ON THE DETECTION OF FATIGUE DAMAGE PRIOR TO SURFACE INDICATION

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ABSTRACT

The aim of this study was to investigate the failure mechanism of riveted aluminium lap joints when exposed to constant load amplitude fatigue. Tests were conducted on lightweight aircraft grade aluminium sheet (2024-T4). Visual observations of the failure behaviour and lifetime records were supplemented by real-time, in-situ structural integrity (SI) measurements. Structural Monitoring Systems Ltd. (SMS) equipment, which owns the patent rights to the Comparative Vacuum Monitoring (CVM™) method, provided the SI measurements of the specimens during their fatigue life. SMS sensors were installed either on the surface or within the lap joint specimens. Observation of fatigue loading from the perspectives of the two differently installed SMS sensors has provided insight into the failure mechanism. Failure of the riveted lap joint is found to occur initially by a process of rivet shank/rivet hole fretting damage and damage accumulation within the anti-chaffing material prior to crack initiation within the aluminium plates and/or rivets. Major fatigue damage was detected at 50-70% of the fatigue life, despite visual indication being absent. The benefits of this technology to the aviation industry are large, as early detection of fatigue damage improves safety and allows increased flexibility in maintenance schedules.

CVM™ is applied to galleries containing a low vacuum and atmospheric pressure. The atmospheric pressure is often contained with a second set of galleries that alternate with the low vacuum galleries. If a flaw is not present, the low vacuum remains stable at the base value. If a flaw develops, air will flow from the atmospheric galleries through the flaw to the vacuum galleries. A transducer measures the rate of flow between the galleries and therefore gives an indication of flaw size. CVM™ is rapidly gaining acceptance as a technique for crack initiation detection, automated crack propagation measurement, localised yield stress determination and composite disbonding indication. The aviation industry has shown the greatest interest, with fatigue laboratories also including SMS technology in their testing equipment.

KEYWORDS

Condition monitoring, crack initiation detection, automated crack propagation measurement, yield stress detection, riveted lap joint

INTRODUCTION

The traditional method of laboratory tests that model industrial experience, followed by modelling is deficient in the study of riveted lap joints. Firstly, the detection of fatigue cracks in the laboratory, and indeed in practice, is complicated by cracks often initiating at the faying surface [1] and tunnelling prior to emerging [2] on the surface. The result is a delayed detection of crack initiation. Secondly, modelling is available in the literature, but it does not accurately model multi-site damage [2]. A simple tensile overload during fatigue can dramatically alter component life [3] and importantly, the in-service situation is not accurately reproduced in the laboratory due to the lack of biaxial stress and the variation of hoop stress [2]. A pessimistic opinion was offered by Schijve, ‘accurate predictions can not be expected’ [4]. To assist in both these problem areas, an in-situ, real-time method of detecting fatigue cracks within a riveted structure would be beneficial.

The aim of this study was to investigate the failure behaviour of riveted lap joints when exposed to fatigue with constant load amplitude. Preliminary data has been presented in a previous paper [5]. Fatigue tests were conducted on aircraft grade aluminium sheet, and further supplemented with real-time, in-situ structural integrity (SI) measurements. Structural Monitoring Systems Ltd. (SMS) technology facilitated SI measurements of the specimens. The specimens were composed of two groups. One group had surface mounted SMS SI measuring sensors while the second group had SMS internally mounted SI sensors installed.

Structural Monitoring Systems Ltd. (SMS) offers equipment for real-time, in-situ detection of fatigue cracks. Structural Integrity (SI) measurements are determined by CVM™ of a steady-state, low vacuum maintained within the galleries of a sensor that is installed either on or within the component to be tested. When a fatigue crack grows to a certain length (cf. Fig. 1), the crack intersects the alternating galleries maintained at vacuum and atmospheric pressure. A variety of sensors and, if required, specialist consulting services to address specific testing issues are available.

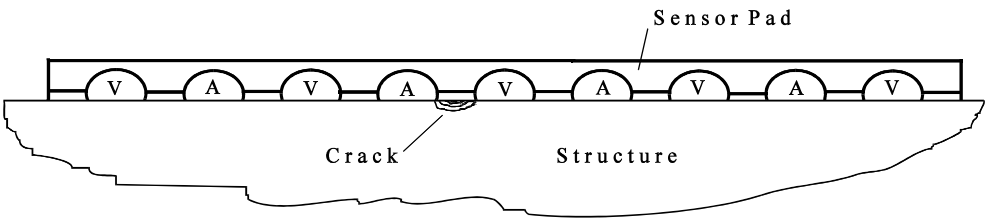

Figure 1: SMS surface sensor mounted on specimen (schematic). An increase in ΔP results when a crack intersects adjacent channels maintained at vacuum and atmospheric pressure.

The sensors are produced in a range of materials and have a sensitivity down to 250μm with an accuracy of 10μm (4%). An automated crack propagation measurement system for laboratory or industrial application is also available. SMS sensors are in use as localised yield stress indicators for self-piercing rivets and for the detection of disbonding within composite repairs/structures.

EXPERIMENT

The fatigue tests were performed under laboratory conditions at the University of Western Australia (Department of Mechanical and Materials Engineering). Testing was conducted upon an Instron 8501 servo-hydraulic testing machine with the SI measurements recorded on a lap top computer, via the SI monitor (SIM). No mathematical processing of data was carried out.

Two types of specimens were fabricated from 2024-T4 aluminium sheet. The first group of specimens was formed from two plates each measuring 60X115 mm and 1.8 mm thick. A chaffing protection layer of polysulphide material (PR-1440) was applied to the area of the plates that were to be riveted. Masking tape was applied to the edges of the plate and PR-1440 was spread with a spatula using the tape to control the thickness. After full cure of the PR-1440, the plates were fastened together with 6 countersunk rivets by using a squeeze rivet gun. No sealant was applied to the rivets during construction. Surface mounted SMS sensors were installed over approximately 2/3 of the rivet heads, cf. Fig. 2.

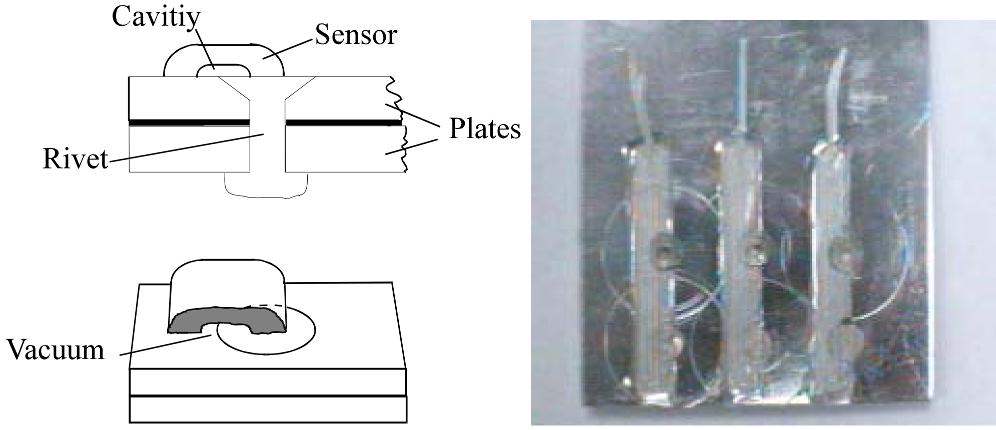

Figure 2: Placement of the surface sensor over the rivet (schematic - left).
Tested specimen with SMS surface sensors (right).

The sensors were connected in parallel and then to the SIM. In this manner, the SIM would detect failure from any sensor. A tensile test was carried out initially to determine a suitable fatigue testing waveform. A sinusoidal load profile with a maximum fatigue load of 7.0 kN, a load ratio of R = 0.1 and a frequency of 20 Hz was used in all tests. Testing was continued until failure and the cycle number recorded.

The second group of lap joint specimens were fabricated from 2mm thick 2024-T4 aluminium plate. Each plate was 60X140 mm. The plates were joined in an identical manner to group 1 specimens. Masking tape (width = 6 mm) was used as a stencil to mark out a cavity in the sealant. A photograph of a cavity is presented in Fig. 3. An exit from the cavity was provided and a SMS surface sensor attached to facilitate connection to the SIM.

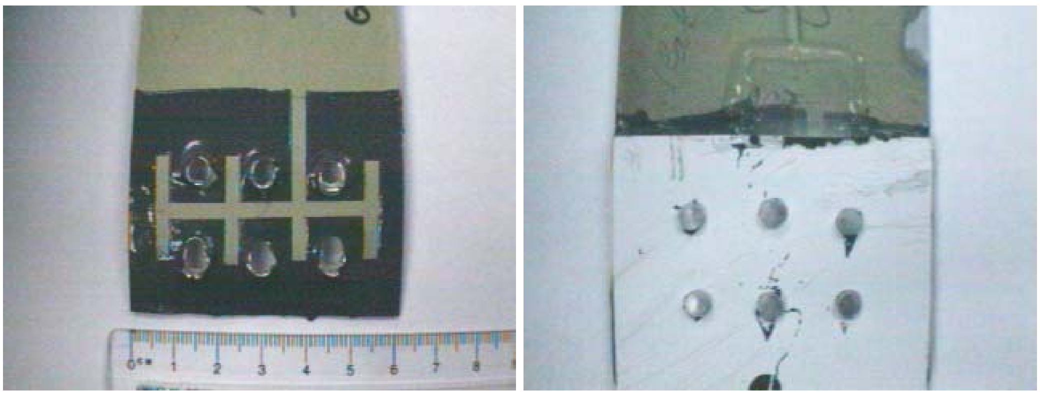

Figure 3: Single plate of lap joint illustrating PR-1440 sealant and cavity - note exit of cavity (left).

The masking tape was removed after the PR-1440 was applied. The plates were riveted together following full cure. No sealant was applied to the rivets during construction. The edge of the lap joint was sealed with a polyurethane based sealant (Sikaflex 221 T). In this manner, a gallery was created within the lap joint, cf. Fig. 4.

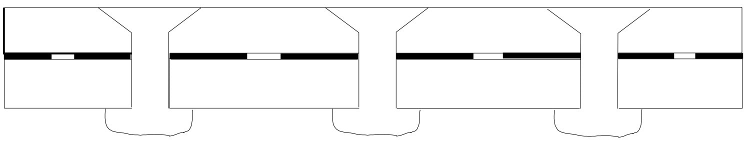

Figure 4: Cross-section of the SMS Integral Sensor within the lap joint (schematic).

Tensile tests were initially carried out to identify the critical load, P_C. Fatigue was then initiated at approximately 50% of this value. A maximum load of 7.0 kN, a load ratio of R = 0.1 and a frequency of 20 Hz was used in all tests. Crack initiation was observed optically. Fatigue loading was continued until failure and the cycle number recorded.

RESULTS

A representative plot of one specimen with surface mounted SMS sensors is presented in Fig. 5. The plots of Fig. 5 have the differential pressure (ΔP) as a function of the cycle number (left) and the percentage of fatigue life (right). The data to the left of the vertical axis indicates the differential pressure as a function of static loading. Fatigue loading begins from cycle number zero. The plateau at approximately 2 kPa was the ΔP reading when no load was applied. When the static load was increased to the mean load for fatigue cycling, ΔP increased to approximately 13 kPa. Initiation of fatigue saw a further increase in ΔP. A steady, but gradual increase in ΔP is observed with continued cycling. A full-scale reading of ΔP is observed at approximately 50% of the fatigue life. No visible fatigue damage was observed prior to catastrophic failure, which occurred at the rivets.

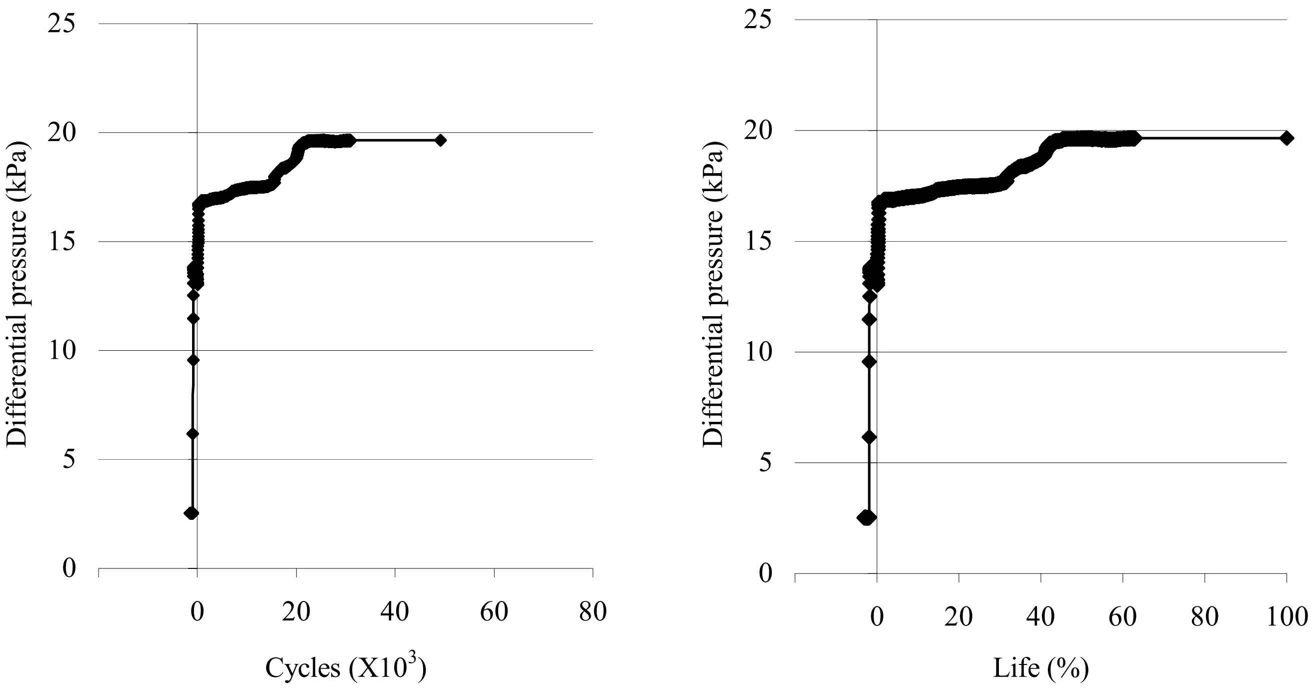

Figure 5: Differential pressure (ΔP) as a function of fatigue cycles (left) and as a function of percentage of fatigue life (right) – One specimen with surface sensors.

Representative plots of two specimens with internally mounted sensors are presented in Fig. 6. As with Fig. 5, ΔP is plotted as a function of fatigue cycles (left) and percentage of fatigue life (right).

The fatigue life of this group of specimens is slightly higher than group 1 as these specimens were slightly thicker. As the sensors are mounted within the specimen and do not detect relative motion between the rivet and plate, there is no increase in ΔP as a result of static loading. A reading close to zero remains until failure begins to initiate. In contrast to the surface sensors, the internal sensors are remote to the rivets and therefore only the initiation of damage will cause an increase in ΔP. The early stage of failure is detected by the sensors at 50-70% of the fatigue life. Damage was detected prior to any surface indication. After the full-scale SI reading, fatigue cracks were observed at 90-95% of the fatigue life and grew to 3 and 5 mm prior to specimen failure for the specimens shown in Fig. 6. The sudden drop in ΔP observed at 50% of the fatigue life for one of the specimens was due to finger pressure on the loosening rivet. This pressure sealed the rivet and caused the drop in ΔP. Fatigue cracks were observed to initiate from the rivet that was identified to be loosening.

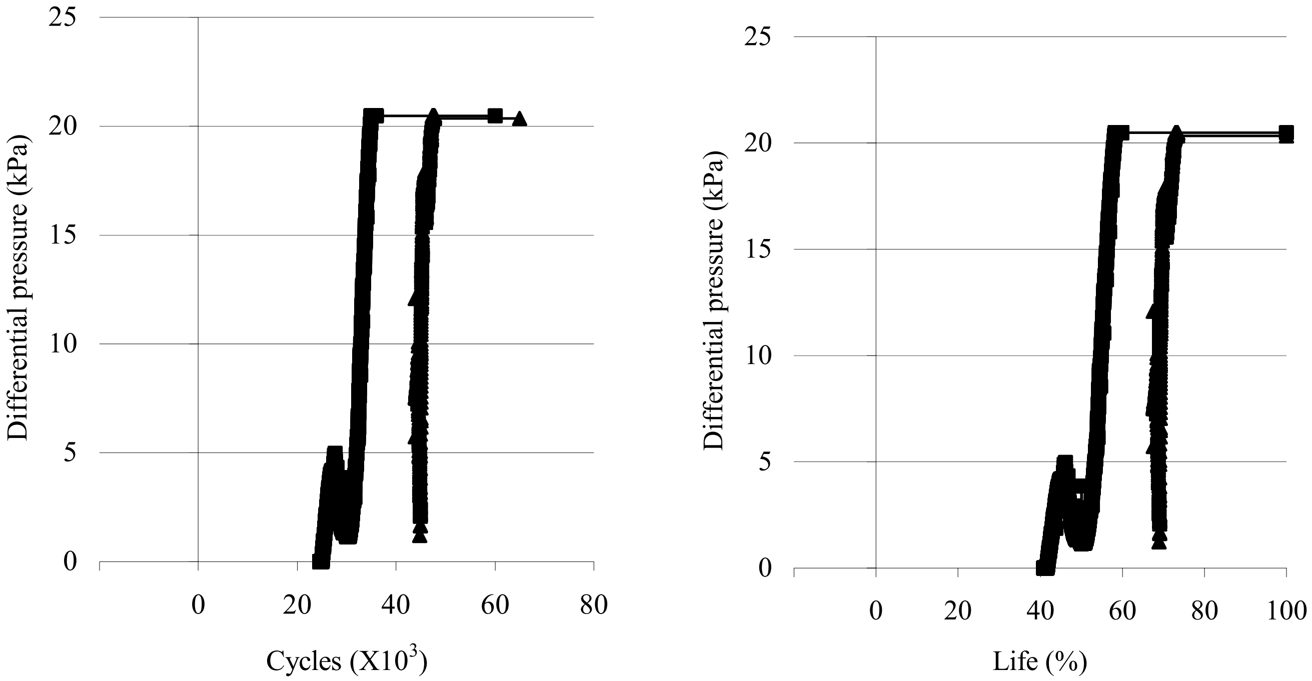

Figure 6: Differential pressure (ΔP) as a function of fatigue cycles (left) and as a function of percentage of fatigue life (right) – Two specimens with Integral sensors.

DISCUSSION

As the rivet tail is mainly deformed during rivet installation, mechanical contact is higher between the rivet tail and the plate than between the rivet head and the plate. Figure 5 shows that static load on the specimen results in a reduction in the seal between the rivet head and the plate. The drop in sealing between the rivet head and plate is illustrated in Fig. 7.

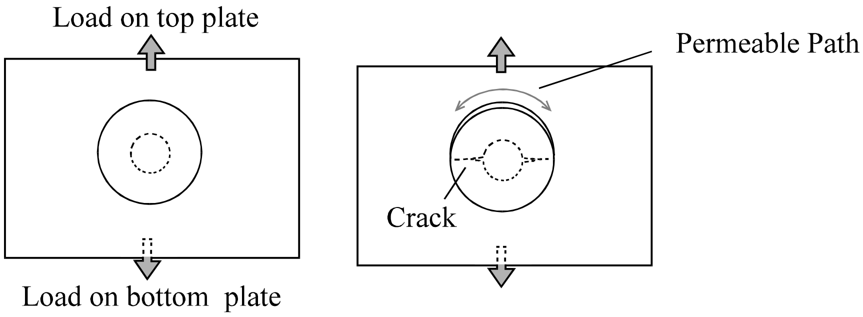

Figure 7: Behaviour of plate and rivet during fatigue loading (schematic).

The SI sensors are laid over 2/3 of the head of the rivet and therefore allow an ingress of atmosphere from the other portion of the rivet. This behaviour is currently being exploited by an SMS customer for the purpose of detecting the local yield point of the parent material around self-piercing rivets. Fatigue loading would repeat this relative motion between rivet and plate and cause fretting between the plate and the rivet head. The fretting initiates damage in the aluminium plate, the rivet shank and the anti-chaffing material.

Failure of the tested specimens occurred on the rivet head side. A consequence of Fig. 5 is that fatigue loading causes elastic deformation of the material around the rivet hole and therefore relative motion between the rivet hole and rivet shank. The fretting between the rivet hole and shank then results in damage that causes fatigue crack initiation. In Fig. 6, the SIM reading is seen to increase to full-scale over 4-5,000 cycles. Fatigue loading was such that a fatigue crack was grown over about two thousand cycles.

The SMS system indicated a reduction in structural integrity prior to any external visible indications of fatigue damage. The externally mounted sensors indicated the effect of static loading and the more gradual increase in ΔP as fretting damage increased in the rivet head or shank. The internally mounted sensors indicated the breakdown of the anti-chaffing material between the riveted plates and then fatigue crack initiation.

CONCLUSIONS

This investigation has revealed a number of observations. Firstly, surface mounted SMS sensors reveal the degree of mechanical contact between the plate and the rivet while the internally mounted sensors give only an indication of the early stages of crack initiation. Secondly, the loss of structural integrity of the lap joint is detected at 50-70% of the overall fatigue life. The mode of failure is concluded to be that of crack initiation as a result of fretting damage. The fretting results from relative motion between the plate and rivet.

Industry need for early detection of fatigue damage is recognised. The benefits of CVM™ are many. In terms of safety, the ability to detect a fatigue crack prior to external evidence of such is important. CVM™ is able to detect damage as a result of fatigue loading before it can be detected on the surface. In terms of scheduling, this system also offers the ability for operators to repair loosening rivets, monitor detected damage by other means and to monitor the damage as it accumulates.

CVM™ has gained a reputation with leading technical and scientific organisations for reliably detecting minute fatigue cracking in the specialised area of testing airframe structures. In fatigue testing the SMS technology has the advantage of detecting crack initiation and measuring crack propagation without stopping the test to carry out an NDT inspection. The monitoring system has been developed for installation on civil and military aircraft fuselage bulkheads and frames, wing stringers, spars and landing gear. SMS sensors have the capability of covering large areas and lengths and detecting minute flaws under painted surfaces to the extent of current tests. The SMS sensor can be used on peened surfaces. The SMS sensor is lightweight, will not corrode and is electrically inert, it will not interfere with on-board electrical systems, initiate corrosion or ignition. The sensor once installed can remain in-situ to record measurements continuously or periodically from locations that are either very difficult or impossible to inspect, by other than major disassembly of the structure.

An automated crack propagation measurement system for laboratory or industrial application is also available. SMS sensors are in use as localised yield stress indicators for self-piercing rivets and for the detection of disbonding within composite repairs/structures.

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