High Aspect-Ratio Flat Optical Fibres for In-Situ Multi-Axial Strain Sensing in CFRP Laminates

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Abstract. Interlaminar stresses in carbon fibre reinforced polymer (CFRP) laminates govern the initiation of matrix cracking and delamination, yet remain difficult to quantify experimentally due to their internal nature and multi-axial character. Experimentally, stresses must be inferred from measured strains, however, conventional embedded fibre optic sensors, such as fibre Bragg gratings (FBGs), provide primarily strain in the axial direction of the fibre. A high aspect-ratio flat fibre (µHARFF) is presented that has a cross-section geometry designed to enhance sensitivity of the FBG to through thickness strains. The proposed sensor geometry enables stable alignment within the composite laminate stack and incorporates microstructural features to amplify birefringent response under through-thickness deformation. Strains were monitored during the cure of a cross-ply CFRP laminate using both a conventional SMF-28 FBG and the proposed µHARFF sensor. Distinct differences in spectral response were observed. While the conventional FBG exhibited peak broadening followed by splitting only during cooldown, the µHARFF sensor demonstrated earlier onset of peak splitting from gelation onwards. This behaviour is attributed to enhanced sensitivity to strain asymmetry arising from cure shrinkage and thermal contraction. The results demonstrate the potential of geometry-engineered optical fibres for detecting multi-axial strain states within composite laminates, providing a pathway towards improved understanding of residual stress development and interlaminar behaviour.

Introduction

CFRP laminates are designed by tailoring ply orientations and stacking sequences to align fibre directions with dominant load paths, thereby minimising matrix-dominated failure. Balanced and symmetric layups are commonly employed to reduce residual stresses and mitigate delamination risk. However, structural features such as ply drops, free edges, geometric discontinuities and thermal loading inevitably generate interlaminar stresses and associated through-thickness strain components. These are further amplified by defects such as voids and inclusions, making laminates susceptible to progressive damage mechanisms including matrix cracking and delamination.

Experimental characterisation of these mechanisms requires techniques capable of resolving multi-axial strain states within the laminate. However, current measurement approaches are limited. Surface-based techniques such as strain gauges and digital image correlation are restricted to external observations, while non-destructive evaluation methods such as ultrasound and thermography are not suitable for continuous in-situ monitoring.

Embedded optical fibre sensors, particularly FBGs, provide a practical solution for in-situ strain measurement during both manufacture and service. However, their response is primarily limited to axial strain along the fibre direction. As a result, key components of the multi-axial strain state, particularly through-thickness strains, remain difficult to resolve experimentally. Birefringence-based approaches have been explored using circular optical fibre to extend sensing capability, but are constrained by low sensitivity or practical challenges associated with identifying the optical axes during composite manufacture and after curing.

Sensor concept and experimental method

To address the limitations of circular optical fibre, a high aspect-ratio flat optical fibre sensor is proposed (Fig. 1). As the µHARFF geometry is significantly wider than it is thick, stable placement between plies is enabled, which prevents fibre rotation during processing. This ensures consistent alignment of the optical axes with the laminate coordinate system, overcoming a key limitation of orientation-sensitive birefringence measurements. In addition, internal microstructure is tailored to enhance strain asymmetry at the waveguide, increasing sensitivity to through-thickness deformation.

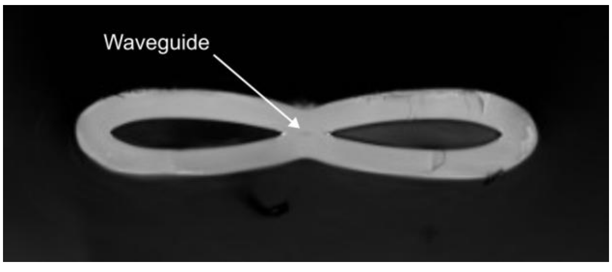

Figure 1: Cross section of µHARFF sensor

Strains were monitored during the manufacture of a cross-ply CFRP laminate with stacking sequence $[90/0]_3$ /sensor/$[0/90]_3$ where the sensor was positioned at the laminate mid-plane and aligned with adjacent 0° plies. Two sensor types were investigated: a stripped SMF-28 optical fibre and an uncoated µHARFF sensor, both with FBGs written into their waveguides. The laminate (140 mm × 84 mm) was cured in a cavity hot-press tool under 6 bar pressure. The thermal cycle consisted of heating at 2 °C min^{-1} to 180 °C, followed by a 2 h dwell, and subsequent fan-assisted cooling. A thermocouple embedded at the mid-plane recorded temperature, while optical spectra were acquired continuously to capture strain evolution throughout processing.

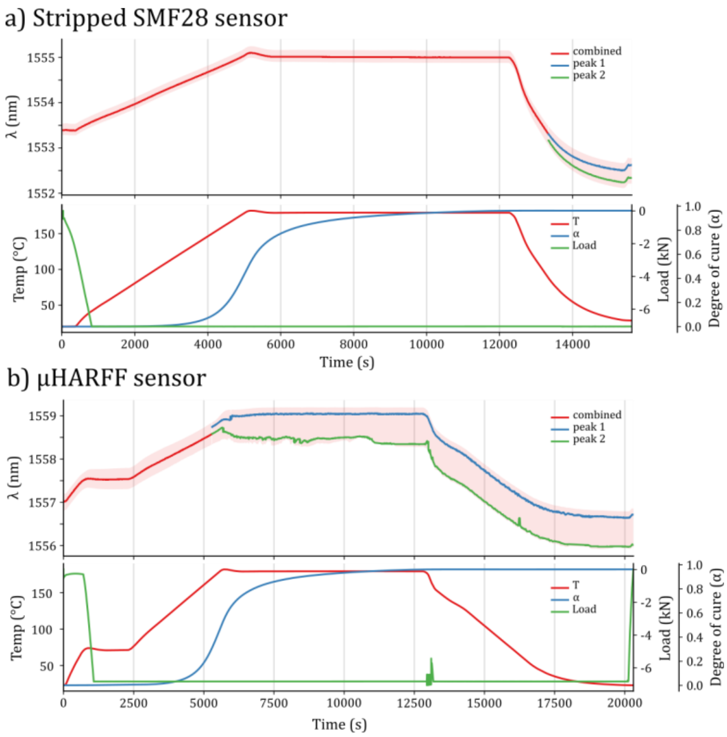

Figure 2: Comparison of reflected Bragg peak wavelength for a) SMF28 and b) µHARFF sensors during cure.

Results and discussion

Clear differences in spectral behaviour were observed between the two sensor types (Fig. 2). The conventional FBG exhibited peak broadening from the onset of gelation, with resolvable peak splitting only appearing during the cooldown stage. In contrast, the µHARFF sensor demonstrated peak splitting from gelation onwards, indicating earlier sensitivity to strain development transverse to the optical fibre. However, a reduction in peak intensity during cooldown limited resolution of peak separation at later stages. These observations are consistent with the development of transverse strains in the laminate. Following gelation, the laminate through-thickness strains associated with cure shrinkage and thermal contraction exceed the laminate in-plane strains, which remain constrained by the laminate architecture. This generates strain asymmetry at the sensor location, inducing birefringence within the optical waveguide. In conventional optical fibre sensors, this birefringence is insufficient to produce resolvable splitting until larger strain differentials arise during cooldown. The µHARFF sensor, by contrast, amplifies the transverse strain at the waveguide through its geometry and microstructure, resulting in enhanced birefringent sensitivity. The transition from peak broadening to distinct splitting reflects the increasing refractive index difference between orthogonal eigenmodes, leading to two separate Bragg wavelengths. The µHARFF sensor exhibited reduced peak intensity during cooldown, limiting resolution of peak splitting at later stages. This is attributed to increased optical loss, possibly arising from microbending and local deformation during thermal contraction.

Conclusions and future work

A high aspect-ratio flat optical fibre sensor has been demonstrated for in-situ monitoring of composite processing strains. Compared to a conventional FBG, the proposed sensor exhibits earlier and enhanced detection of birefringence, enabling improved sensitivity to transverse strain development during cure. This approach provides a new pathway for accessing multi-axial strain states within CFRP laminates and offers potential for improved understanding of residual stress formation and interlaminar damage mechanisms.

Ongoing work is focused on identifying the dominant loss mechanisms and mitigating them through improved sensor geometry and embedding strategies. While the observed response is consistent with the development of the strains transverse to the fibre, the relationship between birefringence and the underlying three-dimensional strain field has not yet been fully quantified. The current measurements therefore provide direct sensitivity only to the transverse strains. Future work will address this by extending the sensing approach to enable quantitative multi-axial strain reconstruction. In particular, the use of multiple sensing elements to decouple strain components will be explored [1].

References

[1] C. Holmes, M. Godfrey, D. J. Bull, & J. Dulieu-Barton, *Optics and Lasers in Engineering* **133**, 106111 (2020).