COMPOSITES & POLYCON 2007
American Composites Manufacturers Association
October 17-19, 2007
Tampa, FL

FABRICATION OF SECONDARY BONDED VARTM COMPOSITE DOUBLER-PLATE JOINT PANEL WITH EMBEDDED FIBER BRAGG GRATING STRAIN SENSORS FOR FATIGUE CRACK MONITORING

by

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Abstract

In the present work a methodology to fabricate secondary bonded composite doubler-plate joints with embedded Distributed Strain Sensors (DSS) arrays of the fiber Bragg grating (FBG) type, through Vacuum Assisted Resin Transfer Molding (VARTM) processing was developed. The embedding technique, egress points, and some fabrication issues are discussed. Four doubler-plate joint panels of 36 inches in length by 18 inches in width were fabricated. Ten 2 inch by 30 inch specimens with three embedded DSS arrays in different locations were projected to be fabricated. Five specimens with three embedded sensors, one with two sensors, and two with only one sensor were obtained. Of the twenty-nine embedded DSS, ten were broken during the fabrication process. Of nineteen successfully embedded DSS, only one was found to be inoperable after the fabrication process was completed. The embedded DSS are intended to monitor longitudinal crack initiation and propagation in the doubler-plate joint specimens under fatigue tension loading. A description of the fatigue test plan and the finite element modeling which supports the design of the experiment are also presented.

Introduction

In recent years, the US Navy has shown increased interest in ship construction using advanced Fiber Reinforced Polymers (FRP) composites. In addition to all the benefits of using composites, there are some uncertainties regarding to life prediction and integrity of composite structures. A structural monitoring system may lessen these uncertainties. By updating the material properties, locating damaged areas or recording the loading and strain of a structure during service, the remaining life of a structure can be estimated.

A system installed on a structure to identify damage is generally referred to as a structural health monitoring (SHM) system (Johnson, Lam et al. 2000). Damage prognosis is possible through the combination of the information produced by such a system with a model to predict the remaining life of a structure. Since there are many potential applications for SHM and many possible methods of constructing a SHM system a significant amount of research has been conducted in the area.

Embedded fiber optic strain (FOS) sensors such as Extrinsic Fabry-Perot Interferometers (EFPI) and the distributed fiber Bragg grating (FBG) type have been incorporated in SHM applications

Embedded EFPI sensors have been used to monitor axial strain and evaluate residual bending stiffness in sandwich composite panels subjected to fatigue loading using the Hydromat Test System. Embedded EFPI sensors have also been used to perform a long-term monitoring of selected structural elements (glulam beams) of the Advanced Engineered Wood Composites (AEWC) Center office building expansion (Haskell 2006).

While still primarily used for telecommunications applications, developments in the use of fiber Bragg gratings for optical sensor applications are quite promising (Hill and Meltz 1997).

Distributed sensing systems consisting of FBG sensors were used to monitor crack growth on aircraft panels (Gifford, Childers et al. 2003) and on reinforced concrete beams (Li and Wu 2007). FBG strain sensors were embedded in CFRP cross-ply laminates to detect transverse cracks (Okabe, Yashiro et al. 2000). Embedded FBG sensors were used to monitor the cure process of CFRP composite laminates with and without damage (Jinsong Leng 2003).

The main objective of this paper is to present a methodology to integrate Distributed Strain Sensors (DSS) of the type FBG in the fabrication of secondary bonded composite doubler-plate joints, through VARTM processing. The embedding technique, egress point, and the fabrication procedure will be addressed in the following sections. The embedded DSS are intended to monitor longitudinal fatigue crack initiation and propagation in doubler-plate joint specimens under tension loading.

One of the expected outcomes of this work is to propose a methodology for large-parts fabrication with embedded fiber optic strain and temperature sensors to be used for the Navy.

A general description of the fatigue experiment plan and the finite element modeling which supports the design of the experiment are presented as well.

Fatigue test experiment

Objectives

Fatigue fracture tests of secondary bonded composite doubler-plate joints will be conducted using the tension test configuration and materials implemented by the University of Maine for a previous research work conducted for the Office of Naval Research (ONR) (see Figure - 1). Embedded Bragg grating fiber optic strain sensors will be used to monitor crack propagation (see Figure - 10).

The importance of a doubler joint for Navy ship applications is clearly described in an NSWC-CD report: "The typical use of a doubler in composite structure is to locally increase the laminate thickness to accommodate a stress riser, such as a hole or bolted connection. The thickness of the doubler is easily selected as the amount of material needed to reduce the in-plane stress concentrations to allowable levels. However, the connection between the doubler and the base laminate must have sufficient strength to avoid separation (delamination) of the doubler under the anticipated loads. The principal design parameters affecting this strength (for a given material system and bonding technique) are the degree of taper at the ends of the doubler and the thickness of the doubler relative to the base laminate thickness."(Gaies and Leasure 2002). Therefore, the doubler joint was selected as a representative joint to monitor crack propagation.

The objectives of the fatigue fracture experiment are:

1) Assess feasibility of monitoring fatigue crack initiation and propagation using embedded Bragg grating fiber optic strain sensors.

2) Evaluate scale effects by comparing with fatigue response of composite coupons tested at a partner institution (Virginia Tech)

3) Correlate experimental strain measurement with finite element model prediction.

Experimental plan

The materials adopted for the secondary bonded composite doubler-plate joints are Vetrotex-Certain Teed woven roving 324 fiber glass and Ashland Derakane 8084 vinyl ester resin. DSS of the Fiber Bragg Grating (FBG) type were embedded at different locations in the composite panel. The sensors were provided by Luna Innovations.

The dimensions of the panels are 36 inches (914.4 mm) long by 18 inches (457.2 mm) wide. From each panel between two and five 2 inch (50.4 mm) wide specimens can be obtained. The general dimensions of the specimens and the configuration of the embedded fiber optic sensors used in this work are shown in Figure - 11.

An initial ¼" (6.35mm) flaw was induced in the interface of the base plate and doubler-plate by means of a Teflon insert (see Figure - 10). The crack will be extended to ½" (12.7 mm) length during the fatigue experiments (see Figure - 12).

For this work, each specimen has three embedded FBG sensor cables in the following locations (see Figure - 12):

- In the base plate, four plies below the interface (on top of the 20th layer, counting from the bottom up).
- In the base plate, one ply below the interface (on top of the 23rd layer).
- In the doubler plate, four plies above the interface (on top of the 4th layer, counting from the bottom up).

It was initially planned to place a sensor in the interface of the base and doubler plate. However, potential damage during the fabrication process, particularly the sanding of the base plate previous to the second infusion, and during the fatigue test was anticipated.

Fifty percent of the quasi-static failure load was selected to develop stable crack propagation. The estimated duration of each test is 35 hours at 4 Hz frequency (500000 cycles) to propagate the crack from ¼" (6.4 mm) to ½ in (12.7 mm). Ten samples will be tested.

The durability of the sensors during fabrication and fatigue loading will be determined. The ability and optimum location of the sensors to detect crack propagation will be established.

The fatigue load will be stopped every 50000-100000 cycles. The crack length will be measured. The specimen will be loaded in quasi-static ramp test up to 50% of the failure load, while the FOS sensors are interrogated. The distribution of strain through the length of the sensors will be correlated with crack growing and location of the crack tip.

Macroscopic evaluation of the damage will be performed visually and if possible, will be correlated with changes in longitudinal strain in the embedded DSS. Images of the specimen will be acquired after each step of the fatigue loading regime.

Distributed Sensing System

The Distributed Sensing System^{TM} is a fiber-optic sensing tool for making distributed measurements of temperature and strain. The Distributed Sensing System uses swept-wavelength interferometry to simultaneously interrogate multiple Fiber Bragg Grating (FBG) sensors integrated within a single optical fiber. The swept-wavelength interferometry approach enables robust and practical distributed temperature and strain measurements in standard fiber with millimeter-scale spatial resolution over tens to hundreds of meters of fiber with strain and temperature resolution as fine as 1 μstrain and 0.1 °C (Luna-Innovations 2006).

A Fiber Bragg grating is a periodic permanent perturbation of the refractive index along a section of an optical fiber, which is formed by exposure of the core to an interference pattern of intense UV-laser light (Hill and Meltz 1997). This periodic perturbation (gratings) produces successive coherent scattering for a narrow band of the incident light. The grating acts as a stop-band filter, reflecting light with wavelengths close to the wavelength λ_B, and transmitting wavelengths sufficiently different from λ_B (see Figure - 13). Any change in the local strain or temperature of the fiber which modifies the grating period and the refractive index, will change the Bragg wavelength. This wavelength shift can be linearly related with the strain (Measures 2001).

The DSS arrays and the interrogation unit utilized in this work were provided by Luna Innovations Incorporated. The fiber consists of a Ge-doped silica core of 5.4 µm diameter surrounded by a cladding of silica with diameter 127 µm. A polyimide buffer of 14 µm thickness is applied to the outside of the cable as a protective layer and to improve the interface with the matrix resin when the sensor is embedded. The discrete FBG are 5mm in length and positioned every 10 mm along the length of the fiber.

A picture of one of the DSS is shown in Figure - 2. A photo of the Distributed Sensing System unit interrogating one of the doubler-plate joint samples is shown in Figure - 14.

Finite element simulation

Finite element modeling of the doubler-plate joint in tension was performed. The objectives of this analysis were:

- Understand what kind of outputs are to be expected from the embedded fiber optic strain sensors as the crack grows.
- Estimate and compare the sensitivity of the sensors to changes in longitudinal strain due to crack growing.
- Correlate experimental strain measurements with finite element model predictions.

The dimensions of the model are shown in Figure - 15. The structure was meshed with 4-node plane strain elements, where one row of finite elements corresponds to one layer of composite. Anisotropic material properties were considered for the 45/-45 degrees layers. The software utilized in the linear elastic analysis was ANSYS 10.0. Symmetric boundary conditions at the center of the doubler-plate were applied. The transverse displacements were constrained at the fixed end (grips). A 14 kN (≈ 50% of failure load) tension load was applied at the left end. Two analyses were conducted:

- The initial stage, with a ¼" flaw length.
- The propagation stage, with a ¼" additional crack propagation length.

The mechanical properties of the woven E-glass/Vinyl Ester composite used in the model are shown in Table 1 (Gauthier and Thompson 2006).

The sensitivity of the strain sensors is defined as the change in strain from the initial to the final stage. The post-process to compute the expected sensitivity of each sensor is as follows:

1) The theoretical longitudinal strain at the location of each sensor is obtained for both stages. This strain is not the expected reading of the sensors, because the grating's output can be understood as the average strain over a 5 mm gage length.

2) A moving average of the longitudinal strain from in step 1 is computed for each sensor for both stages. This averaged strain represents the expected reading of the distributed sensors for all possible location of the gratings. This is done because the exact location of the gratings with respect to the beginning of the crack is not known before the fabrication.

3) The sensitivity of each sensor is computed by subtracting the initial averaged strain from the final averaged strain.

Results for the expected and averaged strain in sensor 2 and the sensitivity of the three sensors are presented in Figure - 16. From the finite element analysis it was concluded that:

- The change in strain relative to the initial stage (1/4" flaw) can be correlated with crack extension during the fatigue tests.
- Readable variations of strain changes are expected only near the crack tip (first 30 mm from the beginning of the crack).
- The most sensitive sensor is the one located closest to the interface of the base plate and doubler-plate.
- The expected sensitivity of the other two sensors is relatively small. However, if sensor 2 is damaged by the crack extension during the fatigue loading, these sensors may still give some useful information.

Fabrication of the doubler-plate joint panels with embedded fiber optic sensors

In this section, the fabrication procedure of secondary bonded doubler-plate joints with embedded DSS sensors is briefly explained. The results, issues and recommendations are presented at the end of the section.

Fabrication procedure.

Fabrication of the base plate.

The fabric lay up to be used in this work is [0/+45/-45/0]3sf. Twelve 36"x18" plies of fabric are cut with the long side oriented in the warp direction, six fabric with the warp direction oriented in 45 degrees and six oriented in -45 degrees with respect to the long side.

The plies are placed on the infusion table according to the lay up, and straightened using a square at three evenly distributed locations. The centerline and edges of the 2-in wide specimens and the location of the doubler plate are marked.

Consistent with Figure - 11 and Figure - 12, sensor 1 is placed on the top face of the 21st layer from bottom to top, and sensor 2 is placed on the bottom face of the 24th layer. The idea is to align the fibers with the fabric oriented in 0 degrees. In the crack side, the tip of the bare fiber optic cables is placed between 20 and 30 mm from the edge of the doubler plate. A small amount of spray adhesive is applied only to the bare fiber optic cables and the metal connectors in order to hold them to the fiber glass fabric. The spray adhesive coated sensors are then applied to the fiber glass fabric in the desired position and orientation. The metal connector is stitched to the fabric with regular thread in two points, to keep it straight when the vacuum is applied.

In the egress side, the egress points of the fiber optic cables are located between 1.5 and 4 inches from the edge of the doubler-plate. A little hole is opened in the fabric to let the metal connector of the fiber optic cable pass the above fabric plies. It is recommended that the complete metal connector and a small length of the lead be embedded in the fabric, so that the egress point is not right after that joint, which is the weakest zone of the fiber optic cable.

The standard procedures of VARTM based on the Seemann Composites Resin Infusion Molding Process (SCRIMP) technology are followed for setting up the flow media, peel ply, spiral wrap for resin distribution, resin and vacuum hoses and vacuum bag. In order to avoid risk of breaking the fiber optic cables when demolding, the flow media was placed below the fabric stack, between the glass mold and the peel ply. Low tack vacuum bag sealant tape is applied where the fiber optic cables exits the vacuum bag. See Figure - 4.

Approximately 4500 grams of resin is required for the base plate. A 40-minutes gel time range is generally used. The resin additive and cure package is as follows:

- Styrene Monomer: 5%
- 24P: 0.25 %
- Trigonox 239a: 2%
- Cobalt: 0.3%
- DMA: 0.2%

The panel is cured at room temperature overnight. The next day, after de-molding, the panel is cured in oven at 82^{o}C for a period of 8 hours.

Fabrication of doubler-plate

After the panel has been post-cured, the top surface must be sanded to facilitate adhesion of the secondary bonded doubler plate. The egress zone of the fiber optic cables is protected with fabric backed pressure sensitive tape.

The fabric lay up is the same as in the base plate. The length of the 24 fabric plies is reduced from 16 to 6.8 inches, a 0.4 inch decrease in length per layer. A Teflon insert is placed on the crack side at the edge of the doubler-plate, to provide an initial flaw.

Consistent with Figure - 11 and Figure - 12, sensor 3 is placed on the top face of the 4th layer from the bottom to top. The same procedure for embedding the sensor in the base plate is adopted in the doubler-plate. On the egress side, the entire metal connector and a small length of the fiber optic cable lead are embedded into the fabric (see Figure - 5). If possible, the bare fiber optic cable is extended beyond the edge of the doubler plate. In such case, mechanical protection should be provided to the non-embedded part of the sensor after de-molding the panel.

The standard procedures of VARTM/SCRIMP infusion are followed for setting up the flow media, peel ply, spiral wrap for resin distribution, resin and vacuum hoses and vacuum bag.

On the egress side of the base plate, a rectangular perimeter of approximately 14 inches by 7 inches is created with vacuum bag sealant tape, such that the egress points of the fiber optic sensors in the base plate are inside the rectangle. The edge of the rectangle adjacent to the doubler-plate is about 1-1.5 inches away from the doubler-plate. The fiber optic cables leads and connectors from the base plate and doubler-plate are placed inside the rectangle. Vacuum bag sealant tape is applied over the cables coming from the doubler-plate. After the vacuum bag is taped to both the exterior and interior vacuum bag sealant tape perimeters, the vacuum bag inside the perimeter is cut, such that the fiber optic cables and connectors are exposed to the air (see Figure - 6), which facilitates leak detection if necessary.

For the doubler-plate, approximately 3000 grams of resin are required, prepared using the same additive and curing package as in the base plate.

The panel is cured at room temperature overnight. The next day, after de-molding, the panel is cured in oven at 82^{o}C for a period of 16 hours.

Finally, the panel is cut using a wet saw to obtain the 2-inches wide specimens.

A picture of a final doubler-plate joint panel with six embedded DSS, before cutting the specimens, is shown in Figure - 7.

Fabrication results

Three doubler-plate joint practice panels were fabricated with several embedded fiber optic cables and two dummy Fiber Bragg gratings (FBG) sensors prior to fabricate the final panels. Different embedding techniques and egress alternatives were investigated. Possible solution to issues such as excessive bending of the fiber optic cables at the egress zone and broken cables during demolding were explored during the fabrication of these practice panels.

Four final doubler-plate joint panels were fabricated with 2, 4, 2 and 2 specimens respectively.

The major difficulty in avoiding damage to the fiber optic cables was to not break the cables during demolding. Generally in VARTM infusion, after the resin is cured, the flow media becomes very stiff and brittle, and is adhered to the composite panel. For this reason, the process for removing the flow media involves rough peeling and breaking of the flow media. In the practice doubler-plate panels and in the first two final panels, the flow media was placed on the top surface of the panel, as shown in Figure - 8. This was the common practice in a previous work conducted at the University of Maine for the US Navy while infusing similar parts. A small square hole in the flow media was cut around each egress point.

This method worked fine in the practice panels and in the first final panel. However, in the second final base plate, six of the eight embedded cables were broken in the process of removing the flow media and peel ply, and the other two were broken during handling before the specimens were cut from the panel. It was concluded that the cables did not break only due to the de-molding process. They were already damaged during the fabrication by the sharp edges resulting from the slit in the flow medium and peel ply (Figure - 9), so they easily broke when the flow medium was peeled off.

Even though the fabrication technique was improved to protect the DSS fiber optic cables, it is the opinion of the author that they may be reinforced with an extra outer cladding in order to make them more suitable for large composite parts fabrication.

As explained above, a successful solution to this issue was to infuse with the flow media on the face of the panel opposite to the sensor egress point. After this improvement, all the panels were successfully fabricated without loosing any DSS.

The final product of the fabrication was five specimens with three embedded sensors, one with two sensors, and two with only one surviving sensor (the sensors in the doubler-plate). Of the twenty nine DSS used in the fabrication, nine were broken because of using the flow media on top the stack and one was broken during handling. A picture of the specimens after being cut from the panels is shown in Figure - 10.

Condition of the embedded DSS sensors after fabrication

The survival of the sensors through the entire fabrication process, including embedding in the E-glass fabric, VARTM infusion, curing, demolding and cutting, was evaluated using a Distributed Sensing System reading unit. A summary of the condition of the sensors after fabrication is presented in Table 2.

The condition of a sensor is defined as "Good" when the interrogation unit is able to locate the reflection produced by the gratings. The three embedded DSS in a doubler-plate joint sample are combined in one network by means of an optical splitter (see

Figure - 14). Figure - 17 shows a typical time-domain graph of a reflected test signal through the three embedded DSS, where each reflection produces a peak. The three dark areas indicated in Figure - 17 (a) represent the three sets of gratings in the fiber optic cables. A green dot over a peak, as shown in Figure - 17 (b), indicates a functional fiber Bragg grating sensor.

From Table 2 it can be noted that of nineteen successfully embedded DSS, only one is not operational.

Conclusions

A methodology to fabricate secondary bonded composite doubler-plate joints with embedded Distributed Strain Sensors (DSS) arrays of the type FBG, through VARTM processing was developed. The embedding technique, egress point, and some fabrication issues were discussed.

When the flow media was placed on the same face as the egress point of the fiber optic cables there was a high probability of breaking the sensors. This happens because the flow media becomes too stiff and brittle after curing, and the slits in the flow media and peel ply produces sharp edges in the base plate.

When the flow media was placed on the face of the panel opposite to the sensor egress point, between the glass mold and the peel ply, the risk of breaking the cables during de-molding was minimized, and the panels were successfully fabricated.

Four doubler-plate joint panels were fabricated. Five specimens with three embedded sensors, one with two sensors, and two with only one surviving sensor were obtained. Of the twenty nine embedded DSS, nine were broken because the flow media was located on the sensor egress side of the stack and one was broken during handling.

The survival of the sensors during the fabrication process including was evaluated using a Distributed Sensing System reading unit. Of nineteen successfully embedded DSS, only one was found to be not operational.

The embedded DSS are intended to monitor longitudinal fatigue crack initiation and propagation. A general description of the experimental and analytical plan for the fatigue experiment was presented.

Research status

Two more doubler-plate joint specimens are being fabricated in order to complete the number of samples of the original plan.

Preliminary quasi-static tension tests to check the strain measurement capabilities of the embedded DSS will be conducted. The linearity of the load versus strain curve for each sensor will be established. The strain distribution through the length of the sensors will be correlated with the longitudinal strains obtained from a finite element model of a non-cracked specimen.

The fatigue experiment is scheduled for September and October 2007.

Acknowledgment

This work was sponsored by the Office of Naval Research through a contract with Virginia Tech. The authors thank the project technical advisor Mr. Brian Jones from the Naval Surface Warfare Center, Carderock Division, and the program manager Dr. Ignacio Perez from the Office of Naval Research, Materials Science & Technology Division (Code 332). The authors are also thankful to Dr. John J. "Jack"Lesko from Virginia Tech for his support and technical insight, and Mr. Thomas Plaisted from Luna Innovations for his contribution to the fiber optic sensor technology. The first and second authors were partially supported by the National Science Foundation through the CAREER Grant No. CMS-0093678.

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Tables

E_x	25.46 GPa
E_y	11.46 GPa
E_z	22.32 GPa
G_{xy}	3.64 GPa
G_{xz}	4.86 GPa
G_{yz}	3.64 GPa
ν_{xy}	0.400
ν_{xz}	0.150
ν_{yz}	0.400

Table 1. Material properties used in the finite element model of the doubler-plate joint.

Specimen	Sensor 1	Sensor 2	Sensor 3
1	Good	No gratings detected	Good
2	Good	Good	Good
3	Good	Good	Good
4	Good	Good	Good
5	Good	Good	Good
6	Good	Broken during fabrication	Good
7	Broken during fabrication	Broken during fabrication	Good
8	Broken during fabrication	Broken during fabrication	Good

Table 2. Summary of condition of the embedded DSS sensors after fabrication

Figures

Figure - 1. Fatigue test set-up used in a previous work at the University of Maine (Fadi El-Chiti 2007).

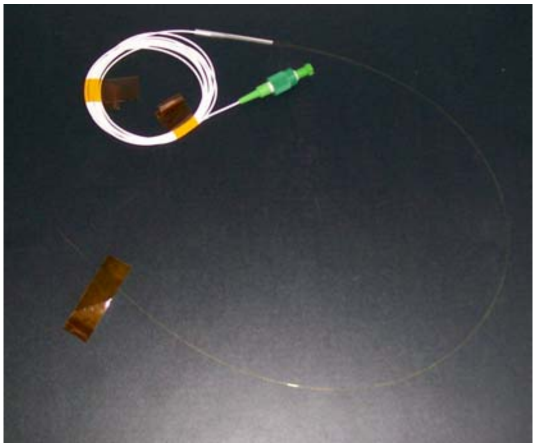

Figure - 2. Luna DSS fiber optic sensor for integration into composites.

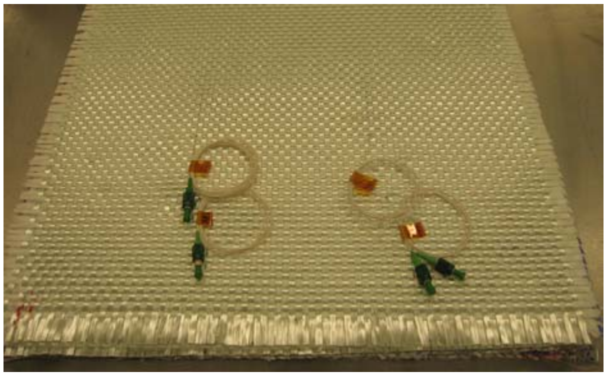

Figure - 3. Base plate with four embedded DSS sensors.

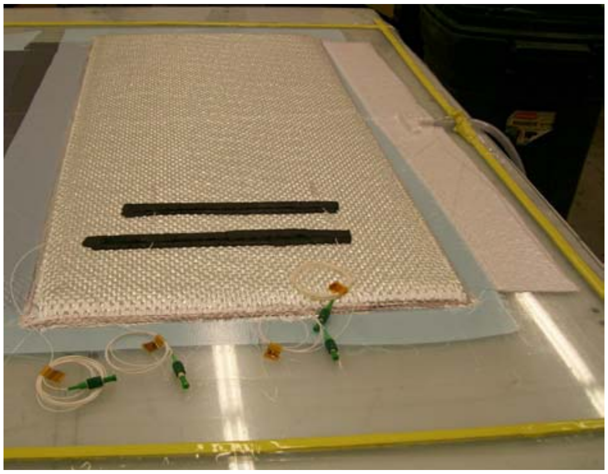

Figure - 4. Base plate panel with embedded DSS sensors before to VARTM infusion.

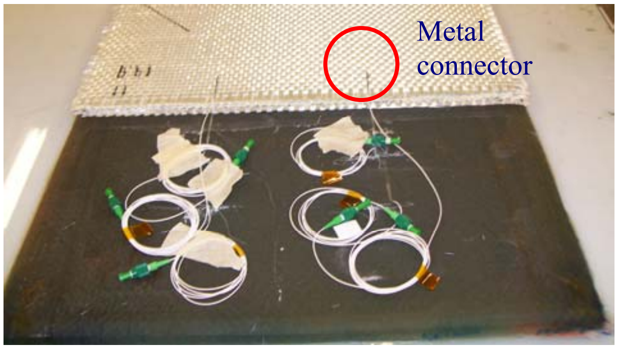

Figure - 5. Embedded DSS sensors in the doubler-plate before second infusion.

Figure - 6. Doubler-plate panel with embedded DSS sensors before second VARTM infusion.

Figure - 7. Doubler-plate joint panel with embedded DSS sensors after second infusion.

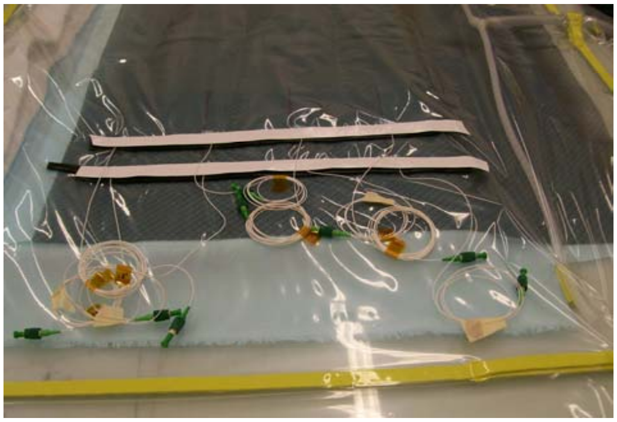

Figure - 8. Base plate with embedded DSS sensors. Flow medium placed over the fabric stack.

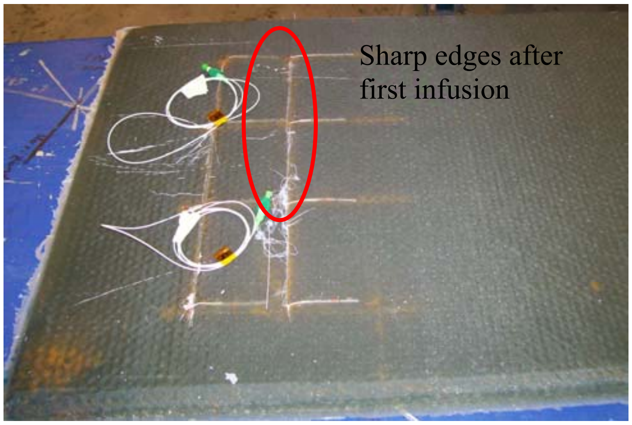

Figure - 9. Broken fiber optic cables after first infusion due to the sharp edges produced by the slits in the flow medium and peel ply.

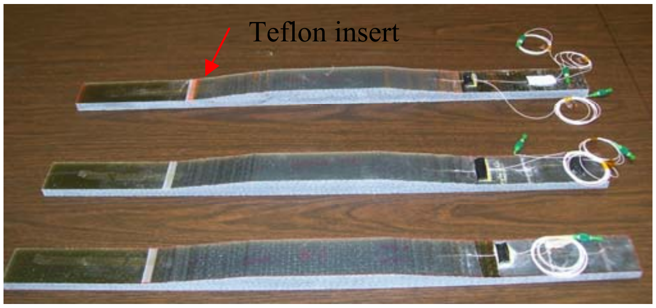

Figure - 10. Doubler-plate joint specimens with three (top), two (center) and one (bottom) embedded DSS sensors.

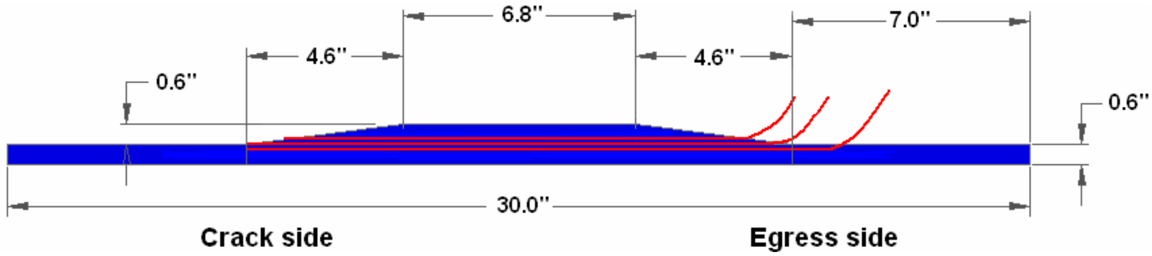

Figure - 11. Dimension (in inches) of the 2" wide doubler-plate joint specimen with the sensor configuration used in the fatigue test experiment adopted in this work.

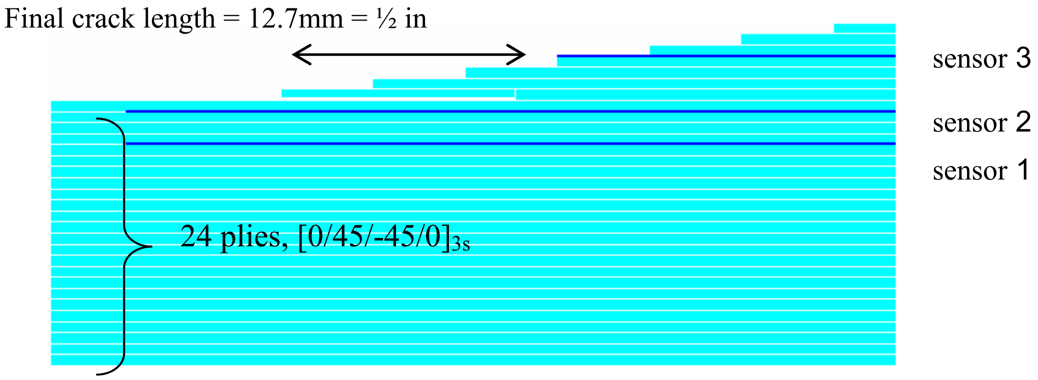

Figure - 12. Location of the fiber optic sensors relative to the crack.

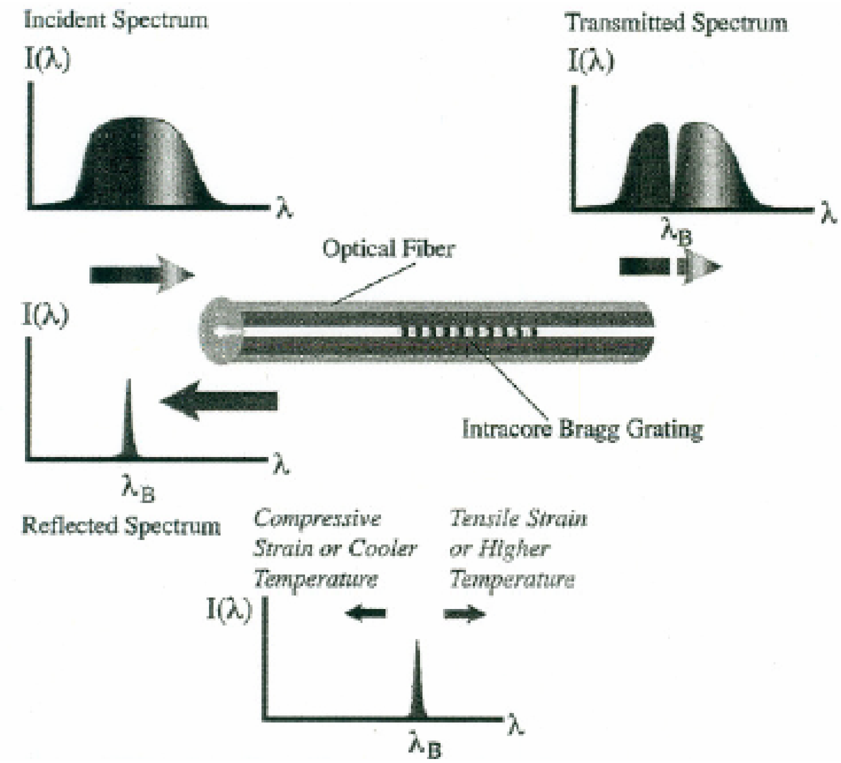

Figure - 13. Schematic of a fiber Bragg grating (FBG) sensor (Measures 2001).

Figure - 14. Distributed Sensing System unit interrogating a doubler-plate joint sample with embedded DSS.

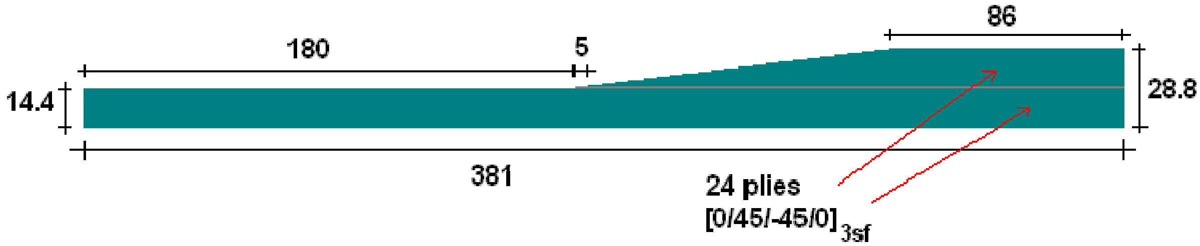

Figure - 15. Dimensions (in mm) and lay up of the doubler-plate joint finite element model.

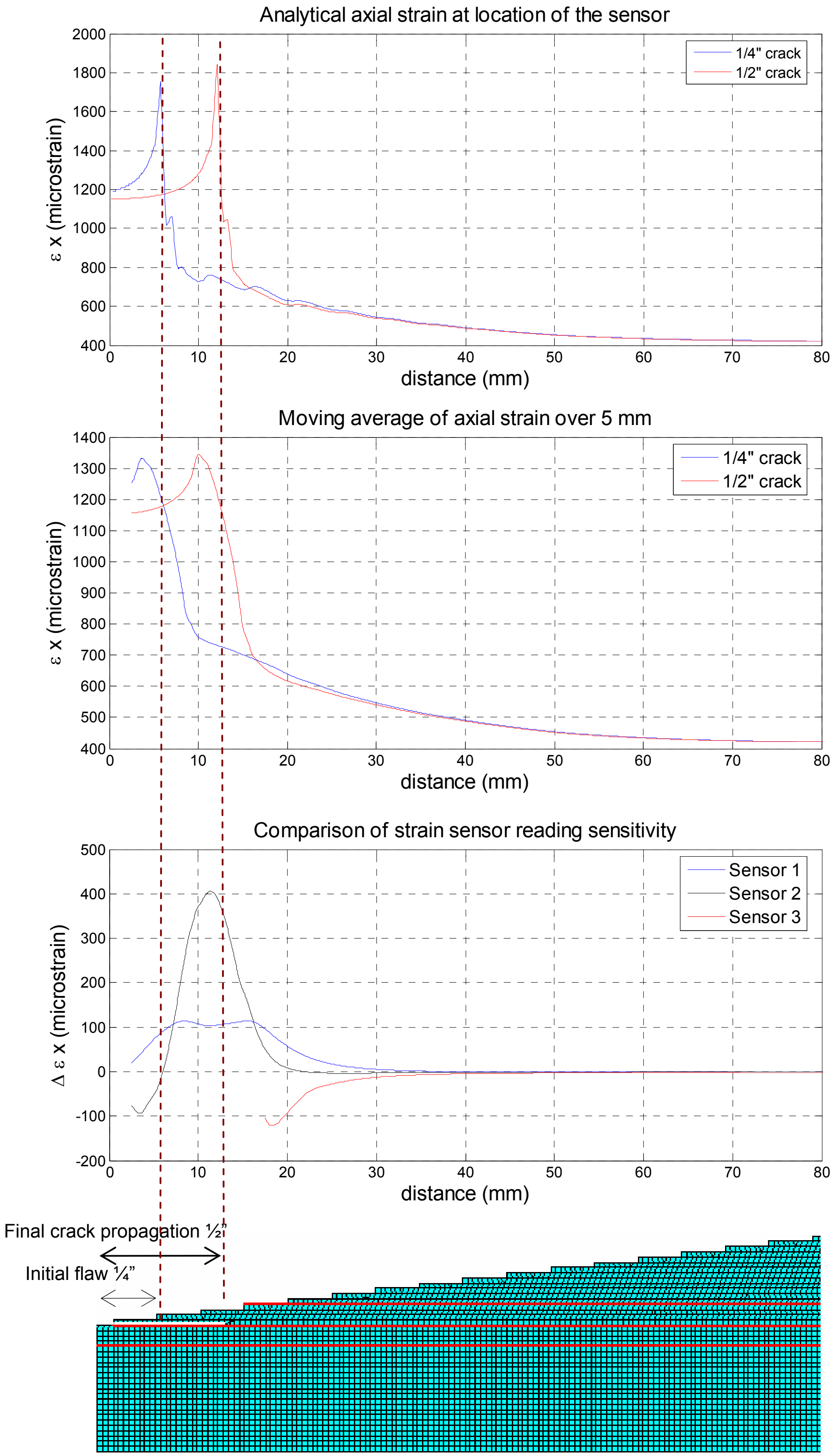

Figure - 16. Finite element prediction of strain and sensitivity of the embedded sensors.

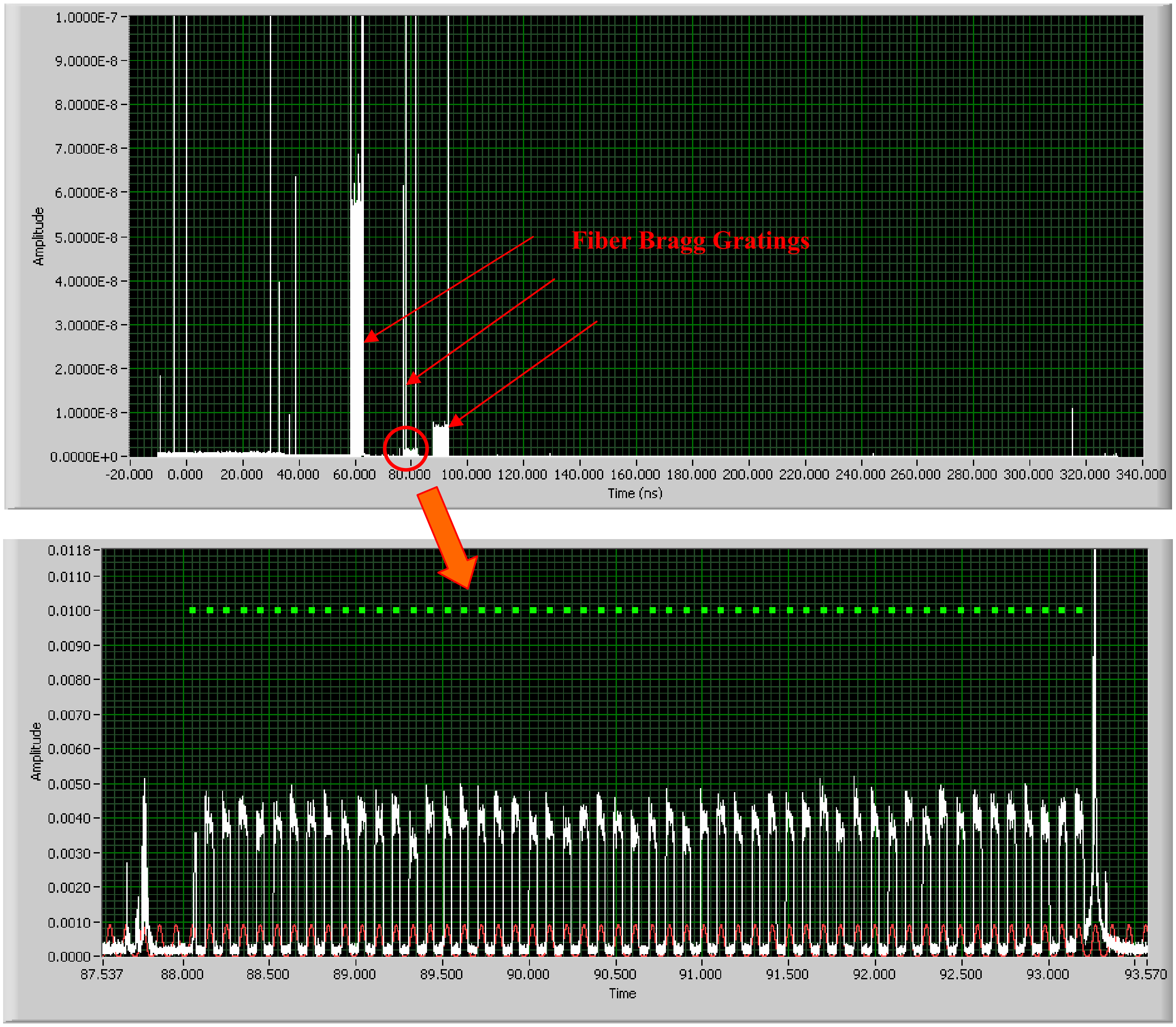

Figure - 17. Time Domain plot from the Optical Backscatter Reflectometer (OBR). a) Network defined by the three DSS and the connecting fiber optic cables. b) Zoon and location of each grating in one of the DSS.