ON MINIMISING THE OBTRUSIVITY OF AN OPTICAL FIBRE SENSOR WITH RESPECT TO MATRIX CRACKING

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SUMMARY: A numerical study has been carried out to minimise the obtrusivity of a fibre optical sensor located near the 0/90 interface of a model GFRP crossply laminate. The results show that minimum obtrusivity can be achieved with an appropriate choice of coating thickness and Young's modulus. The numerical modelling results are in good agreement with previous work on sensors embedded in unidirectional composites. An experimental study using three different optical sensor coatings for a sensor in a model GFRP crossply laminate showed no effect on matrix crack initiation and accumulation under quasi-static loading due to the incorporation of the sensor.

KEYWORDS: obtrusivity, fibre optic sensor, crossply GFRP, numerical analysis and experiment

1.INTRODUCTION

This study is part of a wider programme on the use of a fibre optic sensor to monitor damage in composite materials. 'Smart structures' consisting of sensors embedded in a composite material to monitor damage are of increasing interest. Ideally, an optical sensor should not degrade the performance of the structure and an important issue in the design of such systems is the 'obtrusivity' of the sensor. Obtrusivity refers to the mechanical interactions between the fibre and the host leading to stress concentrations around the fibre. Previous work has shown that it is possible to minimise the perturbation in the host material, where the host is a unidirectional composite material, by choosing the optimum fibre optical sensor coating and its thickness [1-3]. In the first phase of this work a finite element analysis has been carried out to assess the optimum coating for a fibre optic sensor embedded in a model cross-ply GFRP laminate.

In the experimental part of this study on the obtrusivity of a fibre optic sensor, matrix cracking has been used as the sensitive parameter for two reasons. Firstly, matrix cracking is the predominant mechanism in the initial stages of the mechanical degradation of laminates containing off-axis plies and, secondly, the overall aim of this programme is to detect crack development using an optical fibre sensor. Hence, this is a reasonable parameter to use, although others, e.g. [4,5], have used composite strength as an indicator of obtrusivity.

2. FINITE ELEMENT ANALYSIS

The finite element (FE) method has been used to study the effect of the optical fibre sensor coating modulus and coating thickness on the stress distribution around the optical fibre; full details will be given elsewhere [6]. The aim was to investigate the role of these parameters for a sensor of diameter of 125 μm embedded in the 0^0 ply, parallel to the reinforcing fibres. FE models have been developed for a fibre optical sensor with coatings of different thicknesses and different Young's moduli for a sensor located at three places in the 0^0 ply of a cross-ply laminate (i.e. near the 0/90 interface, at the centre of the 0^0 ply, and near the surface of the 0^0 ply). The main objective has been to minimise the stress concentration in the host material around the fibre. The model with the sensor in the middle of the ply, for which the sensor is distant from both the surface of the laminate and from the 0/90 interface, has enabled validation of the modelling against previous work [7,8].

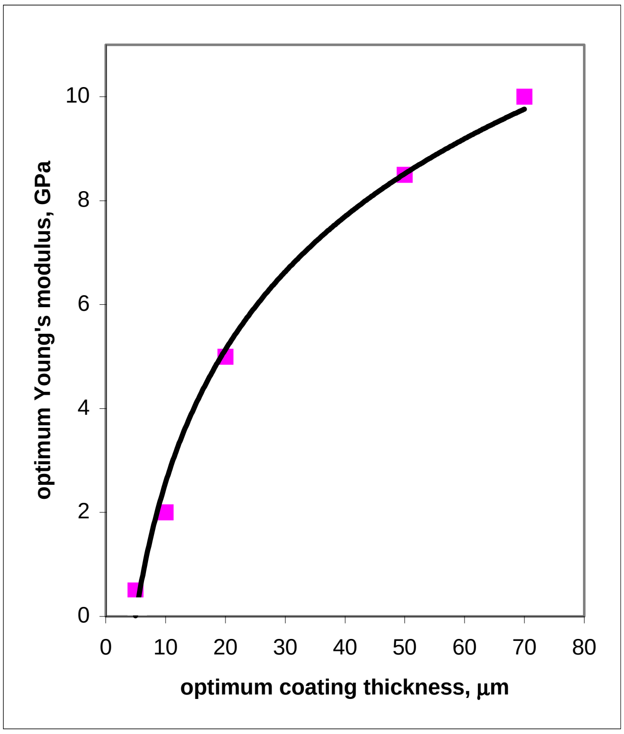

Fig. 1 Design curve for the optimum coating of a fibre optical sensor embedded in the 0° ply near the 0/90 interface of a crossply GFRP laminate.

The results of the numerical modelling (for details, see [6]) can be summarised in a design curve [Figure 1] which shows a relationship between optimum Young's modulus and optimum thickness for the coating of an optical fibre sensor near the 0/90 interface of a GFRP crossply laminate (a similar curve, but for a unidirectional composite has been shown in [8,9]). It is clear from Figure 1 that, as the coating thickness increases, the optimum modulus progressively moves to a higher value, being about 10 GPa for a coating thickness of 70 µm. However, the large physical size of such a sensor (i.e. a total diameter of 265 µm) is impractical, and small coating thicknesses are to be preferred. Two practical possibilities emerge for small coating thicknesses. A 10 µm coating thickness and a modulus of 2 GPa is one possibility, which corresponds to a commercially available optical fibre having a polyimide coating. A second possibility which emerges is a sensor surrounded by a sheath of epoxy resin matrix (which has a modulus of 4 GPa), with the reinforcing (glass) fibres spaced about 10-20 µm from the sensor.

3. EXPERIMENTAL

For the experimental study on obtrusivity under quasi-static loading, three types of coating have been studied: (i) a 10 µm polyimide coating (Young's modulus, 2 GPa); (ii) bare fibre surrounded by epoxy resin matrix; and (iii) a 70 µm acrylate coating (Young's modulus, 0.045 GPa). The first two cases represent minimum obtrusivity solutions from the point of view of the FE modelling. The third case is a high obtrusivity case from the point of view of the modelling. The samples were made in-house and the fabrication procedure is described below.

3.1 LAMINATE FABRICATION

Cross ply 0/90/90/0 glass/epoxy laminates were fabricated, both with and without optical fibres, using a filament winding/wet lay-up technique. The optical fibre sensors were embedded in the 0^0 ply, parallel to the reinforcing fibres and adjacent to the 0/90 interface. This was achieved by gluing the fibres into the grooves of a square frame around which the reinforcing fibres were filament wound. The epoxy matrix was Stag Epoxy Resin 300 (100 parts by weight) cured with Nadic Methyl Anhydride (60 parts by weight) and Stag curing agent K61B (4 parts by weight). The average fibre volume fraction for the laminates was about 0.5. The 0^0 plies on the surfaces, and the centre 90^0 ply, were each about 1 mm thick (giving a total thickness of about 3 mm). A reasonably thick transverse ply was chosen to facilitate later studies on the detection of damage initiation and growth using an active sensor. A cross section is shown in Figure 2.

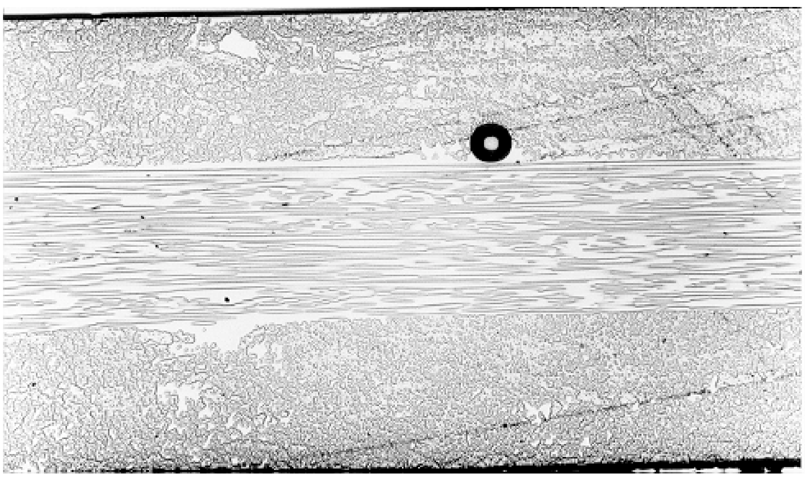

Fig. 2 A cross section of a crossply laminate with the optical fibre near the 0/90 interface.

The resulting laminates are optically transparent since the refractive indices of the reinforcing fibres and the matrix are closely matched. Aluminium end-tags were bonded to the specimens for testing. In all cases, the optical fibre sensor is located towards the centre of the coupon.

3.2 TESTING PROCEDURE

Quasi-static tensile tests were performed using an Instron 100kN-capacity screw-driven machine and an Instron servo-hydraulic testing machine under position or strain control. The testing speed was equivalent to 0.5 mm per minute for all tests. A 50mm gauge-length Instron extensometer was used for monitoring longitudinal strain. The extensometer knife edges rested on grooved seats, made of epoxy adhesive, to prevent them from slipping during the test. During each test, the specimens were loaded to progressively higher strain levels and unloaded for damage observations. Load and strain were measured using a data logger, while the damage state was recorded directly in transmitted light using a digital camera.

3.3 RESULTS

Figure 3 and Figure 4 show crack accumulation with applied strain for the optical fibre with a 70 µm acrylate coating (Fig. 3) and a 10 µm polyimide coating (Fig. 4).

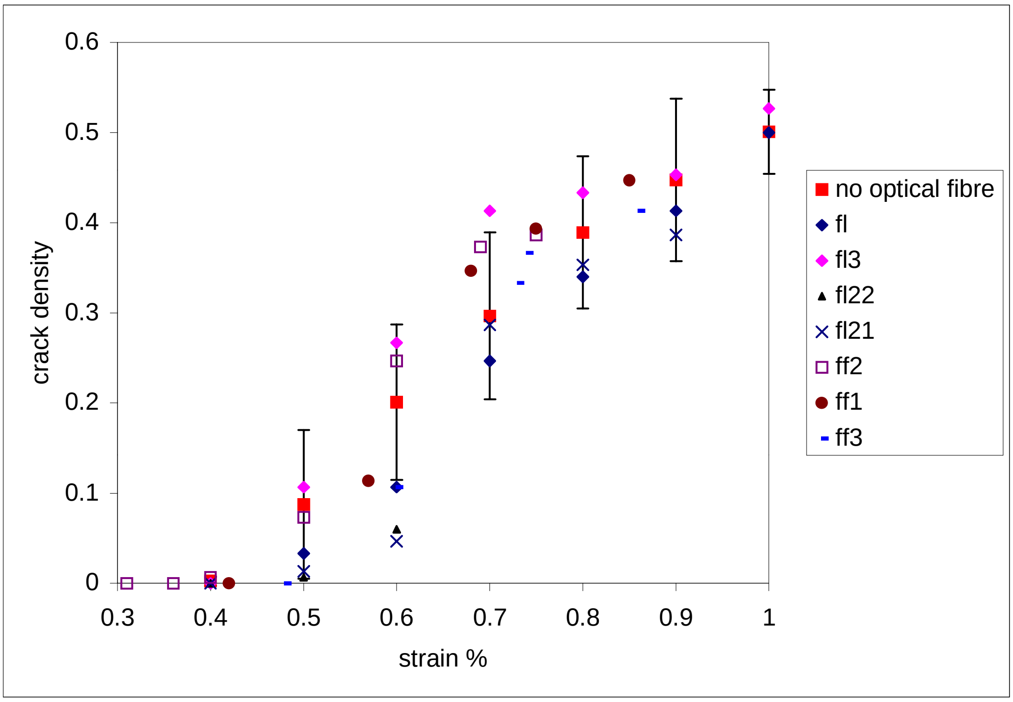

Fig. 3 Average values for crack density as a function of applied strain for the coupons without optical fibre (error bars show one standard deviation) and results for coupons with embedded optical fibre having a 70µm acrylate coating.

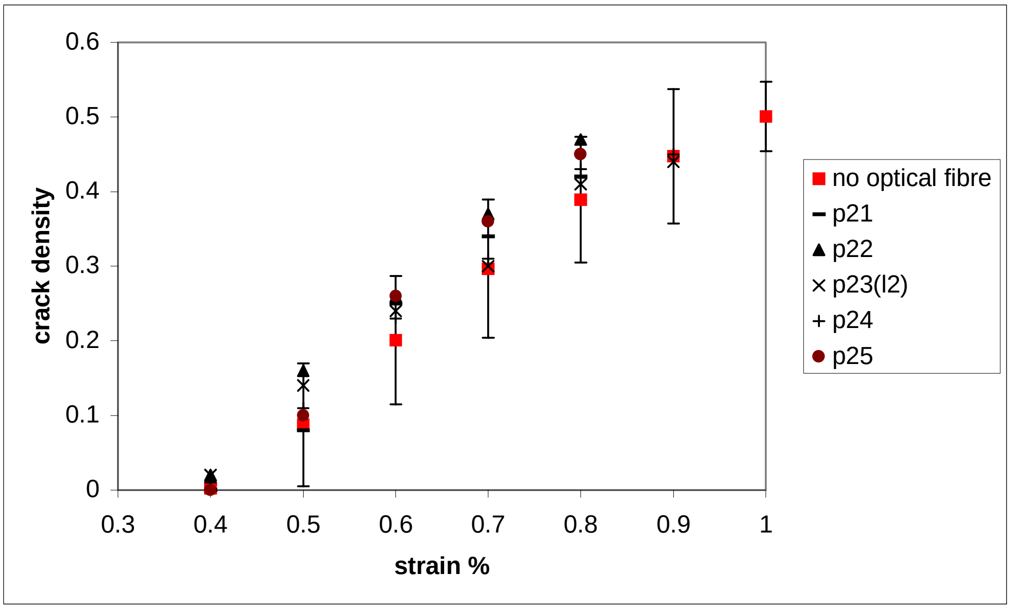

Fig. 4 Average values for crack density as a function of applied strain for the coupons without optical fibre (error bars show one standard deviation) and results for coupons with embedded optical fibre having a 10μm polyimide coating

The data has been superimposed, in both cases, onto crack accumulation/strain data for coupons tested without optical fibre sensors. It is clear that the results for both optical fibre coatings fall within the normal sample to sample variation of the laminates. In particular, it is important to note that, in both cases, the inclusion of the optical fibre sensor does not affect the cracking threshold. None of the cracks were initiated near the optical fibre sensor and almost all of the cracks were initiated at the edges of the coupons. Hence, for this model GFRP laminate under quasi-static loading, the stress concentration caused by the inclusion of an optical fibre with an obtrusive coating (i.e. the acrylate) or with the optimum coating (i.e. polyimide) is less, in both cases, than any free edge effect.

Figure 5 shows similar crack accumulation/strain results for the embedded bare optical fibre. These results appeared to show a difference with the samples tested without optical fibres since the crack density at all strains appears lower. Further tests were therefore carried out using coupons from the same laminate plate, but without optical fibres. The results (shown in Figure 6) indicate that for this panel the crack accumulation with strain was lower than for the panels tested previously with and without optical fibres. Hence, the inclusion of a bare optical fibre has not affected the accumulation of cracks.

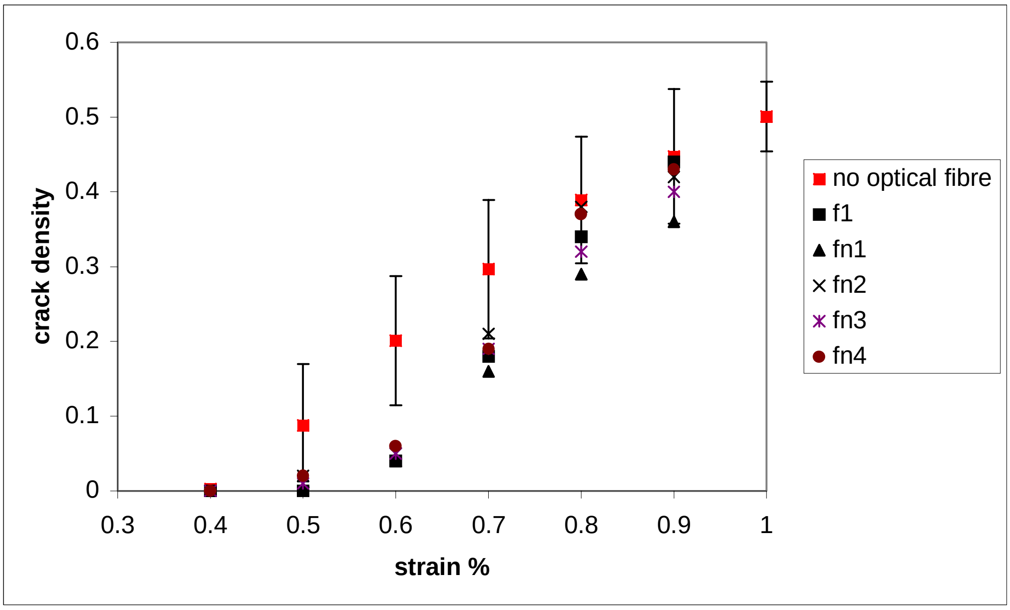

Fig. 5 Average values for crack density as a function of applied strain for the coupons without optical fibre (error bars show one standard deviation) and results for coupons with embedded 125μm diameter bare optical fibre.

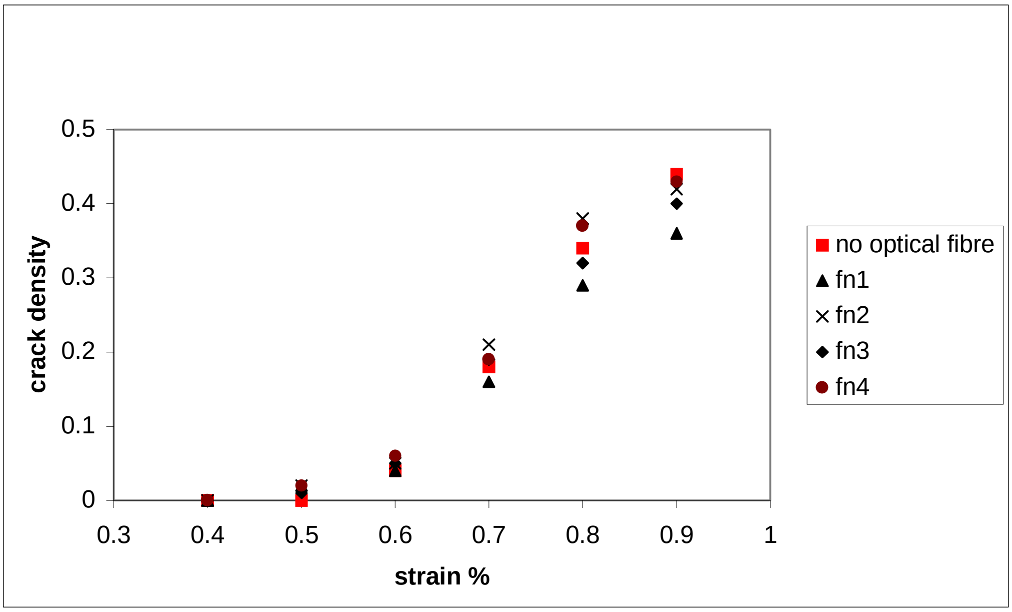

Fig. 6 Comparison of damage accumulation for coupons with embedded 125μm diameter bare optical fibre and coupons without optical fibres taken from the same panel.

4. CONCLUSIONS

A design curve for the optimum modulus and thickness of a coating on a fibre optical sensor embedded in the 0^0 plies near the 0/90 interface of a GFRP cross-ply laminate has been developed. The FE model indicates that for minimum obtrusivity the optimum Young's modulus for the coating increases with coating thickness.

The experimental work shows that for a model GFRP cross-ply composite laminate having a thick transverse ply, the inclusion of (i) bare optical fibres, (ii) optical fibres with a polyimide coating, and (iii) optical fibres with an acrylate coating does not affect crack initiation or crack accumulation under quasi-static loading.

5. ACKNOWLEDGEMENTS

The authors are grateful for the financial support of the Engineering and Physical Sciences Research Council (EPSRC).

6. REFERENCES

1. Dasgupta, A. and Sirkis, J.S, "Importance of Coating to Optical Fibre Sensors Embedded in 'Smart' Structures", *AIAA*, Vol. 30, No. 5, 1992, pp. 1337-1343.
2. Hadjiprocopiou, M., Reed, G.T., Hollaway, L., and Thorne, A.M., "Optimization of Fibre Coating Properties for Fibre Optic Smart Structures", *Smart Mater. Struct.*, Vol. 5, 1996, pp 441-448.
3. Carman, G.P., Averill, R.C., Reifsnider, K.L., and Reddy, J.N., "Optimization of Fiber Coating to Minimize Stress Concentrations in Composite Materials", *Journal of Composite Materials,* Vol.**27**, No 6, 1993, pp. 589-612.
4. Roberts, S.S.J., and Davidson, R., "Mechanical Properties of Composite Materials Containing Embedded Fibre Optic Sensors", *SPIE*, Vol. 1588, 1991, pp 326-241.
5. Case, S. W., and Carman, G.P., "Optimization of Fiber Coatings for Transverse Performance. An experimental study", *Journal of Composite materials*, Vol. **28**, No. 25, 1994, pp. 1452-1466.
6. Barton, E., Ogin, S., Thorne, A., and Reed, G., "Optimisation of a Coating of a Fibre Optical Sensor Embedded in a Crossply GFRP Laminate", (in preparation).
7. Lekhnitskii, S.G., *Anisotropic plates*, Gordon and Breach Science Publishers, New York, 1968.
8. Carman, G., and Reifsnider, K., "Analytical Optimization of Coating Properties for Actuators and Sensors", *Journal of Intelligent material Systems and Structures*, Vol. **4**, 1993, pp. 89-97.
9. Sirkis, J.S., and Dasgupta, A., "The Importance of Optimal Coatings to Structurally Embedded Optical Fiber Sensors in Smart Structures", *AIAA Journal*, Vol. **30**, No. 5, 1992, pp. 1337-1343.