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European foreword

This document (prEN 4533-001:2024) has been prepared by ASD-STAN.

After enquiries and votes carried out in accordance with the rules of this Association, this document has received the approval of the National Associations and the Official Services of the member countries of ASD-STAN, prior to its presentation to CEN.

This document is currently submitted to the CEN Enquiry.

This document will supersede EN 4533-001:2020.

The main changes with respect to the previous edition are as follows:

— update of the document to remove trademarks.

Introduction

a) The handbook

The purpose of EN 4533 is to provide information on the use of fibre optic components on aerospace platforms. The documents also include best practice methods for the through-life support of the installations. Where appropriate more detailed sources of information are referenced throughout the text.

The handbook is arranged into 4 parts, which reflect key aspects of an optical harness life cycle, namely:

— Part 001: Termination methods and tools;

— Part 002: Test and measurement;

— Part 003: Looming and installation practices;

— Part 004: Repair, maintenance, cleaning and inspection.

b) Background

It is widely accepted in the aerospace industry that photonic technology offers significant advantages over conventional electrical hardware. These include massive signal bandwidth capacity, electrical safety, and immunity of passive fibre-optic components to the problems associated with electromagnetic interference (EMI). Significant weight savings can also be realized in comparison to electrical harnesses which may require heavy screening. To date, the EMI issue has been the critical driver for airborne fibre-optic communications systems because of the growing use of non-metallic aero structures. However, future avionics requirements are driving bandwidth specifications from 10s of Mbits/s into the multi-Gbits/s regime in some cases, i.e. beyond the limits of electrical interconnect technology. The properties of photonic technology can potentially be exploited to advantage in many avionic applications, such as video/sensor multiplexing, flight control signalling, electronic warfare, and entertainment systems, as well as sensor for monitoring aerostructure.

The basic optical interconnect fabric or ‘optical harness’ is the key enabler for the successful introduction of optical technology onto commercial and military aircraft. Compared to the mature telecommunications applications, an aircraft fibre-optic system needs to operate in a hostile environment (e.g. temperature extremes, humidity, vibrations, and contamination) and accommodate additional physical restrictions imposed by the airframe (e.g. harness attachments, tight bend radii requirements, and bulkhead connections). Until recently, optical harnessing technology and associated practices were insufficiently developed to be applied without large safety margins. In addition, the international standards did not adequately cover many aspects of the life cycle. The lack of accepted standards thus leads to airframe specific hardware and support. These factors collectively carried a significant cost penalty (procurement and through-life costs) that often made an optical harness less competitive than an electrical equivalent. This situation is changing with the adoption of more standardized (telecoms type) fibre types in aerospace cables and the availability of more ruggedized COTS components. These improved developments have been possible due to significant research collaboration between component and equipment manufacturers as well as the end users air framers.

1 Scope

1.1 General

This document examines the termination of optical fibre cables used in aerospace applications. Termination is the act of installing an optical terminus onto the end of a buffered fibre or fibre optic cable. It encompasses several sequential procedures or practices. Although termini have specific termination procedures, many share common elements and these are discussed in this document. Termination is required to form an optical link between any two network or system components or to join fibre optic links together.

The fibre optic terminus features a precision ferrule with a tight tolerance central bore hole to accommodate the optical fibre (suitably bonded in place and highly polished). Accurate alignment with another (mating) terminus is provided within the interconnect (or connector) alignment mechanism. As well as single fibre ferrules, it is noted that multi-fibre ferrules exist (e.g. the MT ferrule), and these are also discussed in this document.

Another technology used to connect 2 fibres is the expanded beam. 2 ball lenses are used to expand, collimate and then refocus the light from and to fibres. Contacts are not mated together. It helps reducing the wear between 2 contacts and allows more mating cycles. This technology is less sensitive to misalignments and dust. Losses are remaining more stable than butt joint contact even if the nominal loss is higher.

NOTE Current terminology in the aerospace fibre optics community refers to an optical terminus or termini. The term optical contact can be seen in some documents and has a similar meaning. However, the term contact is now generally reserved for electrical interconnection pins. The optical terminus (or termini) is housed within an interconnect (connector is an equivalent term). Interconnects can be single-way or multi-way. The interconnect or connector will generally house the alignment mechanism for the optical termini (usually a precision split-C sleeve made of ceramic or metal). It is important that the reader is aware of these different terms.

An optical link can be classified as a length of fibre optic cable terminated at both ends with fibre optic termini. The optical link provides the transmission line between any two components via the optical termini which are typically housed within an interconnecting device (typically a connector) with tight tolerancing within the alignment mechanisms to ensure a low loss light transmission.

This document explains the need for high integrity terminations, provides insight into component selection issues and suggests best practice when terminating fibres into termini for high integrity applications. A detailed review of the termination process can be found in Clause 4 of this document and is organized in line with the sequence of a typical termination procedure.

The vast number of cable constructions and connectors available make defining a single termination instruction that is applicable to all combinations very difficult. Therefore, this handbook concentrates on the common features of most termination practices and defining best practice for current to near future applications of fibre optics on aircraft. This has limited the studies within this part to currently available 'avionic' silica fibre cables and adhesive filled butt-coupled type connectors. Many of the principles described, however, would still be applicable for other termination techniques. Other types of termination are considered further in EN 4533-004.

It is noted that the adhesive based pot-and-polish process is applicable to the majority of single-way fibre optic interconnects connectors and termini for multi-way interconnects and connectors. They share this commonality.

1.2 Need for high-integrity terminations

In order to implement a fibre optic based system on an aircraft, it is vital to ensure that all the constituent elements of the system will continue to operate, to specification, over the life of the system. An important aspect of this requirement is the need for reliable interconnection components.

Interconnects are a key component in any fibre optic system or network. Digital communications links, sensor systems, entertainment systems, etc. all require interconnects both at equipment interfaces and for linking cables and harness sections together over the airframe.

Interconnects need to be robust to mating and demating operations, environmental changes and also the effects of contamination. They need to be amenable to inspection and cleaning for through life support.

The choice of technology used in optical links and connections is mainly dependant of the environment. In service performance is a pillar in the component selection. Cable to connector interface needs to be assessed to prove the effectiveness of the solution.

High-integrity terminations are required to ensure reliable, low loss light transmission through the interconnection. High-integrity terminations are produced by observing best practice and using the correct materials, tools and procedures with appropriate controls.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

No terms and definitions are listed in this document.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp/

— IEC Electropedia: available at https://www.electropedia.org/

4 Component selection

4.1 Elements

All interconnection technologies are taken into account in the context of EN 4533-001.

It is important to recognize that a fibre optic termination, while appearing straightforward, is in fact a complex interaction of the constituent elements such as: fibre, ferrule, fibre coatings, connector design, cable strength member anchorage method, adhesive type, and cure regime (where used), material properties and so on. Each of these elements will have an impact on the termination, in terms of reliability, integrity and process complexity.

The following sections discuss the key elements to the termination.

4.2 Fibre optic cables

4.2.1 General

There are many types of fibre optic cable on the market today. Cables are essentially assemblies that contain and protect the optical light guide (used to carry the system light signal). The central light guide is usually made from silica glass although other materials can be used. Glass is inherently strong although it must be protected from external damage and other factors that could cause weakening (generally moisture and fluid contamination in the presence of any defects and stress). The cable provides the protective layers to the glass and generally also incorporates a strength member (this element is important in the termination for providing strain relief) and a protective outer jacket.

For aerospace applications, most encountered cables will carry a single, central optical fibre (suitably protected as discussed in the following sections). There can be variation in single fibre cable designs.

Some may be of tight jacket construction, some of loose jacket construction. Cables are also being developed with many fibres contained within a protective tube construction. It is noted that many of the cable designs used in terrestrial telecommunications and data communications will not be suitable for aerospace use. This is generally due to environmental capability limitations often due to environmental characteristics.

4.2.2 Cable construction

As mentioned in the introduction, the cable construction provides the protection to the central lightguide(s).

Although the design of fibre optic cable for use on aircraft is fairly similar from one manufacturer to another there are important differences between cables. The two main areas of difference are fibre coatings and the cable strength member materials. Each has its own positive and negative attributes in the context of termination procedures. Avionic fibre optic simplex cables are typically constructed as in Figure 1.

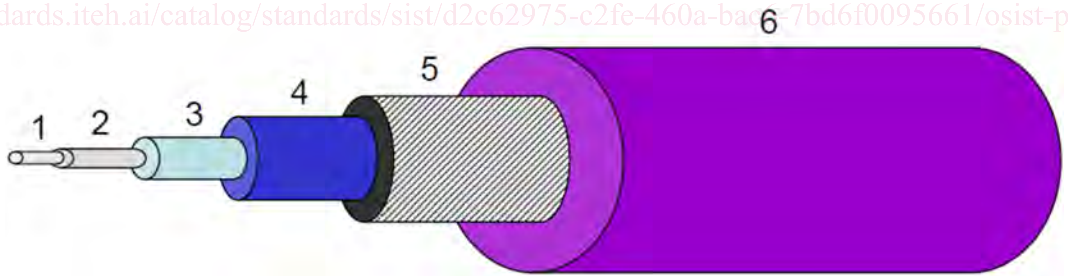
Another distinction between cable designs is whether all the coatings are “tight” or “semi loose” onto the underlying layers. This will also impact the operation of the terminated cable, (referring to full pull proofness achievable with loose structure cables)

A tight cable is a cable which shows no movements between all layers.

A semi-loose cable is a cable which shows limited movements between layers. It could be a movement between the fibre and the buffer (case of 900 µm cables) or between the buffer and the above layers (case of simplex 1,8 mm cables)

A tight construction is generally easier to terminate but can be more sensitive to environmental changes if materials are not well chosen. Some cable designs have a semi-loose construction where the central fibre has some mobility within one of the cable layers (usually an inner sheath). This design is generally more difficult to terminate but can have superior environmental performance (because the fibre is isolated from the other layers).

The behaviour of the connector is different whether the cable is tight or semi loose. Generally, on tight construction fibre contact is interrupted when pulling. The semi loose construction permits a pull safe termination.



Key

1 Core

2 Cladding

3 Primary buffer

4 Secondary buffer

5 Strength member

6 Outer jacket

Figure 1 — Typical avionic fibre optic cable construction

NOTE The glass fibre lightguide comprises the core and cladding regions.

Figure 2 highlights the key elements of an aerospace fibre optic cable. These elements are now discussed in more detail.

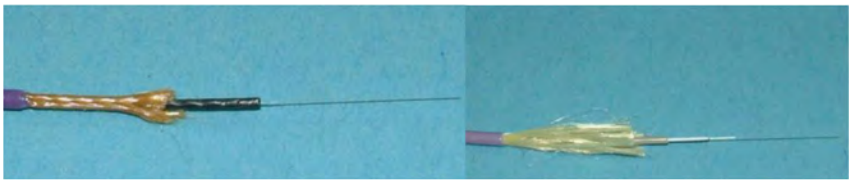


Figure 2 — Examples of EU standardized cables

4.2.3 Fibre choice

The central lightguide is defined by the core/cladding region. This is the fibre that needs to be suitably protected by the cable. It is noted that both the core and the cladding are generally formed from glass. The glass in the core is of higher refractive index than the cladding and this allows light guiding along the fibre via total internal reflection. Whilst most aerospace fibres are made from glass it is recognized that other fibre constructions exist including plastic optical fibre (POF), plastic clad silica (PCS). Very novel fibres such as photonic crystal fibres (PCF) or polarization maintaining fibre (PM) may also find some specialized aerospace applications in the future.

One of the primary distinctions between cables is whether the cable carries a single-mode or a multimode optical fibre lightguide. The choice of lightguide will be dictated by the system or network. Most current data communication systems on aircraft use multimode based cables. The relatively short lengths encountered on aircraft mean that multimode fibres can currently provide sufficient bandwidth (up to ~10 Gbps) and their relatively large cores are easier to interconnect (compared to single-mode). Sensor systems will generally require single-mode-based cables. Future bandwidth requirements or the need for data multiplexing down common fibres may drive the need for more single-mode fibre cables in aerospace although it must be recognized that single-mode fibres (~9 µm core size) are harder to align and keep free from contamination.

Multimode fibres can be either Step Index (SI) or Graded Index types. Graded index fibres have a graded profile to the refractive index of the fibre. In essence this increases the bandwidth of the fibre by equalising the various possible light paths within the core region (thus reducing any dispersion or data pulse spreading that can occur). Higher data rates are possible with graded index fibres. Step index fibres may be seen particularly on legacy systems. As its name suggests, the refractive index profile shows a step change in value defining the change from core to cladding material.

Historically, avionic fibre sizes have tended to be larger than the standard high-volume fibres such as those used in the data communication and telecommunication market and have therefore had an associated cost and availability penalty (associated components required for termination have also been non-standard and therefore more expensive). Examples of larger fibre sizes are 200 µm/280 µm, 100 µm/140 µm (where the convention denotes the core/cladding dimension). The data communications and telecommunications industries typically use fibres of size 62,5 µm/125 µm, 50 µm/125 µm (multimode) and 9 µm/125 µm (single-mode). The last fibres are now being specified for new systems on aircraft with these fibre sizes, which is becoming the standard configuration.

Importantly for termination, these fibres have a common outer cladding diameter of 125 µm. This means that the ferrules used in fibre optic termini can be lower cost (these components are mass produced for the telecommunications market). A number of companies are now packaging these data communication and telecommunication standard fibres in an aerospace cable meaning that higher bandwidth cables are now available to the aircraft industry.

Other factors worth mentioning in the choice of fibre are:

— bandwidth:

  o Multimode fibres (within the cable) are designated by the OM identification (meaning ‘optical multimode’). OM1 describes 62,5 µm/125 µm fibre, OM2, OM3 and OM4 describe 50 µm/125 µm fibres of increasing bandwidth;

— radiation resistance (radiation hard):

  o these may be specified on some military programs;

— bend resistance:

  o cables with bend tolerant or bend resistant fibres are now also becoming more widely manufactured. These cables exhibit lower losses when bent compared to the ones which are based on bend sensitive fibres. However, as noted elsewhere in EN 4533, fibres should not be bent beyond their recommended minimum bend radius. They are no stronger than conventional fibres.

Table 1 is summarizing the basics feature of a fibre. Fibres have been categorized according to ITU rules.

Table 1 — Basics feature of a fibre according to ITU rules

Mono/multi-mode	**Ø core** (µm)	**Minimum modal Bandwidth** (MHz.km) 850 nm/1 310 nm	**Category**
Mono	9	n/a	G652
Mono	9	n/a	G657
Multi	62,5	200/500	OM1
Multi	50	500	OM2
Multi	50	1 500/2 000	OM3
Multi	50	3 500/4 700	OM4

From the perspective of termination there is little difference between small and larger core optical fibres. The main fibre issues that impact upon the termination process relate to cladding size and primary coating materials.

The use of multifibre array connectors (e.g. those based on the MT ferrule discussed later) in some aerospace applications means that cables with multiple fibres are required. A typical construction is shown below. Early multifibre cables designs were of a flat ‘ribbon’ type. However more recent designs have been of a round profile cable with loose fibres (suitably protected) within. The cables typically also include a strength member. This technology is not yet standardized. Figure 3 shows an example of a multi-way cable.

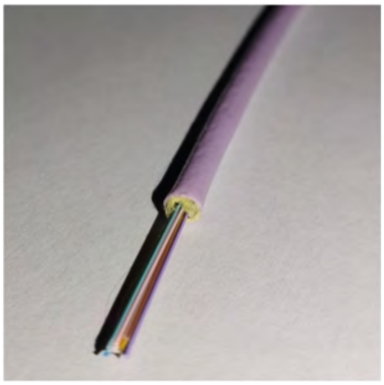


Figure 3 — Example of multi-way cable

4.2.4 Cladding materials

4.2.4.1 Coatings and buffers — A note on terminology

The central lightguide is protected in the cable by various layers of material. The reader should be aware that different texts will refer to these layers in different ways. Common to most texts however is the designation of the order of layers. Thus, primary layers exist immediately next to the lightguide (usually applied onto the cladding layer of the fibre). Secondary layers will be applied above the primary layer and so on.

Where there is sometimes confusion is the inconsistent use of terms such as coatings, buffers and sheaths. For instance, it is common for the terms primary buffer and primary coating to be seen in different texts. Terms such as secondary coating and secondary buffer would also refer to a coating lying above the first (primary) layer of protection. Secondary layers can sometimes be hybrid, composed of different materials (sometimes difficult to separate). Finally, a boundary sheath layer may exist in the cable. The term boundary sheath implies a tube type construction that allows the coated fibre to move within the cable (semi loose).

4.3 Primary buffer materials

4.3.1 Function

Immediately above the optical fibre is a primary buffer layer. The major function of the primary buffer is to protect the fibre from abrasive and environmental damage. It also limits micro-bending losses in the fibre. Generally, this coating is applied at the time of fibre manufacture. It provides the first layer of protection to the glass. It shall provide protection but also be easily removable when performing a termination.

Most fibres use an acrylate type material for the primary buffer, other materials can be encountered however, such as silicone, polyimide, proprietary polymers and even metal, such as gold or aluminium (although these are somewhat specialized and will not be considered here). These alternative buffer materials can extend the operating temperature of the fibre. Carbon is sometimes applied to special fibres to hermetically seal the fibre surface and prevent moisture reaching the glass surface (typically used on space applications). For a detailed review of materials see below sections

It should be emphasized that the temperature capability of a glass fibre is not limited over the operational envelope of an aircraft. Glass will survive (and indeed is used in other applications) at very high and very low temperatures. It is the temperature range of the protective layers (which are essential in preventing damage to the fibre) that limit the temperature performance of the cable. In comparison, other types of fibre (e.g. POF and PCS) may be fundamentally limited by the operating temperature of the fibre material itself.

In aerospace applications, the most widely used primary coating materials are, acrylate, polyimide and silicone. A brief description of each material is placed below.

4.3.2 Acrylate

This is perhaps the most common of all the optical fibre primary buffer materials and is relatively easy to remove with hand tools. The buffer is usually a UV cured acrylate that is translucent and is typically the same thickness as the fibre. Standard acrylates have a limited temperature performance of up to approximately 90 °C to 100 °C (above this temperature they can break down and become discoloured and brittle) however in recent years higher temperature acrylate (HTA) has become a standard buffer material and is now being packaged in aerospace cables. HTAs extend the operation to the region of 150 °C and up to 180 °C. Low temperature limits are in the region of −60 °C. Acrylate is subject to degases when used in unpressurised environments. Some manufacturers have operated these buffers down to − 65 °C with no degradation.

4.3.3 Polyimide

This buffer has a higher temperature range than UV cured acrylates and can be used in temperatures up to 300 °C and up to 400 °C short term. Although useful for high temperature applications, polyimide buffers are difficult to remove using common mechanical tools. Fibres employing this material are designed to be installed into connector ferrules without the need to remove the primary buffer. This is only possible because the core/cladding/primary buffer concentricity and outer diameter tolerances are tightly controlled. This would appear to be an ideal design solution because the fibre surface does not need to be touched. However, the enlarged polyimide diameter is not compatible with standard connector ferrule bore dimensions, thus non-standard ferrules need to be used with an associated cost and availability penalty. Removal of polyimide buffers is discussed later in this document (see subclause 6.4.4). Polyimide is not degassing when used in unpressurised environments.

4.3.4 Silicone

The main benefits of silicone as a primary coating are the reduction of fibre micro-bend effects due to the “cushioning” effect of the soft primary coating layer, its high temperature capability (up to 200 °C), its resilience to water penetration and its low flammability. However, as with acrylate, this material needs to be stripped prior to inserting optical fibres into fibre optic connectors. This is by no means easy (see later section on removing troublesome primary coatings) and can leave a residue which could compromise fibre/ferrule bonding. Again, removal of silicone is also discussed in subclause 6.4.4 some ‘soft silicone’ coatings may allow lower temperature operation of fibres e.g. down to −100 °C.

4.3.5 Strength members

Almost all fibre optic cables employ some form of strength member layer. Its function is to isolate cable external loads from the fibre within and provide excellent longitudinal strength; it is usually in the form of stranded fibres running along the fibre axis or woven in a braid. The most common material used for this purpose is a very tough, strong material known as aramid yarn. However, it is by no means the only material used for this purpose – fibreglass being one of the main alternatives. New designs of aerospace fibre optic cable are now implementing a fibreglass/aramid yarn mix to provide a strength member with lower smoke emissions than that of a pure aramid yarn strength member.

Fibreglass is better matched to the optical fibre’s thermal coefficient of expansion compared to aramid yarn and has been used where high temperature (>135 °C) dimensional stability is required of a cable. This aspect shall be considered if a cable is to be subjected to prolonged exposure of rapid thermal cycling stresses over a wide temperature range. However, aramid yarn appears to meet most current avionic temperature requirements (−65 °C to 150 °C).

These two materials need to be treated in quite different ways in order to achieve effective optical fibre load isolation during the termination process. Aramid yarn and other similar materials can be crimped directly onto a connector or termini; fibreglass cannot because it is too brittle. Cables employing