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Factors Affecting The Embedding of Optical Fibre Sensors in Advanced Composite Structures

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1. INTRODUCTION

Composite materials offer tremendous benefits for engineering applications and are now specified for use in several safety critical structures. However, despite extensive materials research and development, they do have a number of areas where their behaviour is still not fully understood.

This is particularly so with the more complex mechanical parameters in larger structures. Current structural design attempts to allow for these unknowns by over-designing, extensive testing and frequent inspection.

Embedded optical fibre sensors offer the potential to monitor many of these parameters, and are additionally of a similar physical and mechanical nature to the reinforcement fibres used in advanced composites.

Westland Aerospace have been involved in the development of fibre sensors for composite monitoring for over five years, and pioneered the application of embedded fibre sensors in thermoplastic composites during earlier joint research projects with the United Technologies Research Centre.[1]

Previous programmes have shown that research and development into both optical fibre sensors and materials is a key to the success of "smart structures" technologies.

The BRITE sponsored Optical Sensing Techniques in Composites (OSTIC) programme represents the largest European research programme to date. Similar research is underway at several centres worldwide, mainly in the USA and Canada.

It was decided to set up a joint sensors/materials project under the UK Government supported LINK Structural Composites collaborative research programme. The project will be performed by Westland Aerospace and the Optical Fibre Sensors Group at the UK Optoelectronics Research Centre.

This paper addresses factors relating to the development and application of optical fibre strain sensors for the monitoring of composite structures, and in particular the factors relating to the embedding of these optical fibres in composite laminates.

2. APPLICATIONS OF FIBRE SENSORS IN SMART STRUCTURES

2.1 Advantages of Fibre Sensors

Embedded fibre optic sensors offer the potential to measure several parameters in their host material, such as dynamically varying strain and temperature. In addition, they are immune to corrosion, lightning strike, and electro-magnetic interference.

Fibre sensors are particularly attractive for structural monitoring since they offer both point and distributed sensing. Since the fibre transmits the measurement signal, multiplexed point sensing can be easily realized.

The optical fibre contains both the sensing and the telemetry system without the need for any mechanical discontinuities, which would occur with electrical sensors and their connections. Thus the fibre sensor should give a more reliable sensing system and is compatible with the adoption of optical fibre based data transmis sion links in modern aircraft.

In the longer term it will be possible to actively control the shape or properties of the composite by means of embedded actuators, which can be monitored and hence controlled by the same sensing system.

2.2 Structural Health Monitoring

Composite materials are currently used in critical structure applications where they may be simultaneously subjected to extremes of temperature and high levels of mechanical loading.

The long term reliability of composites in such environments is uncertain. There is therefore a need to monitor the integrity under such conditions. **Continuous monitoring** will allow inspection or replacement scheduling to be based on a true record of loading history and structure performance (rather than simply on the basis of a pre-determined life which must be conservative to cater for worst-case scenarios). Safety will also benefit, since structural damage will be detected immediately even in inaccessible areas. Continuous monitoring will also offer enhanced design efficiency since information on structure performance in service can be applied in the design of future structures.

A structural monitoring system should have the ability to memorise the strain field distributions resulting from normal structure performance, and be able to recognise potentially dangerous uncharacteristic behaviour. It also should be capable of determining the natural frequency of the structure, which are known to be related to structural health. Fibre optic sensors have been shown to be capable of accurate measurement of at least the first three natural frequencies of composite structures.[1]

2.3 Integrated Sensor/Actuator Packages

It is envisaged that embedded fibre sensors could be used with integral actuating capabilities. Such a sensor/actuator package is presented in Figure 1.[2] The package features an optical fibre strain sensor with an electro-strictive coating. Due to the fast response time, this can operate in separate modes:-

1) actuator
2) sensor
3) time shared sensor/actuator.

In the actuator mode, a control voltage applied across the coating will produce strain in the optical fibre and in the surrounding host composite. By combining several actuators we could control the behaviour of the host structure.

In the sensor mode, loads applied to the structure produce an electrical signal which can be used to calibrate the optical fibre sensor.

In the time share mode, the coating is used both as a sensor and an actuator in the following way: an electrical control signal is applied to the coating so as to produce in it a mechanical strain which will depend on the stiffness of host material local to the sensor/actuator, and this strain is monitored with the fibre sensor. The control voltage is now switched off and the relaxation of the host structure is monitored with the fibre sensor.

We are thus able to monitor or control static and dynamic mechanical properties, both of the host material local to the fibre/actuator package and of the host structure.

2.4 Process Monitoring

Reliable processing of composite materials and bonding of cured laminates relies on the precise measurement of process critical parameters such as pressure and temperature.

The trend towards increasing use of co-curing of components, together with increasing component size and complexity, can cause difficulties in maintaining consistency in process parameters.

Embedded fibre sensors, integrated prior to processing, may provide valuable potential for measurements in the following areas;

1) Pressure
2) Temperature
3) Cure state
4) Residual strain.

3. FACTORS AFFECTING EMBEDDING

3.1 General Discussion

Many practical issues relating to the embedding of optical fibres need to be resolved before the commercial application of smart structures can become feasible. Introduction of the optical fibre sensor into the manufacturing cycle of the composite structure presents a considerable technological challenge, since current manufacturing processes are generally incompatible with fragile optical fibres. Ideally, the embedding of optical fibres would be accomplished with only minor changes to such processes.

The large number of sensors required, together with the complexity of associated sensing optics and signal processing electronics, are likely to represent significant cost increases in the near term. It is important therefore to examine the embedding process to minimise the fabrication costs.

The successful embedding of optical fibres into engineering structures requires the solution of several practical difficulties. The key areas requiring attention are:

1) development of specialised optical fibres and coatings for embedding,
2) development of methods for handling the fragile optical fibre,
3) development of a reliable method of connecting the embedded optical fibre to the external monitoring system.

3.2 Special Optical Fibres and Coatings

Optical fibres suitable for embedding as sensors in composite materials present very different requirements to those for communications fibres. The range of optical fibres which have been specially developed for sensing purposes are very limited, and there are presently no fibres developed specially for monitoring in composite materials which are commercially available. We therefore intend in our programme to develop and manufacture fibres specifically for this purpose.

The fibre construction must satisfy the following requirements:

1) Small diameter. Embedded sensor fibre diameter should be optimised so as to produce minimum perturbation to the very small (approx. 10 micron diameter) composite material reinforcement fibres.
2) Robustness. The fibre must possess adequate handling properties, and be capable of surviving the high pressures and temperatures encountered in composite materials processing, and should be resistant to abrasion from the composite reinforcement fibres.
3) Mechanical property compatibility. Mechanical design of the coating, to ensure efficient performance of the sensor as a strain transducer, and to prevent the sensor fibre behaving as a significant strain concentration within the composite, is required.
4) Environmental compatibility. The sensor fibre must be inert with respect to the resin used in the composite,
5) Buffering from microbends. Microbending of an embedded sensor fibre occurs when either bare or coated fibres are embedded in woven reinforcement composite materials. Tiny microbends increase the optical attenuation and can introduce

mechanical strain in the optical fibre. They must therefore be minimised by suitable coatings.

Buffering of the embedded fibre against microbending loss may require the use of coatings with a degree of lateral compliance.

6) Adhesion promotion. Strong and robust bonding between the embedded sensor fibre and the host composite is essential if the embedded fibre is to perform as a reliable transducer without weakening the host material.

Since the range of properties of the optical fibres themselves is generally limited, it is anticipated that multiple coatings could be required.

Figure 2 shows a generic fibre sensor/coating package. The optical fibre is afforded environmental protection by a primary coating. A secondary coating is present to optimise mechanical coupling and promote adhesion between the fibre sensor and the composite.

3.3 Embedding Methods

A primary concern is in the handling of the fragile optical fibres during lamination of the composite. A method allowing production of an insert layer of optical fibre/composite material is required. This layer can then be laminated with other layers in the normal production process.

Figure 3 shows a new method for introducing optical fibres into pre-preg laminates.[3] The method involves the following stages:

1) The optical fibres are laid into grooves in a non-stick pattern tool.
2) Resin of the same type as that used in the composite pre-preg is applied as a film. A controlled amount is applied to maintain the resin/fibre ratio of the composite.
3) The resin is cured to the same state as the resin in the host pre-preg.
4) Pre-preg ply #1 (ie one of the pre-preg plies used next to the fibre sensor in the laminate) is pressed onto the optical fibre in the resin film and the two are withdrawn leaving the optical fibre/resin film now held in place by the tackiness of the partially cured resin.
5) Pre-preg ply #2 (ie the other pre-preg ply used next to the fibre sensor in the laminate) is pressed onto the optical fibre/resin film so as to sandwich the optical fibre/resin film between the two plies of pre-preg.
6) A protective backing film is applied to the sandwich, allowing it to be handled and stored.

The above method has the following advantages;

1) The fibre sensor/pre-preg sandwich is robust and easy to handle, with the fragile optical fibre afforded protection by the pre-preg when sandwiched.
2) Testing of the optical fibre in the fibre sensor/pre-preg package can be performed prior to final laminating to minimise the chance of embedding a damaged optical fibre.
3) The fibre sensor/pre-preg sandwich is easily integrated into the structure manufacturing cycle, as it may be treated almost as any other ply of pre-preg, and hence does not slow the laminating sequence significantly.
4) The sandwich can be bulk manufactured to reduce cost. Generalised forms, such as tapes, could be used in many different structures.
5) The method is suited to automated production. Automated placement of optical fibres as a separate operation would be much more difficult to achieve during typical lamination operations.

3.4 Connecting The Fibre Sensor

Development of a reliable method of connecting the embedded fibre to external fibre links is particularly critical. Such a method should be;

1) consistent with the manufacturing processes of composite structure, such as autoclave moulding and edge trimming,
2) environmentally insensitive, ie should not be affected by vibration, temperature fluctuation, moisture ingress, etc,
3) low cost and repairable.

Many types of fibre sensor require the use of monomode optical fibre which have core diameters of typically less than 10 microns. Clearly, achieving reliable connection between two fibres (ie end alignment) with such small dimensions presents practical difficulties in an industrial environment.

3.5 Possible Deleterious Effects of Embedded Fibre

Researchers have generally agreed that optical fibres tend to produce only minimal perturbation to reinforcing fibres when embedded parallel to them, but a large disturbance may result when the optical fibre is embedded across the direction of the reinforcement fibres.[4,5,6] The non-parallel alignment results in a greater distortion of the reinforcement fibres and a large resin-rich region, both of which may be detrimental to the strength of the laminate.

Several groups of researchers have performed mechanical test programmes in which composite testpieces containing optical fibres have been tested in a number of configurations. Conflicting results have been obtained, with the effects of embedding ranging from relatively insignificant to severe.[7] Further investigation may yet reveal other problems, such as reduced fatigue performance or inferior failure behaviour. Therefore, it is essential that any detrimental effects on the mechanical properties of the host composite material are fully quantified.

4. DETAILS OF THE CURRENT PROJECT

4.1 Background to the Project

As mentioned in the introduction, a three year research project has been set up as part of the U.K government supported LINK Structural Composites Programme. This project between Westland Aerospace Ltd and the University of Southampton's Optoelectronics Research Centre is being undertaken in response to the perceived need for smart structures research and development within the civil aerospace industry.

Under the LINK scheme, collaborative research projects benefit from shared expertise. Technological developments in advanced materials and optical fibre sensors are undoubtably a key to advancement in smart structures, and the joint programme is designed to stimulate progress in both of these areas.

Within the two broad disciplines several other activities arise. Figure 4 illustrates the range of these activities. These activities are addressed in detail in the following paragraphs.

4.2 Fibre Sensors for Composite Material Monitoring

4.2.1 Basic Principles

In order to sense a parameter affecting the composite, it must produce a measurable effect on the properties of the fibre (*modulation*). Modulation of the optical path length is (in contrast to modulation of the intensity) convenient to use since delays in the optical signal are not influenced by changes of the optical attenuation in the system.

Optical delays may be interrogated using either:
1) an interferometric sensor, or
2) optical time domain reflectometry (OTDR).

An interferometric sensor is very sensitive to changes in the order of the wavelength of light (ca 1μm) or less, but can suffer from ambiguity when measuring larger changes, unless considerable care is taken to provide complex phase referencing schemes. It hence lends itself to local strain measurement in short lengths of fibre, using the remainder of the fibre for signal transmission only.

Conventional OTDR systems measure the optical propagation delays to and from reflective points in a fibre. They can interrogate long lengths of fibre (kilometres) for inhomogeneities (ie reflective points), but can typically only discern such points with centimetre resolution. Monitoring the difference between the time delays from each of the inhomogeneities allows the measurement of averaged strain between these inhomogeneities.

4.2.2 Proposed Optical Fibre Sensor

Our measurement philosophy attempts to combine the "best of both worlds" to achieve a very efficient sensor system. We propose to construct an enhanced OTDR system to track the position of inhomogeneities along the length of a fibre, and to use the inhomogeneities themselves as local strain sensors (Fig 5).

To achieve the first aim, we have designed a novel OTDR system intended to improve the spatial resolution of current OTDR systems. Our enhanced OTDR will monitor the location of inhomogeneities in the fibre. Bragg gratings are an appropriate form of inhomogeneity as they provide suitable reflective points for OTDR monitoring.

In addition each grating also provides a discrete-point sensing capability since they respond to local strain by changing their reflected wavelength.[8] In this manner they act as an interferometric sensor which can be interrogated unambiguously.

By using both the time delay of the reflections from the gratings and the reflected wavelength of the gratings, a system can be developed which provides information on both line-averaged and local strain (Fig 5). When multiple gratings are incorporated in one fibre a multiplexed sensor system can be produced. Such a configuration greatly reduces the number of fibres needed to interrogate a given structure.

In general, the response of a fibre to temperature variation is of the same order of magnitude as the response to strain. Therefore considerable effort will be directed into providing temperature compensation to realize a practical system capable of operation over an extended temperature range.

One of the most promising approaches is a system having different responses to strain and temperature, thereby allowing independent measurement of the two responses.

Work is well under way on our enhanced OTDR system and we are looking forward to publishing further details of the basic concepts and the first results on the strain response in the near future.

4.3 Mechanical Modelling of Sensors in Composites

Preliminary analytical studies of the micromechanics of optical fibres embedded in composites have attempted to predict the complex interaction between the embedded optical fibre sensor and the host material.[9,10,11] To date however, many of these models have considered only the simplest case conditions and have generally been applied only to interferometric type sensors. Developments are needed which will predict strain fields within the optical fibre itself and which may be applied to more general conditions of structural loading and environmental effects. Such models will prove indispensable in deriving more precise and useful measurement data from the optical signals, and in establishing optimum coatings etc. for the embedded sensors.

One of the sensor systems which we are developing will employ Bragg gratings, which can be produced with lengths of the order of 1 mm. Hence we can effectively model the embedded fibre sensor as a point sensor. Much of the analytical micromechanical modelling reported to date has concerned standard interferometric type optical fibre sensors, and will require some adaption to apply it to Bragg type sensors.

Micromechanic modelling will be used to provide information on the optimum diameter and mechanical properties of embedded fibres and their coatings. Models will be based on observations of embedded fibres and will include, for example, regions of resin richness. Models will predict the concentration of strain in the fibre, in its fibre coating and in the host composite. These will allow an optimised fibre/coating, compatible with the composite matrix to be selected (ie one producing minimum strain concentration).

Finite element techniques have been applied to the problem of micromechanical modelling of embedded optical fibres in composites. Such approaches have been shown to yield useful information on the intensity and distribution of strain fields. Within the scope of the present project it is intended to make further use of such techniques to predict strain levels and states in embedded fibres, and to aid in the optimisation of fibre sensor coatings.

4.4 Mechanical Tests of Composites with Embedded Sensors

As mentioned earlier, it is important to assess the effects of the presence of an embedded optical fibre on the mechanical properties of the host laminate, and to establish the long term service durability of fibre coatings. The two main reasons for this are:-

1) The usefulness of embedded fibre sensors in long term structure health monitoring is lost if the sensor package fails prematurely.
2) The advantages of the embedded sensor are dubious if its presence compromises the performance of the host structure.

Previous research has shown that the nature and dimensions of the embedded optical fibre and its coating are significant in determining the effect on the mechanical properties of the host material.[12,13] It is proposed to investigate this aspect further to ensure that the optical fibre and its coating are optimised to produce minimal degradation of the host laminate properties. The optimisation will involve designing the embedded fibre for optimum performance as a mechanical strain transducer, whilst ensuring the long term survival of the fibre sensor and composite.

Longitudinal compressive testing is likely to be sensitive to the presence of an embedded optical fibre since bridging of the optical fibre by the reinforcement fibres represents an approximation to a pre-buckled condition.[14] Interlaminar shear testing is also envisaged to be a sensitive test as the combination of fibre bridging and a resin rich zone will tend to aggravate laminate de-lamination in the presence of applied shear strain. Both tests will be part of this programme.

It is also proposed to perform fatigue assessment studies in which the service environment is simulated as closely as possible.

A number of material characterisation methods are intended to be used to study in detail the effect of embedded optical fibres on both the mechanical properties and the quality of the host composite materials. Figure 6 lists the main classes of tests proposed within the scope of the current project.Non-destructive Tests (*NDT*) of Composites with Embedded SensorsAs mentioned before, defects arising from the embedding of optical fibres in laminates have been shown to include resin-rich regions and distortion of reinforcement fibres. One method of assessing the extent of these is by micrographic examination of polished sections of laminate, but clearly alternative, non-destructive techniques need to be developed.

Typical aerospace techniques include ultrasonic scanning and X-ray imaging. The applicability of both of these techniques will be investigated. However, preliminary studies have indicated that the small size of the optical fibre will in some cases restrict the applicability of such techniques.

5. PRELIMINARY FINDINGS

This section describes our results achieved so far. Some of the earlier results were achieved before the LINK programme.

5.1 Embedding trials with thermoset materials

Embedding of optical fibres in thermoset pre-preg material was investigated. The composite was in this case processed by the autoclave moulding technique.

5.1.1 Method of manufacture and test

Embedding of optical fibres in thermoset pre-preg material (ie reinforcement fabric pre-impregnated with resin) was investigated. The composite was in this case processed by the autoclave moulding technique.

125 μm diameter multimode optical fibre was stripped of its protective coatings and cleaned. Various narrow bore tubes, as detailed below, were used to protect the fragile optical fibre at the points of exit from the test-panels. Approximately 10 cm of optical fibre was embedded in each case, with 9 cms unprotected and with the protective tube extending approximately 1 cm into the panel.

The test panels were fabricated from 8 plies of a carbon fibre reinforced pre-preg material (NARMCO® R5250-T300 Bismaleimide thermoset resin/ 3K 5-Harness satin woven fabric). The cure cycle for this material involve curing at 175°C (350°F) under a pressure of 586 kPa (85 p.s.i) for 6 hours. This material was used because the higher than typical cure pressure, and the longer than typical cure periods associated with it, were reasoned to provide a more demanding test of the effectiveness and durability. Optical loss measurements were performed (i) before application of vacuum consolidation pressure, (ii) after application of vacuum consolidation pressure, and (iii) after curing of the composite.

5.1.2 Results of trial panel manufacture tests

The results of our embedding tests, in terms of the optical attenuation during curing, are shown below. Loss measurements were made using flying leads fitted with temporary mechanical splices. The losses were measured relative to unstrained sensor fibre, connected via leads to source and detector. This was measured before embedding in the composite to provide the zero loss reference level in column 1 in table below.

Protective tube	Loss before consolidation (dB)	Loss after consolidation (dB)	Loss after cure (dB)
Polyimide			
140/160 μm ID/OD	0	0.09	0.50
Silicone			
250/2250 μm ID/OD	0	0.07	0.43
PTFE			
140-250 μm ID/OD	0	0.07	0.43
Stainless Steel			
200/400 μm ID/OD	0	0.15	0.87

5.1.3 Summary

In each case, relatively small increases in optical attenuation were suffered as a result of consolidation and curing of the host laminate. The increase can in each case be attributed to increased microbend attenuation. Optical fibre fracture would be expected to produce larger losses. From this we conclude that protection of the fragile optical fibre at the laminate exit may be afforded by means of a close fitting polymer or metal tube. Further investigations will attempt to confirm that failure has not occurred, for example by using short distance resolution OTDR to examine for reflections from breaks. The OTDR will also help to locate the origin of microbend induced losses.

5.2 Embedding trials with advanced thermoplastic materials

Embedding of optical fibres in advanced thermoplastic composite materials was investigated.

A twin-core fibre sensor, with an external diameter of 125 μm, was embedded in carbon fibre reinforced thermoplastic material (ICI APC2 PEEK/AS4). The composite material was moulded into a tube (Figure 7). The tube was manufactured by laying the pre-preg onto a rigid mandrel and subsequently consolidating using an inflatable diaphragm process.

A reinforcement fibre orientation of +30°,-30°,0°,0°,-30°,+30°, was used, where the 0° direction is that of the tube length axis. The fibre optic sensor was placed in 0° direction between the two 0° reinforcement fibre plies with a layer of pure PEEK film either side to give further protection. The assembly was transferred to a split female cavity tool (Figure 8) which was placed between the platens of a 500 ton electrically heated press. The tool was heated to

380°C and internal pressure was increased in increments of 1 bar up to a maximum of 14 bar. After dwelling for 15 minutes, the press was cooled to room temperature and the tube removed. The internal diaphragm was removed by acid digestion.

Early attempts invariably resulted in fracture of the embedded fibre at the point of exit from the composite laminate. The following three approaches were adopted with the aim of overcoming this problem:

1) The tube was moulded with no end support for the emerging optical fibres, which were simply run directly along the mandrel and through holes drilled in the tool end plates. Moulding resulted in fracture of the embedded fibre at the point of exit from the laminate.

2) Support tape, 3 plies thick (ie the thickness of the laminate between the fibre sensor and the diaphragm) was wrapped around the diaphragm between the pre-preg and the mould tool ends to provide a smooth even thickness over the transition area. This was then overwrapped with tape to form a cushion for the emerging optical fibres. The ends of the emerging optical fibre were wrapped around the mandrel ends and secured. Moulding again resulted in fracture of the fibre sensor at the point of exit from the laminate.

3) A very small bore stiff tube was slipped over the fibre sensor, penetrating approximately 1 mm into the laminate. The tube was subsequently removed after moulding. A successful moulding operation resulted which did not cause optical fibre fracture.

5.3 Securing of Fibre Sensor Connectors

Bare optical fibre, terminated with modified FC type connectors, was moulded into a test laminates to demonstrate the feasibility of this technique.

Molex FC connectors were modified for embedding by removing the threaded securing sleeve, leaving only the ceramic ferrule and the plastic body of the connector. The connector was further modified by turning the plastic body down to a diameter of only 2.5 mm. A PTFE block was machined to accept the connector and was designed to restrict the outward flow of resin from the pre-preg during consolidation. Bare 125 μm optical fibre was terminated with the modified connectors and embedded between plies 8 and 9 of a 16 ply BMS 8-79 type woven glass/epoxy pre-preg material. An optical attenuation measurement was made. The test panel was cured at 125°C under a pressure of 293 kPa for two hours.

The cured laminate was examined visually and appeared to be of reasonable quality. The connectors appeared to have been slightly displaced and some resin had flowed into the PTFE block and adhered to the connectors. Optical loss measurement confirmed only a slight increase in attenuation of 3 dB which was probably due to increased microbend attenuation, confirming that the optical fibre had survived the embedding process. Investigations of the effect of the connector on the host material are underway. Further research will attempt to develop improved connectors with reduced overall diameters.

5.4 NDT Investigation of Fibre Sensor Embedding

Experiments were designed to study the effectiveness of aerospace type NDT techniques in assessing the effect of an embedded optical fibre on the host material.

5.4.1 Effect of varying embedded fibre diameter

Rings of optical fibre (of various types and diameters) were manufactured by fusion splicing the ends of short lengths of fibre together. The rings were laid down as concentric circles in a 25 cm square laminate between plies 4 and 5 of 10 plies of BMS 8-79 3K 5-Harness satin woven, glass reinforced epoxy pre-preg.

Three fibres were embedded

1) a 125 μm outer diameter (*OD*) bare glass fibre,
2) a 200 μm OD bare glass fibre and
3) a 125 μm glass fibre with a 900 μm OD acrylate coating.

The panel was cured and investigated using "C" type ultrasonic scanning (Figure 9).

Only the 900 μm OD fibre was clearly visible in this preliminary investigation. Optimisation of the various ultrasonic NDT parameters may allow detection of the smaller fibres. However these and other results suggest that the problem of resolving inclusions of dimensions typical of bare optical fibres will require development of special NDT techniques. It is possible that detection of the embedded fibre is made more difficult by the fact that the host laminate already consists mainly of glass fibre, and hence the ultrasonic attenuation properties are similar.

5.4.2 Detection of embedded fibres in carbon reinforced laminates

In another experiment, 20 metres of 125/250 micron diameter (fibre/polymer coating) was embedded in a 16 ply (R52-50/T300-3K 5-Harness satin woven carbon reinforced Bismaleimide) pre-preg laminate, approximately 80 x 130 cm. Approximately 10 metres were embedded between plies 4 and 5, and the remaining 10 metres embedded between plies 11 and 12. The fibre was laid into the panel so as to follow a serpentine pattern. A single piece of fibre was used, with a short length of 1 mm diameter silicone tube used to protect the fibre in the region where the fibre entered and exited the laminate and in the connecting region. The laminate was cured and examined by ultrasonic C scanning shown in Figure 10.

The embedded fibre can be seen quite clearly as a green line against a pink background. The effect of the fibre is to increase the ultrasonic attenuation by 1 dB above the background. The white regions represent the regions where the protective silicone tube extends into the laminate. These regions show markedly higher attenuations, and are significantly larger than the tube diameter. The top region of the panel shows increased attenuation, which is due to porosity resulting from a manufacturing defect (the bag seal failed early on during cure, and the laminate was simply re-bagged and the cure process continued).

We are proposing to investigate other techniques, such as ultrasonic "A" scan and conventional and advanced forms of X ray such as X ray tomography.

5.5 Investigation of Microbending Attenuation of Embedded Sensor

A 60 cm circular loop of bare 50/125 μm optical fibre was embedded in the mid plane of an 8 ply (R5250 3K 5HS woven carbon fibre reinforced Bismaleimide) laminate. The emerging ends of the fibre sensor were sleeved in silicone tube for protection. The fibre ends were terminated previous to embedding to facilitate measurements of optical loss.

Loss measurements were made;

1) Prior to embedding with no mechanical pressure on fibre 0 dB,

2) after embedding 0 dB,

3) after applying vacuum consolidation pressure to the laminate 0.02 dB,

after curing the laminate 3.20 dB.

Embedded bare 125 μm optical fibre apparently does not suffer from increased microbend attenuation even when the laminate experiences applied pressures of 1 bar. Curing of the laminate occurs under applied pressures equivalent to about 5 bar. At these higher pressures the fibre sensor apparently suffers from increased microbend attenuation. This microbending is presumably retained in the cured laminate. The increased loss of 3.18 dB over a length of 60 cm of embedded fibre will not be significant for measurement, but could indicate a risk of later strain corrosion of the fibre sensor.

Further investigations will attempt to discern whether the increased loss occurs at the point of exit of the embedded fibre from the laminate or in the sensor fibre.

5.6 Summary

Investigations into aspects of fibre sensor embedding have revealed that:

1) Exiting the fibre through narrow diameter tubes, of either polyimide, silicone or steel, affords sufficient protection of the fibre to allow bare optical fibres to survive typical (pre-preg/bag moulding) composite processing environments.

2) Moulding of connectors into laminates can be accomplished without damaging the fragile fibre sensor.

3) Ultrasonic "C" type scanning techniques are not completely effective for locating optical fibres of the dimensions typically used for embedded sensors.

4) Micro-bend attenuation of fibre sensors in typical woven fibre composites is an issue which requires further investigation. However preliminary investigations have revealed this effect may not be particularly severe, at least for moderate sensor lengths of the order of 1 metre.

6. CONCLUSION

Past experience and extensive recent literature searching has allowed us to establish clearly the technological areas of smart structures requiring detailed further development. We have therefore set up a three year collaborative research and development project which will further our expertise in;

1) Fibre optic sensors and sensor signal processing,

2) Materials and manufacturing of smart structures.

We aim to develop novel multiplexed Bragg grating type sensors capable of multiple independent discrete measurements of strain and temperature. We will also develop materials and manufacturing techniques, and generate design information, consistent with advanced composite structures. During the project we aim to explore the use of embedded fibre sensors in the monitoring of advanced materials and structures manufacturing.

The project will culminate in the manufacture of a demonstrator component. Extensive materials and processes related research and development, performed during the project, is intended to allow the demonstrator to be both technically and industrially relevant.

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3.patent pending

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- CALIBRATION OF SENSORS
- STRUCTURE CHARACTERISATION

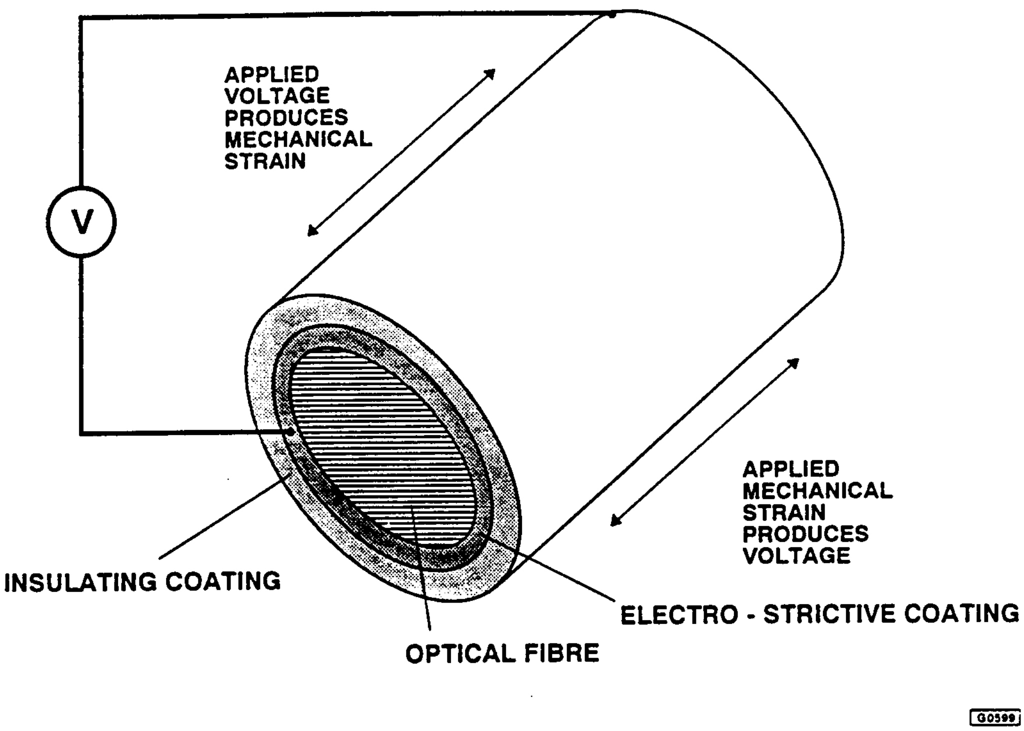
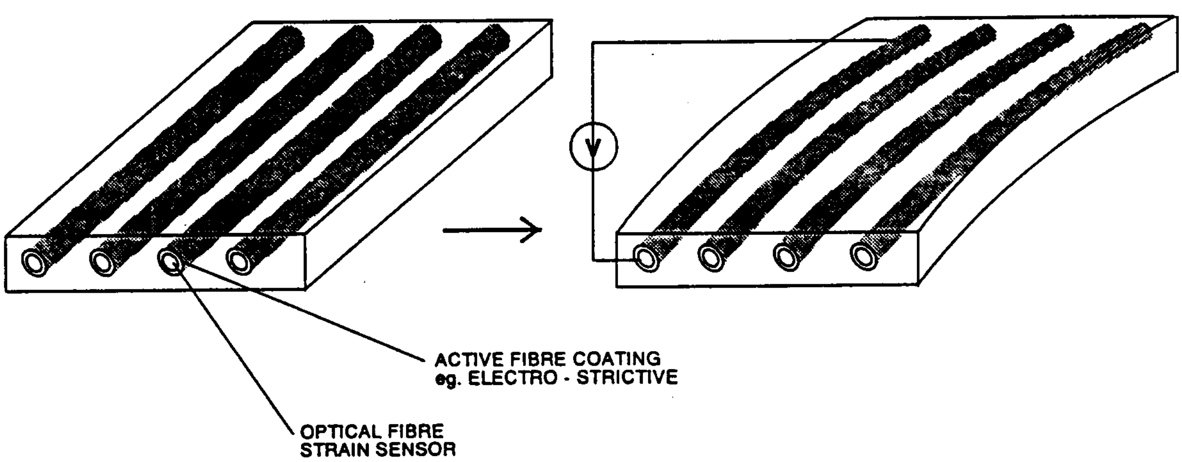


FIGURE 1a - INTEGRATED SENSOR/ACTUATOR PACKAGE

DAMAGE / DEFECT DETECTION - COMBINATION OF OPTICAL FIBRE SENSING AND 'ACTIVE' FIBRE COATINGS PROVIDE MEANS FOR INTERROGATING MATERIAL AND STRUCTURE HEALTH



ARRAY OF COMBINED SENSOR / ACTUATOR PACKAGES MONITOR MATERIALS MECHANICAL RESPONSE

STRUCTURE IS DRIVEN BY ACTIVE ELEMENT, AND MODE SHAPES AND FREQUENCIES DETERMINED BY SENSOR ELEMENTS

FIGURE 1b - HEALTH MONITORING BY FIBRE SENSOR/ACTUATOR PACKAGES

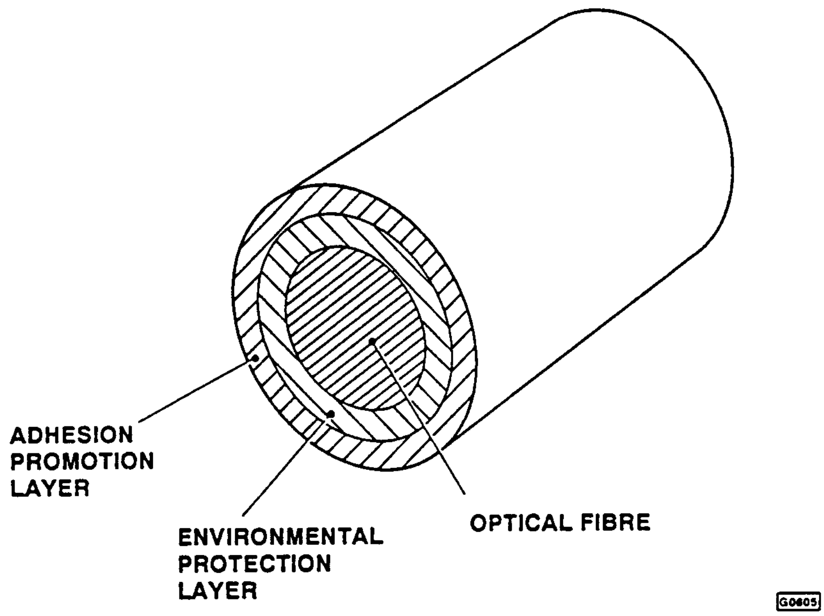


FIGURE 2 - GENERIC SENSOR/COATING PACKAGE

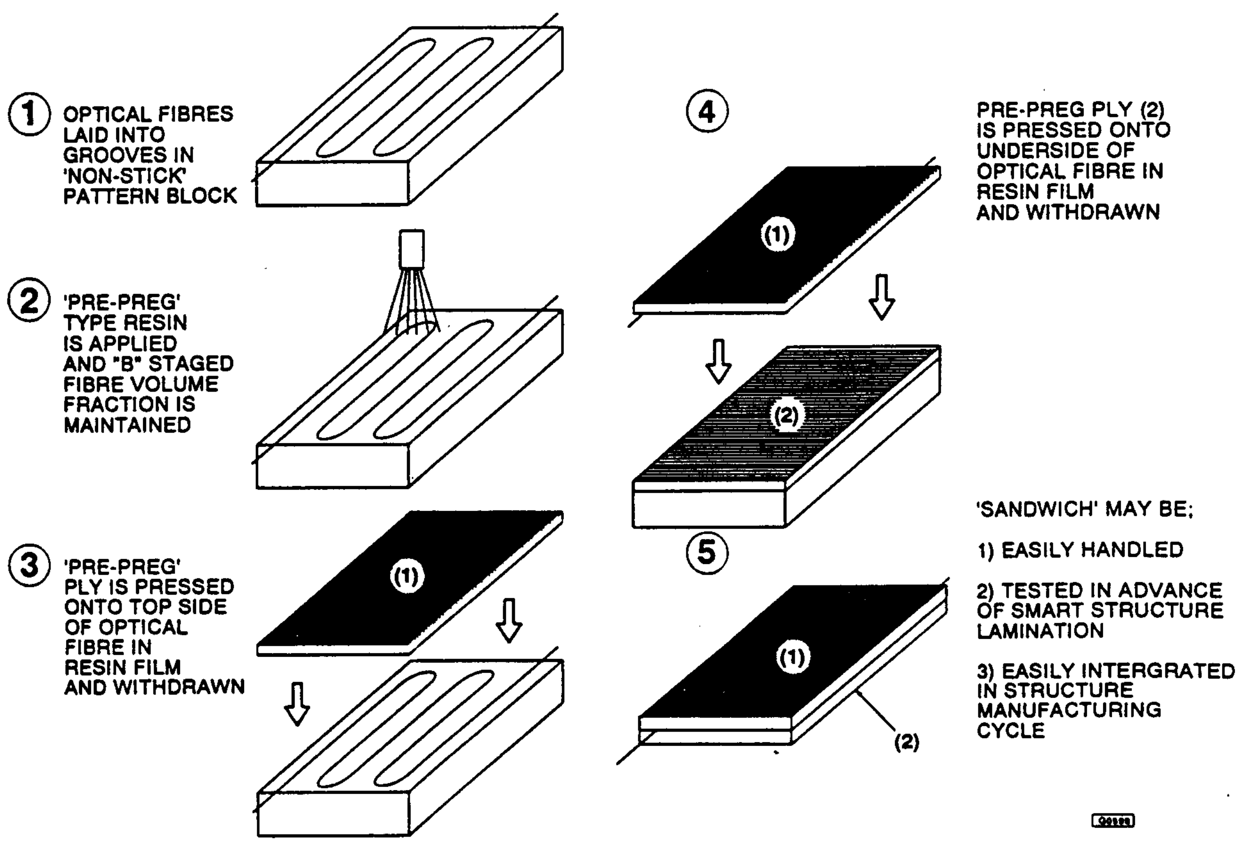


FIGURE 3 - EMBEDDING METHOD

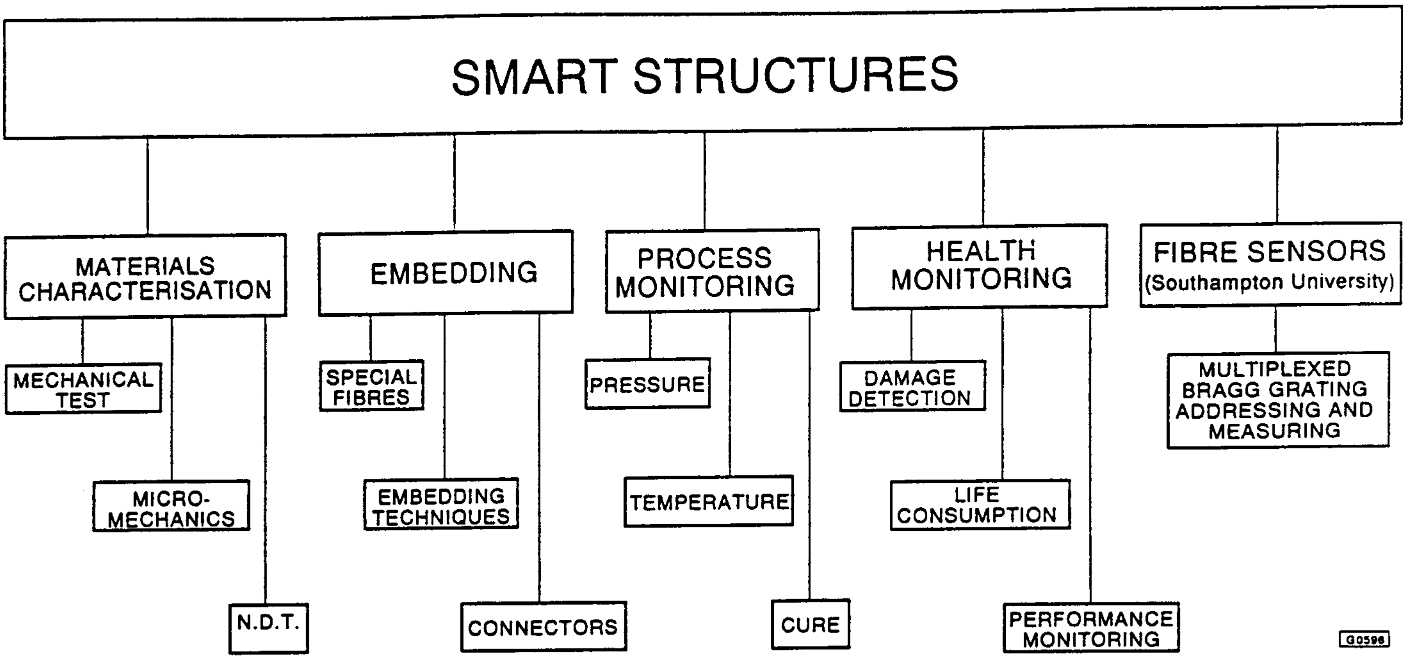


FIGURE 4 - SMART STRUCTURES RESEARCH ACTIVITIES

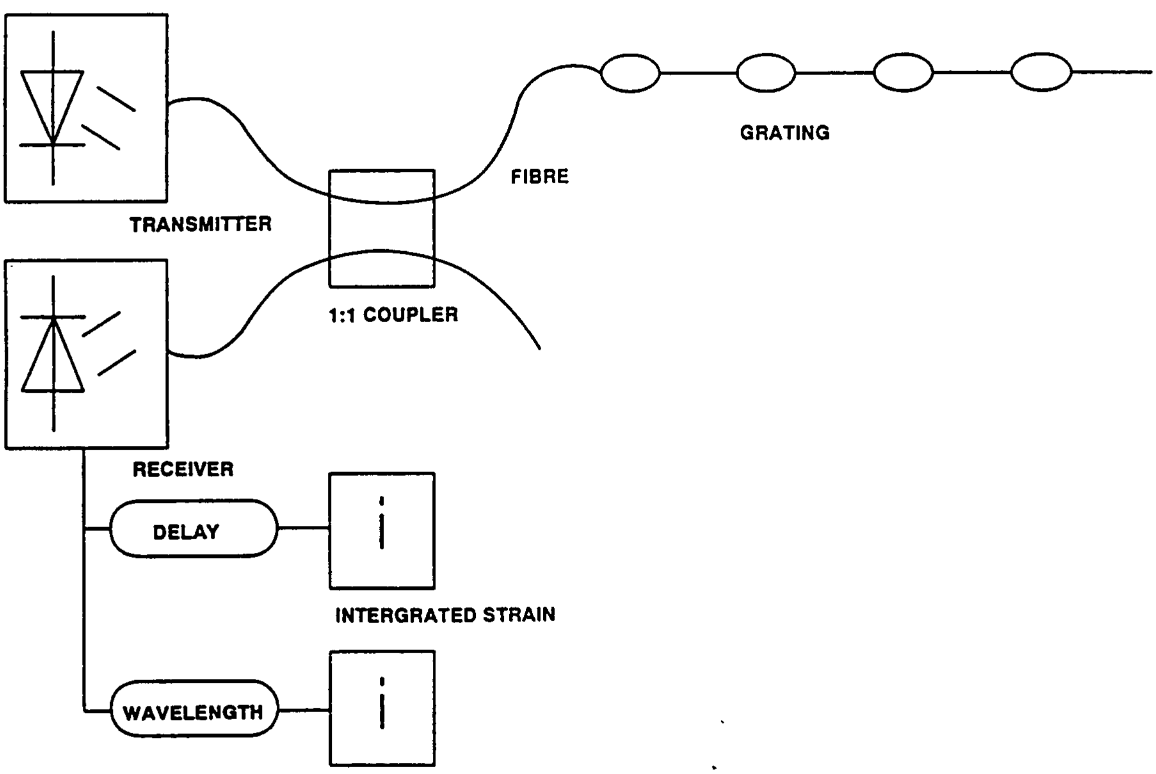


FIGURE 5 - PROPOSED FIBRE SENSOR SYSTEM

1. MECHANICAL TEST

- TENSION
- COMPRESSION
- INTER LAMINAR SHEAR
- FATIGUE ASSESSMENT

2. NON-DESTRUCTIVE TEST

- ULTRASONIC "A" AND "C" SCAN
- X-RAY - TRANSMISSION
- X-RAY - BACK SCATTER AND TOMOGRAPHY

3. MICRO-MECHANICAL MODELLING

- STRESS FIELDS IN OPTICAL FIBRES
- STRESS FIELDS IN HOST LAMINATES

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FIGURE 6 - PROPOSED MATERIALS CHARACTERISATION PROGRAMME

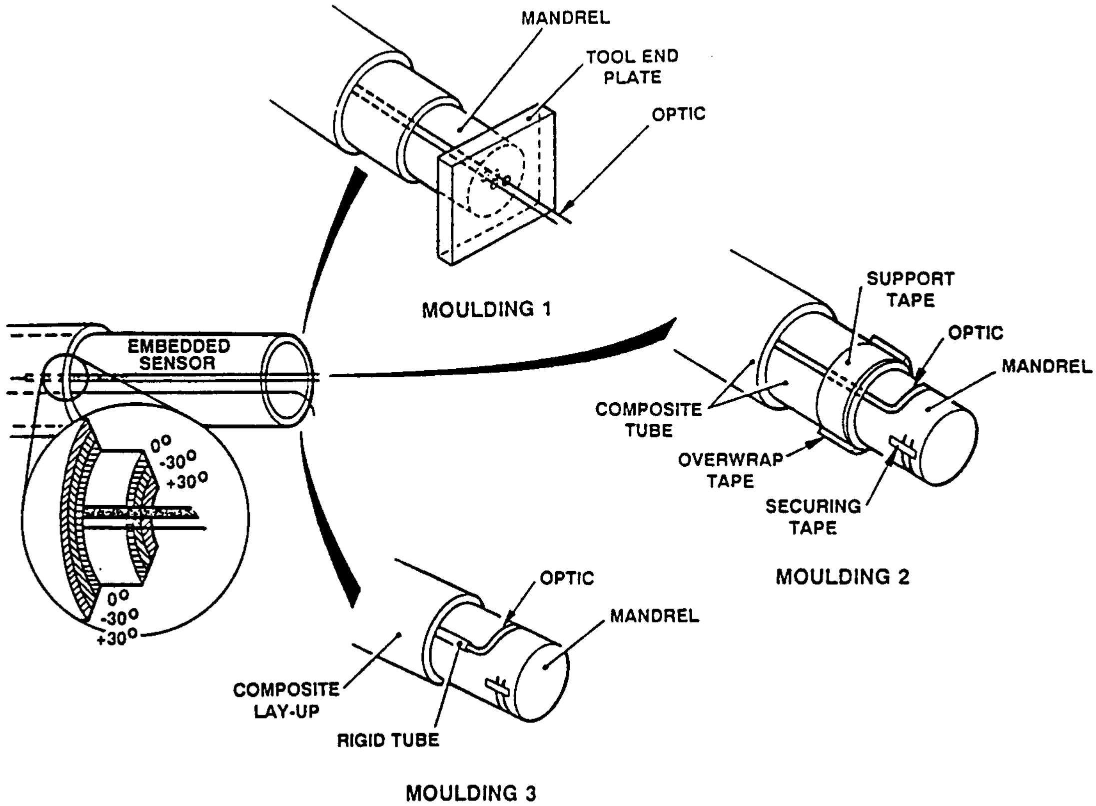

FIGURE 7 - SCHEMATIC OF THREE MOULDING APPROACHES

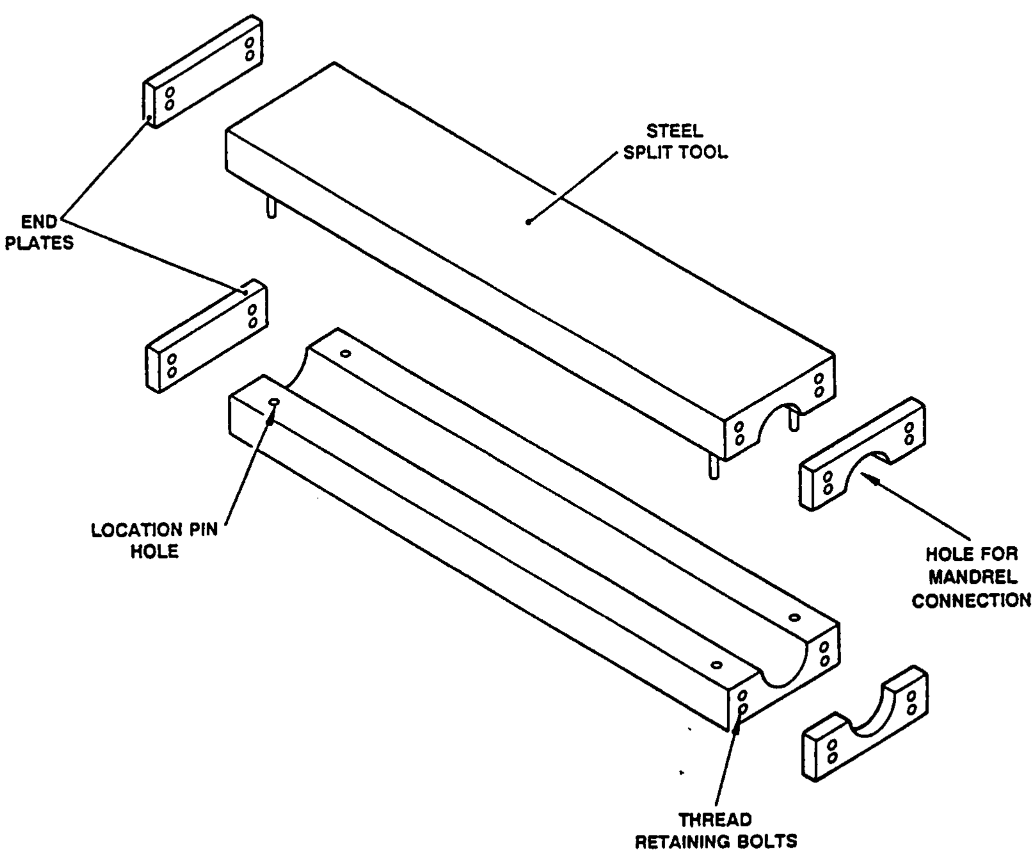

FIGURE 8 - MOULDING TOOL

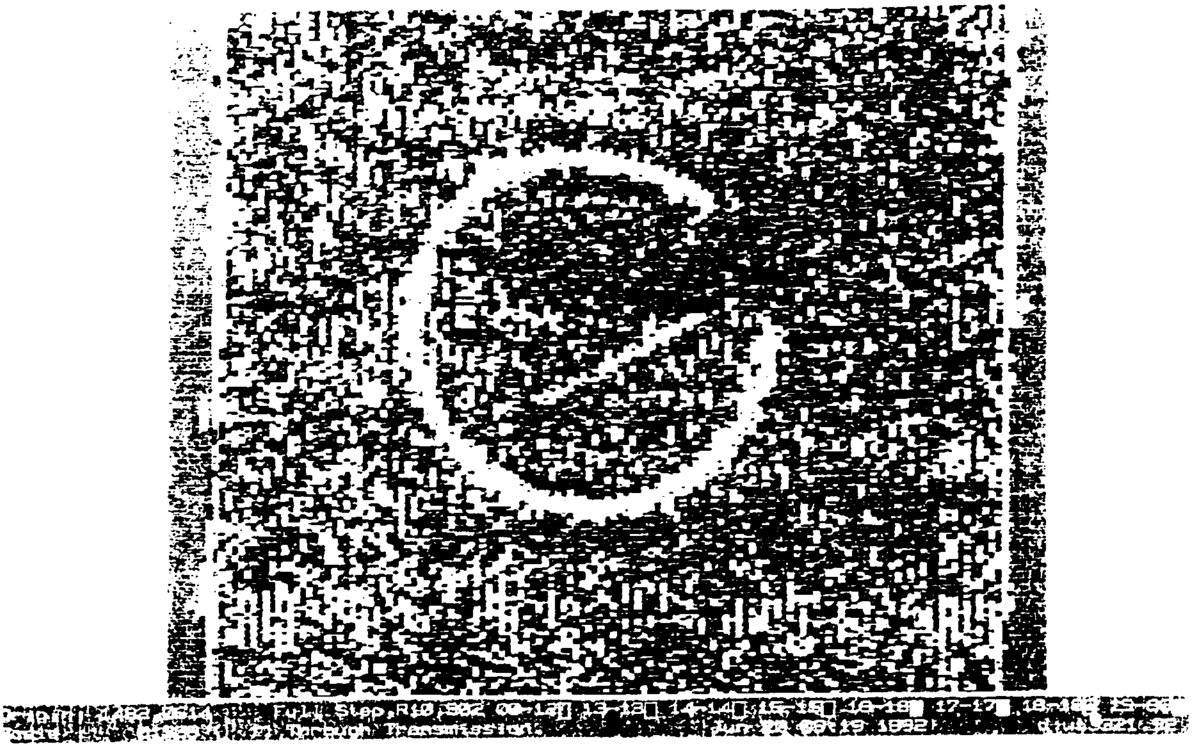

FIGURE 9 - 'C' SCAN INVESTIGATION - OPTICAL FIBRES IN GLASS PANEL

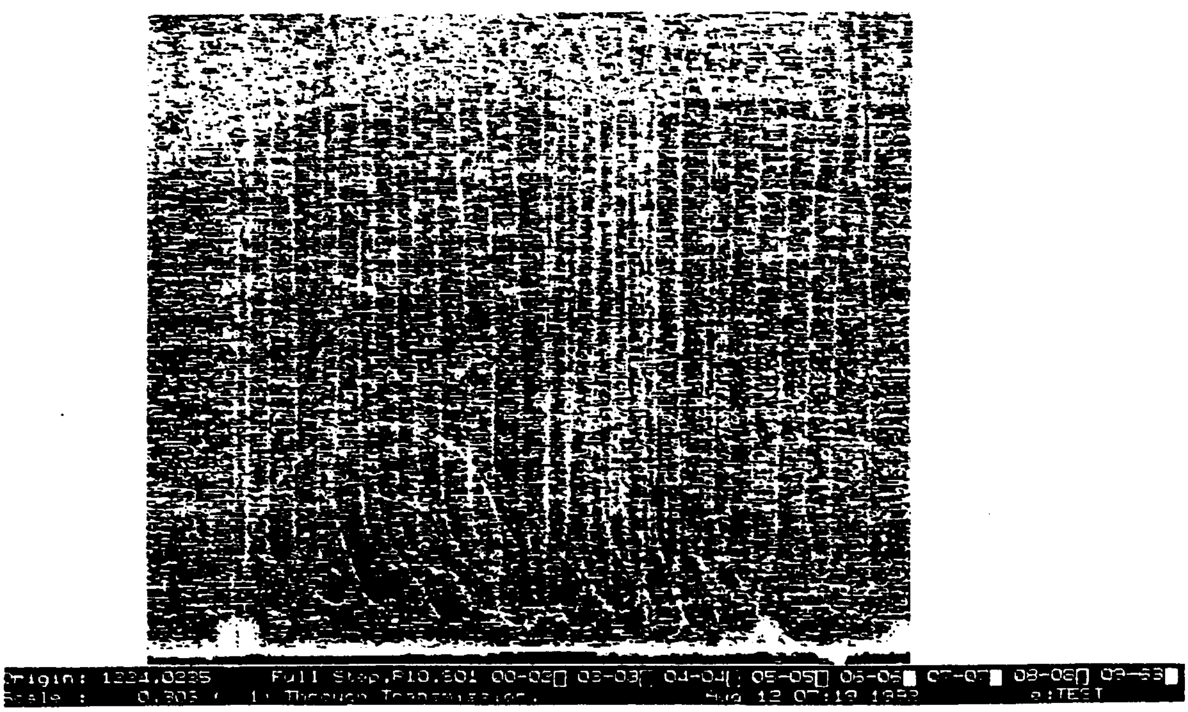

FIGURE 10 - 'C' SCAN INVESTIGATION - OPTICAL FIBRES IN CARBON PANEL