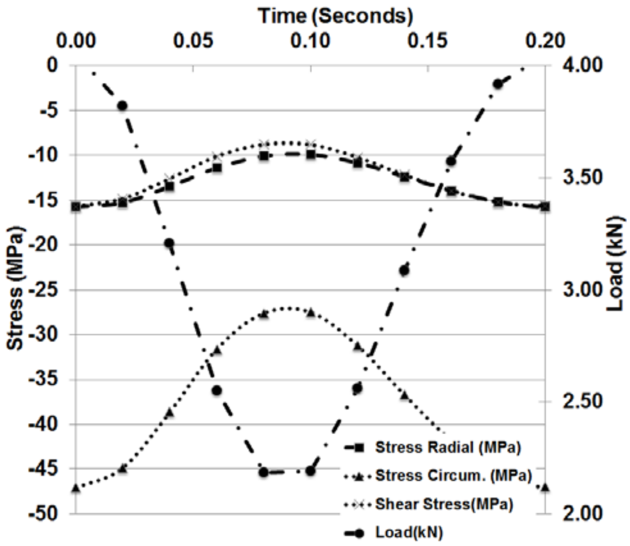

Figure 5. Dynamic stress / load against time, joint in tension at 5Hz.

5 Typical test regime

No single environmental condition is the single ingredient in degradation of fuel tank containment integrity. A combination of structural loading, fuel inertia, tank pressures, thermal and chemical effects influence the structural integrity of the fuel tanks. A test spectrum can be written for the control system that addresses some of these parameters. An example flight cycle is shown below:

- **Start position** – Room temperature
  Fuel exposure
  Atmospheric pressure
  Zero load

- **Stage 1** - Cooling to -55°C
  Fill tank and circulate fuel
  2 hours duration
  Apply a pressure pulse to the fuel (6 x 5 second pulses)
  Static loading, 4.5kN, closing the sealant joint

- **Stage 2** - Cooling to -55°C
  2 hours duration

Circulate fuel

Cyclic loading, 5 Hz (-1.5kN to -4.5kN, opening the sealant joint)

- **Stage 3** - Cooling to -55°C

  2 hours duration

  Circulate fuel

  Cyclic loading, 1 Hz (1kN to 4kN, closing the sealant joint)

- **Stage 4** - Cooling to -55°C

  2 hours duration

  Circulate fuel

  Cyclic loading, 5 Hz (-1.5kN to -4.5kN, opening the sealant joint)

Repeat stages 1 to 4, three times for a total of 24 hours. This is then repeated, in this case 14 times, which is equivalent to a 14 day test.

6 Results

Two nominally identical coupon sets have been tested so far. These both comprised of overcoat and fillet sealing. The first coupon set leaked after approximately 42 days (18,144,000 cycles at 5 Hz approx) applying the loads to open (-1.5 to -4.5 kN) and close (2.0 to 4.0 kN) the joint in 2 hr cycles as referred to in the previous "Typical Test Regime" section, at a variety of temperatures. This coupon set was in the MSS whilst the controller and circulator were being fitted to the MSS, and commissioning and familiarisation of the equipment was being carried out. Consequently, temperatures, loads etc. were not logged completely but it showed that a leak could be initiated within a reasonable time span. The second set leaked within 11 days (4,752,000 cycles at 5 Hz approx.) at temperatures down to -55°C. This may have been a badly made coupon set and may be unrepresentative, but it did show that the concept worked. A third coupon set was fabricated and tested for a total of 127 days with no leak being detected between these two tests. This test was stopped at the request of Airbus, because it was deemed that this coupon set had passed the test and as such no new test data could be gained by continuing the test any longer.

7 Conclusions

The MSS is a modular test system that can simulate a combination of structural loading, fuel inertia, fuel tank pressures, thermal and chemical effects. So far the MSS has produced joint failure at 11 and 42 days (and a third that produced no failure at 127 days). More research needs to be carried out to define a test regime that produces a joint failure within a certain time frame and consistently. Realistically, this may be difficult to achieve because even with much simpler mechanical fatigue testing a very wide range of failure cycles/times can be seen. However, if this factor is taken into consideration the MSS should enable the:

- evaluation and comparative testing on new experimental sealants to be carried out early in their development
- preliminary screening of sealants for new aircraft to be accomplished
- maintenance and operational cost to be reduced, since field use conditions can be simulated, thereby reducing the need for costly and time consuming flight tests.

Early indications are that the MSS with the Si-Plan data logging and control system enables:

- test programs to be written relatively easily
- real flight data to be imported to the control module (although this hasn't been tried yet).
- the MSS to be a fully automatic test machine with programmable fatigue, environmental, pressure and empty/fill cycles.
- the MSS to have safety cut-outs to stop a test if any of the test parameters are exceeded.
- the MSS to be programmed for tests of any duration.
- leak acceleration and detection in a representative aerospace standard joint, within a realistic time frame using realistic test parameters.

In the future, the MSS may enable realistic physical and environmental cycles to be simulated, enabling qualitative and comparative testing of combinations of sealants, joint geometries, substrates, surface preparations and cure times.

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