Fiber Optic Terminations for Subsea Applications

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Abstract

Subsea optical connectors have enabled underwater industries to build modular components for subsea use. In particular wet-mate technologies have allowed systems to be assembled on the seafloor allowing the user to take full advantage of underwater optical communication systems. Optical cable designs for underwater use are major components of these systems. These are available in many differing formats to suit particular and specific requirements and applications. The differences of underwater optical cable construction are presented here along with an analysis of the inherent problems associated with terminating optical fibers for subsea use and a presentation of a range of solutions for fiber optic terminations in underwater connectors.

1. Introduction

A subsea cable may terminate into a connector, a subsea splice box, or a penetrator assembly in order to take an optical or electro-optical cable into an instrument housing. The application may be working with a cabled construction or with oil filled jumper hoses. In all cases, the above assemblies will have in common the need to reliably terminate the cable or hose into the connector, splice box or penetrator. In all cases the features of the cable or hose termination remain the same and proper attention to details ensure that strength is achieved in the termination, that water is sealed out from the termination area and that the critical communication elements within that assembly will provide reliable service for the life of the application.

The telecommunications industry has pioneered the 2.5mm diameter fiber optic ferrule connection. This concept for joining optical fibers has proven to be reliable and practical in a variety of uses and has had great success in optical connections for subsea use. The design details of ferrule connections are well established, well understood, and are suitable for most applications.[1] Much of subsea connector design deals with the termination of the cable into the "back-shell" of the connector and is particular to specific cable construction and operational requirements. Proper consideration of the issues relating to the cable termination leads to a superior system of subsea connections.[2]

2. Typical Optical Constructions

2.1 Introduction

The most basic unit of fiber optic cable construction is the 125 micron diameter fiber itself. It is the "conductor" of the light signal traveling within the core and cladding of the optical fiber.[3] At this most basic level of fiber construction the fiber unit is very vulnerable to damage due to the physical stress of bending. As a means of protecting the fiber from physical and environmental damage it is common to add a coating to the fiber as a bulk protective layer. This is the fiber unit most often found in bundled fiber constructions. Additional protection is also commonly added to the coated fiber in the form of a "buffer" layer. This layer of protective thermoplastic brings the standard fiber unit up to 900 microns in diameter and results in a fiber with greatly increased resistance to damage by bending, pulling and exposure to the elements. This is the minimum level of fiber protection necessary for a termination system that will experience movement or manipulation of the fibers.[4]

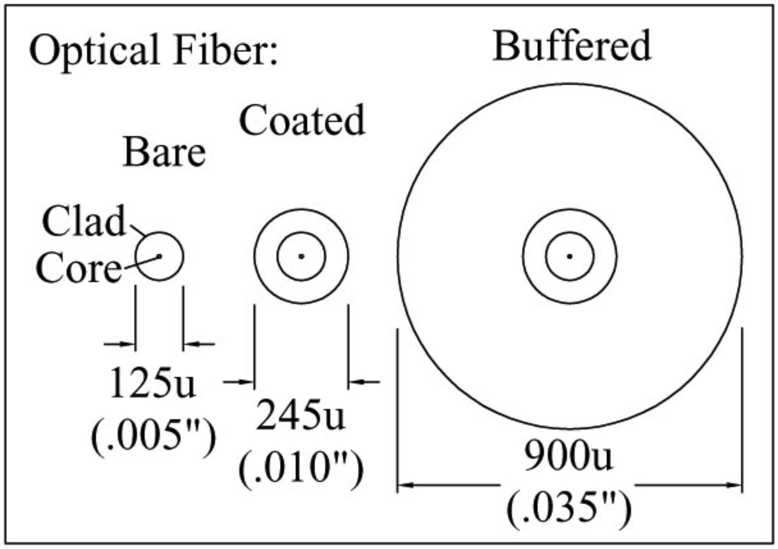

Figure 1 - Basic optical fiber construction.

2.2 The Next Level of Protection

In order to give an individual fiber sufficient strength to be a stand-alone unit, a Kevlar strength member may be served around the fiber and an overall jacket added to contain the assembly. At this point the fiber unit is nominally 2 or 3 millimeters in diameter and is robust enough to take regular handling and bending without damaging the fiber.

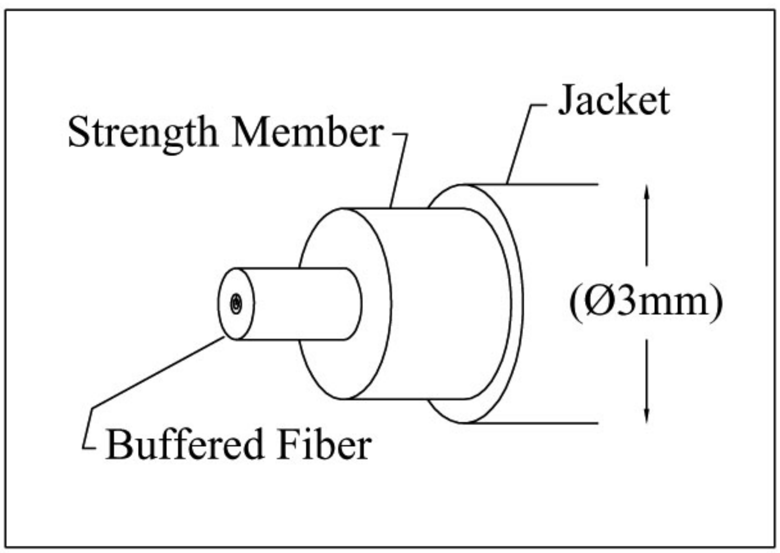

Figure 2 - The stand-alone optical fiber unit.

A common means of packaging multiple fibers for severe applications is to place them within a rigid protective tube or conduit. For oceanographic applications, the tubes will be metallic, generally stainless steel. Often the fibers are bedded in a gel, which maintains a stable consistency over a broad temperature range in order to support the fibers along the length of the tube and prevent relative motion and wear within the tube. Stainless steel tubes effectively isolate the fibers from the outside environment. This feature makes stainless steel tube construction a natural for oceanographic applications.

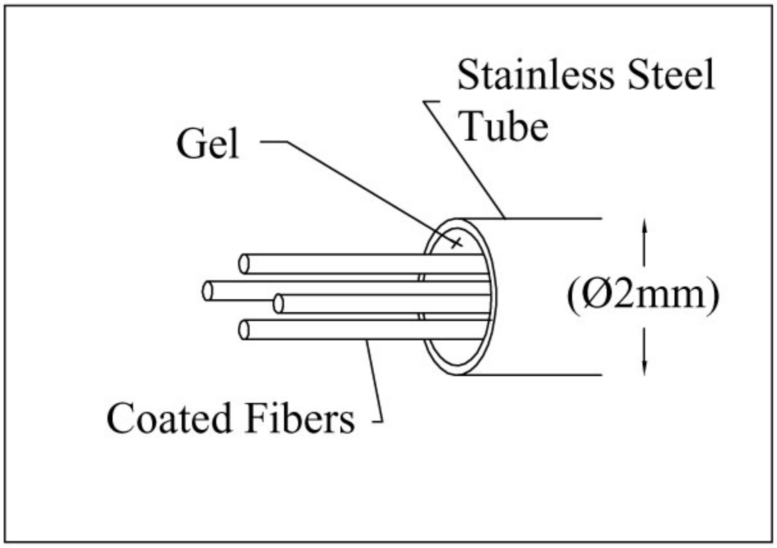

Figure 3 - Multiple optical fibers bundled in a "stainless steel tube".

Another method of fiber packaging that has found widespread acceptance for oceanographic applications is the "Embedded Matrix". In this construction multiple fibers are embedded within a thermoplastic matrix surrounding a central strength member or "King Wire". The matrix is additionally protected by a welded metal over-tube jacket, which hermetically seals the assembly and isolates the internals from the outside environment. Fibers packaged in this manner are well isolated from the outside environment and from each other, are prevented from small radius bends, and are isolated from external stress.

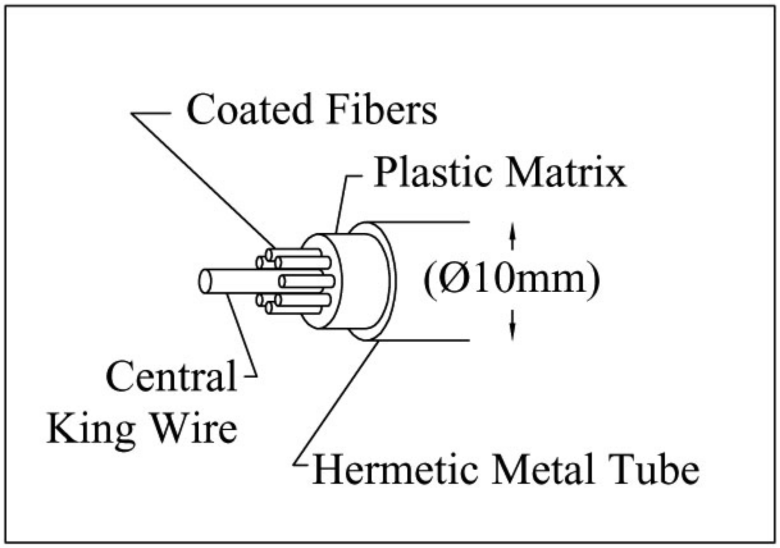

Figure 4 - Multiple optical fibers in an "Embedded Matrix".

This seems an ideal solution to the use of fiber in the sea but has the disadvantage of higher initial cost and greater difficulty in taking the fibers out of the matrix for termination.

a. Additional armoring with steel or Kevlar strength members and over-jacketing with water-resistant materials yields an ocean-capable cable assembly. Any of the above fiber constructions may be found in oceanographic cables, often combined with conventional conductive copper elements as "Hybrid" electro-optic cable assemblies with application specific design features.

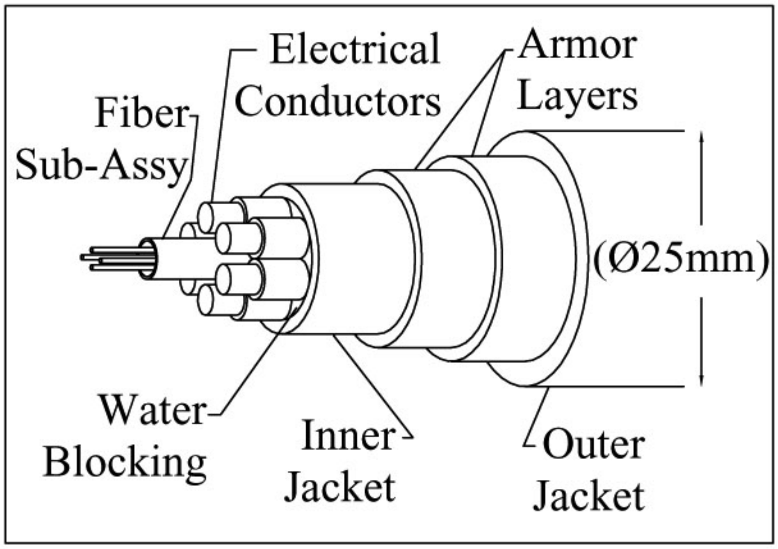

Figure 5 - Typical oceanographic electro-optical cable.

b. A popular method of utilizing fibers in subsea oilfield applications is to house them inside oil-filled and pressure-balanced hoses. This method is particularly suitable when a relatively short distance is required and custom cable construction is impractical or uneconomical. Any number of fibers may be placed within a hose along with electrical conductors where necessary to create hybrid assemblies. Such "Oil-Filled-Jumpers" are commonly used for making subsea connections between umbilical cables and subsea equipment. Jumpers allow components to be installed individually and subsequently "wet-mated" as a system on the seafloor by divers or Remotely Operated Vehicles (ROV's).

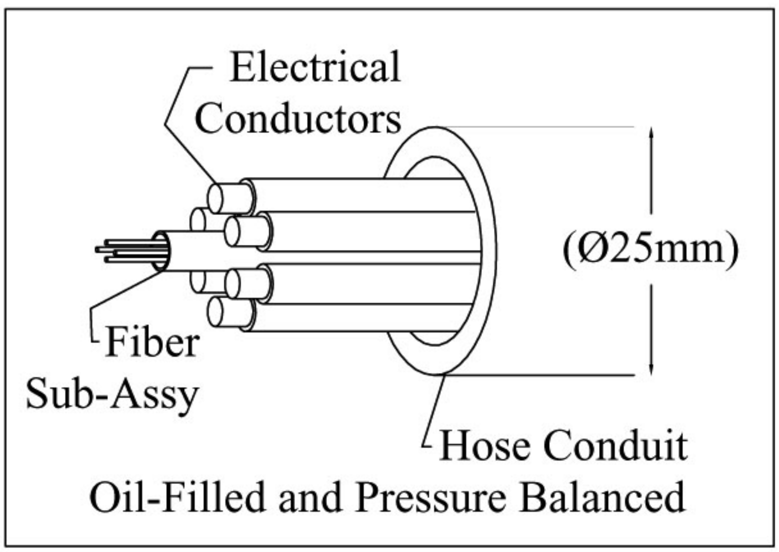

Figure 6 - Typical oil-filled jumper hose assembly.

3. Inherent Problems with Optical Fibers

3.1 Tensile Loads

The basic 125 micron diameter clad fiber is proof tested at manufacture to 100,000 psi to insure uniform tensile strength.[5] With a cross sectional area of only 1.9×10^{-5} square inches the fiber should be good for tensile loads to about 1/2 lb. Applied loads to the fiber itself beyond this capability will result in fiber failures. Applied loads must be considered beyond the static value. Dynamic motion of ships and equipment operating on and in the ocean lead to transient peak loading and vibration of cables which may stress fibers beyond their mechanical limits.

3.2 Environment

Glass fiber itself is compatible with water and oil environments although long term exposure to water (a source of hydrogen) has been found to cloud the glass and decrease the efficiency of light transmission. Corrosion of materials in direct contact with the fiber may lead to detrimental stresses within the fiber.

3.3 Attenuation

Small imperfections and flaws within the glass material scatter some of the light traveling within that fiber. Scattered light will either be reflected back along the fiber to the source or outside of the capture angle of the fiber so that it is lost.[6] This results in a measurable attenuation per unit length of fiber, typically less than -0.2 dB/kilometer as manufactured.[5] Stresses imposed on an optical fiber due to external pressure will cause an increase in attenuation and can be measured as an increase in attenuation per unit length of fiber. Fiber will take uniform tri-axial pressure with only a slight increase in rate of attenuation but problems arise when non-uniform pressure is applied. Bending of fibers directly affects amount of light lost to the cladding and decreases the efficiency of light transmission within the fiber. Bending occurs at two levels, “Macro” bending and “Micro” bending. Macro bends are relatively large radii bends of the fiber as a whole and typically become critical when bend radii go below 0.5 inches. Micro bends are very short radii bends of the fiber, in the range of the dimension of the fiber itself. These bends may result from stresses applied by materials in contact with the fiber and can have significant impact on fiber attenuation.

3.4 Pressure

A challenge exists when transitioning a fiber from a high-pressure environment to a lower pressure environment such as from the deep sea into the one-atmosphere environment of an electronics vessel. In order to accomplish this the fiber must be fixed axially and sealed against water intrusion. This results in localized stress and is an inherently difficult aspect of fiber termination.

3.5 Vertically Hanging Fibers

Unique to oceanographic applications is the fact that cables are often suspended vertically from a surface ship or facility to subsea equipment many kilometers below. As with armored cable assemblies, the weight of a suspended fiber must not exceed the tensile strength of the fiber. In practice it is desirable to distribute support along a suspended fiber.

3.6 Contact"Yield"

The actual optical contact termination in a larger cable termination is typically done after much other work on that termination has been completed. As optical fiber is very fragile, optical contacts are vulnerable to damage from handling and costly to replace after other "value added" work has been performed.

3.7 "Dynamic Contacts"

For effective optical performance, terminated optical ferrule contacts must meet face to face with no gap.[6] In order to compensate for manufacturing tolerances in connector components it is necessary to have the contacts on at least one side of the connection mounted with axial compliance.

4. Solutions

4.1 Strength Member Termination

Most basic to terminating a cable into the back of a connector is to fix it in place relative to the connector itself. In an armored cable the layers of armor, whether they are steel or Kevlar, can be fanned out and locked into a cone by means of tapered wedges or by epoxy potting. A connector may need to transmit mechanical load across the connection where full cable strength must be developed in the armor termination. Various methods and materials have been developed to effectively deal with these issues. It is important to protect the cable core from crushing due to forces experienced in clamping the armor by using an anti-crush device. The outer jacket may be compression-clamped to the armor at the termination.

4.2 Isolation from Movement

One may well expect some movement of the core relative to the armor in a dynamic application as the cable is cyclically manipulated and loaded. The core must be secured to the shell in the termination. Components within the core must also be fixed in place if there is a possibility of movement in those components.

4.3 Barriers

Once all of the levels of cable construction are secured, they must be sealed to prevent the ingress of water. It is preferable to effect seals to every available layer of cable barrier including outer jacket, inner jacket, conductor insulation, common fiber unit and individual fibers. Seals to jackets can be made by over-molding and bonding to the jacket surface or by compression and boot seals. It is often the case that the outer jacket is damaged at some point in the life of the cable and that barrier to water is then lost. As long as the inner jacket on the core is sealed, the internals of the connector are still isolated from the outside environment. If the inner jacket fails at any point, it will allow the core of the cable and the interstices between the components to flood. Note that a "water-blocked" cable has a blocking compound added to these spaces to prevent the flow or "hosing" of water through the cable. "Water blocking" serves as an impediment to flow but is not an absolute seal. Water will eventually seep through the cable and flood the back end of a connector unless additional sealing measures are taken at the core breakout of the cable. Each individual core component should be sealed to the inner jacket of the cable and to the body of the connector.

Optical fibers within a cable present another set of circumstances to be considered in a connector termination. Consider a cable constructed with fibers in a stainless steel tube. If the cable above the termination is damaged such that the stainless steel tube floods, it now becomes a conduit for water to flow into the termination. It is desirable to seal the stainless steel tube at the terminal subsea end. The outside diameter of the tube is easily sealed by conventional means but the internal seal must allow the fragile fibers to exit without damage. Optical fibers in the embedded matrix construction would be handled in much the same way. The major difference is the difficulty in removing sufficient length of fiber from the plastic matrix without damage. This is a delicate operation that requires experience to perform successfully.

Where fibers are individually located within the interstices of the cable construction, separation is not necessary and the fibers can be treated as any other cable component taking into account the necessary precautions to seal to the fiber itself. This cable construction makes the connector termination easier but has the disadvantage of the fibers being subjected to stresses resulting from external pressurization of the cable. These stresses are detrimental to optical performance. Generally, this type of construction will perform satisfactorily in shallow water applications.

4.4 Pressure Isolation / Penetration

Dynamic optical contacts must touch before the connector shells bottom out and push back as the shells come together. The fact that the contacts are sealed means that there is an inherent change of volume in the connector termination area. This area may be air or dry nitrogen filled at one-atmosphere which allows for compression or it can be fluid filled with a compliant member that allows the volume to move with respect to the outside environment. If the area is maintained as a 1-atmosphere cavity, all of the seals to this cavity are subjected to the pressure differential to ambient.

4.5 Leak Paths

When a fiber penetrates a pressure barrier there is a possible leak path along the outside surface of the fiber and between its layers if they were to delaminate. Fibers may be sealed to pressure headers by bonding or by compression; both create stresses on the fiber and must be handled properly to minimize this stress. Actual penetrations can be eliminated in optical headers if the fiber is terminated into contact ferrules and the ferrules sealed to the header. In this case only the "light" penetrates and the fibers stop at mating ferrule interfaces. The ferrule interface will have the characteristic optical losses associated with a connection as opposed to a continuous fiber penetration. Terminated ferrules are a very effective pressure barrier and have been proven by testing to 20,000 psi.

Where the losses and costs of ferrule penetrators are not acceptable it is necessary to develop a reliable through-fiber pressure header. Selection of materials is critical to this effort, as the seal will require a bond to the fiber and to the housing.

4.6 Reinforced Penetrations

A fiber can be reinforced with a bonded strength member in the area of penetration. The correct combination of materials, clearances and bond lengths will yield reliable pressure capable barriers. The bonded strength member is a more robust element that may be handled by conventional sealing technologies to complete the penetrator assembly.

Elastomeric compression glands may be employed when care is taken to distribute the stress over a sufficient length of fiber so as not to create stress within the fiber resulting in optical loss. In all applications it is critical to have good bend relief control over the path of the fiber.

With any method of fiber penetration there is an advantage in handling the individual fiber penetrations as modules. In a multiple fiber system a failure in one fiber should not require all of the fibers to be cut off from the assembly and re-terminated again

4.7 Fiber Handling and Termination

With the cable elements secured, sealed and penetrated into the space behind the connector interface it now remains to terminate the individual fibers. Fibers should be routed such that they do not have any excessive bends in either the unmated or mated positions when the contacts are "pushed back." Bend radii should be kept as large as possible to minimize bend-induced attenuation. Fibers should be well supported in this area and kept separated from other bulky elements of the termination such as electrical conductors.

If this space is to be oil-filled and pressure-compensated it will result in force being applied to the back of the sealed optical contacts if the connector interface is not also pressure-compensated. The ambient pressure will act upon the effective surface area of the sealed contact and result in additional load on that optical contact. With time, this will affect the optical performance of the connection. Dry-mated connectors usually have a one-atmosphere interface but can be pressure equalized through a valve in one of the connector halves. Note that with the interface pressurized, the opposite side of the connection now sees ambient pressure and must be designed to withstand that pressure.

4.8 Storage and Splicing

It is particularly useful in multiple fiber terminations to have a space in which to store extra fiber. This spare fiber greatly enhances the field maintenance capability of the product. Terminated optical fibers can be a modular component, which are readily available for inclusion into the product for production or repair. Repairs in the field may take the form of removing a damaged optical contact and re-terminating a new contact onto the end of that fiber. Alternatively, a pre-terminated contact may be fusion-spliced onto the fiber in question. Fusion-splicing is a useful repair method in field situations. There is a slight additional optical loss incurred with a fusion-splice, on the order of -0.02dB per splice.[7] A fusion-splice is a fragile joint that must be protected with a "splice closure" device. Splice closures are massive relative to the fiber itself and must be stored securely in the termination in order not to cause damage to fibers in the near vicinity.

5. The End Result

As with any subsea assembly, the more complex it is the more it will cost. In reality, true cost goes beyond the initial cost of acquisition and includes the costs of operation. A bit more expense put into the design and manufacture of an optical termination is often repaid in lower operating cost and increased productivity. Optical terminations do have a few nuances unique to optical fiber that have not previously been a consideration for electrical terminations. Proper attention to detail will result in a reliable long-term optical termination solution.

References

1. Christiansen: "Fiber Optic Connections in the Sea" proceedings UWI '99, New Orleans
2. Christiansen: "Integration of Requirements and Capabilities in Cable and Connector Systems" proceedings UWI 2000
3. Understanding Fiber Optics, 2nd Ed.. Jeff Hecht, Sam's Publishing, 1993
4. Technicians Guide to Fiber Optics, 2nd Ed., Donald J. Sterling, Jr., Delmar Publishers, 1993
5. Corning SMF-28 Single Mode Optical Fiber. Product Information PI1044, Corning Incorporated, 1996
6. Fiber optic insertion loss measurements...how they relate to system use. Ronald Cooper, AMP Inc. 1983
7. Fiber Optic Connector Splice Losses: The Laboratory vs. the Real World. Ronald Cooper, AMP Inc. 1981