DEVELOPMENT OF A ROBUST, LOW-COST INTERFACE FOR EMBEDDED OPTICAL FIBERS

THE PROBLEM AND THE OPPORTUNITY

Intelligent filament-wound composite structures hold great promise for reducing the cost and improving the performance of many commercial and military products. The realization of this promise has been delayed by the cost and difficulty of terminating the optical fiber at the structure surface, and reliably connecting it with appropriate apparatus. If the fiber is left to project out of the structure unprotected, it is subject to breakage. If it is terminated at the surface of the structure, as a practical matter, it is difficult to cut and polish the end appropriately since small bits of debris lodge in the adjacent composite and manage eventually to scratch the interface [Udd, 1995]. Furthermore, this approach makes it difficult to align an external device with the fiber, since required tolerances are on the order of a few microns.

An ideal fiber termination design will have the following characteristics:
1) It will leave the fiber and ferrule in a protected position, and protect the polished fiber end from inadvertent scratching.
2) It will provide an easy and positionally accurate way to plug a device into the fiber.
3) It will be easily manufacturable, with reasonable dimensional tolerances for the manufacturing processes involved.
4) It will be simple to design for a wide variety of connecting devices.
5) It will not excessively impact the strength of the composite structure.

A robust optical fiber interface design will make it possible to incorporate optical fiber sensors in commercial products. For instance, fiber-reinforced pressure vessels for the storage of natural gas fuel on cars, trucks, and buses could be built with embedded optical fiber pressure sensors. These sensors will allow evaluation of the structural integrity of the tank every time it is filled, and eliminate the need to remove it from the vehicle for periodic proof testing. Such a product would give the manufacturer a significant competitive advantage, provided an optical fiber interface design meeting the criteria outlined above is available.

PHASE I TECHNICAL OBJECTIVES

1. Examine the excitation and sensing light frequencies, amplitudes, and tolerable signal/noise ratios for various applications to identify minimum transmission requirements. Compare them with the capabilities of standard connectors and termination techniques, since these, or portions of them, will be used where appropriate.

2. Identify a conceptual design or designs for an interface. Identify appropriate materials, and study the manufacturability and reliability of the design. Use finite element analysis techniques to study the effect of the design on the surrounding composite, and refine the design accordingly.

3. Construct one or more prototype composite test plates incorporating a fiber and the interface design. Examples with fiber ingress/egress both parallel and perpendicular to the laminates will be built.

4. Test and evaluate the design concept for function, manufacturability, durability, cost, and commercial potential. Identify appropriate design improvements.

PHASE I WORK PLAN

Task 1. Study Optical Requirements and Standard Techniques and Components

Initial work will determine necessary functional specifications and appropriate off-the-shelf hardware to use in the design. Since the interface design should be generally applicable, requirements and connection hardware appropriate to a wide array of fibers and mating devices will be investigated. Various LED and laser sources will be studied, in particular at the commonly used frequencies of 1550 nm, 1300 nm, and 850 nm. The use of single mode, multimode, and polarization maintaining optical fibers will be investigated. The efficiency and design of standard connectors and splices will also be studied, and whenever it is possible and appropriate, these, or portions of them, will be used in the design. Devices or stratagems currently used for easing the alignment requirements of optical fibers will be studied. Polished optical fiber ends are sometimes subject to disabling scratches, and the use of lenses or other techniques for minimizing this problem will be studied.

Task 2. Develop a Conceptual Design

Designs for the ingress and egress of optical fibers can be divided into two general categories: those in which the embedded fiber is terminated at or beneath the surface of the structure, and those in which it projects beyond the surface. Optical fibers that are joined to a more robust fiber or encased in a simple protective sheath just before they emerge from the structure will be considered in the latter category. In both designs, the polished fiber ends can be scratched and damaged. Fibers that project beyond the surface, with a terminating device attached outside the structure, will typically be built with several centimeters of excess fiber between the structure and the termination so that damaged terminals can be repaired. However, the excess fiber and its interfaces with the structure and the terminal are potential sites for additional damage, and must be protected. Such a design is not always easy to protect, especially during the manufacture of the structure. For this reason, fibers terminated at or below the surface of a structure will always have a lower failure rate than those that project beyond the surface. The drawback, of course, is that embedded terminals cannot be easily repaired. The design approach taken here will be to terminate the fibers at or below the surface of structure, and find ways to mitigate or eliminate the risk of damage to the polished fiber end.

Design concepts that are inexpensive, reliable, and manufacturable will be developed. One concept currently under consideration is to cut the fiber to length, attach special ferrules to each end, polish as necessary, and embed this assembly in the composite structure with the ferrules at its surface. The ferrules will be partially encased in a dissolvable or removable 'pattern' that will serve as a small male mold in the composite. The pattern may be made of a salt, a high density foam, or a eutectic metal, or it may simply be a removable cap placed on the ferrule. After the structure is cured or otherwise set, the pattern will be removed, leaving a cavity of some desired shape around an exposed section of the ferrule (see Figures 1 and 2). This concept will allow the end of the ferrule to be recessed below the surface of the composite, protecting it from damage. It also allows the surrounding composite to be contoured for some purpose, for example, to accept a bayonet connector housing.

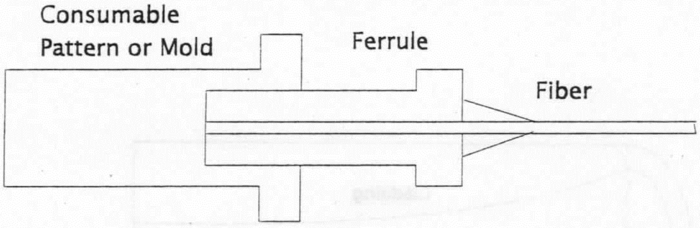

Figure 1: A ferrule with attached consumable pattern, or mold.

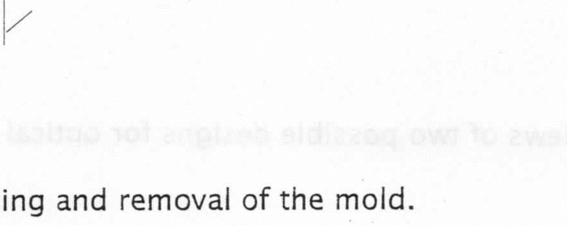

Figure 2: Ferrule after embedding and removal of the mold.

Alignment requirements for optical fibers are often stringent and costly, especially for single mode fibers. Traditionally, alignment is maintained with an alignment sleeve manufactured to extremely small tolerances. The design approach outlined above will permit the use of these sleeves, but means will be sought to reduce alignment requirements. One possible strategy might be to mate a single-mode fiber to a short section of larger fiber within the ferrule, presenting the larger fiber end externally. The larger fiber might be a multimode fiber, or a specially made short fiber section in which the core diameter varies, and is large at the exposed end. Similarly, a sensor fiber might be manufactured to length with this characteristic (Figure 3). Strategies requiring custom manufacture of the optical fiber will be discussed with fiber manufacturers to assess manufacturability and cost concerns, and functional concerns will be investigated analytically. This concept will be studied, but it is unconventional, and it is unlikely it will be included in the test samples built in Phase I. The use of GRIN lenses or other devices may present other opportunities for easing alignment requirements as well.

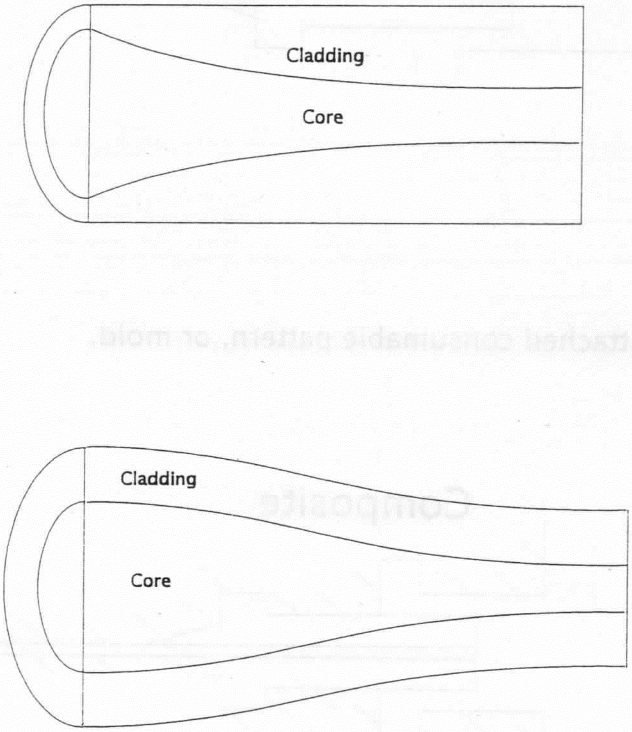

Figure 2: Cut-away views of two possible designs for optical fibers with custom end geometries.

The smallest scratch on the exposed face of the fiber core can destroy its usefulness, and in practical applications such scratches are common. A recessed ferrule may help reduce the risk of scratching, but further steps are possible. It may be possible to attach a small conventional or graded index lens to the face of the embedded ferrule, and mate up to that. The relatively large surface area of the lens will make scratches less detrimental to performance. Furthermore, the lens attached to the embedded ferrule may be designed to be replaceable in the event of damage. Since such replacement would be infrequent, it could be done under controlled conditions, virtually guaranteeing the safety of the optical fiber beneath it.

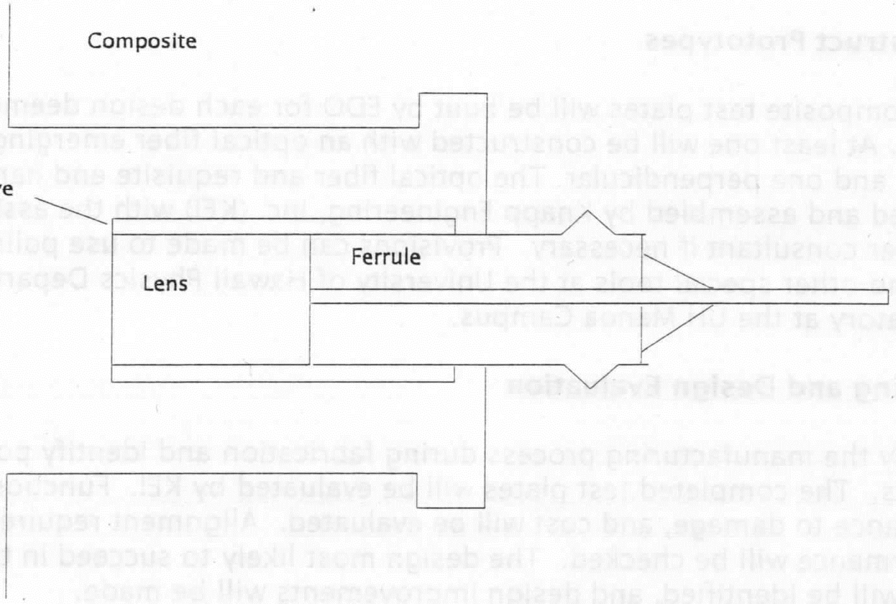

Figure 4: An embedded ferrule with a lens attached. In this realization, the sleeve is pressed onto the ferrule. It is intended to be a permanent assembly, but it may be removed and replaced, with the lens, should the lens be damaged.

This concept for embedding the ferrule will produce a small hole in the surface of the composite structure. The effect this has on the strength of the structure can often be mitigated by suitable placement of the ferrule in the structure. Consider, for instance, filament-wound composite natural gas fuel tanks with embedded optical fiber pressure sensors. The ferrule could easily be placed in the end of the tank, since the wall thickness there is up to five times greater than necessary. That is an artifact of the manufacturing process, because every reinforcing filament must be wrapped around each end of the tank, at a much smaller radius than that of the main body of the tank. The ferrules may have no deleterious effect on the strength of the structure in this location. Another alternative is to deliberately build up a small amount of structurally insignificant excess material to accomodate the optical fiber end. For instance, the fuel tank might be built with a filament-wound circular rib on its outside diameter specifically to accomodate the optical fiber ends. This rib could serve other purposes as well, possibly as a mounting surface.

Optical terminal designs will be evaluated for inclusion in filament-wound and prepreg composites, both perpendicular and parallel to the plies. A finite element analysis of each design will be conducted by KEI using ANSYS FEA software to determine the effect of the terminal on the strength of the part. Approaches for minimizing the impact will be studied. EDO Corporation, a manufacturer of composite structures including natural gas fuel tanks for vehicular use, will be consulted regarding manufacturability of the embedded sensors with various composite construction techniques.

Task 3. Construct Prototypes

One or two composite test plates will be built by EDO for each design deemed worthy of evaluation. At least one will be constructed with an optical fiber emerging parallel to the laminate, and one perpendicular. The optical fiber and requisite end hardware will be constructed and assembled by Knapp Engineering, Inc. (KEI) with the assistance of an optical fiber consultant if necessary. Provisions can be made to use polishing equipment and other special tools at the University of Hawaii Physics Department Fiber Optics Laboratory at the UH Manoa Campus.

Task 4. Testing and Design Evaluation

EDO will study the manufacturing process during fabrication and identify potential improvements. The completed test plates will be evaluated by KEI. Functionality, ease of use, resistance to damage, and cost will be evaluated. Alignment requirements and optical performance will be checked. The design most likely to succeed in the marketplace will be identified, and design improvements will be made.

All optical tests will be performed at the University of Hawaii Physics Department Fiber Optics Laboratory, which can be rented by private business. It is fully equipped for the study and evaluation of fiber optic sensors as described here, with assorted stabilized light sources, a single-mode/multimode fusion splicer, two optical power sensors, and two OTDRs, one of which is capable of 5 cm accuracy. The optical fiber consultant will perform these tests.

Proposed Schedule

TASK	Months					
	1	2	3	4	5	6
Study requirements / components	■	■				
Conceptual / detail design		■	■			
Fabricate terminals / test plates				■	■	
Tests					■	■
Design evaluation / revision						■

RELATED WORK

Fiber optic connections are amply described in the literature (Yeh, 1990; Powers, 1993). Details of specific components are readily available from manufacturers. Designs incorporating embedded ferrules have also been developed (Udd, 1995; Morgan, Ehlers, and Jones, 1991), although these did not involve a removable or consumable casing around the embedded ferrule. The basic approach, though, appears to be viable.

The use of GRIN collimating lenses in couplings is described in the literature (Udd, 1995). However, the construction of sensor fibers made to length, with expanded core or cladding diameters at each end, appears to be novel. Existing fiber drawing machines appear to be capable of producing such a fiber (Powers, 1993).

Related Experience

KEI is currently working on a small ARPA-funded contract to develop and commercialize a low-cost composite submersible pressure hull. The firm has developed a good understanding of composite materials and manufacturing processes in the course of this work. KEI, in concert with EDO, is also exploring the possibility of incorporating a simple optical fiber pressure sensor in a line of filament-wound composite natural gas fuel tanks used in the transportation industry. KEI has special expertise in the stress analysis of composite structures, and may use that expertise to design a fuel tank with a simple, low-cost, embedded, intensiometric fiber optic sensor.

KEI also has extensive experience with finite element analysis. The firm is designing the ARPA hull using ANSYS FEA software, and performed all the FEA analysis for Kauai Community College's "Sunraycer" solar powered car as well. KEI staff members are also very experienced in mechanical design, as is documented in the section "Key Personnel".

To augment the firm's knowledge of filament wound composites and enhance its ability in this area, KEI has enlisted the interest and support of EDO Corporation. EDO is a large manufacturer of composite structures, including a variety of filament-wound tanks, radomes, submersible sonar housings, and other products. Specific EDO projects include Piaggio P180 aircraft wing components, LORAL launch tubes, EH-101 fuel tanks, MineSweeper fuel, water, and waste tanks, NPS/NREL advanced wind blades, and BART train interiors. KEI has generated interest at EDO in incorporating fiber optic sensors in some of its products, starting with natural gas fuel tanks for vehicular use.

To provide special expertise in fiber optics, KEI has arranged to retain the services of an expert in this field. This consultant is currently in charge of the fiber optical sensor array being constructed for the DUMAND project. The consultant and his experience is discribed in the section "Consultants".

RELATIONSHIP WITH FUTURE RESEARCH OR R&D

Anticipated Results of the Proposed Approach

The successful completion of both phases of this project will yield a robust, inexpensive design and manufacturing approach for embedded optical fiber connections, for a wide array of fiber types and uses. Several different strategies for improving durability and serviceability, reducing alignment requirements, and reducing costs will be thoroughly evaluated, and the best combination will be identified. The design will largely overcome all the obstacles associated with fiber termination that presently prevent embedded optical fiber sensors from being commercially viable. Specifically, the terminal will be well protected during manufacture and use, insensitive to scratches, repairable, and it will have reasonable manufacturing tolerances.

Significance of the Phase I Effort as a Foundation for Phase II

One strategy that will only be partially investigated in Phase I is the possibility of manufacturing a fiber to a desired length, with a cross-section that varies near each end, as suggested in Figure 2. This concept has the potential of reducing alignment tolerance requirements at the connector, and may make it more robust. It may also simplify the design of low-cost embedded pressure sensors based on light power fluctuations. Some concepts for these sensors rely on microbending of the fiber, which generates a more effective signal at lower fiber stress when single mode fibers are employed (Marcuse, 1976; Lagakos and Bucaro, 1986). The alignment requirements for single mode fibers presently make it difficult to design cost-effective commercial sensors this way. If phase I research indicates variable cross-section fibers are desirable and technically feasable at reasonable cost, prototypes will be built and