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Evaluation of a Distributed Fibre Optic Strain Sensing System for Full-Scale Fatigue Testing

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Abstract

The Defence Science and Technology Group has been conducting full-scale fatigue tests of ex-service F/A-18 Hornet centre fuselages, in support of the Royal Australian Air Force's structural integrity management programs for its frontline fighter fleet for over 12 years. Historically, conventional electrical resistance foil strain gauges have been used extensively on these tests to monitor and record the structural response to loading; however, there are limitations with these in terms of cost, installation times and physical complexity. Developments in commercially available, distributed fibre optic strain measurement systems presents the opportunity to overcome these limitations, as demonstrated on the most recent centre fuselage test article. Based on Rayleigh scattering, the system ('ODiSI B' by Luna Innovations) was trialled which allowed comparisons of strain response, spatial resolution and noise levels with conventional foil gauges. Comparisons were also made of the full-field strain mapping capability of the system with full-field stress mapping by thermoelastic stress analysis. Furthermore, the distributed fibre optics demonstrated their potential to detect crack propagation on a coupon with induced crack growth.

Keywords: Distributed fibre optics, Rayleigh scatter, Testing, Strain sensing, Crack detection, Structural integrity, Thermoelastic stress analysis

1. Introduction

Australia's Defence Science and Technology (DST) Group have been conducting full-scale fatigue tests (FSFTs) of ex-service F/A-18 Classic Hornet centre fuselages for over 12 years. For the most part, the primary aim of these

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tests has been to support the structural integrity management programs for the Royal Australian Air Force's frontline fighter jet fleet (Swanton and Robertson, 2011). The tests have proved to be a great success by providing crack growth data which has allowed a reassessment of the safe life limits of critical structural locations to be undertaken, with the outcome being an elimination of the requirement to carry out costly refurbishment programs. These reassessment analyses rely heavily on strain measurements which are typically recorded at multiple points across the airframe, with higher density measurements at known fatigue critical hot spots and areas of interest.

The industry standard method of measuring strain has been to use conventional electrical resistance foil strain gauges (FSGs). This measurement technique is well established and has been in use for decades. However, the installation of FSGs for detailed strain surveys can be complex, time consuming and costly. Developments in commercially available, distributed fibre optic strain measurement systems now provide an alternative, and the F/A-18 FSFT articles provide a valuable opportunity to evaluate their effectiveness. Such systems present an opportunity to significantly reduce installation complexity and weight since strain sensing is distributed along an optical fibre with a cross section approximating the dimensions of a human hair. These sensing systems are insensitive to electromagnetic interference, resistant to fatigue and corrosion, and do not require ongoing calibration.

Significant advances in the Rayleigh scattering technique to measure strains using optical fibres have been made in recent years (Samiec, 2012). This paper presents an experimental evaluation of the "ODiSI B" system, developed by Luna Innovations Incorporated, for discrete and distributed strain measurements on a FSFT using high and standard resolution modes. In addition, a coupon test was used to demonstrate the employment of the ODiSI B as a potential means of detecting cracks.

2. Optical fibre based strain measurement

Optical fibre based strain sensors have been available for many years and are a potential alternative to FSGs. Optical fibre sensors do not have the same electrical or mechanical drawbacks of FSGs. A single patch cord can multiplex multiple optical fibre sensors, which reduces the connection and installation issues that are inherent to most FSGs for broad area measurements. Fibre optic sensors can be broadly classified into two main types; discrete or distributed.

Discrete sensors, such as Fibre Bragg Gratings (FBGs) rely on transducers incorporated into the optical fibre at discrete locations that provide a reading of the strain experienced by the fibre at that point (Davis et al., 2012). Multiple sensors can be multiplexed onto a single optical fibre to provide a pseudo-distributed strain measurement.

Truly distributed fibre optic strain sensors rely on the material properties of the fibre itself. In these cases the entire fibre acts as the sensor and changes to the back-scattered light are used to characterise the strain experienced by the fibre. They rely on the principle that every optical fibre has a unique scattering signature based on its material properties. This scattered signal remains constant in the absence of external factors. Changes in strain and/or temperature along the optical fibre cause changes to the fibre's material properties influencing its scattering signature within this region. The changes in scattered signal can be quantified to provide a distributed measurement of strain. The three main scattering mechanisms which may be interrogated to provide a measure of strain are Rayleigh, Brillouin and Raman (Bao and Chen, 2012).

3. ODiSI B system overview

The ODiSI B by Luna Innovations is a commercially available distributed strain measurement system based on Rayleigh scattering. The basic operating principle of the ODiSI B system is the use of Optical Frequency Domain Reflectometry (OFDR) combined with a Mach Zehnder interferometer to characterise the Rayleigh scattering. Using these elements in tandem enables a relatively high sampling rate and increased spatial resolution. The system can provide both static and dynamic measurements with sampling rates up to 250 Hz over sensing lengths up to 20 m.

4. F/A-18 centre fuselage full-scale fatigue test – discrete point strain sensing

The first trial of the ODiSI B on the FSFT compared its discrete strain sensing performance with a FSG and FBG at a single approximately co-located point. The sensing location was on the lower flange of the left hand side central bulkhead (designated "Y470.5") as shown in Fig. 1.

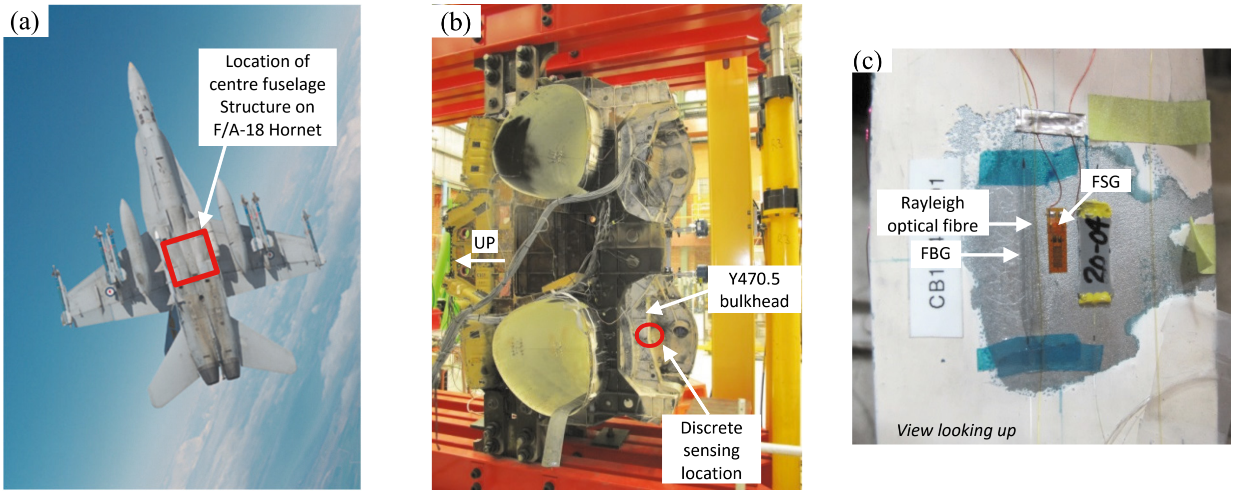

Fig. 1. (a) Underside of F/A-18 Classic Hornet, showing location of centre fuselage structure; (b) centre fuselage FSFT showing Y470.5 bulkhead and discrete sensing location; (c) close-up view of discrete strain sensor locations on the left hand side lower flange of the Y470.5 bulkhead.

The same surface preparation was used for all the sensors. All the protective coatings were removed and the surface was stripped back to bare metal in the region where the sensors were to be applied, followed by light abrasion and cleaning. The FSG was applied using a standard strain gauge adhesive (AE-10) according to standard procedures. The Rayleigh scattering fibre and the optical fibre containing the FBG were bonded to the surface using an ultraviolet (UV) curable liquid photopolymer (Norland Optical Adhesive, NOA-61) (Van Roosbroeck et al., 2009). The adhesive was applied using a small paintbrush and the UV exposure was achieved using a UV LED torch (OPTIMAX 365 UV). Both optical fibres had approximately 50 mm of fibre bonded to the structure in order to avoid edge effects in the region of the sensor. The gauge length of the FBG was 5 mm and the gauge length for Rayleigh sensing fibre was 5.12 mm in standard resolution mode and 1.28 mm in high resolution mode.

The measurements from the Rayleigh optical fibre were recorded in high and standard resolution modes using the ODiSI B system. The measurements from the FBG were made using a Micron Optics si-425 optical interrogator and the FSG measurements were recorded using the existing data acquisition system for the centre fuselage test program which was a Hewlett Packard (HP) 3852A data acquisition unit powered by a HP 6632A system 100W DC power supply.

4.1 Stepped strain survey results

For the purposes of assessing the ODiSI B system, the FSFT article was subjected to a stepped load sequence in 10% increments up to 100% of the maximum test load (730 kN-m of pure wing root bending moment applied via the wing attachment lugs) followed by variable amplitude accelerated fatigue spectrum loading. Each load spectrum was applied twice so that the Rayleigh system could acquire data in both high and standard resolution mode. Fig. 2 shows the response of all the strain sensors at a single point during the 100% load survey. All five tests are overlaid with the insert showing a single test (Test 1). The results show that there was reasonable agreement between all measurement systems for a single point measurement of strain. The high resolution strain measurement from the Rayleigh system over-estimated the strain by approximately 0.8%.

The noise level from the ODiSI B system was approximately 15 $\mu\varepsilon$ to 20 $\mu\varepsilon$ for the high resolution measurement and 10 $\mu\varepsilon$ to 15 $\mu\varepsilon$ for the standard resolution measurement which equate respectively to 0.72% and 0.54% of the strain at this load level. The high resolution mode has a standard deviation in the signal of 5.4 $\mu\varepsilon$ and the standard resolution mode has a 3 $\mu\varepsilon$ standard deviation. The noise on the FBG measurement system (< 1 $\mu\varepsilon$) was considerably less than the Rayleigh scattering measurement for both high and standard resolution modes. Occasionally during this testing, some data drop outs and anomalous data points were observed from the ODiSI B measurements which coincided with momentary mechanical instabilities from the load actuation system during changes in the applied load.

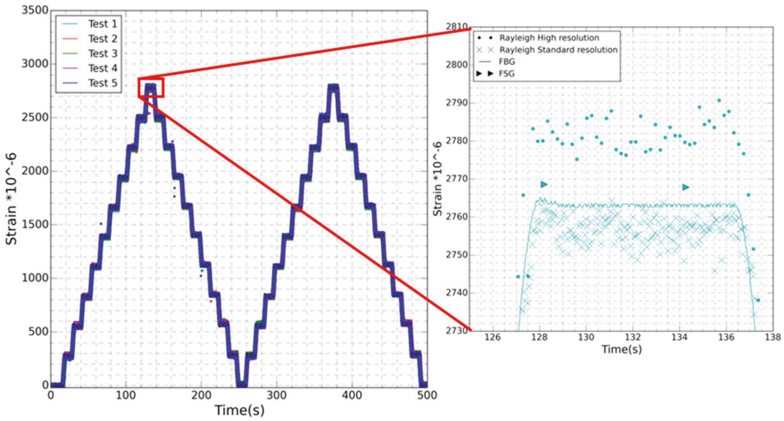

Fig. 2. Response of all sensors to stepped strain survey loading. The inset shows detail from Test 1 over a ten second interval.

4.2. Variable amplitude spectrum results

Fig. 3 shows the measured strain response under spectrum loading at the same location as a function of time for the FSG, FBG and the ODiSI B system in high and standard resolution modes. Several spectrum tests are overlaid with the inset showing a single test (Test 5) in detail over a 10 second measurement interval. The FSG measurement system was configured to only measure the strain at the turning points, thus only one point was recorded at each strain level. The results show that there was reasonably good agreement between all measurement systems for a single point measurement of strain. The high resolution measurement showed a peak to peak noise level of 15 με (0.87% of peak strain) and the standard resolution gave a peak to peak noise level of 10 με (0.58% of peak strain). As with the stepped strain survey, the FBG results by comparison showed a much lower noise level (< 1 με).

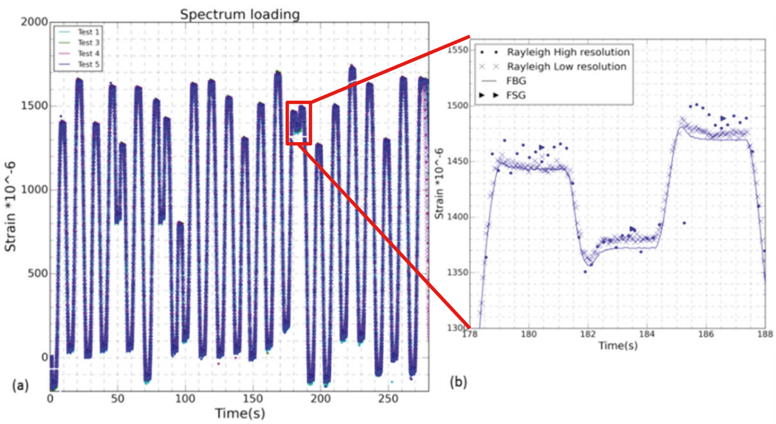

Fig. 3. Response of all sensors to spectrum loading. The inset shows some detail from Test 5 over a ten second interval.

5. F/A-18 centre fuselage full-scale fatigue test – distributed strain sensing

The second part of the FSFT trial investigated the potential of Rayleigh scattering to provide a broad area strain map using a dense optical fibre lay-up geometry. The strain distribution as measured by the optical fibre was compared to a full-field stress map in the same region as measured by Thermoelastic Stress Analysis (TSA) using a

FLIR A615 microbolometer (Rajic et al., 2014). Unfortunately, there was no detailed finite element analysis available in this region to enable a comparison with model predictions.

The measurement region was on the lower flange of the left hand side central bulkhead (Y470.5), just outboard of the location where the discrete measurements were taken. The surface of the bulkhead in the measurement region was stripped of all paint and protective coatings back to bare metal. As the optical fibre and any adhesive used to adhere it could influence the TSA measurements, the latter were taken first. To facilitate the TSA measurement, the region of interest was spray painted with acrylic matt black aerosol paint; see Fig. 4(a). The centre fuselage was loaded to 8% of the maximum test load at approximately 1 Hz for 20 to 30 minutes to acquire the TSA scan.

Afterwards the black paint was removed and the surface was cleaned and lightly abraded before adhering the optical fibre. A 10 m long fibre was laid up in 12 parallel lines approximately 6.4 mm (±0.2 mm) apart along a flange length of 240 mm starting at the aft edge as shown in Fig. 4(b). The fibre was bonded to the surface using the same adhesive as for the discrete point testing (NOA-61). In this case, the adhesive was applied to the test area while it was in a predominantly vertical orientation. To prevent the uncured adhesive running down the part, the adhesive was built-up in a series of light coats using a broad area Maxima ML-3500 S UV-A lamp to partially cure (30-60 seconds exposure) the adhesive between coats. Three coats were applied to the fibre to just cover the top surface of the fibre. After all the layers were applied, the region was fully cured under the UV lamp for three hours. The application of the fibre in this region required two operators; one to roll out the fibre from the spool and pre-tension the fibre section and one to apply the adhesive and cure the material.

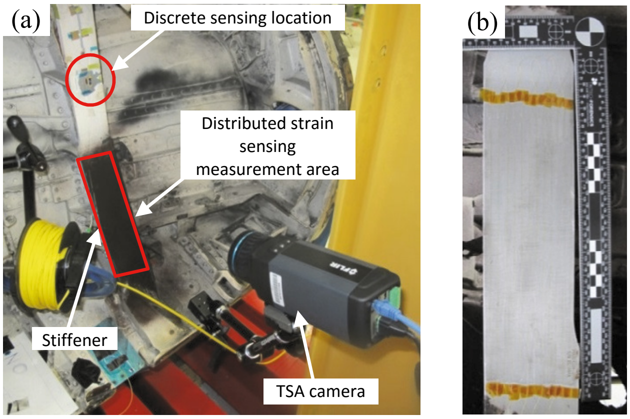

Fig. 4. (a) TSA scan area on Y470.5 bulkhead; (b) close-up of optical fibre lay-up geometry.

Figs. 5(a) and 5(b) show the strain distribution in the lower bulk head region as measured by the optical fibre in high and standard resolution modes respectively. Fig. 5(c) shows the stress distribution as measured by TSA. While a direct numerical comparison is not possible, the colour maps should show a similar distribution as the stress and strain are directly proportional to one another. For these colour maps the entire region is in compression with the dark blue representing the highest compression and the red the lowest compression.

The pixelation of the colour maps generated from the optical fibre measurements is due to a relatively low measurement resolution. Although the strain distribution broadly agreed between the high and standard measurement modes, there was more noise observed in Fig. 5(a) as opposed to Fig. 5(b) where the strain contours were more monotonic. In the standard resolution mode there were data drop-outs where the fibre transitioned from a bonded to a non-bonded region. These drop-outs were caused by the large strain differences in this region of the fibre which limited the ability of the cross correlation software to reliably measure the shift in Rayleigh scatter between the strained and unstrained states. These drop-outs were not observed in the high resolution measurement mode where the measurement is more tolerant of strain gradients. Another notable feature of the colour maps generated from the optical fibre was the band of high compression in the centre of the measurement region. This coincided with an integral vertical stiffener located on the opposite side of the flange which acts as a stress concentrator when the flange is under compression. There was also a region in the bottom right hand side of the flange which showed a localised drop in strain in the region where the flange increases in cross-section.

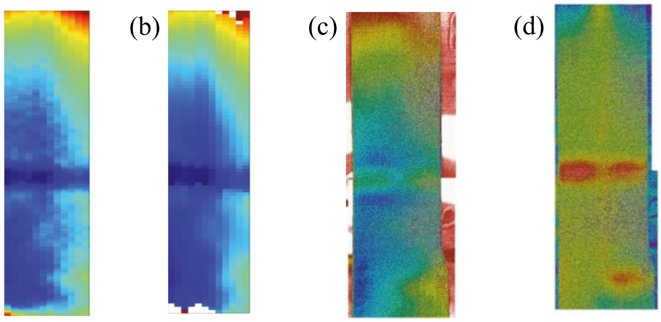

Fig. 5. Strain distribution across lower bulkhead as measured by the optical fibres in (a) high resolution mode at 50% load; (b) standard resolution mode 50% load. TSA scans showing (c) nominal stress distribution; and (d) quadrature signal at 8% load.

The stress distribution measured by TSA broadly agreed with the strain distribution measured by the optical fibre. The most notable difference was that there was a reduction rather than an increase in compressive stress in the centre band of the flange. This was investigated by examining the quadrature response from the TSA scan which is shown in Fig. 5(d). Ideally, the quadrature response across the structure should be uniformly zero indicating an adiabatic response. However, in this case, there is non-uniform response along the stiffener and in the bottom right hand side of the flange where the cross sectional area increases. This is a result of heat conduction driven be the presence of stress gradients and confirms that the loading rate was too low to achieve quasi-adiabatic test conditions. Unfortunately, it was not possible to increase the loading frequency due to mechanical limitations. This meant that stress measurements provided by the TSA scan were inaccurate in these regions. This result highlights one of the limitations of full-field stress mapping using TSA; it is not always possible to achieve an adiabatic response on complex structures under FSFT loading rates.

6. Crack growth monitoring

The ability to detect and track crack growth during a FSFT is one aspect that is often desired, yet difficult to achieve practically without significant costs, or without having to halt testing periodically to inspect for, and measure any cracking. Early detection allows the crack growth to be monitored prior to any potential structural failure. This information can assist the engineer in their decision making on whether to continue testing or take remedial action, and could ultimately result in a repair or redesign of the area.

The strain field induced by a crack tends to be highly localised particularly during the early stages of crack initiation and growth. Hence, in the case of FSGs, these tend to detect the crack only if they are located in close proximity to it. If the crack propagates under a FSG, this is usually indicated by a failure of the gauge. Therefore, a coupon test was devised in order to understand the response of the ODiSI B system to a crack located in close proximity to the optical fibre, as well as when the crack propagates underneath the fibre.

The coupon was made from aerospace grade aluminium alloy 2024-T3, and measured approximately 4 mm thick by 100 mm wide by 400 mm long with a through thickness hole of 20 mm diameter at the centre as shown in Fig. 6(a). The optical fibre, 2 m in length, was arranged into six parallel bonded lines (Fig. 6(b)), each 180 mm in length which gave 421 sensing points in standard resolution mode and 1687 in high resolution mode. The optical fibre was bonded to the coupon using UV curable adhesive (NOA-61) with the strain sensing axis aligned with the long edge of the coupon. In addition, six strip FSGs (KFG-1-120-D9-11N10C2) each comprising five 1mm long elements were adhered to the right hand side of the hole.

A small notch was introduced at the edge of the hole on the optical fibre side using a micro-file to initiate crack growth. The coupon was cyclically loaded in tension at 5 Hz to initiate stable crack growth. Measurements were taken at regular intervals using the ODiSI B system in high and standard resolution modes at a static load of 15 kN. A digital microscope (Dino-Lite) was also used to measure the crack length. In addition to the optical strain measurements, TSA (using a FLIR A35 microbolometer camera and MiTE analysis software) was used to track the crack initiation and propagation.

The response to the uncracked coupon for all six fibre sensing lines from both the high resolution mode and TSA is shown in Figs. 7(a) and 7(b) respectively. The optical fibres show a strain distribution which is consistent with the TSA measurements. The TSA scan shows slight asymmetry on the LHS due to the notch.

Fig. 8(a) shows the response of the optical fibres as the crack has progressed to the third sensing line. The data shows a dropout from Lines 1 - 3 which was caused by the high (theoretically infinite) strain across the crack face. The other important feature to note is that, although the data drops out in the region surrounding the crack (due to the extremely high strain gradient), the signal integrity from the remainder of fibre remains intact. The inference from this result is that there is no physical damage induced in the fibre as the crack propagates beneath it. Lines 1 and 2 also show strain relief behind the crack tip which is consistent with theory and is also observed in the TSA scan (Fig. 8(b)). Lines 4 to 6 also show a change in strain response to the undamaged state with the increasing strain near the crack tip being detected by all fibres.

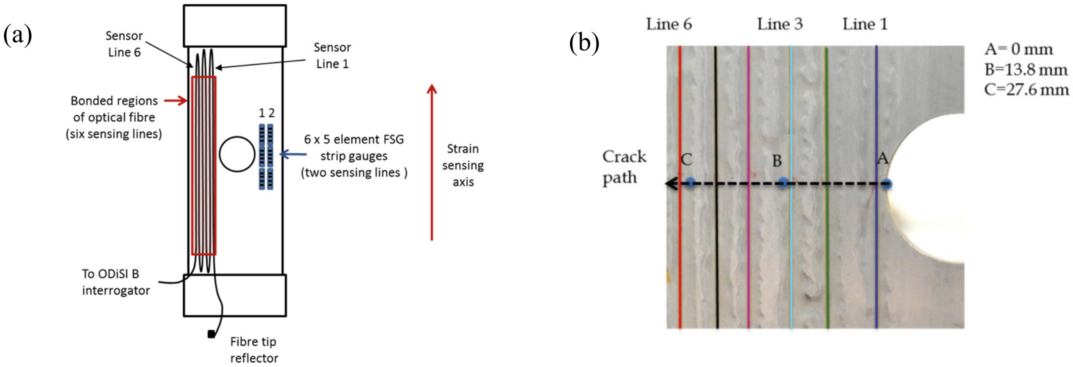

Fig. 6. (a) Schematic drawing showing locations of strain sensors on aluminium coupon; (b) close-up photograph of optical fibre, with the fibre lines coloured to match the strain distributions in Figs. 7(a) and 8(a) at notch location A and crack location B respectively.

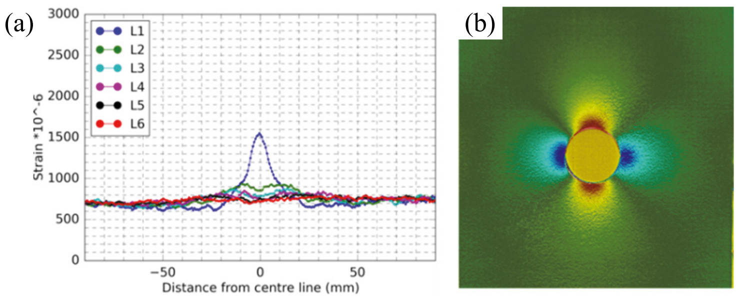

Fig. 7. (a) Strain distribution of six optical fibres after notch applied (prior to crack initiation); (b) TSA scan of notched coupon at same point.

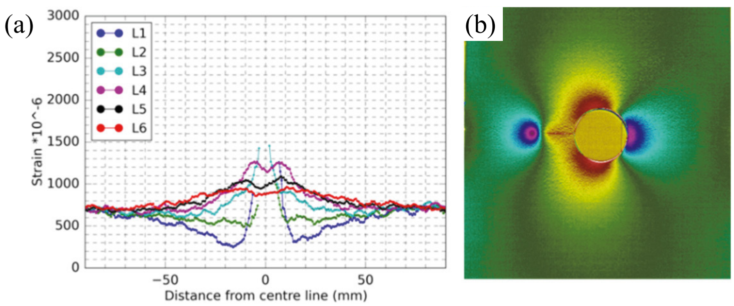

Fig. 8. (a) Strain distribution of six optical fibres after crack has reached position B (13.8 mm); (b) TSA scan of cracked coupon at same point.

7. Conclusions

The ODiSI B distributed fibre optic strain measurement system has a measurement resolution and acquisition rate which is suitable for application to full-scale fatigue testing for broad-area strain distribution measurements. However, it should be noted that, although not explicitly shown here, the measurement length and spatial resolution come at the cost of data acquisition speed. For long fibre lengths and/or high resolution measurements, it is necessary to post-process the data to achieve the maximum acquisition rates specified by the manufacturer. This results in very large data files that are time-consuming and processor intensive for long-term testing.

The experiments presented in this paper demonstrate that Rayleigh scattering can be used to provide distributed measurements of strain with reasonable agreement to point strain measurements made using FSGs and FBGs in regions without a significant strain gradient. The unfiltered noise levels from the Rayleigh system were higher than those from the FBG system. In addition, the noise levels from the Rayleigh system were higher when measuring across a smaller effective gauge length (i.e. in high resolution mode).

In regions of high strain gradient (e.g. near a crack tip), the cross correlation software, which measures the shift in Rayleigh scatter between the strained and unstrained states, can fail to measure the shift reliably resulting in data loss.

The reasonably narrow lateral footprint of the sensing fibre (250 μm) means that relatively large distances between consecutive sensing lines are likely in many applications. For structural features or defects that cause highly localised strain perturbations, it is possible that the distributed fibre will not detect them if they occur between the fibre optic sensing lines. Thus, distributed fibre optic sensor networks are unlikely to eliminate the need for full-field stress mapping techniques such as TSA. They do however, offer certain advantages in that there is no requirement to cyclically load the structure and the measurements relate to a component of strain rather than to a stress invariant. Further work is required to compare the measured strain distributions in complex structures to model predictions and to assess their effectiveness in model validation and refinement.

The application time to bond a 10 m sensing fibre to the FSFT was approximately two hours. Twelve sections of the fibre were bonded which provided approximately 5000 sensing points in high resolution mode. This equates to a cost per sensing point of approximately 5 cents (not including installation costs). There are further economies of scale with longer fibres and/or bonded areas. These are significant cost savings over conventional FSGs.

In summary, the results from this preliminary testing have shown that the use of Rayleigh scattering from optical fibres to make distributed strain measurements shows promise for application to FSFTs, particularly when used in tandem with other techniques. The benefits are greatest when the structure under test has a smooth flat surface profile and high density distributed measurements over a large area are required. Further testing will be required to develop and refine fibre lay-up and bonding processes for complex geometries, multi-axis sensing and to investigate the reliability and durability of the fibre, adhesives and the measurement under long-duration structural testing.

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