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Th-D18 – High Strain FBG sensors for structural fatigue testing of military aircraft

Australian Government
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Summary

This poster reports on a series of tests investigating the performance of Draw Tower Gratings (DTGs) combined with custom-designed broad area packaging and bonding techniques for high-strain sensing applications on Defence platforms. The sensors and packaging were subjected to a series of high-strain static and cyclic loading tests. A summary of these results is presented and compared to the performance of stripped and re-coated Fibre Bragg Gratings (FBGs)

Introduction

The structural airworthiness of the Royal Australian Air Force (RAAF) is founded on a rigorous program of full-scale fatigue testing. Test loads simulating the extremes of aircraft flight conditions are generated and applied to the aircraft using custom-designed servo-hydraulic or mechanical loading systems as shown in *Figure 1*.

These full-scale ground fatigue tests require large amounts of experimental strain data from across the structure to validate the predicted strain fields. The strain sensors are required to operate under relatively high strains for a large number of cycles in order to determine the fatigue limits of the structure. These measurements are conventionally made using electrical resistance foil gauges which require three insulated leads per sensor. There is a significant weight associated with the foil gauge wiring which can affect the structural response. The foil gauges can also be less durable than the structure under test which requires replacement of the sensors midway through the testing cycle.

Although FBGs potentially offer many advantages over conventional foil gauges, there is limited conclusive information regarding these sensor's reliability and durability.

This poster studies the performance of FBGs inscribed during the fibre fabrication process known as DTGs. The performance of these DTGs under static and fatigue loading conditions on a series of fibre glass test coupons using different surface-mount adhesive techniques is presented and compared to the performance of stripped and re-coated FBGs.

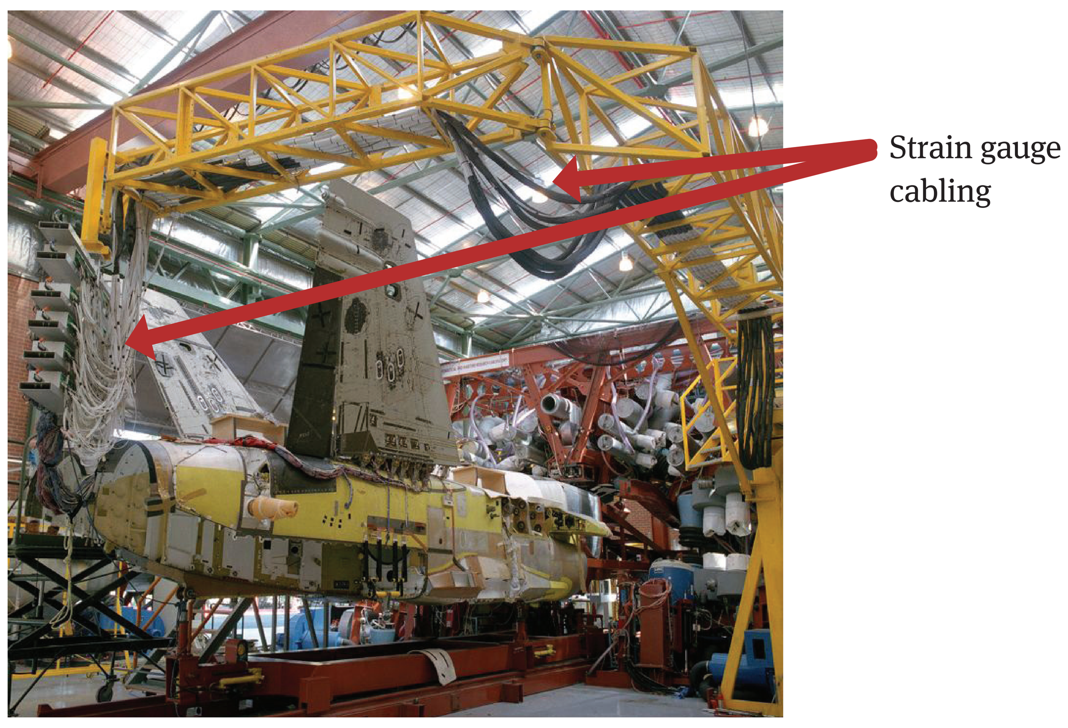

Figure 1: Structural Fatigue test of an F/A18 aircraft showing support frame for foil strain gauge wiring

Sensor Fabrication

There are typically four main steps involved in fabrication of a fibre Bragg grating:

1. Removal of the fibre coating.
2. Photosensitization of the fibre.
3. Exposure of the grating to UV laser light.
4. Annealing and Re-coating/packaging.

Each one of these steps in the process has the potential to introduce structural flaws to the glass surface which weakens its ultimate strength and long-term reliability. Nearly all of the commercially-supplied gratings are fabricated in this way.

FBGs may also be inscribed during the fibre fabrication process, these gratings are commonly referred to as draw-tower gratings (DTGs). *Figure 2* shows a schematic diagram of the production process for a DTG.

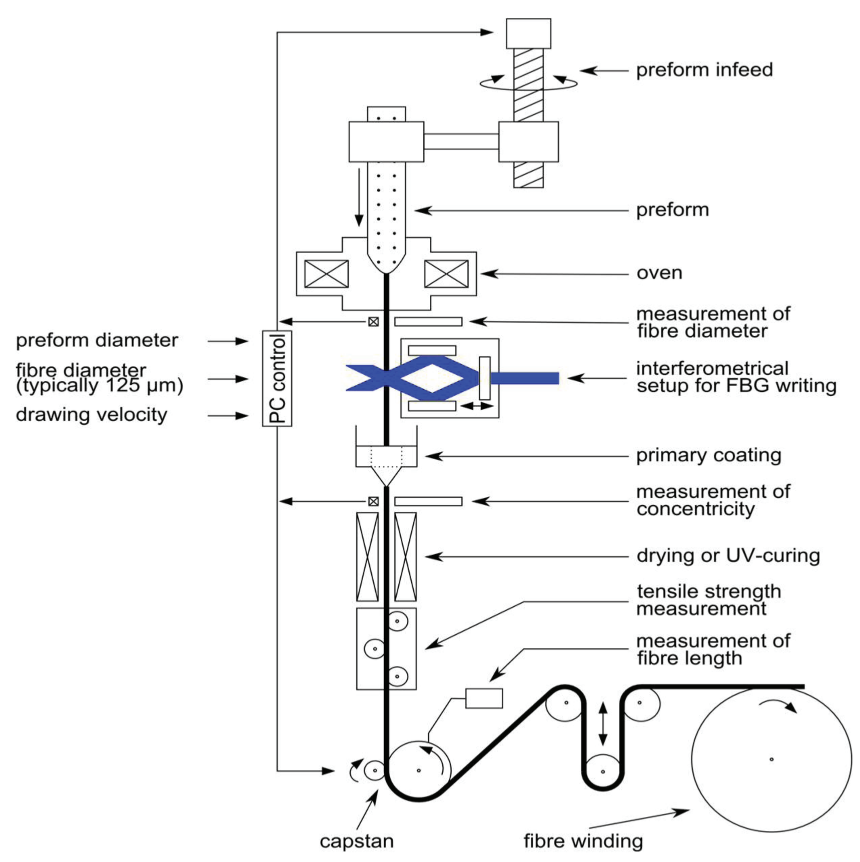

Figure 2: Schematic representation of draw tower set-up (Diagram supplied courtesy of FBGS International).

Sensor Packing Techniques

For broad-area structural assessment and health monitoring of large Defence platforms, a robust and reliable technique is required for surface-mounting a network of sensors onto a large structure, as shown schematically in *Figure 3*.

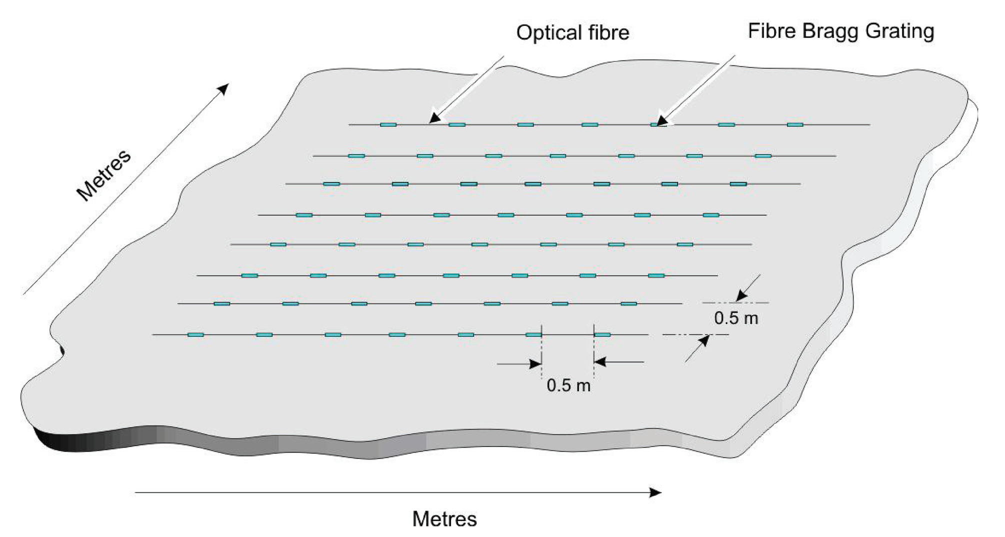

Figure 3: Schematic of a typical sensor distribution over a representative structure surface.

DSTO have developed two different packaging techniques considering pre-packaging, transportation, alignment, packing, mounting and protection. The first technique is a Vacuum Assisted Resin Transfer Moulding (VARTM) as shown in *Figure 4*.

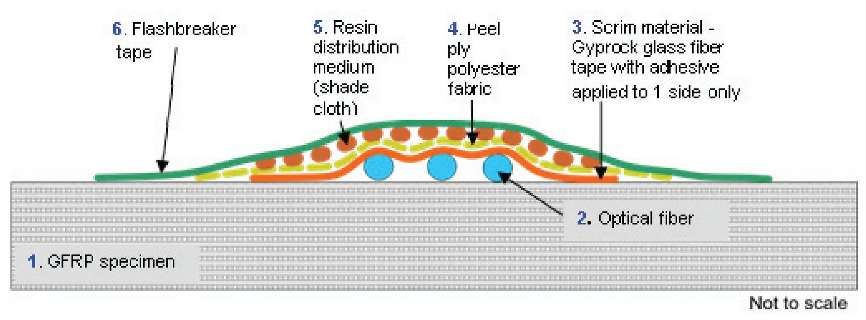

Figure 4: Cross sectional view point of materials used in VARTM. Note that after infusion layers 4, 5 & 6 are removed.

The second technique involves curing the optical fibre into a resin impregnated nylon carrier tape, Redux®312. This tape can either be co-cured with the structure or cured separately with the optical fibre and then bonded to the structure with a secondary adhesive, i.e. M-Bond 200, as shown in *Figure 5*.

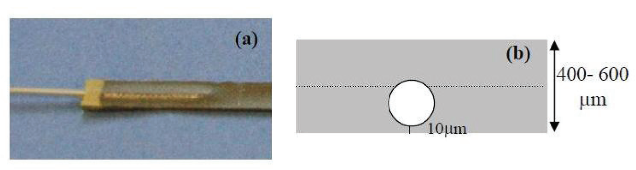

Figure 5: (a) Redux®312 tape with embedded optical fibre, (b) Cross sectional view of an embedded optical fibre in Redux®312.

Reliability and Durability Testing

Two types of Glass Fibre Reinforced Composite (GFRC) coupons were fabricated for the testing program using MTM57 E-glass pre-preg. The first set of coupons comprised 12 **unidirectional** plies [0]12 with dimensions of 200 mm × 25 mm manufactured to American Society for Testing and Materials (ASTM) Standards (D3039). The second set of coupons comprised 12 plies laid up in a **cross-ply** orientation [(+45,-45)3]s with dimensions of 200 mm × 25 mm also manufactured to ASTM standards. Aluminum grip tabs were bonded to each coupon to protect the coupon from the load-cell grips during tensile loading in a mechanical test machine as shown in Figure 6. The uni-directional test coupons had a predicted strain-to-failure of 20,000 με with a linear stress-strain response curve to the yield strain at approximately 18,000 με. The cross-ply coupons had a much higher strain-to-failure (8%), with a non-linear response beyond the yield point of the material at approximately 1,000 με.

Figure 6: Test coupon connected to the laboratory 50kN MTS System.

Testing was conducted in two parts; strain to failure testing on a series of 26 cross-ply coupons and sinusoidal fatigue loading in tension to a peak strain 10,000 με on a series of 26 uni-directional coupons. A single FBG or DTG was surface-mounted front and back to each coupon using the VARTM and Redux packaging techniques respectively as shown in *Figure 7*.

An electrical resistance foil gauge was also surface mounted to each coupon to provide an independent measurement of strain, however their performance proved to be inadequate for the strain levels experienced.

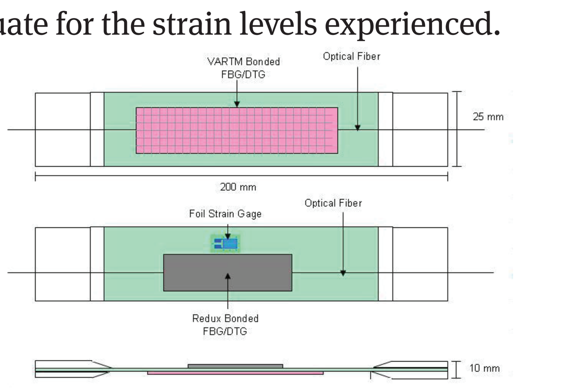

Figure 7: Top, bottom and side views of GFRC coupon showing placement of packaged and bonded sensors.

Results

Optical fibres are typically coated to provide a hermetic seal which provides environmental and mechanical protection. The FBG inscription process requires the removal of this coating which has been reported to reduce the mechanical strength of the optical fibre [1]. Five of the most common coating removal methods were investigated in previous work [2] which showed that CO_2 Laser ablated fibres endured the highest strain to failure tests of stripped and re-coated FBGs.

Figure 8 shows the average strain-to-failure levels for both the CO_2 stripped FBGs and the DTGs using both the VARTM and Redux packaging. The results indicate that for both packaging techniques, the strain-to-failure for the DTGs is approaching the expected level for that of the pristine optical fibre (approximately 5% or 50,000 με). The strain to failure levels for the CO_2 stripped FBGs are significantly lower than for the DTGs.

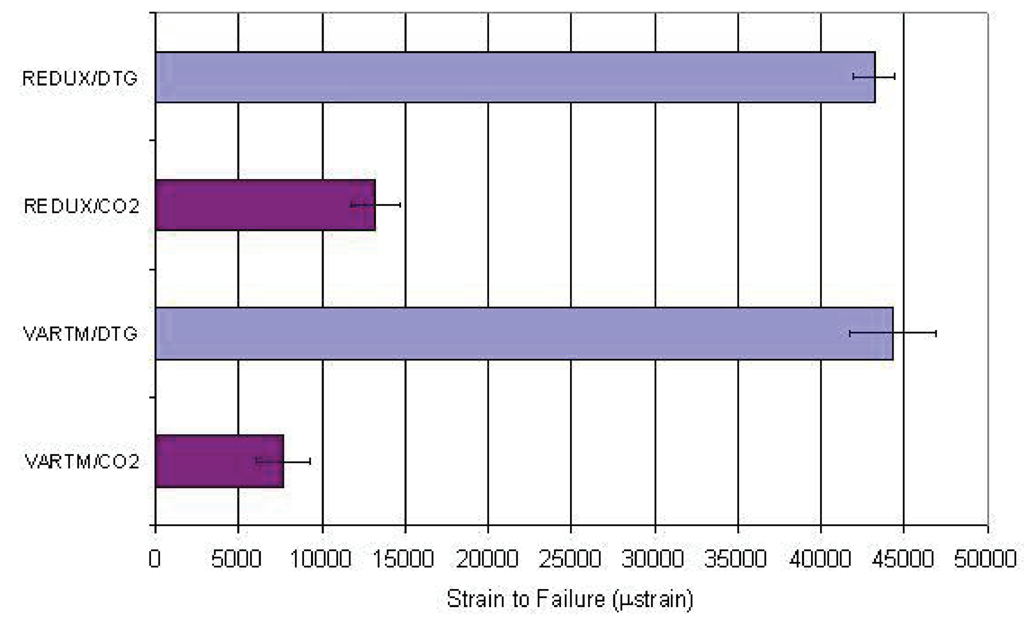

Figure 8: Comparison of Average Strain to Failure for DTGs and CO2 laser stripped FBGs in Redux and VARTM packaging.

Figure 9 shows the number of cycles at 10,000 με before fibre failure for the DTGs only. The results indicate that the Redux packaging performs slightly better than the VARTM packaging under fatigue loading conditions. As the fatigue loading progressed there was also evidence of strain gradients along the length of the grating as indicated by peak splitting of the FBG reflection spectra particularly for the VARTM packaging. This may be occurring due to micro-cracking which was observed in the resin matrix.

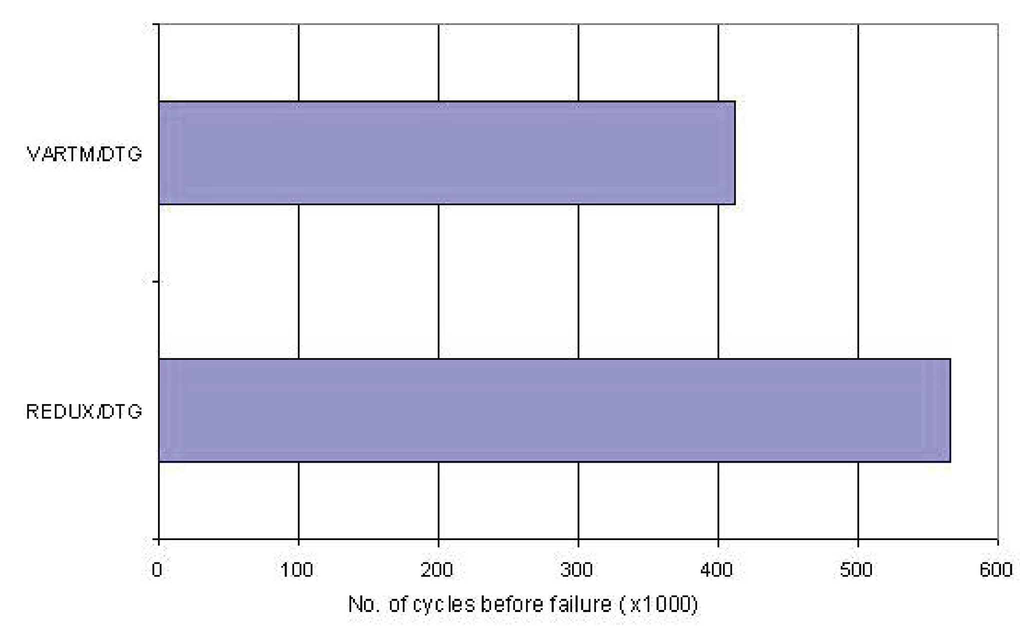

Figure 9: Comparison of number of cycles for DTGs in Redux and VARTM packaging.

Conclusions

The results of the investigation into the effect of the manufacturing process on the reliability and durability of Fibre Bragg Gratings (FBGs) clearly show that Draw Tower Gratings (DTGs) demonstrate significantly better performance than FBGs which have been written into stripped and re-coated fibres. The associated packaging has also performed well under these extreme loading conditions. With recent enhancements in DTG fabrication technology, the reflectivity of these gratings should be suitable for use with many commercially available FBG interrogators. For these reasons, the use of DTGs show promise for structural health monitoring applications where long-term use in harsh and high strain environments is required.

References

[1] Mrad, Nezih, Sparling, Sherri and Laliberte, Jeremy "Strain monitoring and fatigue life of Bragg grating Fibre optic sensors". Proceedings of SPIE - The International Society for Optical Engineering Volume 3670, 1999, Pages 82-91

[2] "Reliability and Durability studies for Fabricating, Packaging and Bonding Fibre Bragg Gratings". A. Rizk and C. Davis. Proceedings of 35th Australian Conference on Optical Fibre Technology, December 5-9, 2010. Melbourne, Australia.

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