Technical Note

EN-FY1601
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High Density Fiber Optic Sensing (HD-FOS) in Composites

Contents

1. Introduction

Many industries, such as the aerospace, marine, and petrochemical industries are increasingly utilizing composite structures [1]. In the 1960s, the aerospace industry started using laminated composites [2], and these continue to be popular especially carbon fiber reinforced polymer composites (CFRP), due to their high strength, stiffness, stiffness-to-density ratio, high specific modulus, and fatigue resistance. Since CFRP is considered to be transversely isotropic, the fibers must be oriented in the direction of the applied load to maximize effectiveness, but one of the challenges is determining the variability of the applied load direction. Another challenge in the use of CFRP is the local non-homogeneity of the structure that is created during the manufacturing process, resulting in non-uniform mechanical properties.

In order to fully characterize the behavior of non-homogenous composites, it is advantageous to incorporate sensors that are able to provide global coverage of the test article. Optical fiber used with the Optical Frequency Domain Reflectometry (OFDR) method [3], is ideal for this. Luna developed OFDR into High Definition Fiber Optic Sensing, HD-FOS, with the capability to provide the user with strain measurements along the length of an unaltered fiber with a spatial resolution of 1.25mm. The sensor itself is lightweight, small in diameter (155µm), immune to EMI, and composed of fused silica, which is materially compatible with most composites used in the industry. This allows it to be either surface mounted or more interestingly, embedded in composite structures. The continuous high spatial resolution nature of the measurement then allows HD-FOS to measure strain gradients that are present in woven CFRP composite structures.

Previously, fiber sensors have been embedded in composites to detect impact damage, delaminations, and other failures during testing [4-6]. OFDR has been used to detect localized regions of high surface strain prior to the formation of a visible crack on a 9-meter CX-100 blade cycled to failure [7] and embedded optical fiber in a CX-100 wind blade effectively elucidated the presence and propagation of defects within the blade [8]. More recently, the use of embedded fiber sensors as a built-in structural integrity assessment system was demonstrated in a composite overwrapped pressure vessel (COPV) [9], and embedded fiber sensors were used to characterize the adhesive layer in composite double lap shear joint specimens [10].

Figure 1: Example composite applications that could utilize HD-FOS. Clockwise from top left: car body, wind turbine blade, pressure vessel, car seat frame, aircraft. Images courtesy of: Zoltek, Inhabit, UTC Aerospace, Tillett, NASA websites.

Embedding fiber HD-FOS sensors in composite structures provides many advantages including:

- The ability to gain insight into the complex internal strains that build up during a structural test
- Greater sensor coverage due to the continuous high spatial resolution nature of the measurement
- The ability to elevate the structure into a smart structure that both monitors and reports on their current state of health. In this way, critical manufactured parts can be monitored throughout the manufacturing process, the transport schedule, and its service life, increasing the efficiency of the bring-up and tear-down process.
- The ability to protect the sensor. The sensor is made of silica and while very strong in tension, is weak in shear. Therefore embedding it into the composite structure itself provides protection against external environmental influences and impacts.

This Technical Note covers the various methods available for embedding fiber sensors into composite parts. The challenges of each method are also described.

2. Fiber Placement

2.1. Methods for Placing the Fiber

The way in which the optical fiber is initially held in place as the composite structure is assembled prior to cure is very important in order to maintain positional location throughout the curing cycle of the laminate. This can be accomplished in various ways, and different methods will work better for different applications. The most important consideration is for the fiber sensor to ultimately remain in the location of interest for strain or temperature measurements to be captured.

2.1.1. In Epoxy

The most fundamental method for placing fiber in a composite layer is by pressing it into the epoxy that is applied to the part. The epoxy is tacky, and due to the small mass of the fiber sensor, is able to hold the sensor in its general location. This method is best carried out when instrumenting simple and straight long sections. However, this method may not be suitable for sensors that need to follow a path with bends and turns in it. As the uncured laminate is moved into the mold, or as the part is bagged, there is a chance that the fiber may migrate from its placed position. The strongest advantage to this method is that it does not introduce any potential sources of defect that might cause the composite to delaminate.

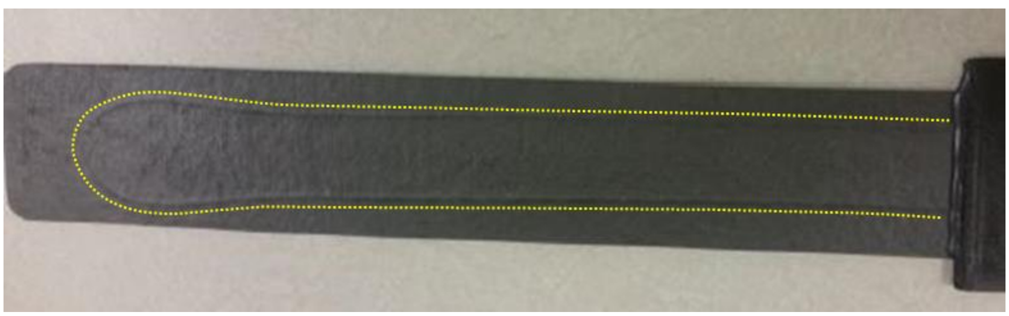

Figure 2: 12" coupon with embedded fiber sensor. Sensor is seen to meander slightly along the path, intended to be U-shaped turn with straight legs. Yellow dotted line follows beside the sensor path.

2.1.2. Pre-Preg Tack

If using pre-preg fabric, the same method of pressing the fiber into the epoxy can be used as the tackiness of the resin on the fabric will hold the fiber in place. It is also possible to apply low heat to the area where the fiber is placed to increase the tackiness of the pre-preg epoxy. Once it is tacky the fiber can be pressed down into place. This method can be used for some resin systems, but not all. It is recommended that the specifications of the epoxy system are checked before this method is used. However, a concern with this method is that the application of localized heat would change the final local material properties.

2.1.3. Woven In Veil

Perhaps the best method for integrating a fiber sensor into a composite structure is to lay the fiber out in the path of interest, in a surfacing veil and embedding it. A veil consists of contentious carbon fibers randomly oriented to form a tissue paper-like material. The fiber sensor can be woven into sections of the veil to keep it in its place. The use of a veil is advantageous because when the optical fiber is woven in, it will experience minimal micro bending while keeping the fiber secured in place. The whole veil, with integrated fiber, can then be easily handled and placed across the composite structure at the location of interest. In this way, curvature of the tool or mold can be well-handled as the sensor pattern is all self-contained in the veil.

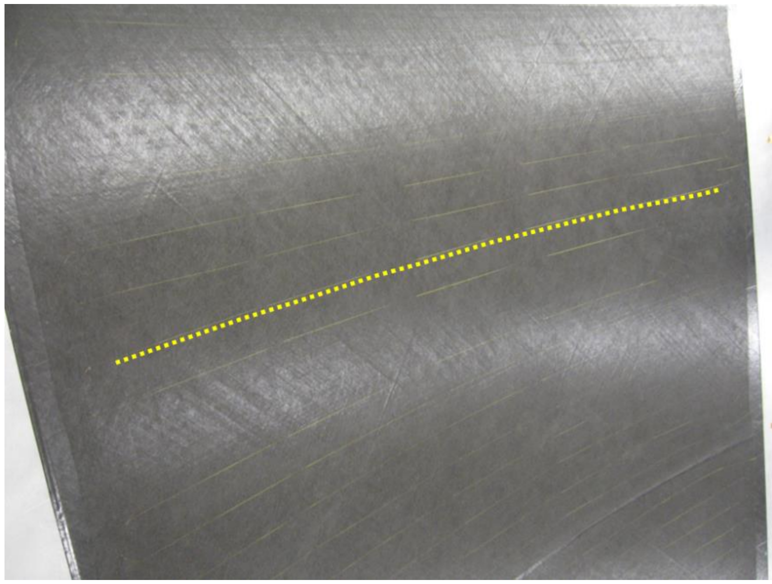

Figure 3: Fiber sensor woven back and forth in a serpentine pattern across the veil. The dotted yellow line marks the general trajectory of each straight path.

2.1.4. Tacked to Veil

Alternatively, the optical fiber can be tacked down to the veil using some form of epoxy or glue to keep it in place rather than weaving it into the fibers. The glue will help the fiber stay in place, however the downside to tacking the fiber down is the actual tack may be a delamination source.

2.1.5. Tacked to or Woven into Ply

If the use of a veil is not possible, the fiber can be tacked to or woven into a structural ply of the laminate itself. However, similar to other tacking considerations above, there is concern that the tack would prevent full curing of the part together, resulting in the creation of a delamination source. Weaving the sensor into the laminate itself may also result in significant microbending of the fiber sensor.

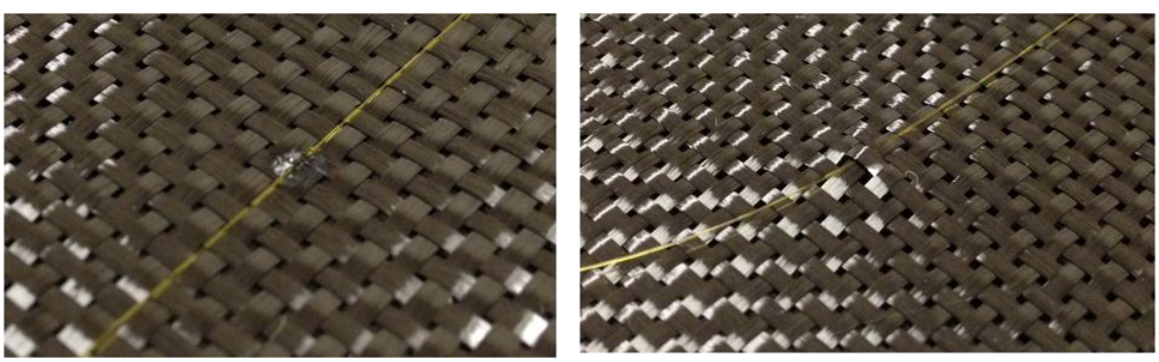

Figure 4: Fiber tacked to (left) and woven into (right) carbon ply.

2.1.6. Tape Dots

The last option is the use of tape dots, typically with thin kapton tape as the kapton can withstand cure temperatures without degrading or outgassing. Tape dots will hold the fiber in place on a ply, but if left in the laminate they will cause a larger delamination than any of the other fiber placement methods, and would therefore be a method of last resort.

2.1.1. Woven in with the Composite Structure

The methods described above incorporate the fiber sensor into layers of the plies for more manual layup processes. It is also possible to incorporate the sensor into the weaving process of the composite structure itself, making the fiber sensor one of the other carbon fibers that are to be woven. This has previously been done with planar beams [11] and also helically wound cylindrical pressure vessels [9].

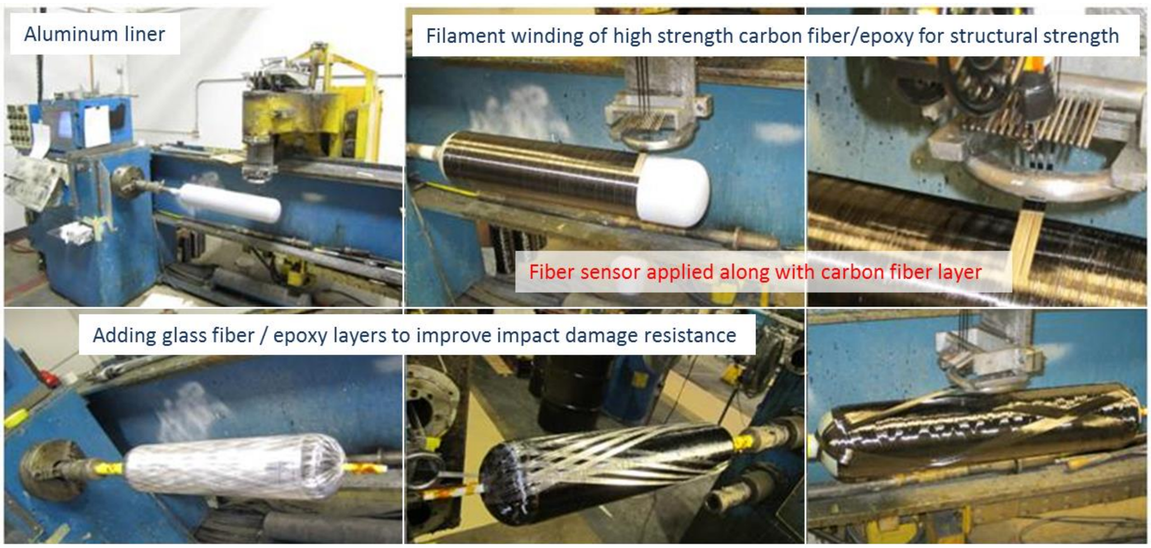

Figure 5: Filament winding of fiber sensor into composite overwrapped pressure vessel [9].

2.2. Selecting Suitable Fiber Location

The fiber location and path design would depend on the strain distribution profile that is expected across the structure as well as the ease of fiber handling. It is also important to note that the fiber sensor can be sensitive to accumulated microbends due to repeatedly crossing carbon toes. Microbending is more likely to occur in situations in which the ply of the strength members on either side of the optical fiber are not oriented in the same direction, and when significant transverse pressure is applied during the cure cycle. Microbend of the optical fiber results in excess optical loss which can degrade the Rayleigh scatter signal strength. Epoxy resin pockets on the side of the fiber sensor may also result when the optical fiber is not collinear with the strength member ply direction. Smaller diameter fibers reduce the extent of epoxy pockets opn the sides of the fiber, but increases the optical loss due to microbending. Therefore where possible, it is advantageous to be able to run the fiber sensor in the direction of the tows instead of across them.

2.2.1. On the neutral Axis

Placement of the fiber on the neutral axis of the part being tested will not necessarily result in a meaningful bend-induced strain measurement, but can be used to measure the temperature of the part. A calibration curve would need to be created in order to relate the expansion seen to the temperature applied.

2.2.2. Off Neutral Axis

The type of measurement desired will determine the pattern of the sensor layout.

2.2.3. Patterns

2.2.3.1. Linear

The most common, and easiest, way to lay out a fiber sensor is linearly down the length of the part. This method allows for minimal bends in the fiber as well as an easy fiber layout process before embedding.

2.2.3.2. Serpentine / Spiral

Linear sensor layouts connected by 180° turns are termed serpentine patterns. Serpentine and spiral sensor layouts are useful for obtaining a greater coverage of the strain profile across large surface areas.

2.2.3.3. Strain Rosette

In some cases, a strain rosette may be required in order to capture the principal axes of strain. A fiber rosette can be created by looping the fiber into a circle [12], or by criss-crossing the fiber into 3 directions as is typically available with foil gage rosettes. Crossing the fiber over its path is inadvisable if the high compressive pressure will be applied during the cure cycle as the sensor fiber may break at the crossing point.

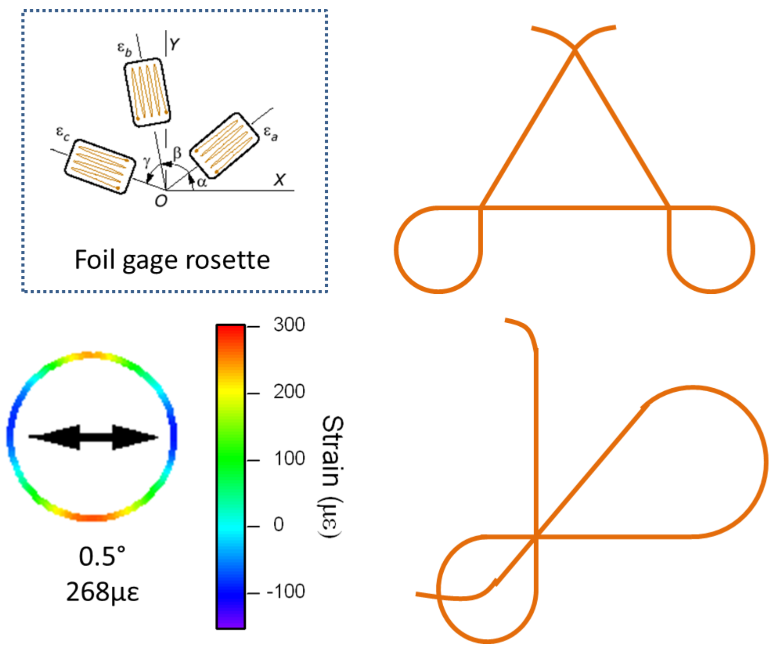

Figure 6: Various options for laying out fiber rosette patterns.

3. Fiber Ingress and Egress

One of the most challenging aspects of embedding fiber is handling the fiber ingress and egress from and to the part. While it is obvious that the sensor lead cannot be embedded as access to it is necessary in order to connect to the interrogator, the sensor termination may or may not need to egress the part. The benefit of having the fiber termination egress the part is the convenience and ability to modify the termination were it to become damaged. However, it can be argued that an embedded termination would be more difficult to damage since it is protected in the laminate.

The sensor ingress and egress must be appropriately protected, but cannot be a source of defect. The most common practice is to use a short piece of tubing made fromTeflon or other flexible cure temperature tolerant material   to protect the fiber as it enters or exits the laminate. This means the Teflon will go inside the part and it will be an area prone to delamination. The protective tube therefore cannot be located in a load-critical area. One end of the Teflon would need to be plugged with epoxy, to prevent resin flowing up the tube and caking up the fiber sensors.

3.1. Edge

There are multiple ways for the optical fiber to enter the laminate. The easiest and most simple is though the edge of the laminate. This is the most suitable choice when the edge does not require any trimming or “cleaning up”.

3.2. Surface

If the edges of the part will need to be trimmed or clear of any fiber, the fiber sensor can be made to enter and exit the part through the surface of the laminate. In order to accommodate this, plies lying on top of the embedding layer would need to be slit to provide access. This is possible even if the optical fiber needs to be embedded deep in the laminate, by stepping the fiber out through each ply. Entering or exiting through the surface may result in more of the Teflon tube being inserted into the laminate.

Figure 7: Teflon protects the sensor ingress / egress location at the edge of this square composite spar.

3.3. Mold

Using a closed mold system introduces more complexity to the ingress and egress issue. A path for the fiber would need to be machined into the mold in order to allow its ingress and egress.

4. Vacuum Bagging

Once the layup is complete, the part needs to be vacuum bagged. Care needs to be taken when bagging to ensure that the fiber is not put through any sharp turns. As an example, the fiber sensor should not come off of the tooling surface around a sharp radius. If it does, then when the vacuum pulls down on the part, it will bend the fiber around the sharp radius and cause the sensor to break.

4.1. Fiber Inside Bag

If the part does not need to be monitored during the manufacturing process, then the fiber sensor can remain in the vacuum bag. However, it needs to be separately bagged to ensure the resin does not cake over the sensor, rendering it useless. The Teflon tube protecting the fiber’s ingress to the part should be sealed with epoxy, and be long enough such that it is sandwiched between the mastic tape (vacuum bag tape) of this secondary bag. When vacuum is pulled, pay attention to the layout of the sensor to ensure it stays intact and is not forced into any awkward configurations that might cause it to bend and break. If this secondary bag rests on the part, it can create unwanted fillets and patterns on the surface of the part due to excess resin filling in this space. Adding a layer of peel-ply and breather fabric between the part and the secondary bag will reduce the chances of this happening.

4.2. Fiber Outside Bag

If the part needs to be monitored during the manufacturing process, for example to measure the internal strains and temperatures when the part is curing, then the fiber sensor needs to exit the vacuum bag. Here too, the lead leaving the vacuum bag should be carefully sandwiched between two pieces of mastic tape when sealing the bag.

For both these methods, a razor blade can be used to carefully cut the Teflon tube out of the mastic tape when unbagging the part. Careful attention needs to be exercised during this process to ensure the Teflon tube and fiber are not accidentally cut too.

5. Manufacturing Process

Different considerations come into play when deciding on which methods as described above are most suitable for use in the various manufacturing processes.

5.1. Wet Layup

The wet layup process is one where dry fabric is wetted by hand with epoxy, and then placed by hand onto the tooling surface. All of the fiber placement, ingress/egress, and vacuum bagging methods described above are suitable for consideration. For parts that ingress and egress though the edge, the Teflon can be taped to the table or mold while the layup in conducted, and once everything is in place it can be removed for bagging. For surface ingress and egress, the same procedure can be followed, but often the Teflon can be taped to the top ply using painters tape to keep the Teflon from pulling out of the laminate. The tape must be removed prior to the vacuum bagging of the part. Whenever the Teflon lead passes over the part, it can create a fillet of excess resin. Adding a layer of peel-ply between the tube and part surface will help in preventing this.

5.2. Vacuum Assisted Resin Transfer Molding (VARTM)

VARTM is a process where dry fabric is placed onto the tooling surface and bagged, before epoxy is pulled though the tool to wet the fabric. For VARTM applications, it is critical that the fiber not move when the resin is infused into the laminate. Due to this, the fiber must be more securely held in place. Ideally, the optical fiber would be woven into a veil, or tacked to a veil for this application. These methods provide better control of the path of the fiber, and keep it from being pulled away as the resin flows into the mold. The other alternatives are weaving into the fabric ply, tacking the fiber to the ply, or using tape dots. All of these methods should work, but at the cost of increasing the risk of delamination.

Due to active resin flow for the VARTM process, extra precaution needs to be taken to ensure that the sensor connector and leads do not get encased in epoxy. Fiber exiting the part at the edge is likely going to be completely exiting the vacuum bag so is of minimal concern. For sensors egressing through the surface, unless the leads are to exit the bag, the leads and connector should be sealed inside a secondary vacuum bag and arranged as described above between peel-plies and breather fabric to preserve the part surface.

5.3. Closed Mold /Compression Molding

Closed mold process or compression molding is a manufacturing method where pre-preg fabric or a wet layup is placed into a heated or non-heated press. The process of placing the fiber is usually much simpler when pre-preg fabric is used. The least intrusive way is to tack the fiber with the pre-preg resin as described above. This works fairly well for fiber paths that are relatively two-dimensional. The use of a veil would also be helpful for better tolerance to curvature. The other alternatives are weaving into the fabric ply, tacking the fiber to the ply, or using tape dots. All of these methods should work, but at the cost of increasing the risk of delamination. Any of the ingress/egress methods described above can be considered.

The primary concern for the closed mold process is crushing the tube. It is beneficial to have a relief area for the tube to pass though. This can also help with fiber placement. Whenever the Teflon lead passes over the part, it can create a fillet of excess resin, to prevent this, add a layer of peel-ply between the tube and part surface.

5.4. Three-Dimensional (3D) Woven Composites

3D composites utilize fiber arranged into complex 3D structures, using winding, weaving, and braiding processes. A resin is then applied to the 3D preform. The fiber placement method is pre-determined by the specific manufacturing process, for example having the fiber incorporated into the winding reel for a pressure vessel winding process. Considerations for fiber egress and bagging apply as above.

5.5. Pultrusion

Pultrusion is a continuous process where reinforcing fiber is pulled through a heated resin bath and formed into specific shapes as it passes through forming guides or bushings. The part then moves through a heated die where it takes its net shape and cures. After cooling, the part is cut to the desired length. The sensing optical fiber can be incorporated into the pultrusion process as one of the reinforcing fibers and used to monitor the curing process. However, complications arise when the part is cut to length as the sensing fiber will also be cut, resulting in an untreated termination that will result in compromised measurement quality.

5.6. Three-Dimensional (3D) Printing

3D printing of composite parts is a continuous process where resin-infused fiber is laid down in successive layers until an entire object is created. The sensing optical fiber can be incorporated into the printing process by laying it down in between successive layers.

5.7. Autoclave Curing

The discussion above covers room temperature and pressure, out-of-autoclave curing process. Traditionally, autoclaves are used to cure composite components to achieve the desired resin-to-fiber ratio and low void content. Autoclave curing achieves this by placing the part under vacuum in an autoclave and pressurizing the autoclave during the heated cure cycle. The fiber sensor will not be affected by the temperature as the autoclave process typically does not exceed 250°C. However, specialty connectors and terminations with a higher temperature rating will need to be considered if these components are to remain inside the autoclave. If measurements are to be taken throughout the cure process, then a fiber optic feedthrough will also need to be implemented. Customers typically utilize third party fiber optic feedthrough suppliers for this. Contact Luna to discuss these options.

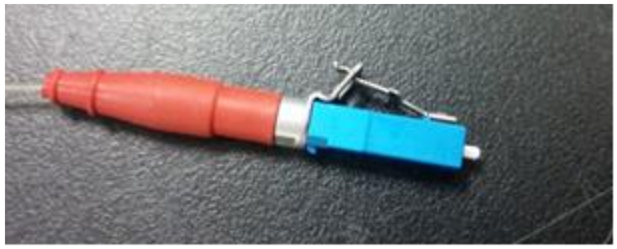

Figure 8: High temperature LC/APC connector rated to 150°C.

6. Managing Leads and Connectors

Once the part is cured and the bagging has been removed, it may be deemed essential to efficiently manage the lengths of sensor lead and connector exiting the part. Housings such as the one below can be machined or 3D printed to protect and manage these components.

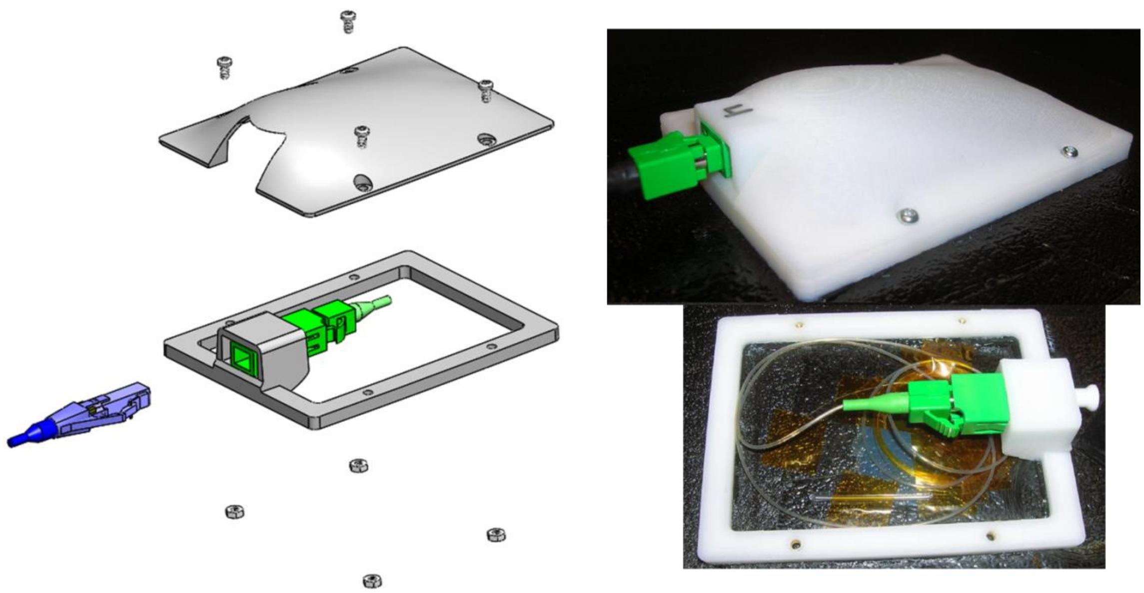

Figure 9: Housing 3D printed to protect the lead and connector.

7. Surface Bonding

While the fiber sensor's form factor lends itself to being embedded within composite parts, the sensor can also be bonded onto the external surface of the structure.

7.1. Surface Preparation

The surface preparation of a composite is key to achieving a good bond with the optical fiber. In some cases, it will be advantageous to use a surfacing ply, such as a veil to improve surface smoothness. The surface of the part should be lightly abraded with sandpaper in a wet condition, initially with 220 grit and then with 400 grit. Depending on the roughness of the surface and the presence of any voids, a basecoat of epoxy may first need to be applied. Once the basecoat has cured the surface should be re-abraded with sandpaper. The relevant conditioner and neutralizer should be used from the epoxy bonding kit before wiping down with isopropyl alcohol. The fiber sensor can then be fixed on the surface along the path of interest, with tape pieces intermittently located along its length.

7.2. Bonding

Standard foil gage epoxy can then be applied over the sensor using a foam -tipped swab. Once cured, the tape should be removed, with those sections bonded using the same method. The choice of epoxy depends on the final application including strain range, temperature range, test duration, and surface finish. A protective coating e.g. of silicone RTV, can be applied over the bonded fiber in order to protect it from future damage.

8. Challenges

While the advantages associated with embedding fiber sensors are many, challenges and concerns remain. There is definitely a learning curve associated with this process, though mastery will improve over time. There is the possibility of micro-bending having an adverse effect on the signal to noise ratio of the measurement. Micro bending occurs when the compressive force of the curing process microscopically and locally bend the optical fiber between the reinforcement fibers of the composite. To mitigate this, as best possible, the fiber sensor should be laid in alignment with the reinforcing carbon fibers. Delamination is another valid concern, especially one initiated at the ingress location where the Teflon tubing is embedded at the edge or surface of the composite part. This is why the location of the insertion point would need to be carefully selected so as not to coincide with a high load area.

The question also arises, of whether a surface bonded fiber sensor is actually sufficient for the application. Typically surface bonded sensors will display the highest strain value as it is the furthest away from the neutral axis whereas an embedded fiber will show a reduced strain for a given load. However internal defects will be missed if the strain gradient has sufficiently decayed between the interior and exterior of the composite part.

9. Conclusion

This Technical Note covers the various methods available for embedding fiber sensors into composite parts. While challenges remain, the steps outlined here provide a good launching pad towards successfully incorporating sensors into composite structures. This may be advantageous for the purpose of creating a smart structure with an integrated sensor, which would result in a component whose health can be monitored from inception throughout the manufacturing process, through deployment, and into decommissioning.

10. References

1. Lapczyk, Ireneusz, and Hurtado, Juan A. “Progressive damage modeling in fiber-reinforced materials.” Composites: Part A 38 (2007): 2333-2341.
2. Pierron, Fabrice, Green, Ben, and Wisnom, Michael R. “Full-field assessment of the damage process of laminated composite open-hole tensile specimens. Part I: Methodology.” Composites: Part A 38 (2007): 2307-2320.
3. Froggatt, Mark, and Moore, Jason. “High resolution strain measurement in optical fiber with Rayleigh scatter.” Appl. Opt. 37 (1998): 1735-1740.
4. Measures, R. M. Structural Monitoring with Fiber Optic Technology. San Diego, California: Academic Press, 2001.
5. Jinsong, L. and A. Asundi, A. “Structural Health Monitoring of Smart Composite Materials by using EFPI and FBG sensors.” Sensors and Actuators A: Physical 103(3) (2003): 330- 340.
6. Guemes, Alfredo, Fernandez-Lopez, Antonio, and Soller, Brian. “Optical Fiber Distributed Sensing – Physical Principles and Applications.” Structural Health Monitoring 9 (3) (2010): 233-245.

7. Kaplan, A., Klute, S. M., and Heaney, A. “Distributed Optical Fiber Sensing for Wind Blade Strain Monitoring and Defect Detection.” Proceedings of the 8th International Workshop on Structural Health Monitoring. Stanford, California, Sept. 13-15, 2011. Stanford University, 2011. CD-ROM.
8. Klute, S. M., Gifford, D. K., Sang., A. K., and Froggatt, M. E. “Defect Detection During Manufacture of Composite Wind Turbine Blade with Embedded Fiber Optic Distributed Strain Sensor.” Proceedings of the 43rd International SAMPE Tech. Conf. Ft. Worth, Texas, Oct. 17-20, 2011. Society for the Advancement of Material and Process Engineering. CDROM-15 pp.
9. Klute, S. M., Metrey, D. R., Garg, N., Abdul Rahim, N. A. “In-Situ Structural Health Monitoring of Composite-Overwrapped Pressure Vessels.” CAMX Conference Proceedings. Dallas, TX, October 26-29, 2015. CAMX – The Composites and Advanced Materials Expo CD-ROM-2509 pp.
10. Meadows, L., Sullivan, R. W., and Vehorn, K. “Distributed Optical Sensing in Composite Laminate Adhesive Bonds.” AIAA SciTech. San Diego, CA, January 4-8, 2016. 57th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference.
11. Castellucci, M., Klute, S.M., Lally, E.M., Froggatt, M.E., and Lowry, D. “Three-Axis Distributed Fiber Optic Strain Measurement in 3D Woven Composite Structures.” Smart Structures/NDE. San Diego, CA, March 10-14, 2013.
12. Gifford, D., Froggatt, M. E., Sang, A. K., Kreger, S. T. “Multiple Fiber Loop Strain Rosettes in a Single Fiber Using High Resolution Distributed Sensing.”

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