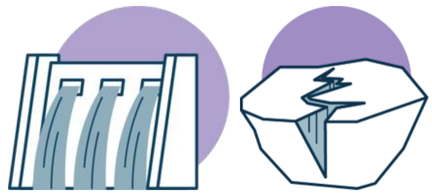
Cable Installation Considerations for Structure Monitoring

Introduction

Distributed fiber optic sensing (DFOS) techniques such as Distributed Strain Sensing (DSS), Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) are powerful tools for continuous monitoring of large assets. Consequently, these approaches fit perfectly with specific requirements of structure monitoring, where they fulfill objectives in various areas:



- Monitoring strain in structures such as pipelines, cables, bridges, foundation piles, walls, wells and buildings
- Detecting ground movements, slope instability, subsidence, landslides and ice flow in glaciers
- Monitoring rock and lining stability during tunnel construction and operation
- Monitoring road and rail track stability
- Monitoring dam and dyke stability
- Detecting activity at the structure (work crews, trespassers, excavation, tunneling)
- Detecting sound and vibrations related to seismic activity, micro-seismic events (rock or ice cracking) and structure movement or cracking

In each of these applications, distributed fiber optic sensing offers clear benefits in the ability to cover a wide area from a central monitoring point, sometimes by taking advantage of spare fibers in existing fiber-optic cables.

Optimum performance for sensing objectives depends on cable type, installation method, cable position and the site environmental conditions. This applies to existing cables as well as those installed specifically for distributed fiber optic sensing.

This document provides guidance on best practice for the selection and installation of cables for fiber optic sensing in structural health monitoring (SHM). The most prevalent sensing technology for structure monitoring applications is DSS, which monitors strain related to mechanical loads of structures. Cables for DSS must be designed and installed in a way that ensures efficient strain transfer from the structure to the optical fiber.

Cable Selection

General

Fiber optic cables should be selected according to their proposed use. For large structures, optical cables are often simultaneously used for fiber optic sensing, communication, and control networks, supporting the operational requirements of the asset. The type of installation (e.g., attached to or embedded into a structure, direct buried or in conduit) and the environment / ground conditions may have an impact on the construction and level of protection / armor necessary to meet local regulations. Depending on various factors, the structure of the cable might affect the sensitivity and performance of the sensing system. Cable selection details should be discussed with your fiber sensing supplier or industry specialists before finalizing installation.

Fiber Selection by Application

Optical fibers should be single-mode or multimode with fiber selection tied directly to the method of interrogation. The following information provides general fiber selection guidance but is not exhaustive.

For most sensing systems used in structure monitoring including DSS, DAS and DTS, single-mode optical fibers should be selected that meet or exceed the performance characteristics described in ITU-T G.652/654/655 (telecommunication grades) and G.657 (bend insensitive telecommunication grades). Ultra-low loss single-mode fibers compliant to the ITU-T G.654 standard should be preferred in applications where large distance and / or optical budget needs to be covered. Non-telecom, engineered single-mode fibers with additional back scattering or reflection centers could be advantageous for certain DAS applications.

For certain DTS applications multimode fibers should be selected that meet or exceed ITU-T G.651 C/D performance guidelines. Selection of multimode fibers that meet or exceed these performance criteria will ensure that the fiber attenuation supports the desired range of the application, while the bandwidth of the fiber provides assurance that the desired spatial resolution of the DTS system can also be achieved.

Common Cable Configurations

Tight buffered and loose tube cables are the most common configurations used for organizing and protecting optical fibers inside the cable core. This helps keeping fiber attenuation low and ensures fiber reliability following installation.

Tight buffered cable constructions place individual fibers in cable subunits, where the cable materials are in intimate contact with the individual fibers they protect. From a sensing standpoint, there is advantage in this style of cable to aid in coupling from the environment to the fibers housed within the cable. This is an important consideration for strain (DSS) sensing applications.

Loose tube constructions allow the optical fibers within the cable subunits (tubes) to float freely, ensuring that the fibers have virtually no exposure to strain or compression induced by the cable materials. This leads to the lowest optical attenuation but cannot be used to measure deformation. Commonly, DTS cables utilize this method of construction. Loose tube cables can be further categorized as gel-filled, or dry-blocked. Gel-filled cables utilize a thixotropic (hydrophobic) gel that surrounds the optical fibers and acts as a water-blocking agent. Alternate methods of water-blocking include the addition of super-absorbent polymer powders that swell into a gel when exposed to water, providing a water block with little to no effect on fiber attenuation.

Bare tight buffered fibers and loose tubes are in general susceptible to kinking and other types of mechanical load. Fiber-optic cables are therefore equipped with additional protection layer(s). Such layers may consist of a second tube layer, stainless steels wires or aramid fibers for strain relief and/or plastics sheath for better handling and mechanical / chemical protection.

When integrating fiber sensing within harsh environment, it is common to use Fiber-In-Metal-Tube (FIMT) to ensure high tensile strength and excellent crush resistance. FIMT implies a loose-tube or tight buffered construction whereby the cable subunit is a welded metallic tube containing optical fibers.

All-dielectric cables could be used as a cost-efficient solution, provided that they are compliant with the expected mechanical and chemical loads. Dielectric cables are usually lighter and easier to install.

Heavily armored cables should be avoided as this type of construction could result in a reduction of system sensitivity to strain and vibrations.

Specific Cable Considerations for DSS

DSS measurement uses one (or two) single-mode fiber(s) depending on the type of interrogator. Single-mode tight buffered fiber must be used to ensure mechanical coupling to the environment. Fibers showing a single Brillouin peak are in general better suited for DSS at large distance than multipeak fibers.

Transfer of strain from the structure to the optical fiber requires good mechanical coupling between all layers. When directly buried in soft soil, the cable outer sheath could exhibit a structured surface or some anchoring methods could be used for enhancing the coupling to the environment.

Depending on the type of DTS interrogation equipment, sensing systems work in either a single-ended or dual-ended measurement method.

In single-ended use, the interrogator couples laser energy into the fiber at the proximal end of the system, relying on backscattered light to determine event magnitude and location.

Dual-ended interrogation systems utilize a loop-back method whereby two optical fibers run in parallel along an asset being monitored. These fibers are joined at the distal end of the system to create a continuous optical path such that the ends of the optical fiber are accessible at the proximal end of the system.

Instruments using single and dual-ended configurations are available, and the choice between them dependends on the application and performance requirements as well as on the user´s preferences.

The tensile strength of the cable shall be large enough to take the tensile load during installation. However, it should be low enough to allow sufficient elongation of the cable under the expected strain levels without exceeding the forces that can be taken by the mechanical coupling means between cable and environment. When large deformation is expected, the cable elastic limit must be taken into account. Plastic deformation is acceptable for unidirectional deformation such as ground movement, while it cannot be tolerated in application with bidirectional deformation by elongation / compression cycles.

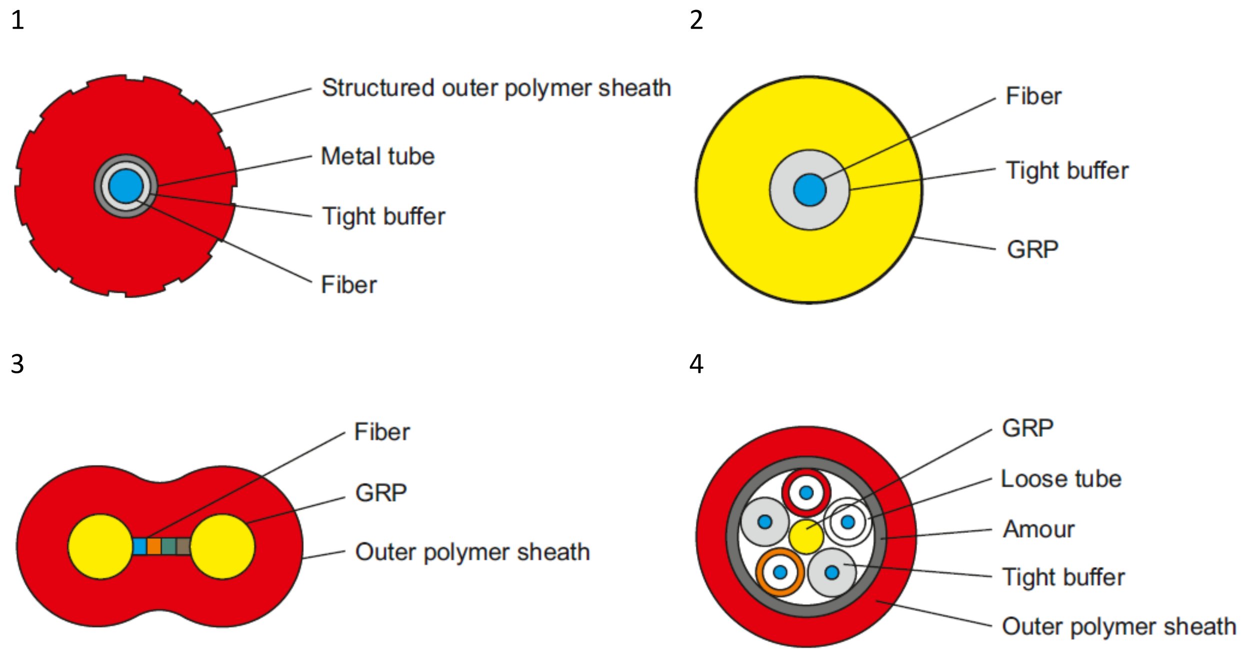


Figure 1: Examples of cable designs for DSS. Tight buffered FIMT with structured plastics sheath (1), tight buffered fiber embedded in glass re-inforced polymer (GRP) matrix (2), compact and all dielectric tight buffered cable (3) and multi fiber loose tube / tight buffered cable for strain and temperature sensing (4).

Embedding optical fibers or cables into composite tapes or geotextiles provides excellent prerequisites for bonding to a structure or for embedding into soil or other soft materials.

Specific Cable Considerations for DAS

DAS works in one single-mode fiber and requires effective acoustic coupling between the fiber, the cable and the environment in which acoustic (vibrational) events are to be detected.

So far good experiences have been made with standard single-mode fiber cables which are used for telecommunication and work with wavelengths between 1530 – 1560 nanometers. The preferred cable specification for DAS is:

- Single-mode
- Tight buffered or gel-filled loose tube
- Single jacket
- Unarmored or single armor
- Spare dark fiber cores (generally one for every 50 km monitored)

This type of cable has proven its capabilities in many different installation scenarios and ranges of 70km or more.

While most installations to date have made use of existing cables, it is expected that in the future cables optimized to enhance acoustic sensitivity will become prevalent.

Specific Cable Considerations for DTS

Loose tube fiber with appropriate excess fiber length (EFL) should be used to minimize micro-bending and fiber strain when the cable is under tension or when the temperature varies in operation. Thermal coupling inside the fiber optic cable is in general no issue because its response is often much faster than that of the asset it is monitoring.

DTS works using one (or two) single-mode or multimode fiber(s) depending on the type of interrogator. Multimode fibers shall have a graded index design with enough bandwidth*length product to achieve desirable spatial resolution over large distances.

Depending on the type of DTS interrogation equipment, sensing systems work in either a single-ended or dual-ended measurement method.

In single-ended use, the interrogator couples laser energy into the fiber at the proximal end of the system, relying on backscattered light to determine event magnitude and location.

Dual-ended interrogation systems utilize a loop-back method whereby two optical fibers run in parallel along an asset being monitored. These fibers are joined at the distal end of the system to create a continuous optical path such that the ends of the optical fiber are accessible at the proximal end of the system.

Single and dual-ended configurations for both Raman and Brillouin based DTS systems are available and the choice between the measurements depends on the application and required performance.

Cable Deployment Methodology

General

The methods used to deploy and protect the cable near a power utility will depend on local geography, environmental conditions and regulations. These will generally be focused on protecting the cable from weather and accidental or malicious damages, but may also affect system sensing performance.

Cable Deployment for DSS

For DSS it is essential to have good mechanical coupling with the asset being monitored. Initial cable strain should not be too high to allow for a wide measurement range for strain and to ensure a long shelf life of the fiber. However, some initial cable strain may be useful to measure compression should the asset being measured shrink rather than elongate. It also helps to minimize strain variations caused by the fiber deployment, e.g., the fiber should be installed with uniform and low strain. Cables with small and uniform initial compression can also be used if cable design and/or embedding in the structure ensure that compression does not lead to micro-bending of the fiber.

Embedding fibers or cables into cement, epoxy or composite structures before hardening can provide excellent mechanical coupling. Pre-tension of cables should be considered where compression is expected.

Bonding to structure surfaces like pipelines or beams using adhesives or adhesive tapes can also provide strong mechanical coupling. Proper selection of materials, preparation of surfaces and large contact areas are required to ensure sufficient force transfer for measuring the expected strain levels.

Brackets, clamps, cable binders or other means for point-wise attachment of optical cables can also provide strong mechanical coupling to structures. Attachment points should be sufficiently closely spaced to enable measurements with the required spatial resolution. Transverse forces shall not exceed the crush resistance of the cable. Attachment means must be strong and rigid enough for transferring the required forces and for not affecting the accuracy of strain measurements.

Cement anchors bonded to the cable can be used to enable point-wise mechanical coupling of optical cables to very soft soil.

Cable Deployment for DAS

For DAS, the key is finding an installation method that places the cable close to the signal of interest and protects the cable both from damage and unwanted noises without unduly reducing sensitivity. Best acoustic coupling is achieved when the fiber optic is integrated into the asset to be monitored.

Buried cables should be embedded in the soil, backfilled with the same soil type, and compacted for best acoustic coupling results.

Cable Deployment for DTS

For DTS it is essential to have good thermal coupling to the asset for accurate monitoring. Best thermal coupling is achieved by any deployment where the fiber optic cable is integrated into the asset. If the fiber optic cable is lashed to the asset being monitored, it is important to optimize contact between cable and asset and to minimize air gaps. If a fiber optic cable is lashed to a power cable it should not hang between cable binders on the lower side but should lay on top of the power cable and industrial tape should be used in addition to cable binders to improve physical contact.

Cable Positioning

General

There are many possibilities for how new or existing cables could be installed, and these can significantly affect performance depending on application, as explained in the following sections.

Cable Positioning for DSS

The fiber must be installed at a location on or along the asset to be monitored where strain appears. This is normally inside or attached to the asset to be monitored. For tension or compression, it is enough to use one fiber (and maybe a loop back for certain types of interrogators). For bending or torsion, multiple fibers at different locations within the asset could be required. It is sometimes of interest to look for variations of the ground around a structure as a means of preventing damage. In this use case the placement of the sensing cable may be burial near the structure.

Cable Positioning for DAS

A major factor in the coupling of acoustic or vibrational signal transmitted to the sensing fiber is the location and installation method of the cable. Distance from the fiber to the sound source must also be considered. The influence of noise (undesirable vibrations) to the DAS system should also be considered, for example vehicles passing or people walking. Care should be taken to route the cable away from these areas to optimize the DAS system's ability to detect and classify signals of interest.

High energy sources such as trucks, excavators or large ships can be detected at a greater distance than low energy patterns like human digging or walking. In addition to distance, the type of medium (water, soil, etc.) through which acoustic energy needs to travel will affect the level of vibration applied to the fiber – for example, a cable buried in loose sand will be less sensitive than one buried in firm sand, clay or loam since the loose media will absorb some of the signal.

Cable Positioning for DTS

The fiber optic cable should be installed as close as possible to the location where the temperature needs to be known. In cases, where this is impossible, thermal simulation software could be used to calculate temperatures at other positions from DTS temperatures using a model of the thermal environment and knowledge about the power of heat sources.

FOSA Technology Committee Contributors:

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Please visit www.fiberopticsensing.org for further information on the application of fiber optic sensing.