Damage Criteria for Fibre Optic Cables Exposed to Fire

Using data transfer as functional criterium

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Abstract
The aim of this master thesis was to analyse the possibility to use fibre optic cables for critical safety features in high reliability facilities. In more detail, this report investigates how transferred data in fibre optic cables are affected by fire and if there is any risk that the data becomes corrupted or lost when exposed to fire conditions. This report also investigates if this risk can be tied to a critical temperature or radiation. This was investigated by testing the fibre optic cables in a cone calorimeter, which exposed them to different heat fluxes. The results from the tests were analysed with regards to data loss, temperature, and functional criteria. A statistical data analysis was conducted as well. The analysis did not show a strong correlation between data loss and temperature, it did however show a stronger correlation between temperature and bend diameter. A correctly installed cable is more vulnerable to elevated temperatures if the thermal influences from a fire causes the bend diameter to decrease.

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Foreword

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Summary

For buildings such as nuclear power plants and nuclear research facilities, it is important to be able to monitor and control several different safety features from a distance. This is achieved by using cables to send data back and forth, which is why it is critical for the cables to function properly during challenging circumstances, including fires. Historically there have been accidents in high reliability facilities that can be connected to signalling problems for critical equipment. Thus, reliability has been proven to be very important. Therefore, copper cables functionality during different fire scenarios has been thoroughly tested. Use of fibre optic cables give a possibility for faster data transfer in critical equipment, but the functionality needs to be studied especially under fire conditions. Studies on fibre optic cables prior to this thesis have measured attenuation of the optical signal which is not possible to correlate to an actual data loss. In 2014, a thesis was written on whether fibre optic cables could be used for the European Spallation Source, and one conclusion was that further analysis should be conducted on data loss. Therefore, the aim and objective of this thesis focused on measuring possible data loss.

The aim of this report is to further analyse the possibility to use fibre optic cables in high reliability facilities by studying the functionality of the cables during exposure to fire. The objective is to develop a probabilistic model for fibre optic cables with data transfer as a functional criterion, i.e., no data being corrupted or lost. With the aim and objective as a basis three research questions were formulated:

- How is the transferred data through fibre optic cables affected by fire?
- What is the risk that data becomes corrupted or lost when fibre optic cables are exposed to fire conditions?
- Can this risk be tied to a critical temperature or radiation?

The method used to answer these questions was to conduct a thorough literature study followed by a set of tests where the cables were exposed to fire conditions while transferring data between two entities over a LAN. The literature study made was extensive as it had to cover multiple areas. The areas studied were fibre optic cables, data transfer, previously conducted experiments, and standards and guidelines for testing and installation of cables.

From test standards on cables together with previously conducted experiments, an experimental setup was created. The first step was to create a sample holder that would resemble a real worst-case installation of a cable. This included the cable carrying its own weight and being bent with the smallest bend diameter recommended by the manufacturer. Second, a setup for data transfer was created. This setup focused on being able to continuously transfer data at the highest possible bandwidth and measuring how much was lost. The setup consisted of a LAN using two computers and two switches with fibre optic connections. Third, the cable was exposed to fire conditions using a cone calorimeter. The cone calorimeter was chosen to make the tests repeatable while being able to measure radiation and temperature.

Using the above-described setup, a group of 15 samples were tested in the same way and became the main tests. Following the main tests, five additional tests were conducted with some deviations. These deviations include installing the cables with smaller bends and/or using a constant high heat flux instead of increasing it gradually. Lastly, one test was performed using a propane burner to see if the flame from a real ignition source had an impact.

The tests resulted in zero data loss until the cable broke or the test was terminated after 90 minutes. The conditions for breaking of the cable were shown to be a relationship between temperature and mechanical strain from smaller bend diameter created by the fibre moving due to thermal influence. For those tests that led to a break in the cone calorimeter, temperatures of 400 – 600 ºC were measured. These temperatures could also be measured in a test with another experimental setup. Besides measured data such as data loss and temperature the cables were also visually examined and interesting events were timed to help draw conclusions. With the temperature measurements at the time of break a data analysis was made where a probabilistic distribution for temperature at the time of break was fitted.

A couple of conclusions could be drawn from this thesis and they are presented as a bullet list below:

- The signal in a single-mode fibre shows resilience to fire exposure.
- Based on this study a probabilistic distribution of the critical temperature resulted in a 5^{th} percentile of 336 ºC, i.e., 95% of the cables have a critical temperature above 336 ºC.
- Even if installed according to the manufacturer's recommendations bends that lead to break can be formed on the cable due to thermal stresses.
- Fibre optic cables have inherent properties such as electrical isolation which makes them useful for critical safety systems in, for example, high reliability facilities.

Lastly, based on the conclusions some ideas for future work that could help further understand fibre optic cables' functionality were suggested.

Sammanfattning

I byggnader som kärnkraftverk och kärnforskningsanläggningar ställs höga krav på möjligheten att övervaka och styra säkerhetsfunktioner från ett säkert avstånd. Detta görs genom att skicka datasignaler genom kablar, vilket ställer krav på att kablarna ska fungera som tänkt även under särskilda omständigheter så som brand. Historiskt har det skett olyckor i dessa typer av anläggningar, vilka kan kopplas till problem med signaler från kontrollrum till kritisk utrustning. Vidare ställer detta krav på funktionsbeteendet hos kablarna, vilka sedan länge ofta bestått av koppar. Under lång tid har kopparkablars beteende vid brand undersökts. Att byta till fiberoptiska kablar ger fördelar så som snabb dataöverföring över långa avstånd, dock krävs det att även dessa kablars funktionsbeteende undersöks. Tidigare studier av fiberoptiska kablar har undersökt attenuering (försvagning) av den optiska signalen. Dock finns det inget sätt att korrelera denna försvagning till faktisk dataförlust. Ett examensarbete från 2014 skrevs på uppdrag av ESS ämnat att undersöka huruvida fiberoptiska kablar kan användas för deras säkerhetsutrustning. En slutsats i det examensarbetet var att vidare studier för dataförlust borde genomföras, med detta som bakgrund fokuserades således syfte och mål i detta arbete på att mäta möjlig dataförlust.

Syftet med rapporten är att vidare undersöka möjligheten att använda fiberoptiska kablar i anläggningar med hög tillförlitlighet genom att studera funktionsbeteendet hos kablarna när de utsätts för brand. Målet är att ta fram en probabilistisk modell för fiberoptiska kablar där dataöverföring används som ett funktionskrav, det vill säga att ingen data ska bli korrupt eller gå förlorad. Med utgångspunkt i detta syfte och mål formulerades tre frågeställningar:

- Hur påverkas dataöverföringen genom fiberoptiska kablar under en brand?
- Vad är risken att data blir korrupt eller går förlorad när fiberoptiska kablar utsätts för brandförhållanden?
- Kan denna risk knytas till en kritisk temperatur eller strålningsnivå?

Metoden som användes för att besvara dessa frågor var att genomföra en litteraturstudie och därefter genomföra ett antal tester där fiberoptiska kablar utsätts för brandförhållanden medan data överförs mellan två entiteter på ett LAN. Litteraturstudien som genomfördes blev omfattande då flera områden behövde studeras innan testerna kunde genomföras. Dessa områden var fiberoptiska kablar, dataöverföring, tidigare genomförda experiment samt regler och standarder för hur provning och installation av kablar bör genomföras.

Från provningsstandarder på kablar och tidigare genomförda experiment togs en testuppställning fram för denna rapport. Det första steget var att konstruera en ställning som håller provkroppen, i detta fall kabeln, i ett läge som motsvarar ett verkligt värsta fall av en installerad kabel. Detta inkluderade sådant som att kabeln skulle bära sin egen vikt och vara böjd med en diameter som motsvarar tillverkarens rekommendationer för minsta böjdiameter. Det andra steget var att skapa en uppställning för dataöverföring. För dataöverföringen var det viktigt att kontinuerligt sända och mäta data med hög bandbredd under hela provtiden, vilken var tills kabeln slutade fungera eller 90 minuter. Denna uppställning konstruerades som ett LAN mellan två datorer genom två switchar med fiberanslutning. Det tredje steget var att konstruera ett repeterbart brandtest, därför användes en konkalorimeter eftersom denna är konstruerad för att genomföra flera prover med samma påverkan. Det är även möjligt att med konkalorimetern välja strålningsnivån och kontinuerligt mäta temperaturen.

Med den ovan beskrivna uppställningen genomfördes 15 identiska tester vilka utgjorde den huvudsakliga testgruppen. Efter dessa 15 tester genomfördes ytterligare fem tester med mindre förändringar. Dessa förändringar inkluderade att montera kablarna med mindre böjdiameter och/eller en konstant hög strålningspåverkan istället för att öka den stegvis. Avslutningsvis genomfördes ett test med en propanbrännare istället för konkalorimetern, detta gjordes för att se om kabeln påverkades annorlunda av en verklig flamma.

Resultatet visade att ingen data gick förlorad innan kabeln gick av helt eller testet avslutades efter 90 minuter. Dock visade sig brottförhållandet vara ett förhållande mellan temperatur och mekanisk påverkan till följd av en liten böjdiameter skapad av att fibret rörde sig till följd av termisk påverkan. I de tester som ledde till brott i konkalorimetern uppmättes temperaturer på 400 – 600 ºC, dessa temperaturer kunde även uppmätas i test med annan försöksuppställning. Förutom att mäta temperaturen observerades även visuella förändringar av kabeln under testet och intressanta händelser antecknades för att styrka slutsatserna. Den uppmätta temperaturen vid brott av kablarna analyserades statistiskt och sannolikhetsfördelningar passades till den uppmätta data.

Efter testerna kunde ett antal slutsatser dras vilka presenteras i punktlistan nedan:

- Signalen genom ett singlemode fiber påvisar resiliens mot brandpåverkan.
- Baserat på resultaten från denna studie kunde en probabilistisk modell för kritisk temperatur skapas. I denna modell var den 5:e percentilen 336 ºC, vilket innebär att 95 % av kablarna klarar temperaturer över 336 ºC.
- Även om kabeln installeras korrekt enligt tillverkarens rekommendationer kan en böj som leder till brott uppstå på kabeln på grund av termisk påverkan.
- Fiberoptiska kablar har inneboende egenskaper så som elektisk isolering vilka gör dem användbara i kritiska system i till exempel anläggningar med hög tillförlitlighet där andra störningar kan förekomma.

Avslutningsvis, baserat på slutsatserna föreslogs vidare områden att studera för att bättre förstå fiberoptiska kablars funktionalitet.

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1 Introduction

1.1 Background

For buildings such as nuclear power plants and nuclear research facilities, it is important to be able to monitor and control several different safety features from a distance. This is achieved by using cables to send data back and forth, which is why it is critical for the cables to function properly under challenging circumstances, including fires. The importance of the cables' function was demonstrated by the Browns Ferry Nuclear Power Plant accident in March 1975. A fire broke out in a cable distribution room when workers fixed an air leak from the cable distribution room to the adjacent secondary containment room (Åslund, 2000). The fire damaged 1600 cables, where 600 of these were cables that monitored or controlled safety features of the plant. The damages to the cables caused several faults to occur; some safety features could no longer be operated from a distance, some safety features were put into motion by themselves, and some instruments on the control panel showed misleading indications (Åslund, 2000). Again, this accident demonstrates why it is so important that cables and their functions are reliable.

The reliability of cables' functions has been thoroughly tested for regular electrical cables made of copper (Andersson & Van Hees, 2005), but it has been less tested on fibre optic cables. This lack of knowledge was identified by the European Spallation Source (ESS) and a bachelor thesis by Rosenqvist (2014) was written regarding how fibre optic cables are affected by fire in terms of attenuation. The bachelor thesis found no way to translate attenuation to loss or corruption of data (Rosenqvist, 2014), and this is where this report will continue to analyse fibre optic cables' behaviour during fire conditions.

This report has been conducted for the course *VBRM10 – Degree Project in Fire Safety Engineering*, which covers 30 higher education credits. This degree project was conducted for the Division of Fire Safety Engineering at Lund University.

1.2 Aim and objective

The aim of this report is to further analyse the possibility to use fibre optic cables for critical safety features in high reliability facilities with regards to the cables' functionality during fire conditions. Nuclear power plants or nuclear research facilities are considered high reliability facilities.

The objective of this report is to develop a probabilistic model for functional performance for fibre optic cables under fire conditions based on critical temperature or specific fire conditions and using data transfer as functional criterium, i.e., no data being corrupted or lost.

1.3 Research questions

- How is the transferred data through fibre optic cables affected by fire?
- What is the risk that data becomes corrupted or lost when fibre optic cables are exposed to fire conditions?
- Can this risk be tied to a critical temperature or radiation?

1.4 Limitations

This report will only analyse fibre optic cables and their transfer of data. Further, the fire conditions analysed will only be those of critical temperature and radiation. The literature study will be limited to publicly available material, which means that literature may be lost due to classified materials of, for example, sensitive building structures. The tests will consider the existing standards, but they will not be conducted according to those standards since the goal with the tests is to contribute with new knowledge. The number of tests was limited to a maximum of 30 due to lack of time and available material. In the tests, the data loss will be examined in the user space, which may cause other programs or operations on the computers to interfere with the data transfer. Lastly, only one cable type was tested, and no fire-resistant cables were tested.

1.5 General method

After the research questions was determined, an extensive literature study was conducted in order to gather all the necessary information regarding fibre optic cables, data transfer, previously conducted experiments and standards for testing and installation of cables. The literature study was conducted in September 2020, by using the databases LUBsearch and Google Scholar. The different areas of the literature study consisted of a variation of key words, which can be found in *Table* 1. Further, the literature was selected based on its relevance to this master thesis. For the areas covering fibre optics literature mentioning computers and data science was chosen. For data transfer it was more difficult to choose due to the lack of expertise in the area. For the report, only the parts focusing on data transfer over the internet was chosen. For the other four areas, the literature that covered fibre optic cables were chosen primarily. Since the research conducted on fibre optic cables is relatively slim in comparison to the research conducted on electrical cables, literature that covered electrical cables were also chosen for a deeper understanding on how fire conditions can affect cables. Regarding literature on standards and guidelines, they were mainly chosen if they specifically covered fibre optic cables. Some standards and guidelines cover all types of cables, which is why they were chosen too.

Table 1. Key words for the different areas in the literature study.

Area	Key words
Fibre optics	Fibre optics, fibre optic cables, Fiber Bragg grating
Data transfer	Data transfer, fibre optic cables, TCP, IP, UDP
Guidelines and regulations for the usage of fibre optic cables	Fibre optic cables, cables, regulations, guidelines, nuclear power plants, nuclear research facilities
Standards for testing and installation of fibre optic cables	Fibre optic cables, cables, testing, installation
Previously conducted experiments on cables	Fibre optic cables, electrical cables, fire conditions
Failure probabilities	Fibre optic cables, electrical cables, failure probabilities, statistical analysis

The literature study made it possible to determine the experimental setup for tests in a cone calorimeter and for tests above a propane burner. After determination of all the details for the tests, they were conducted and data from them were logged and collected. In short, the ambition with the tests in the cone calorimeter was to subject a fibre optic cable to fire conditions, as well as conducting enough tests for a statistical analysis. The ambition with the propane burner test was to get a wider understanding for how a flame affected the cable. A more detailed method for the experiments and their setup is presented in chapter 3. The data from the tests were then compiled and presented in tables and graphs. Following this, an analysis of the results from the tests was conducted, and discussed with regards to data loss, temperature, and functional criteria. A statistical data analysis was also made and discussed from the test results. This report was then finalised with conclusions and suggestions for future work.

The overall workflow of the report can be seen as a flowchart in Figure 1.

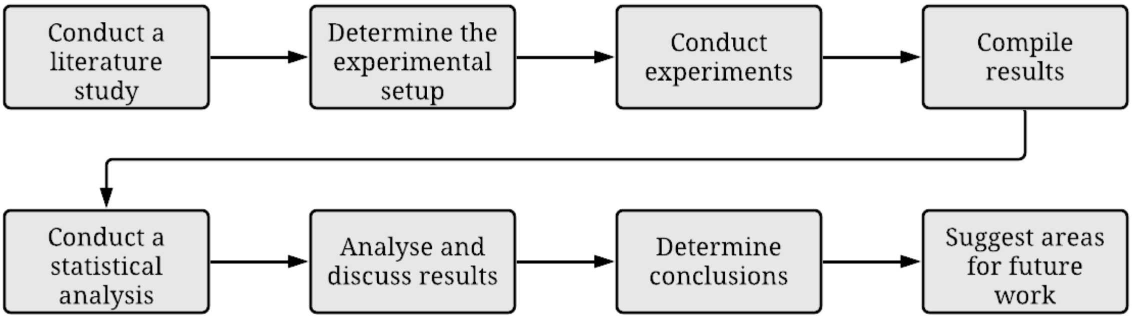

Figure 1. Overall workflow of the report.

2 Literature study

2.1 Fibre optics

2.1.1 Introduction

Fibre optics, as the name implies, are fibres created to transfer an optical signal, light, over a distance (Hecht, 2006, p. 50). What happens is that an electrical signal reaches a light source that produces photons corresponding to the electrical current (Hecht, 2006, p. 50), the photons can be viewed as electromagnetic energy (Wright & Bailey, 2003, p. 42). The photons are then sent through the fibre to a receiver which translates the photons back into an electric current (Hecht, 2006, p. 50). The fibres are usually made by glass, more precise silicon dioxide (Mitschke, 2016, p. 103), but fibres can also be created by polymer mixtures (Abrate, 2013, p. 37). The fibre optical cable most often consists of an outer jacket, some type of protective insulation or strength member, and the fibre itself (IEEE, 2005, p. 6). The specifics of the jacket and insulation varies depending on how the cable will be used and can be designed to give different levels of protection from outside forces (IEEE, 2005, p. 6). The fibre itself consists of a core, where the light travels, a cladding to guide light back into the core and a plastic coating for protection (Hecht, 2006, p. 7). To understand fibre optics in a practical sense this chapter will explain some of the basic concepts of fibre optic cables.

2.1.2 Core and cladding

The fibre guides light from one side to the other, this is possible due to the refractive properties of different materials (Yeh, 1990, p. 4; Wright & Bailey, 2003, p. 48). The fibre consists of a core with a high refractive index, meaning light can travel through it (Wright & Bailey, 2003, p. 45). The core is then surrounded by a cladding with a lower refractive index, thus guiding the light back into the core when it hits the border to the cladding (Wright & Bailey, 2003, p. 47). The amount of light reflected will be dependent on how big of a difference there is between the core and claddings refractive index, a bigger difference reflects a larger amount back into the core (Wright & Bailey, 2003, p. 47). The index of the core and cladding can be uniform creating a cross section as seen on the left in Figure 2, this is called a step-index. As an alternative the refractive index can vary over the cross section of both the cladding and the core creating what is called a graded index, as seen on the right in Figure 2.

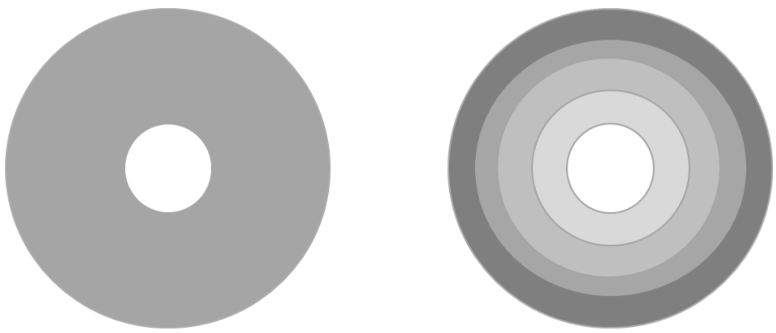

Figure 2. Step-index (left) and graded index (right) of a core.

Even if the factor between the refractive indexes is large, some light will be refracted into the cladding (Wright & Bailey, 2003, p. 47). In order to keep the light in the core, the light needs to hit the border at an angle greater than the so-called critical angel (Wright & Bailey, 2003, p. 47), see Figure 3. This is an angel dependent on the fraction between the refractive indexes in the core and cladding. Light that hits the border at the critical angel will be reflected in a path parallel to the core (Wright & Bailey, 2003, p. 47).

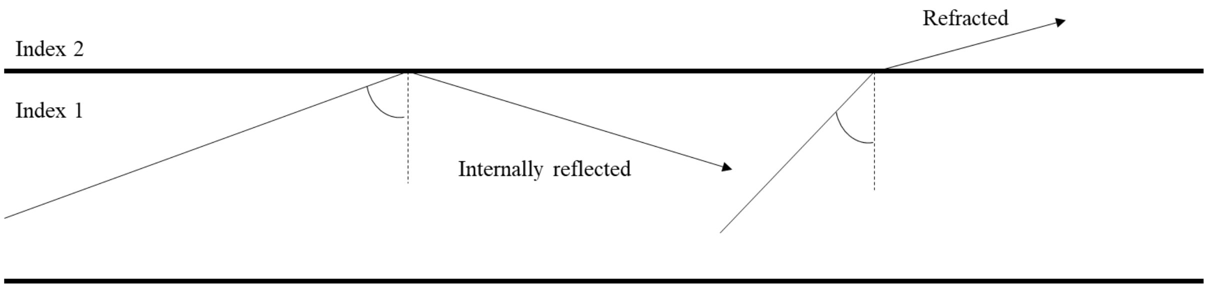

Figure 3. Internally reflected and refracted light in the core.

2.1.3 Single-mode and multi-mode

Fibres used for data transfer comes with different sizes on core and cladding. Usually, the fibre is described by the outer diameter of the core followed by the outer diameter of the cladding, for example 50/125 µm (IEEE, 2005, p. 3). One important term in fibre optics is mode, referring to mode of propagation of the light through the fibre (Wright & Bailey, 2003, p. 54). By choosing a small core, no larger than 10 µm, the light can only propagate in one mode while larger cores can send light through several modes (Yeh, 1990, p. 4; Wright & Bailey, 2003, p. 52). This phenomenon creates two classes of fibre optic cables called single-mode (SM) allowing for one mode of propagation and multi-mode (MM) that allows for several modes of propagation, see Figure 4. The SM fibre allows for data being transferred over longer distances and at a higher bandwidth than the MM (Wright & Bailey, 2003, p. 59 & 65). A MM fibre can send data at a rate of up to 10 Gb/s for around 300 m, and after that SM needs to be used (Offrein, 2014, p. 24). Therefore, MM cables have historically been used for short distances and SM for longer. This is however changing, and SM is being used even for shorter distances. The wavelengths used in fibre optics vary between SM and MM. For MM different wavelengths are used and can be either short wavelengths around 780-850 nm or longer wavelengths around 1300 nm (Wright & Bailey, 2003, p. 59; DeCusatis, 2005, p. 87). SM only utilize longer wavelengths in the range of 1310-1550 nm (Wright & Bailey, 2003, p. 65).

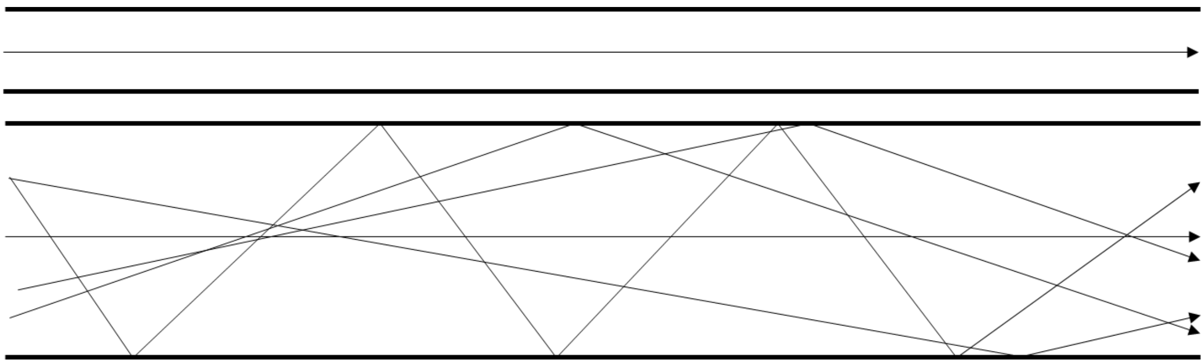

Figure 4. Single-mode (top) and multi-mode (bottom) fibre core.

2.1.4 Light loss

Attenuation is a central parameter when it comes to the distance that light can travel through a fibre (Hui, 2009, p. 62). As the wave of light propagate through the core the amplitude and intensity decrease along the way, and this is called attenuation (Wright & Bailey, 2003, p. 14). If the light propagates over a long distance the amplitude can become too low, thus making the signal uninterpretable by the receiver as there are no distinct differences between on and off, see Figure 5.

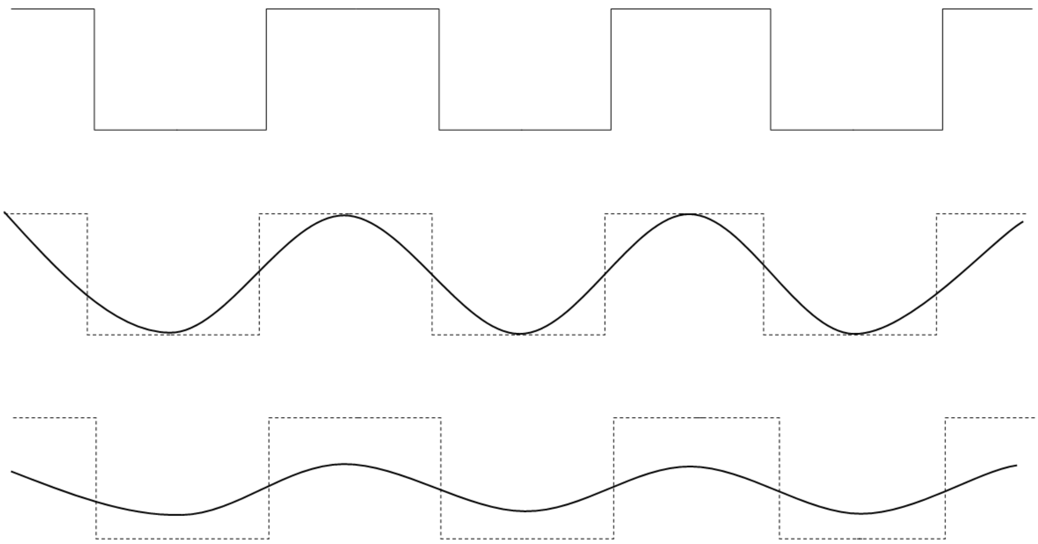

Figure 5. Decrease in amplitude of the light. Top, outgoing signal. Bottom, signal being stretched out due to attenuation, with the original shape for illustrative purposes.

Attenuation as a decrease of intensity, occurs as a result of different properties in the light and the fibre (Hui, 2009, p. 62-63). Three main sources of intensity loss are absorption, scattering and leakage (radiation) (Hui, 2009, p. 62; Hecht, 2006, p. 29). Absorption refers to the light being absorbed into the molecules of the core itself (Hui, 2009, p. 62; Hecht, 2006, p. 29). This effect is minimized by using a highly transparent fibre core and choosing a longer wavelength. Scattering happens both as the light hits the atoms in the silicon dioxide, as well as when it hits impurities in the core (Hui, 2009, p. 63; Hecht, 2006, p. 29). The intensity loss due to scattering can also be decreased by using a longer wavelength. Lastly, leakage (also called radiation loss (Hui, 2009, p. 63)) is the light that is leaking from the core out into the cladding. If the fibre is correctly handled and installed this phenomenon accounts for the least loss out of the three (Hecht, 2006, p. 29). However, micro and macro bending increase the loss associated with leakage. Micro bending occurs due to irregularities during the fabrication of the fibre (Hui, 2009, p. 64). Macro bending is caused by bending the cable more than recommended by the manufacturer, one source specifies that macro loss is significant in a standard fibre if the bend diameter is less than 3 cm (Hui, 2009, p. 64). Attenuation losses are small but accumulate over the length and is therefore usually measured as loss per kilometre (Hui, 2009, p. 64; Hecht, 2006, p. 96).

In section 2.1.3, it was stated that MM fibres cannot operate at the same distance as SM fibres and this is mainly due to what is called modal dispersion. As the multiple modes propagate through the fibre core, they will reach the end at different times (Mitschke, 2016, p. 23; Hui, 2009, p. 74). The mode entering the core with the greatest angle will move a shorter distance than the mode entering with a steep angle (Hui, 2009, p. 74), thus the steeper mode takes longer to reach the receiver as can be seen in Figure 4. This can result in the modes reaching the receiver in the wrong order (Mitschke, 2016, p. 23). As the number of modes are correlated to the size of the core, the modal dispersion is greater in thicker cores (Hui, 2009, p. 74).

2.1.5 Physical properties

Optical fibres can be made from different materials. However, most of them are made from silicon dioxide in a glass structure. This section will give some of the physical properties of silicon dioxide fibres, starting with tensile strength. In theory the tensile strength of silicon dioxide fibres is about 14 to 20 GPa (Hecht, 2006, p. 119; Mitschke, 2016, p. 114). However, these high tensile strengths are unattainable in reality due to the existence of impurities and surface flaws such as micro cracks (Hecht, 2006, p. 119). The real strength of the fibre is only a few percent of the theoretical value, and for a single fibre the tensile strength is around 0,35 GPa (Mitschke, 2016, p. 114).

In a study conducted by Tu & Tu (2014), the tensile strength of SM optical fibres was tested at elevated temperatures. In the study all plastic protection of the fibres were stripped using an acid bath and the fibres were heated to the testing temperature for 30 minutes before testing. Three temperatures were tested: room temperature, 300 ºC and 540 ºC. The result of the study showed that the strength of the fibres was statistically proven to be reduced at a higher temperature. The result also showed a larger spread in tensile strength of the heated fibres compared to those tested at room temperature. According to Tu & Tu (2014) this is an indication that the decrease in strength is due to flaws in the fibre that grows when heated. Further, Tu & Tu (2014) also tested the strength of the fibres that were heated quickly through annealing at 500 ºC and 900 ºC. Followed by testing in room temperature within a maximum of 10 minutes after the annealing. This process further reduced the tensile strength which the authors explain to be a result of cooling and reaction to the moisture in the air.

Another physical property of silicon dioxide is that it expands when heated. However, according to Zeng, et al. (2016) it is difficult to predict how much any type of glass will expand due to the lack of a periodic order among the glass molecules. The melting temperature of pure silicon dioxide is around 1790 – 1900 ºC (Ringdalen & Tangstad, 2016). A change in temperature can also results in a change of reflective and refractive properties in the fibre, a fact that has been used to create Fibre Bragg Grating (FBG) sensors (Gassino, Perrone, & Vallan, 2020). These sensors use a number of different reflective indexes along the fibre to reflect a specific wavelength, this wavelength changes with the temperature (Gassino, Perrone, & Vallan, 2020).

2.2 Data transfer

Above, fibre optics and optical signalling have been explained in short. Now the signal needs to be interpreted by a computer as ones and zeros, in other words as a digital signal (Hecht, 2006, p. 48; Wright & Bailey, 2003, p. 12). Disturbance in the signal due to loss of light or other disturbance can have effects on the end result, for example if the data loss is too large some computer systems can shut down or in other ways malfunction (DeCusatis, 2014, p. 55). Regardless if data is sent through light or electricity there needs to be a unified set of rules, called protocols, for the sending and receiving computer to interpret the signal (Loshin, 2003, p. 18). For a protocol to be complete it needs to describe the following (Loshin, 2003, p. 25-26):

- How to initiate interaction between two entities using the protocol.
- Interactions that are allowed.
- Acceptable responses and requests between the entities.
- How to handle invalid protocol messages.
- The correct way to package data and messages in the protocol.
- Rules about what data and behaviours that are acceptable, unacceptable and preferred.

In computer communications there are protocols working on multiple layers.

For this report, the protocols of interest are transport protocols, meaning protocols for packaging and sending data from one entity (for example computer or server) to another (Loshin, 2003, p. 322). These protocols are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP). This report will not go into the details of the two protocols. However, the main difference between TCP and UDP is that of delivery guarantee (Loshin, 2003, p. 332). The UDP offers no way for the receiver to know if all the datagrams have arrived and in that the sender does not know if all or any of the data has reached its destination (Loshin, 2003, p. 332). TCP on the other hand utilize what is called a three-way handshake for initial contact (Loshin, 2003, p. 357). The three-way handshake starts by the sender calling out for the receiver which acknowledge the call, then the sender acknowledges this before sending the data (Loshin, 2003, p. 357). When contact is established, and the data is sent, the receiver must verify each package with an acknowledgment (Loshin, 2003, p. 354). If a TCP package does not get acknowledged it is re-sent (Loshin, 2003, p. 354). This makes the TCP a much more complex protocol than UDP, but on the same time more resilient in case of error (Loshin, 2003, p. 354). Lastly, regarding data transfer the layer below the transmission layer is the internet protocol (IP) (Loshin, 2003, p. 397). Here the TCP and UDP datagrams are made into smaller IP datagrams or packets (Loshin, 2003, p. 397). Data loss is often counted as packet loss, referring to the loss of IP datagrams.

2.3 Guidelines and regulations for the usage of fibre optic cables

There are no specific regulations concerning the use of fibre optic cables in nuclear power facilities, but there are some general regulations for electrical components and cables. The Swedish Radiation Safety Authority states in their regulation SSMFS 2008:1 that electrical components, including cables, should be divided into classes based on their functionality (Hallström, 2008). Two of the International Atomic Energy Agency's (IAEA) standards NS-G-1.7 and SSG-34 specifies how cables should be used in nuclear power plants, but none of the standards specifically mention fibre optic cables as an option for electrical systems (IAEA, 2004; IAEA, 2016). The Nuclear Regulatory Commission (NRC) also provides regulations for cables in 10 CFR (part 50), but the regulation does not specifically mention fibre optic cables (NRC, 2020). However, in 1993 a report was published by NRC that recommended using fibre optic cables for data communication in electrical environments that are noisy or hazardous (Preckshot, 1993).

The National Fire Protection Association (NFPA) has three standards that specifies requirements for electrical constructions and cables. NEC 70 specifies which cables are allowed and in what way these cables are allowed to be used in buildings (NFPA, 2019a). This standard also contains an extensive chapter about fibre optic cables, as well as a list of which types of fibre optic cables are allowed to be used even in hazardous and classified areas/buildings. NFPA 804 specifies general requirements for light water reactors in nuclear power plants (NFPA, 2019b). Chapter 7 of NFPA 804 states that all cables that potentially could be exposed to fire should be assumed to not function in the design state, and it also states that cables for redundant systems critical to plant safety should be placed in different fire areas. Chapter 8 of NFPA 804 states that insulation- and jacketing material of a fibre optic cable should at least meet the requirements of the test standard called IEEE 383. NFPA 805 specifies requirements for a performance-based design of light water reactors in nuclear power plants (NFPA, 2019c). This standard state that electrical constructions (including cables) should be approved by a flame propagation test, which is decided by the authority having jurisdiction. NFPA 805 also states that sets of cables for different functions or systems should be separated by a fire barrier that lasts at least 3 hours (NFPA, 2019c).

2.4 Standards for testing and installation of fibre optic cables

For fibre optic cables there are several standards for testing and using them in different types of buildings. The following standards have been identified as the most relevant for this master thesis and will be discussed briefly below:

- SS-EN 50200:2006
- SS-EN 60709
- IEC 60331-25:1999
- DIN 4102-12
- IEEE 384
- IEEE 1428

The SS-EN 50200:2006 standard called *Method of test for resistance to fire of unprotected small cables for use in emergency circuit* specifies how a test of a fibre optic cable should be conducted (SEK, 2006). The setup for the test states that the sample should be placed in a U-shape on a non-combustible board, with the bending radius being the smallest one allowed according to the manufacturer of the cable (SEK, 2006). Further, the test sample should be at least 5 meters long and be long enough for the cable to emerge from the test chamber. The test measures attenuation in the nominal wavelength for the cable, which is why the fibres need to be connected in such a manner that the light can travel a sufficient amount of distance to be measured (SEK, 2006). The test uses a propane burner with a specified flow to reach a temperature of 830 ± 40 ºC. In this test, the cable is also exposed to a shock producing device, which strikes the non-combustible board every 5 minutes. The test is ended when a failure is detected in the cable, or at a time required for a specific classification such as 60 minutes for a PH 60 classification (SEK, 2006). Failure of an optical cable is a measured attenuation above what is stated in the product sheet from the manufacturer.

The SS-EN 60709 standard called *Nuclear power plants – Instrumentation, control and electrical power systems important to safety – Separation* specifies how electrical systems, that are critical to safety systems, need to be designed in order to ensure their function (SEK, 2019). This standard state that, wherever practical, flame retardant cables should be used and, wherever practical, fibre optic cables should be used. Fibre optic cables are recommended in this standard because they have insulating properties by default (SEK, 2019).

The IEC 60331-25:1999 standard called *Tests for electric cables under fire conditions – Circuit integrity – Part 25: Procedures and requirements – Optical fibre cables* also specifies how a test of a fibre optic cable should be conducted (IEC, 1999). The length of the cable and the wavelength that is tested has the same requirements as the SS-EN 50200:2006 standard, meaning it should be at least 5 meters long and the nominal wavelength should be used. In this standard however, the test should last 90 minutes if failure does not occur before that (IEC, 1999). The test uses a propane burner with a specified flow to reach a temperature of at least 750 ºC. The maximal attenuation that is allowed for a cable in this test is specified in the cable's product sheet.

The DIN 4102-12 standard called *Fire behaviour of building materials and elements – Fire resistance of electric cable systems required to maintain circuit integrity – Requirements and testing* specifies how a test of electric cables on a cable tray or cable ladder should be conducted (DIN, 1998). This test is based on the ISO 834-curve (ISO, 1999) and the general functionality of the cable is measured by not having a short circuit occur in the given time (30-60 minutes). The test sample should be at least 3 meters long (DIN, 1998).

The IEEE 384 standard called *Standard Criteria for Independence of Class 1E Equipment and Circuits* specifies independence requirements for electrical systems used in nuclear power plants (IEEE, 2018). In appendix C of this standard, there is a discussion whether fibre optic cables should have different regulations than regular electrical cables. The reason behind this discussion is that the difference in the temperature rating for the two types of cables vary, where fibre optic cables generally have a much lower temperature (around 50°C) than electric cables (IEEE, 2018). This discussion is based on data from 1990 and has in this version from 2018 still not been updated.

The IEEE 1428 standard called *Guide for Installation Methods for Fibre-Optic Cables in Electric Power Generating Stations and in Industrial Facilities* specifies how installation of fibre optic cables should be conducted (IEEE, 2005). There is an explanation of the general structure of a cable, as well as where different types of cables should be used in different locations of a building. This standard also contains how a fibre optic cable is affected by stresses, for example temperature, radiation and fire (IEEE, 2005).

2.5 Previously conducted experiments on cables

2.5.1 Introduction

In the field of fibre optics, there has not been much research conducted regarding how fibre optic cables behave when they are exposed to different fire criteria. However, there has been more research conducted regarding how electrical cables, made of copper, behave. This research can also be useful when studying and conducting experiments on fibre optic cables.

2.5.2 Rosenqvist bachelor thesis

The most recent research conducted on how fibre optic cables behave during fire is a bachelor thesis written by a student at the Faculty of Engineering at Lund University (Rosenqvist, 2014). The aim of the bachelor thesis was to examine how data transfer is affected by different fire criteria, primarily elevated temperatures and open flames. This was done by measuring the attenuation for two different setups, one using a cone calorimeter and one using free burning. For the cone calorimeter setup, both a SM cable and a MM cable was tested without the protective insulation materials of the cables (Rosenqvist, 2014). Only the fibre was exposed to the radiation from the cone calorimeter, which started at 15 kW/m^2 and was increased by 10 kW/m^2 every fifth minute up to a maximum radiation of 50 kW/m^2. For the free burning setup, SM and MM cables were exposed to four different variations of free burning (Rosenqvist, 2014). Both SM and MM cables were tested with and without the insulation materials, while a small bending radius was only conducted for a SM cable and a cable bundle was only conducted for MM cables. The results from the experiments showed that no attenuation was measured for the cone calorimeter tests, free burning of SM and MM cables without insulation materials, or free burning of MM cables in a bundle (Rosenqvist, 2014). However, for the free burning of SM cables with a small bending radius, and for the free burning of a SM and a MM cable with insulation materials, attenuation was measured. Rosenqvist (2014) came to the conclusions that the measured attenuation could not be translated into a loss or corruption of data. The author also came to the conclusion that the fibre optic cables were sensitive to mechanical and thermal stresses, especially to forces that are crushing or twisting the cable.

2.5.3 The International Cable Connectivity Symposium (IWCS)

A report on fibre optic cables by Ritz, et. al. (2012) analysed how transmission of data is affected by fire. This report did not only cover fibre optic cables, but also regular electrical cables. The fibre optic cable that was tested in this report was a fireproof cable, which contained a total of 24 fibres (15 fibres in the outer layer and 9 fibres in the inner layer). The authors measured the attenuation in both layers and the results showed that the outer layer was more vulnerable to fire than the inner layer. The results also showed that mechanical stresses from the melting of insulation materials increased the attenuation further. Like the bachelor thesis by Rosenqvist (2014), the authors of this report came to the conclusion that the measured attenuation could not be translated into the functionality of the cable and that this problem needs to be further analysed (Ritz, et. al., 2012).

2.5.4 Research Institute of Sweden (SP/RISE)

A number of experiments on electrical and fibre optic cables was conducted by Andersson & Van Hees (2000), at the Swedish National Testing and Research Institute (SP), now called RISE. The aim of the report was to analyse how the cables behave when they are subjected to thermal radiation in a cone calorimeter and observe when short circuit occur for the cables by measuring the current or voltage. For the electrical cables, three different cables were tested several times. For the fibre optical cables however, three different cables were tested one time each. The cables used were all MM cables; a 16-fibre, a 4-fibre and a 2-fibre cable. The results from the experiments showed that the 16-fibre and the 4-fibre cables failed after approximately 73 minutes, and that the 2-fibre cable had not failed after two hours when the experiment was ended (Andersson & Van Hees, 2000). The authors of this report came to the conclusions that no change in current or voltage was measured until the cable short circuited or failed for either electrical or fibre optic cables. Another conclusion was that the fibre optic cables lasted a surprisingly long time before they failed.

Similar to the report done by Andersson & Van Hees (2000) is another report from SP, which in this case had the aim to analyse how electrical cables behave when they are subjected to elevated temperatures (Andersson & Persson, 2001). The electrical cables used in this report is the same as the cables that was used in the previous report by Andersson & Van Hees (2000) for SP, and several different tests were conducted for the same type of cable. The cables were tested in a furnace with the temperature varying from 185 °C to 300 °C, and the temperature inside the cables was also measured by using a dead cable. The time to short circuit was observed by measuring the voltage through the cable. The results showed that each cable had a critical temperature for when it short circuited, which varied between 180 °C and 215 °C depending on the cable type (Andersson & Persson, 2001). Like the previous report from SP (Andersson & Van Hees, 2000), this report also came to the conclusion that no change in voltage was measured until the cable short circuited.

The results from the report by Andersson & Persson (2001) was in 2005 presented at The Eighth International Symposium on Fire Safety Science in Beijing, China. At the symposium, a model was presented on how the time to short circuit could be calculated for different temperatures (Andersson & Van Hees, 2005). This model is based on a one-dimensional heat transfer that treats the cable as a homogenous cylinder, meaning that it is assumed the cable only consists of one material. The model that was presented by Andersson & Van Hees (2005) laid the foundation for the Thermally-Induced Electrical Failure (THIEF) model, which was presented by the Nuclear Regulatory Commission (NRC) (McGrattan, 2008).

2.5.5 Institute for Radiological Protection and Nuclear Safety (IRSN)

More research about how electrical cables behave during fire was conducted by IRSN, where five different cables were tested in a full-scale test and one cable was tested in an oven (Bertrand, et. al., 2001). The tests with the oven were conducted at different temperatures between 200 °C and 400 °C, and the temperature inside the cables as well as the current through the cables was measured. Depending on the temperature in the oven, the cables short circuited between 200 °C and 220 °C, meaning this is the critical temperature for these types of electrical cables (Bertrand, et. al., 2001). The authors came to the conclusion that more research is needed to be able to more certain determine the damage criteria for electrical cables.

2.6 Failure probabilities

No research on failure probabilities for fibre optical cables was found during the literature study, which is why only electrical cables' failure probabilities are covered in this section. The failure probabilities are important when assessing exposed cables that are used for safety features in buildings, especially when these cables are needed to guarantee the safety of human lives or the safety of critical equipment.

A report from NRC has statistically characterized the failure probability for electrical cables (Gallucci, 2017). This was conducted through a number of experiments where three different electrical cables were tested to determine the failure temperature, which was shown to be between 200 °C and 500 °C depending on what type of cable was tested. The failure temperatures were then plotted against the probability of failure, and either a gamma, Weibull or lognormal distribution was fitted to the data. The results showed that a lognormal distribution was the best fit for two of the cable types and that a Weibull distribution was the best fit for the third cable type (Gallucci, 2017). A formula for each of the distributions can be found in the report, and these formulas can be used to calculate the failure probability for a certain temperature.

Another approach to failure probabilities was given by a dissertation paper, where the failure probabilities were estimated based on an Event Tree Analysis (Bucknor, 2013). The analysis was conducted for one type of an electrical copper cable with insulation material, without insulation material and as several cables in a bundle. For each of the setups of the cable, two different scenarios were analysed: one with a fire of 750 kW and one with a fire of 1300 kW. However, it is important to note that these failure probabilities also take into account the fire brigade's response time and suppression time. The results from this dissertation shows that the cable without insulation materials is most vulnerable to fire, the cable with insulation materials is the second most vulnerable and the cables in a bundle are the least vulnerable (Bucknor, 2013). It also showed that the cables are more vulnerable to a 1300 kW fire than to a 750 kW fire.

3 Experiments

3.1 Sample holder setup

The sample holder setup for the tests was both based on standards for how tests on cables should be conducted and on how previous tests on cables has been conducted. Depending on what the standard is testing, the setup for the tests can be designed a bit different, which is why the setup for the tests in this report incorporated details from more than one standard. The sample holder was constructed, and dimensions were chosen with the intention of using the cone calorimeter and the heat impacted the cable from above. Note that the bend on the cable was carefully placed so that it was within the standard square (100 x 100 mm) of the SS-ISO 5660-1:2019 test standard (SIS, 2019).

In the IEC 60331-25:1999 standard, the cable is suspended in the air by resting on metallic rings (IEC, 1999), and in the SS-EN 50200:2006 standard, the cable is mounted in a U-shape on a non-combustible board (SEK, 2006). Both details were incorporated in the initial setup by having the cable suspended in the air in a U-shape, which can be seen in Figure 6. This is in line with the results from Rosenqvist's (2014) master thesis that measured the most attenuation. At the end to the right in the picture, the cable stayed in place by two plates and two pieces of stone wool, which prevented the cable from moving sideways. At the end to the left in the picture, the cable stayed in place by a small ring which prevented it from falling down.

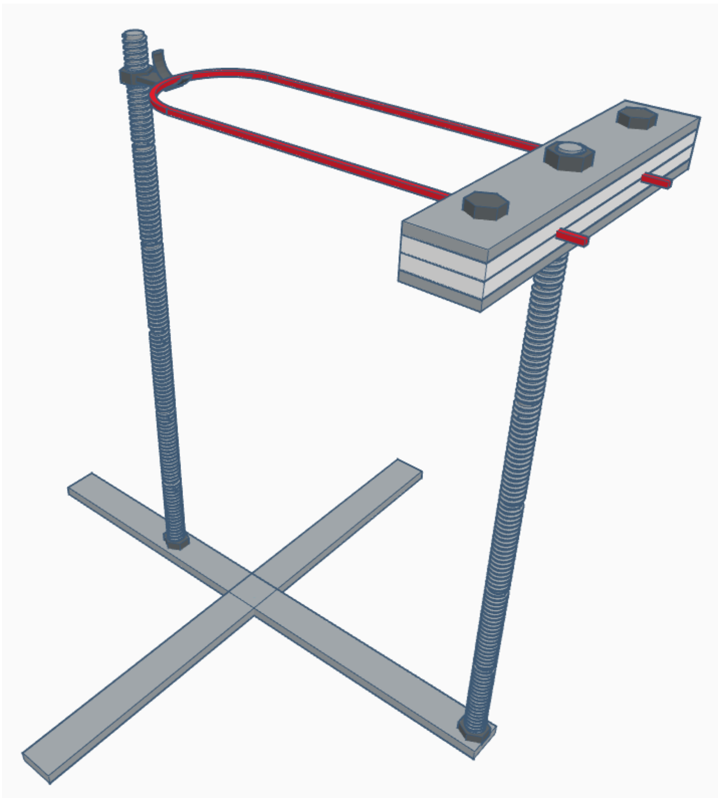

Figure 6. Initial sample holder setup. For dimensions, see Appendix A.1.

The initial setup as presented in Figure 6 was tested during 6 tests, and improvements to the setup were made continuously during those tests. The tests with the initial setup resulted in mainly two changes for the final setup. The first change was that a fibre cement board was placed 2 cm below the cable to minimize loss of radiation from the cone calorimeter. The second change was that a pendulum was installed to strike the sample holder every 10 minutes, starting after 5 minutes. This is used in standardized testing to resemble movement in surrounding materials as a result of a fire. Details from the SS-EN 50200:2006 standard were incorporated for the pendulum, which struck the sample holder with its own weight from an angle of 60° in relation to the horizontal plane (SEK, 2006). The final setup for the tests can be seen in Figure 7, where the yellow marking indicates where the pendulum struck the sample holder.

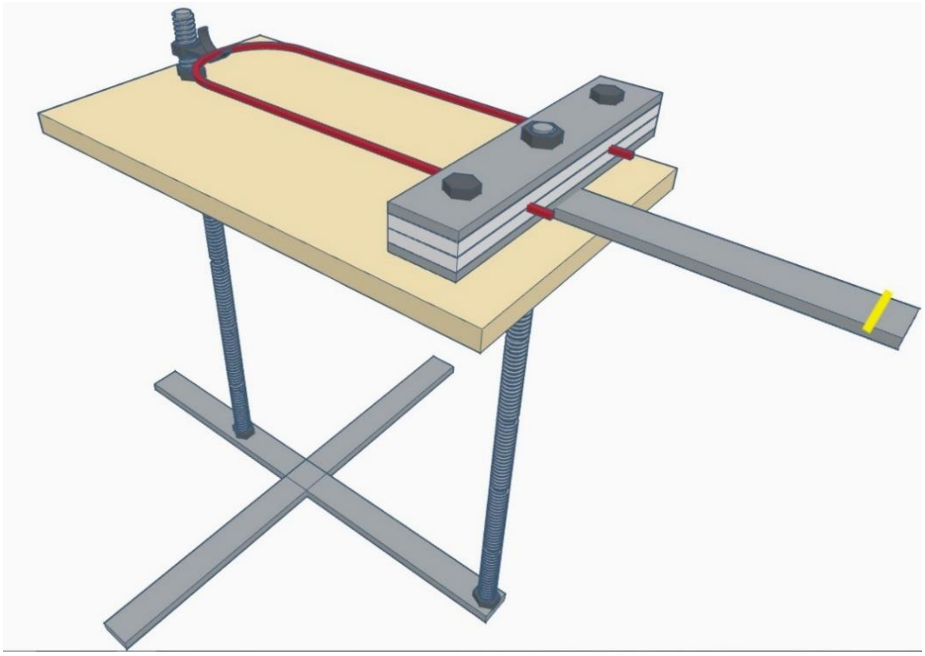

Figure 7. Final sample holder setup. For dimensions, see Appendix A.1.

The cables that were used for these tests were single-mode cables with one fibre, LC/UPC connectors at each end and an outer diameter of 2 mm (Nexans, 2020). These cables were chosen because the goal was to examine the functionality of the fibre, with as little protection as possible. Further, SM cables were used because of the trend where MM cables are slowly being phased out, meaning that SM cables will be used where MM cables are used today. The length of the cables were 3 meters, which according to the DIN 4102-12 standard is acceptable (DIN, 1998). The material of the jacket was a halogen free and flame-retardant polyolefin (Nexans, 2020). Inside the jacket was the fibre along with a strength member of aramid fibre (Nexans, 2020). For the cables used in these tests the cross section can be seen in Figure 8. Note that the aramid fibres are not additionally encased inside the jacket but are free to move around the optical fibre. In the tests, the protective insulation materials around the cables were not removed because, as Ritz, et. al., (2012) and Rosenqvist (2014) concluded, the melting of the insulation materials caused mechanical stresses on the cable which affected the attenuation.

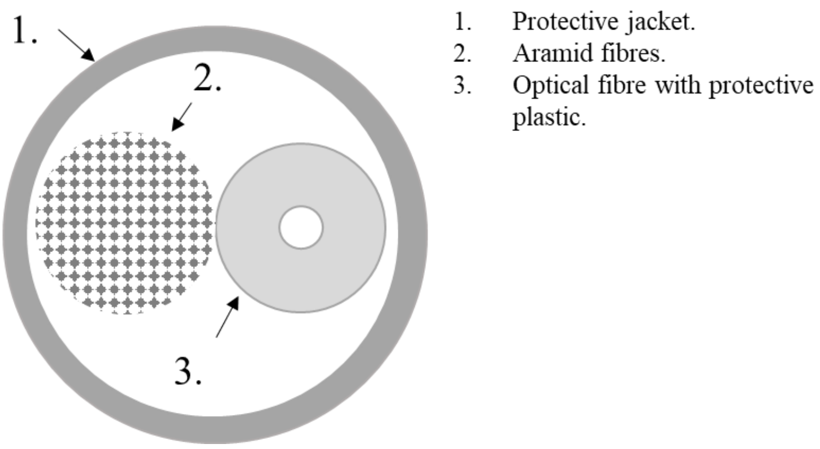

Figure 8. Cross section of the cable.

The sample holder was used for two types of tests. Several tests were conducted using a cone calorimeter with the final setup and one test was conducted over a propane burner with the initial setup.

3.2 Data transfer setup

The setup for the data transfer is illustrated with a flow chart, which can be seen in Figure 9. Two computers were each connected to a switch using an ethernet cable. A switch is a device which can divide one incoming Ethernet connection to multiple outgoing fibre connections, and vice versa. The two switches were then connected to each other by one fibre optic cable running through the cone calorimeter and by another fibre optic cable running outside of the cone calorimeter. The reason for using two fibre optic cables is that the connectors only can transmit data in one direction, thus needing one transmitting and one receiving cable.

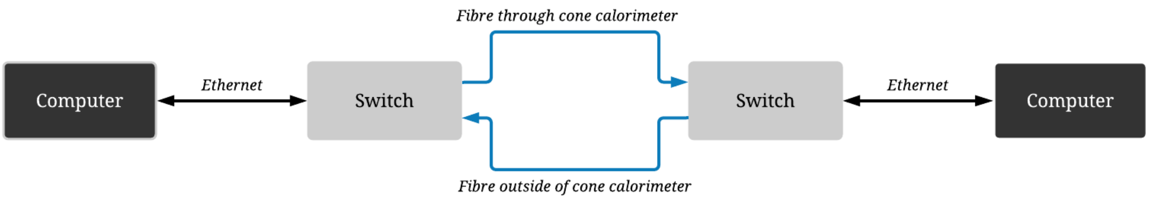

Figure 9. Flowchart of data transfer setup.

This setup created a local area network (LAN) between the two computers. The data was then transferred using a program called iPerf 2 (version 2.0.9), which is a free to use tool for measurement of bandwidth and data loss on a network (Dugan, et. al., 2020). For the experiment iPerf 3 was not used since the developers had removed the possibility to save the results as comma separated values. iPerf allows the user to choose what transport protocol to use for each test. In section 2.2 the difference between UDP and TCP was explained. As stated, the TCP is a much more complex and resilient type of protocol, as it retransmits packages that are lost along the way. This retransmission could affect the overall data loss as it fills in the gaps. By using UDP for this experiment, a more accurate description of data loss could be seen as lost datagrams were not retransmitted. As the UDP datagrams are transmitted they are divided into smaller IP packets. If one of the smaller packets are lost iPerf discards the entire datagram. In these experiments the maximum size of UDP datagrams was sent, which is 65 353 bites. Thus, sending fewer UDP packets every second but getting a more sensitive measurement as a small loss is shown as a loss of a large packet. Besides protocol, iPerf also allow for a choice of bandwidth. In this experiment the fibres were tested at a bandwidth of 1 Gbit/s, which is the maximum possible bandwidth for the LAN setup. Lastly, datagram loss was measured 10 times per second, to allow for a more detailed data analysis.

3.3 Cone calorimeter setup

The cone calorimeter used in these tests is designed according to SS-ISO 5660-1:2019 (SIS, 2019), and the final sample holder setup was used. During the experiments, a cable was gradually exposed to an increasing heat flux from the cone calorimeter which was based on the heat flux used by Rosenqvist (2014). The heat flux started at 15 kW/m^2 and was increased to 25 kW/m^2 after 10 minutes, 35 kW/m^2 after another 10 minutes, and finally 50 kW/m^2 after another 10 minutes. After 30 minutes the heat flux was at the maximum value for the experiment and remained at 50 kW/m^2 until the cable could no longer transfer data or until 90 minutes of the test had passed. The length of the test was chosen based on the IEC 60331-25:1999 (IEC, 1999), it is also reasonable to assume that after 90 minutes steady state has been reached for the 2 mm cable. It was not possible to set a desired heat flux in the cone calorimeter, which instead was determined by a temperature that corresponded to the desired heat flux. Note that the temperature had to be changed manually. Because of this, the increase of the heat flux did not reach its value instantaneously, and it could take some time for the heat flux to stabilize. The problem with the increase of heat flux was solved by testing how the heat flux increased and which temperatures corresponded to the desired heat fluxes before the tests were conducted. To maintain accuracy of the heat flux in the tests, these temperatures were tested at the beginning of each test day.

To determine which temperatures corresponded to the desired heat fluxes, a Gunners meter and a software called ConeCalc was used. This software has been specifically designed to be able to monitor the cone calorimeter with a computer (FTT, 2008). In the tests, this software was used to monitor the heat flux from the cone calorimeter by using a heat flux meter. Besides being able to monitor the cone calorimeter, the software can also log different data (FTT, 2008). This feature was used in the experiments to obtain a graph over how the heat flux changed over time, both when it was increased and when it was set at a specific value, as can be seen in Figure 10. When the heat flux was being measured and logged the Gunners meter was cooled with water, most likely to prevent the creation of re-radiation from the measuring instrument itself.

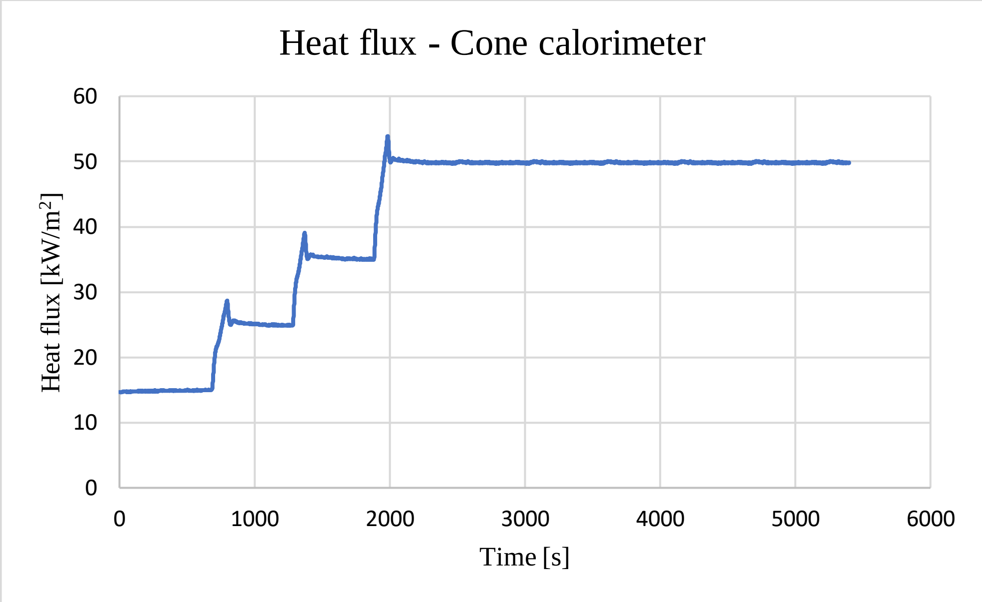

Figure 10. Logged heat flux from cone calorimeter.

In addition, the feature to log data was used to obtain temperature data using thermocouples that could be placed on optional positions in the cone calorimeter. One thermocouple was placed by the small ring, that held the cable, and one thermocouple was placed in the centre of the cone calorimeter at the same height as the cable. The thermocouple placed in contact with the small ring was placed there because the cable always had direct contact with the small ring, and this could potentially affect the temperature of the cable there. The thermocouple that was placed in the centre was covered in the same type of insulation material as the cable. This was done to resemble the temperature inside the cable more accurately.

3.4 Propane burner setup

For the test with the propane burner, the initial sample holder setup was used. This test was conducted to examine how the cable behaved in a flame and if the light from the flame would affect the data loss differently than the heat flux. The propane burner was placed on a piece of stone wool at the bottom of the sample holder, directly under the U-shape of the cable, see Figure 11. The propane burner creates a diffusion flame. In the first part of the test, the flow from the propane burner was set so that the cable was in the intermediate flame region. In the second part of the test, the flow from the propane burner was increased so that the cable was fully enveloped in the flames. As the flow of propane was low, it was not possible to get a reading on the instruments. Therefore, the flow was based on visual observations prior to and during the test. Similar to the cone calorimeter setup, one thermocouple was placed by the small ring and one thermocouple was placed in the centre of the propane burner at the same height as the cable without protective plastic.

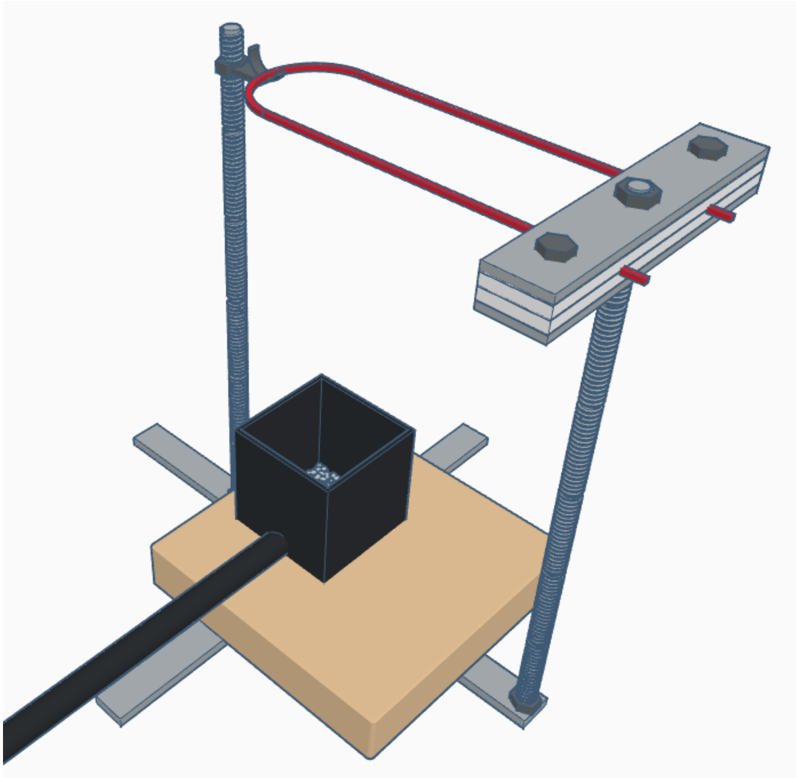

Figure 11. Sample holder setup for propane burner. For dimensions, see Appendix A.1.

3.5 Summary of tests

Above, the experimental setup for the sample holder, data transfer, cone calorimeter and propane burner has been described. For a more detailed experimental protocol, see Appendix A.2.

A total of 27 tests were conducted, where one of them was conducted over the propane burner. The 26 tests that were conducted in the cone calorimeter consisted of 6 initial tests, 15 main tests and 5 additional tests. The main tests were chosen to 15 to enable a statistical analysis, more tests would be preferable but were limited by time and resources. In the 5 additional tests, both the bend diameter of the cable and the heat flux was varied to further test the fibre optic cable's ability to transfer data. A summary of all the conducted tests, both in the cone calorimeter and over the propane burner, can be seen in Table 2 below. Note that "gradually increasing" refers to a heat flux in accordance with Figure 10.

Table 2. Summary of all conducted tests.

	Sample holder setup	Bend diameter [cm]	Heat flux
Test 1	Initial	6	Gradually increasing
Test 2	Initial	6	Gradually increasing
Test 3	Initial	6	50 kW/m^2 from start
Test 4	Initial	6	50 kW/m^2 from start
Test 5	Initial	6	Gradually increasing
Test 6	Initial	6	Gradually increasing
Test 7 – 21	Final	6	Gradually increasing
Test 22	Final	6	50 kW/m^2 from start
Test 23	Final	4	Gradually increasing
Test 24	Final	3	Gradually increasing
Test 25	Final	3	50 kW/m^2 from start
Test 26	Final	2	Gradually increasing
Test Propane	Initial	6	-

4 Results

4.1 Results from main cone calorimeter tests

A total of 15 tests (test 7 – 21) were performed in accordance with the method derived from standards and previously performed experiments, these are the main tests. During the tests, interesting events, data loss and temperature was recorded. Some of the events was based on visual observations, and for these to be repeated they were also photographed. The interesting events observed was timed and a matrix was formed. Table 3 shows what events was observed, and Table 4 shows at what time the event transpired for each of the 15 tests.

Table 3. Observed events during the tests.

	Event
A	Protective plastic started to soften
B	Aramid fibre was tightened
C	Aramid fibre broke
D	Protective plastic was completely melted
E	Protective plastic started to turn black
F	All protective plastic has become black
G	Protective plastic started to glow
H	Protective plastic was completely combusted
I	Cable broke

Pictures of these events can be found in Appendix B.1.

Table 4. Observed time of event [s] for the main tests.

	A	B	C	D	E	F	G	H	I
Test 7	10	30	100	130	340	725	1255	1860	1871
Test 8	13	36	65	130	360	745	945	1530	1792
Test 9	16	30	95	140	340	720	1245	1535	1909
Test 10	15	35	106	180	407	754	840	1735	-
Test 11	16	30	124	150	420	745	1255	1860	1974
Test 12	20	41	85	135	240	660	810	1724	1909
Test 13	14	34	78	105	250	660	1255	1560	1891
Test 14	17	25	98	120	240	700	1245	1920	-
Test 15	20	30	75	150	300	814	1260	1883	1903
Test 16	12	30	82	150	286	756	1275	1860	1865
Test 17	10	30	77	115	200	675	1260	1890	1893
Test 18	10	35	120	150	230	726	1250	1975	4358
Test 19	10	30	85	120	270	725	1250	1970	-
Test 20	10	40	82	128	270	695	720	1910	-
Test 21	10	30	70	88	150	620	900	1900	1900

Data loss was recorded as percentage of datagrams being lost and this can be seen in Figure 12. As seen in the figure, data loss was limited and for most of the experiments it was kept at zero percent, apart from test 7 and test 8. Some of the lines are not visible as they follow the same trajectory as the once that are visible, i.e., they lie behind each other.

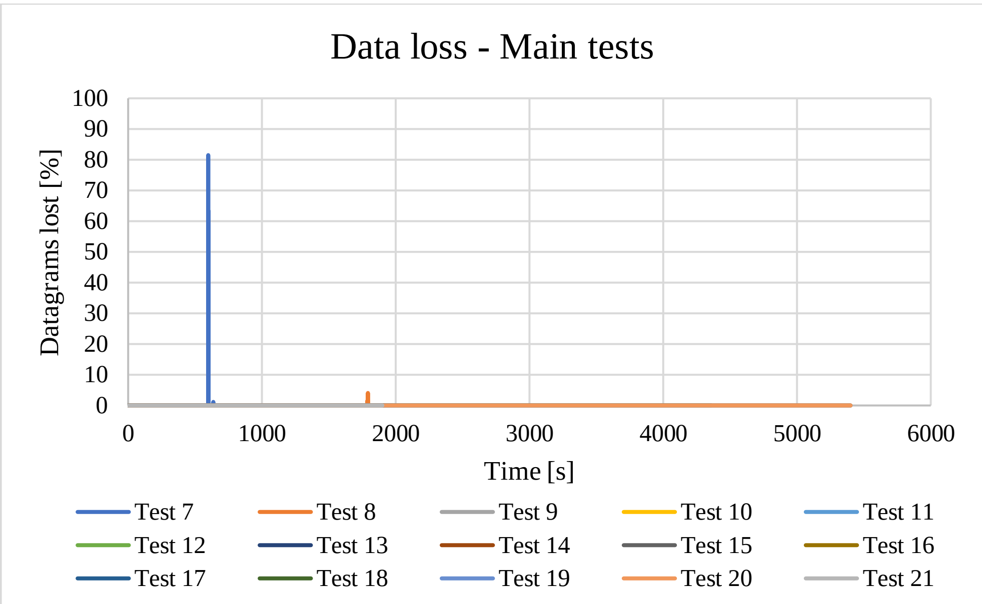

Figure 12. Data loss for main tests.

Test 7 show a peak in data loss of 81 % after about 600 seconds. A closer look of what happened can be seen in Table 5. The "Nan" in the table indicates that there were no datagrams sent or received in that timestep. For test 8 a small percentage of datagrams was lost in the seconds before breaking. This was not seen in any of the other tests.

Table 5. Data loss for test 7.

Time [s]	Datagrams lost [%]
598.6	81
598.7	0
598.8	0
598.9	0
599.0	63
599.1	Nan
599.2	0
599.3	0
599.4	0

The temperature was measured at two points during the experiments and then graphed as minimum and maximum for each timestep, an average was also plotted for the centre temperature. Temperature for the centre and small ring can be seen in Figure 13 and Figure 14 respectively, for temperature measurement from each individual test see Appendix B.2.

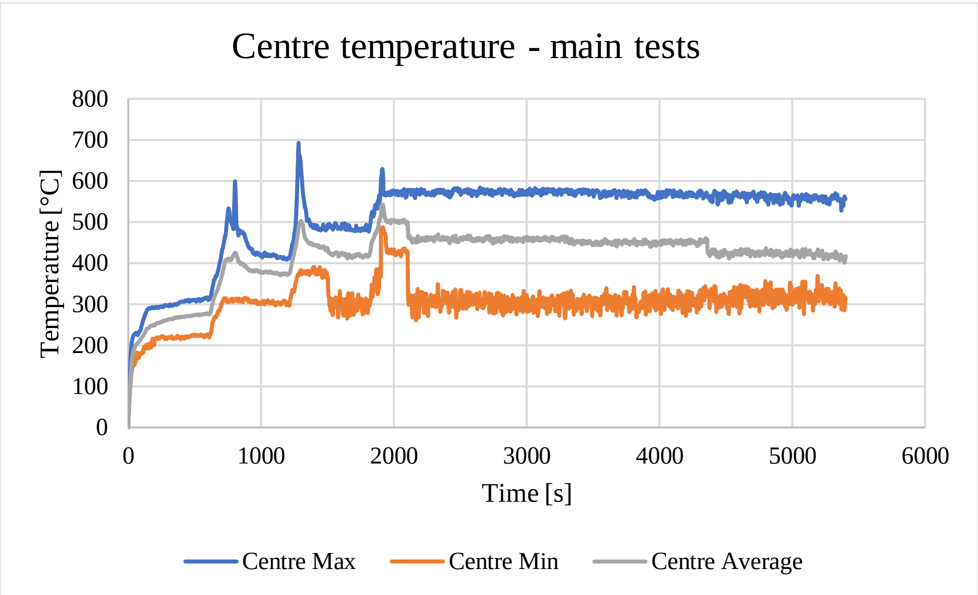

Figure 13. Centre temperature for the main tests.

In the graph above it can be seen that the temperature at the centre increased with the heat flux. It can also be noticed that the temperature at the centre spikes with each step, similar to the heat flux graph in Figure 10. A slight decrease in temperature can be seen in the minimum graph shortly after the maximum heat flux was reached. This decrease corresponds to observations of the charred plastic falling of the thermocouple during some of the tests. The average graph is initially closer to the maximum but after the last increase it stabilises between the maximum and minimum.

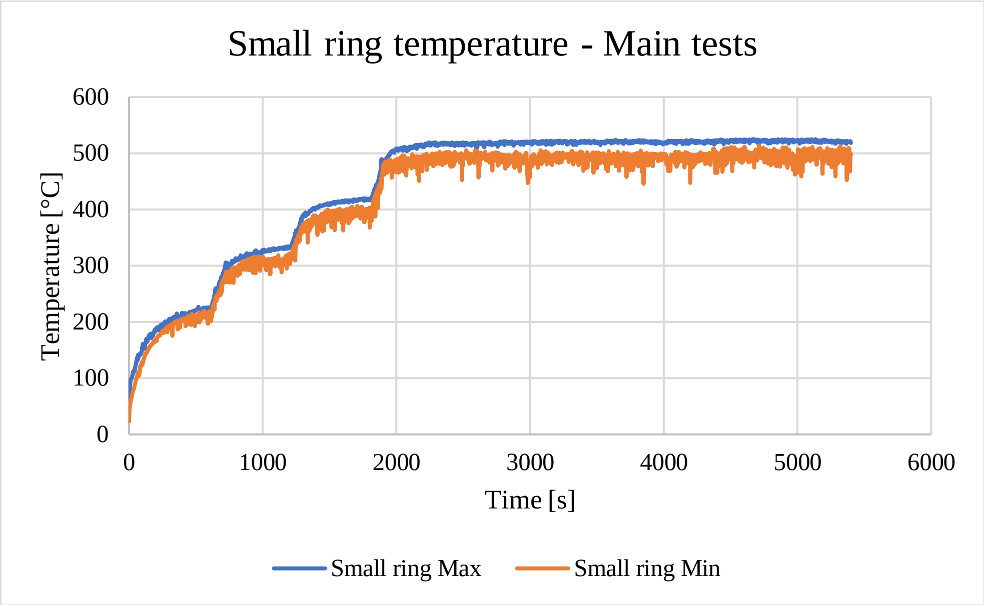

Figure 14. Small ring temperature for the main tests.

For the small ring, the temperature measurement also increased together with the heat flux. However, it can be seen that the measured temperature is more even compared to the centre temperature. This has to do with the thermal inertia of the ring at which the temperature was measured. From Figure 13 and Figure 14 it can be seen that the temperature was higher at the centre than at the small ring.

Finally, at the end of each test the diameter of the smallest bend on the cable was measured. Even though each cable was mounted in the same way, the heating of the cable caused the fibre to bend and twist in different ways. The final bend diameters of each test are presented in Table 6.

Table 6. Final bend diameter for the main tests.

Test	Bend diameter [cm]	Break [Yes/No]
Test 7	4	Yes
Test 8	4	Yes
Test 9	3.5	Yes
Test 10	5	No
Test 11	3.5	Yes
Test 12	3 – 3.5	Yes
Test 13	2.5 – 3	Yes
Test 14	5	No
Test 15	2.5 – 3	Yes
Test 16	2.5	Yes
Test 17	3.5	Yes
Test 18	4.5 – 5	Yes
Test 19	4.5	No
Test 20	4.5 – 5	No
Test 21	3.5	Yes

All tests were placed in the sample holder with a bend diameter of 6 cm and the tests where the cable broke had a final bend diameter less than 4.5 cm, except from test 18. However, test 18 was an anomality both in bend diameter as well as time of break.

4.2 Results from additional cone calorimeter tests

After the main tests, a few additional tests were performed in the cone calorimeter with small deviations from the original setup. As for the main tests, interesting events, data loss and temperature were recorded for these additional tests as well. Table 7 shows at what time the events transpired for each test.

Table 7. Observed time of event [s] for the additional tests.

	A	B	C	D	E	F	G	H	I
Test 22	5	5	10	14	14	25	25	105	-
Test 23	10	30	95	115	180	720	1260	1860	1867
Test 24	10	30	85	115	150	705	1250	1980	3316
Test 25	5	9	11	15	15	30	30	115	619
Test 26	10	40	75	95	180	680	1265	-	1884

In these tests, data loss was monitored in the same way as for the main tests, see Figure 15. None of the tests showed any data loss. Some of the lines are not visible as they follow the same trajectory as the once that are visible, i.e., they lie behind each other.

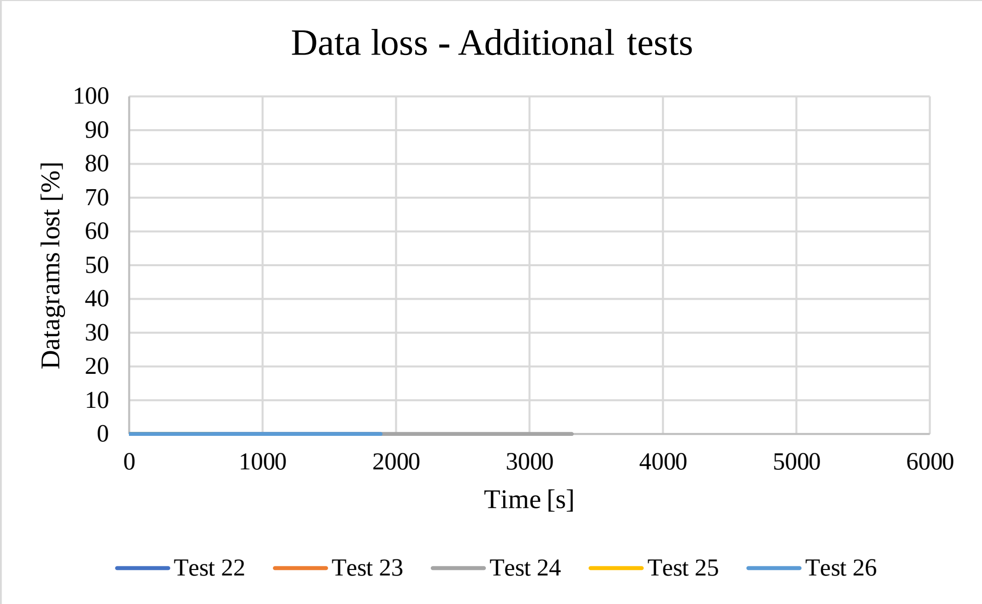

Figure 15. Data loss for the additional tests.

The temperature for the additional test were measured in the same way as for the main tests, meaning measured at the centre and at the small ring. However, each test is graphed on their own because of the variations between the different tests. The temperature at the centre for each of the additional tests can be seen in Figure 16.

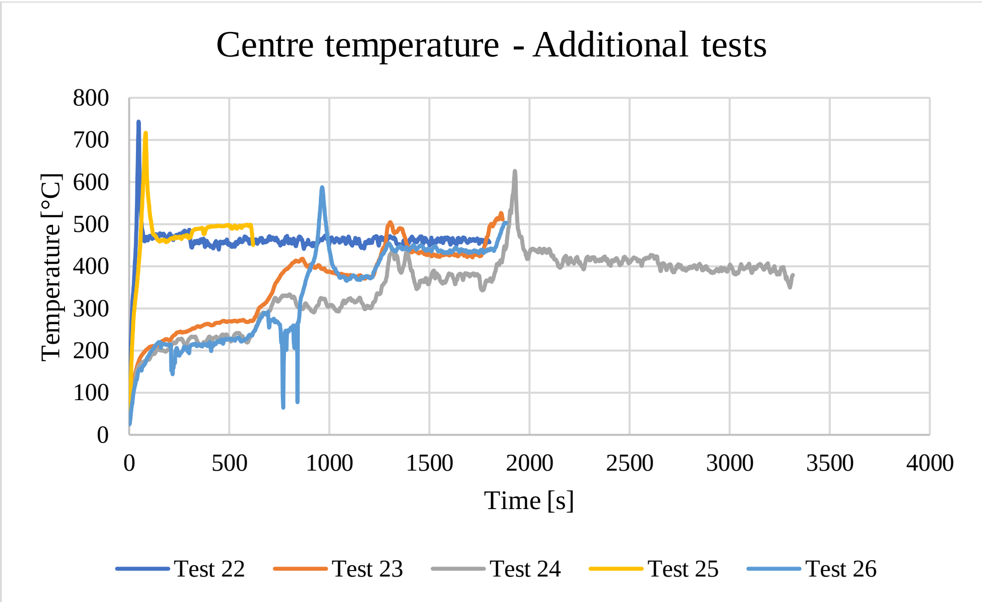

Figure 16. Centre temperature for the additional tests.

The temperature profiles are similar to those of the main tests, except for test 22 and test 25. The variations seen between the different tests were also observed in the main tests, see

Appendix B.2. The temperature profiles at the small ring can be seen in Figure 17. At the small ring the temperature varies less, this is because of the thermal inertia as previously mentioned.

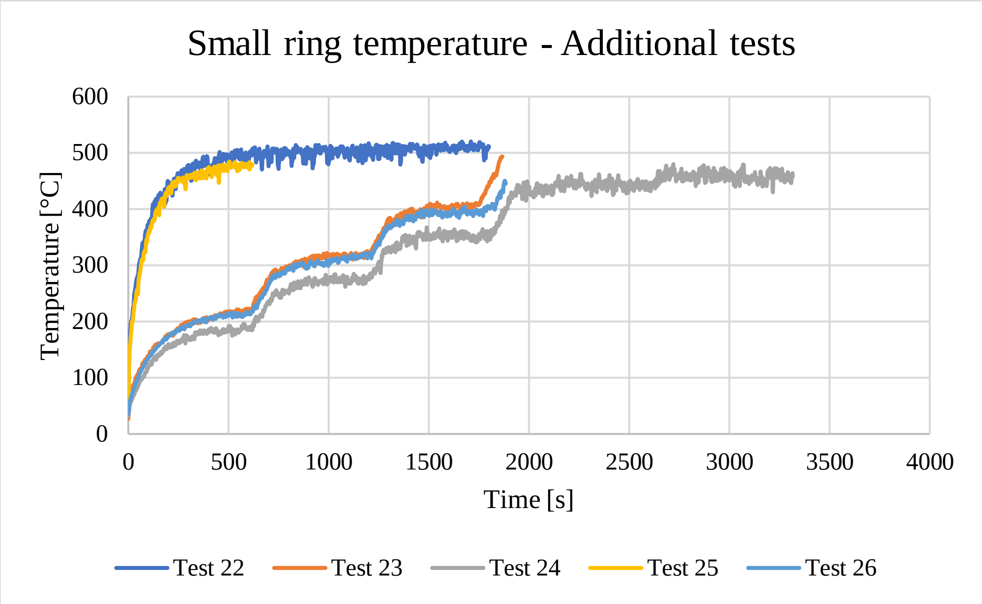

Figure 17. Small ring temperature for the additional tests.

Lastly, the bend diameter of the smallest bend was measured at the end of the tests and these are presented in Table 8.

Table 8. Final bend diameter for the additional tests.

	Bend diameter [cm]	**Break [Yes/No]**
Test 22	-	No
Test 23	2.5 – 3	Yes
Test 24	3 – 3.5	Yes
Test 25	3	Yes
Test 26	2.5	Yes

For the additional tests, the cables were placed with bend diameters from 2 – 6 cm. However, the final bend diameters are similar to those measured from the main tests. The bend diameter for test 22 was undeterminable, see Appendix B.3.

4.3 Results from propane test

One test was made using a propane burner. For the previous tests, the cone calorimeter was used for logging the temperature, this was not possible to do for the propane test. Thus, the temperature was not continuously logged in this test. Instead, thermocouples were placed in the same location on the sample holder and recorded together with observations of noticeable events, see Table 9.

Table 9. Time and temperature during noticeable events for the propane test.

Time [s]	Temperature [°C]	Observations
30	160	Aramid fibre broke.
77	200-250	Some flames on the cable resulting in exposed fibre.
170	250-300	Entire cable became black.
610	-	Small increase of propane, but due to risk of spread it was lowered again.
2350	400-600	Propane flow increased. Again, some flames broke out on the cable.
2440	-	The cable stretched out and hung further down.
3064	-	Cable broke.

For the duration of the propane test the data loss was also monitored as before. The data loss can be seen in Figure 18.

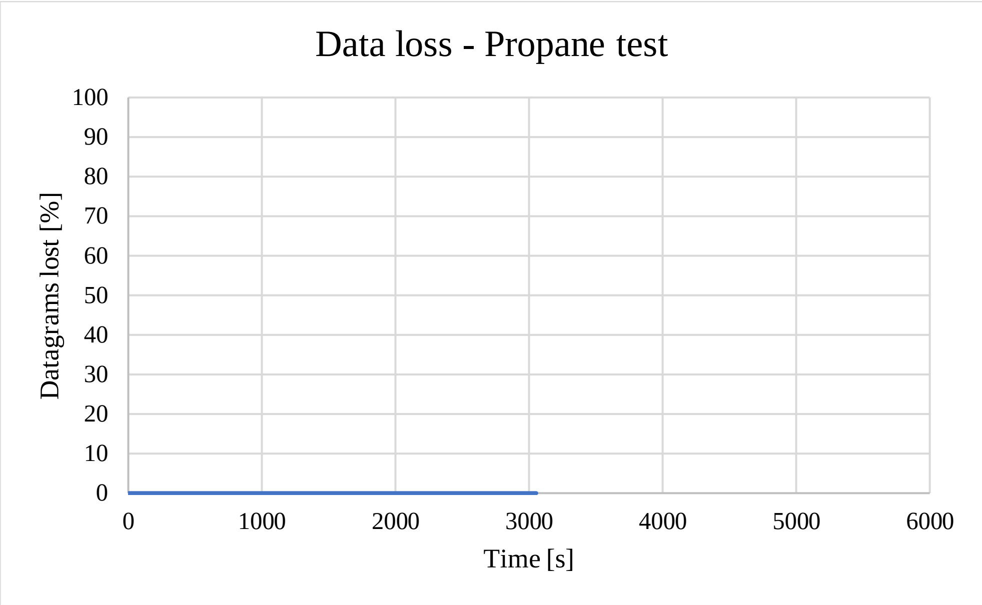

Figure 18. Data loss for the propane test.

As can be seen in the graph no measurable data loss occurred before the cable broke. When the cable broke it fell from the small ring, mening that it was not possible to measure the diameter at the break.

4.4 Statistical data analysis

The temperature measurements from the main and additional tests were further analysed to examine a maximum allowable temperature that does not lead to a break of the cable. Temperature measurements from test 22 and test 25 were excluded from this analysis because of the differences in heat flux. The analysis focused on the time of break of the main tests (7 – 21) since they were installed in accordance with the manufacturer's guidelines. Meaning that as the temperature measurements for the main and additional test were conducted in the same way they were all representations of the temperature exposure of the cables. However, as the cables in the additional tests were incorrectly installed, the time of break for these cables were not representative of a credible case. Therefore, only the time of break from the main tests were analysed but using the temperature measurements from all tests with the same exposure.

A total of three empirical cumulative distribution functions (ecdf) were made for the temperatures measured at the time of break from the main tests. However, as 4 out of the 15 main tests did not break, they are not part of this analysis meaning that a total of 11 data points were used. Then, using @RISK (Palisade, 2020) these were fitted to either gamma, normal, lognormal or Weibull distributions. However, the best fit was shown to be the normal distribution in all three cases. In Figure 19, Figure 20 and Figure 21 these fits are presented.

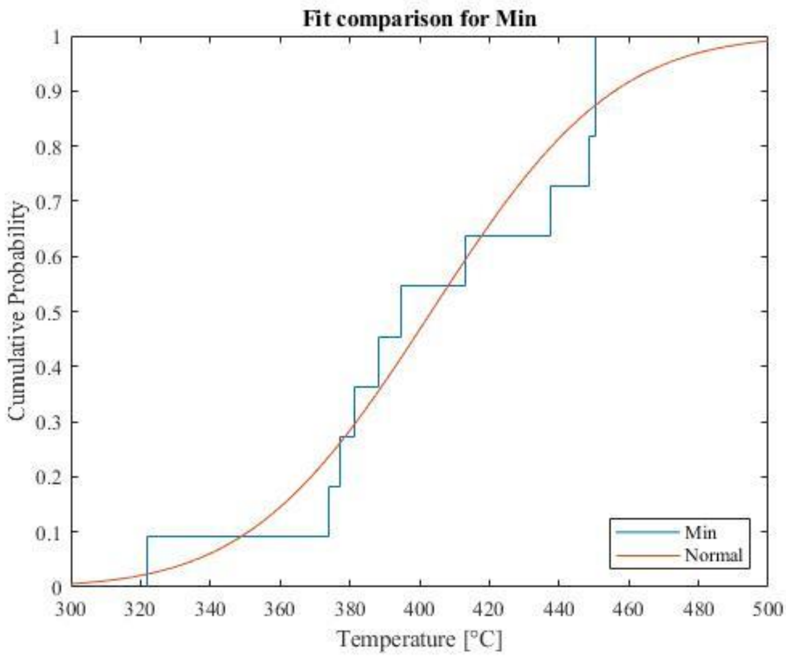

Figure 19. Distribution fit for the lowest temperatures at time of break.

Above the normal distribution fitted to the ecdf of the measured lowest temperatures at the time of breaking is displayed. The lowest temperature measured at the time of breaking considers both points of measurement, i.e., centre and small ring. As can be seen in Figure 13 and Figure 14, the maximum and minimum temperatures vary between the centre and small ring depending on the time of break. The normal distribution fitted is described by parameters [μ; σ] = [403; 41], note that @RISK describes the normal distribution with standard deviation and not variance. The confidence interval for the parameters can be seen in Table 10.

Table 10. Confidence interval for the lowest temperatures at time of break.

Minimum	Mean	95 % lower limit	95 % upper limit	Conf. interval width
μ	403	378	429	51
σ	41	23	60	37

Below the normal distribution fitted to the ecdf of the measured average temperatures at the time of breaking is displayed. Each point is a collected average form every measured temperature at the time of breaking, both at the centre and at the small ring.

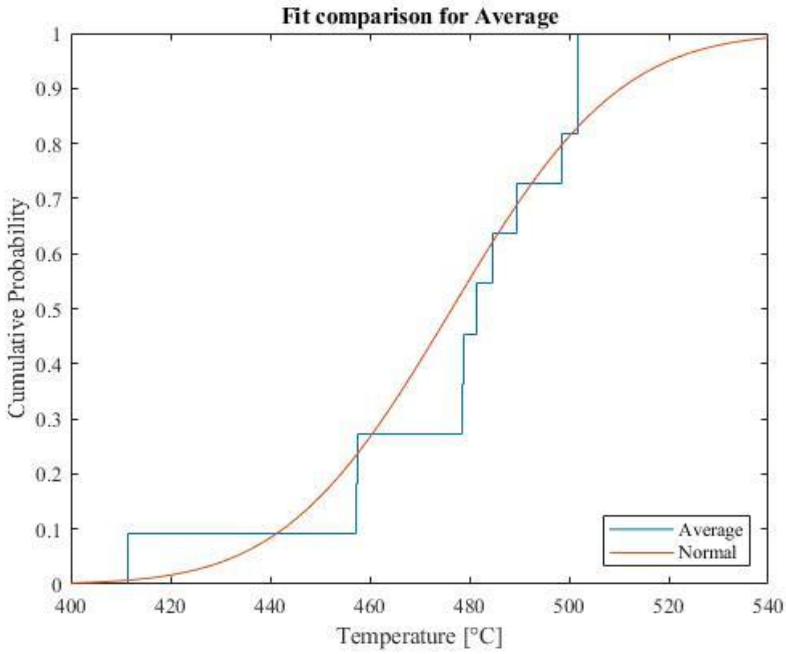

Figure 20. Distribution fit for the average temperatures at time of break.

The normal distribution fitted is described by parameters [μ; σ] = [477; 26]. The confidence interval for the parameters can be seen in Table 11.

Table 11. Confidence interval for the average temperatures at time of break.

Average	Mean	95 % lower limit	95 % upper limit	Conf. interval width
μ	477	460	493	33
σ	26	15	39	24

Below, the normal distribution fitted to the ecdf of the measured highest temperatures at the time of breaking is displayed. The highest temperature measured at the time of breaking considers both points of measurement, i.e., centre and small ring.

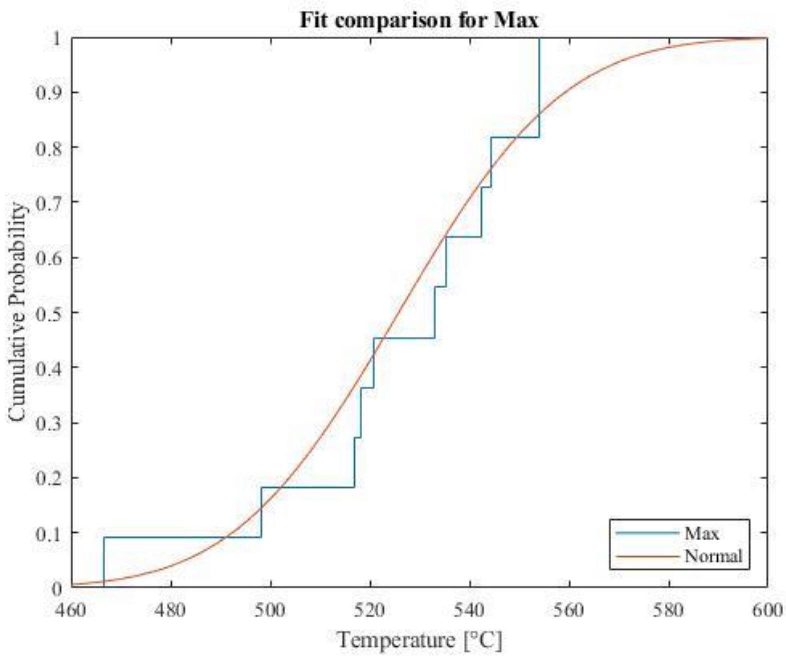

Figure 21. Distribution fit for the highest temperatures at time of break.

The normal distribution fitted is described by parameters [μ; σ] = [526; 26]. The confidence interval for the parameters can be seen in Table 12.

Table 12. Confidence interval for the highest temperatures at time of break.

Maximum	Mean	95 % lower limit	95 % upper limit	Conf. interval width
μ	526	510	542	32
σ	26	15	38	23

From the fitted distributions, percentiles can be examined. In Table 13 the 5th percentile from each of the fitted functions are presented together with the lowest measured temperature from the data.

Table 13. 5th percentile and lowest measured temperature for all distribution fits.

Distribution	5th percentile [°C]	Lowest measured [°C]
Minimum	336	322
Average	433	411
Maximum	483	466

Notice that the 5th percentile from the fitted distributions is somewhat higher than the lowest measured value in the tests. This has to do with the small sample size and the fact that the temperatures were not widely scattered.

5 Discussion

5.1 Data loss

In the thesis by Rosenqvist (2014) it was concluded that further analysis was needed in order to determine whether the attenuation that was measured in the experiments could be correlated to data loss. Thus, making data loss and measuring of data loss a key aspect in this thesis. Therefore, a method for continuously measuring data loss was derived for the tests. In the literature study the functions and weaknesses of fibre optic cables were explored. Properties such as critical angle and refractive index between core and cladding pointed towards that the bending of the cable together with exposure to high heat flux would result in data loss and possibly breaking of the cable. If data loss would be significant leading up to a complete break it could work as an early warning that the functionality is about to become compromised.

However, for the cone calorimeter tests, the result showed no data loss before the break of the cable. As shown previously there were two exceptions to this, test 7 and test 8. Test 7 showed a momentary data loss of up to 81 %. In Table 5 it can be seen that there was data loss in a total of three timesteps. During this time there were no visible changes on the cable, and it was not in connection to the cable breaking. A possible explanation for this phenomenon is problems with the data transfer being measured in the user space, which will be discussed further in section 5.6. Test 8 showed data loss in the seconds leading up to the cable breaking, which was in line with the effects described in section 2.1.4. However, this pattern was not reoccurring in the other tests and can therefore not be seen as a common behaviour for a fibre optic cable.

Since the cone calorimeter tests resulted in zero data loss it was interesting to see what effects an open flame would have on the fibre optic cable, as an open flame could generate a wider spectrum of light that can interfere with the signal in the cable. Also, in the experiments by Rosenqvist (2014), an open flame together with bending of the cable lead to the highest attenuation. The open flame in this test was created using a propane burner. However, as before no data loss could be measured before the cable broke.

Finally, it was found in the literature study that optical fibres being bent smaller than 3 cm would give significant attenuation due to an effect called macro bending. In the additional tests there were three tests performed with an initial bend diameter less than or equal to 3 cm. Even with these tight bends on the fibre no data was lost before the cable broke. Together, these results indicate that the signal through the fibre is resilient to the effects of a fire and no early warning will be given by the cable that it is about to break. However, this cannot be truly stated without further analysis and a larger sample size.

5.2 Temperature

The results from both the main and the additional tests showed that the maximum temperature in the centre was between 300 and 600 °C, while the temperature at the small ring was around 500 °C. These points of measurement were chosen to get a broad picture of the temperature that the cable was affected by. At the centre, an attempt to measure the temperature inside the cable was made. At the small ring, the temperature is initially of the outside but as the plastic melts and burns away the fibre comes in direct contact with the small ring and thus becomes a more accurate representation of the fibre temperature. Even though the temperature at the small ring is consistent over all main and additional tests, the temperature at the centre varies more and that makes it more difficult to draw conclusions regarding how the cables were affected by the temperature. The large variation in the centre could most likely be explained by how the plastic surrounding the thermocouple acted differently from test to test. In some tests the plastic almost completely melted and fell off, in some tests the plastic became completely charred, and in some tests, it became completely charred before it fell off. These different outcomes resemble how the temperature can vary on different places along the cable in the same test. Thus, the measured variation could be seen as a valid representation of the different parts of the cable.

It was also observed in some tests that the glowing of the plastic surrounding the thermocouple caused a significant increase in temperature, meaning that glowing on the cable could be a deciding factor for when a cable will break. As can be seen from Figure B-5 in Appendix B.1, that were taken after the main tests, the cable most often broke at the bend near the small ring. The events that were observed during the cone calorimeter tests only covered when the cable started to glow somewhere and when the whole cable was charred. However, during the tests it was observed that the cable often started to glow close to the small ring last, which means that it happened in close proximity to the time when the whole cable became charred and broke off. As can be seen in Table 4 for those tests where the cable did break, the cable often broke within 100 seconds of it being completely charred. There are however a few exceptions to this, but it still gives an indication that the glowing of the cable could affect when the cable breaks.

Another observation from the main test results is that the highest peak in temperature, which is a direct result of the highest peak in heat flux, corresponds well to the cables' time of break. In Table 4 it can be seen that most cables broke between 1860 and 1910 seconds, and in Figure 13 it can be seen that the temperature at the centre reached its peak after about 1920 seconds. This points to that the cable was most vulnerable when the heat flux was increased from 35 kW/m^2 to 50 kW/m^2, and when the temperature quickly increased to the peak seen in the graph mentioned above. The quick increase of heat could also affect the insulation materials around the cable and cause mechanical tensions.

For the additional tests where the heat flux was gradually increased, the same conclusions that have been drawn above apply here too. It was during the increase to the highest peak in temperature in Figure 16, as well as right before or after the whole cable had been charred according to Table 7, that the cable did break. For the additional tests where the heat flux was at 50 kW/m^2 from start, the same patterns was not seen. This could be because the gradually increasing heat flux gave more room for the cable to twist and turn before it became completely charred and stopped moving.

The propane burner test was mainly conducted to investigate how the light from the flame might affect the data transfer and cause data loss. Due to only one test being conducted and the fluctuation of the flame, the temperature measurements are uncertain. The manual measurements showed that after the flow of propane was increased, the temperature was around 400 – 600 °C as can be seen in Table 9. The temperature at the time when the cable broke was not noted, but since the flow of propane was the same it can be assumed that the temperature also was 400 – 600 °C at this time. This temperature is consistent with the temperature that was measured when the cables in the cone calorimeter tests broke.

The two possible factors for the cable breaking that has been discussed in this section are glowing of the cable and high temperature peaks in the cone calorimeter. Since the cables that did not break also became completely charred and was exposed to the high temperature peaks, there might be another factor that also determine if, and when, the cables break. This factor could be the bend diameter of the cables, which will be discussed in the next section.

5.3 Bend diameter

From the tests there was a clear pattern between temperature, from the glowing on the cable at a specific place, and a sharp bend on the cable. This led to the smallest bend diameter being measured after each test because it was in the smallest bend that the cable broke. Even if all the cables were installed in the sample holder in the same way, there was a clear difference in how the cable reacted to being heated and finally bended due to thermal stress. In all cases where the cable broke during the tests there was a bend diameter smaller than 4.5 cm somewhere on the cable, see Table 6. It was also observed that the smallest bend diameter at the end of the test most often was created around the point of the initial bend. However, in one test the cable twisted more, and the smallest bend was created along the part that initially was straight, see Figure B-5 in Appendix B.1.

When the fibre is bent a mechanical strain is introduced over the cross section. On the inside of the bend a compressive force is applied and simultaneously the outside of the bend is being subjected to a pulling force. If the bend becomes too small the resulting forces on the fibre can become greater than the tensile or crushing strength of the fibre and result in the fibre breaking. In section 2.1.5 a study was introduced on the tensile strength of optical fibres subjected to increased temperature and annealing. The main conclusions from that study were that the strength of the fibre was lowered as the temperature was increased and that the annealing process lowered the tensile strength even more.

This relationship between tensile strength and temperature coincides well with the result from the tests in this report, which show that a small bend diameter in combination with high temperature leads to break. For the main tests, the bend diameter had to be less than 4.5 cm in order for it to break. In some of the additional tests the cables were installed with an initially smaller bend diameter. The final bend diameter in these tests were still in the same interval as the main tests at the time of break, meaning that break occurred in the same way as for the main tests. It was also observed that those cables among the main tests that did not break broke immediately after being removed from the heat source. In some cases, it broke due to the mechanical stress from removing the sample holder from the cone calorimeter and in other cases the cable broke as it was cooled to room temperature. The latter being in line with the annealing scenario from the study by Tu & Tu (2014), where the strength was further reduced due to increase in formation of cracks on the cable during cooling.

5.4 Statistical data analysis

Above, the relationship between the temperature and bend radius is discussed. This relationship makes it difficult to define a critical temperature, which has been done for copper cables. However, since the experimental setup in this report was done to resemble a worst-case proper installation of a fibre cable it is deemed possible to further analyse the measured temperatures.

Thus, with the assumption that the observed bending, melting and glowing of the cable would occur in a similar manner on a properly installed cable, the statistical analysis was made.

Statistical analysis of the 11 cables that broke in the main tests showed that the failure probability in relation to the temperature was approximately normally distributed. As the sample size in this study is small, together with the discussion about temperature measurements in this study, the failure probability was divided in three groups, minimum, average and maximum measurements at the time of the break.

The data were plotted as empirical cumulative distribution functions which then was fitted to either a gamma, normal, lognormal or Weibull distribution through the use of the @RISK plugin for Excel. These distributions were chosen because of their inherent functions which has been proven useful to represent strengths of materials. Ideally the Weibull distribution would be used as it was created for this type of analysis. However, the best fit for the three was the normal distribution. The fit was made using a parametric bootstrap with 1000 resamples and best fit was evaluated by Anderson-Darling statistics (Anderson & Darling, 1952).

From the fitted distributions it is possible to derive percentiles leading to breaking of the cable. The 5th percentile is presented in Table 13 for the three fitted distributions, this value is used by Gallucci (2017) in an assessment of electrical cables and is used in this report for a comparison. Notice that the 5th percentile is higher than some of the measured values from the tests. However, from the discussion about temperature it is stated that the measured temperature at the time of breaking was not the same as the local temperature at the breaking point. For example, the temperature has most likely reached higher temperatures along the cable as the plastic was glowing, but the cable did not break until the glowing occurred in correlation with a sharp bend.

5.5 Damage criteria

A damage criterion is, in this report, defined as a level of strain that result in either data being corrupted or completely lost. In this case the level of strain comes from the exposure to fire conditions, which is quantified as a heat flux or an elevated temperature. As no data was lost before the cable broke it is not possible to say anything about the risk of corruption or similar before total loss. Simultaneously, in the discussion about temperature it is stated that a high temperature, in this case 500 – 600 °C, on its own is not enough to cause cable break. Thus, it is clear that other forces are needed to act on the cable together with the increase in temperature in order for it to break. Important to note is that these statements are based on the tests in this report, and a larger sample size can give a different result due to the non-periodic molecular structure of the fibre, see section 2.1.5.

From this study the minimal distribution could be used for a probabilistic risk assessment of fibre optic cables. The average and maximum might be possible to use in the future, but they require further analysis of the relationship between bend diameter and temperature. The 5th percentile from the minimum distribution was 336 ºC. Similar values for copper cables were presented in a report by Gallucci (2017) and depending on what type of plastic used in the jacket the 5th percentile of the critical temperature was between 200 – 350 ºC. Commonly used for determining the temperature of a cable is the THIEF model (McGrattan, 2008), which is also integrated in Fire Dynamics Simulator (FDS). This is then used together with the critical temperature of the cable to make an assessment of the cable's functionality. As this model is a simple heat transfer model in one dimension it could be possible to use it for fibre optic cables as well, this should be evaluated before being used in a real situation. However, other values for conductivity and specific heat needs to be chosen as fibre optic cables often are thinner and are not made of the same materials as a copper cable.

To conclude this section on damage criteria, due to the cable glowing and melting at different times along the cable and the fact that the glowing occurred last at the sharpest bend, it is reasonable to determine the functionality of the cable based on the lowest temperature measured at the time of breaking in an assessment of the cable as a whole. With further analysis of the relationship between bend diameter and temperature a more detailed criteria could be derived, and from these tests there is reason to believe that the cable could maintain functionality at even higher temperatures than this data analysis shows.

5.6 Sources of error

There were two main issues with the measurement of data loss in the tests. First, the data loss was measured in the user space. This could lead to measurements as in test 7 where there was a sudden spike in data loss. Another issue with this is that other applications and background processes try to communicate over the network even without it being connected to the internet. This has been minimized by having the least possible number of applications on both computers. Second, the fibre optic cables used for the test can handle a bandwidth much higher than 1 Gbit/s. This means that even at the maximum speed on the created LAN (1 Gbit/s) only accounts for a small percentage of what the cable is capable of. If a higher bandwidth is used it is possible that data loss would be measurable.

The temperature measurement was conducted using thermocouples, as has been described in section 3.3. However, these thermocouples are thicker than the actual fibre in the cable, and they also have different thermal properties than the fibre. Because of the different thermal properties, it is conceivable that the temperature-time graph for the thermocouple does not exactly correspond to the actual temperature of the fibre in the cable. This temperature could be higher or lower than what was measured by the thermocouple. It does however seem reasonable that the temperature of the fibre was within the interval presented in Figure 13.

The temperature was further analysed using statistical software, in this analysis only the 11 samples that broke in the main tests were used. This makes the result uncertain in comparison with the population as a whole and the fitted distributions could change as the sample size increase. To make the most of the small sample size bootstrapping was used to minimise the uncertainties.

5.7 Experimental method

One clear advantage of the experimental method used in this report is that the cable was suspended freely in the air. By not being mounted on a board or laying on a board, the cable was subjected to mechanical stresses that arose from the thermal influence on the cable. Being suspended freely in the air could be seen as a worst credible case for a cable. Installation of cables in cable ladders look similar to the sample holder setup used in the tests, thus validating the setup. As the cable is sensitive to mechanical stresses, the free movement of it is considered important when analysing the failure probability. This can be compared to other standards such as SS-EN 50200:2006 (SEK, 2006), where the cable movement is restricted by mounting it on a solid board. Thus, making this setup more accurate for analysing the failure of fibre optic cables. A further advantage was the use of the cone calorimeter, which allows for repetition of the same exposure of the different samples in the tests. It also creates the possibility to build on to the samples as long as a cone calorimeter is available. However, it would be interesting to test the fibre optic cables with an actual flame in a wider extent. As only one test was conducted with a propane burner no definite conclusions can be drawn from this alone. Lastly, the setup for data loss was made using an open-source application, meaning it is publicly available and possible to use for additional studies without extensive knowledge about computer science.

However, some disadvantages could also be found. The first one is that the cable changed the bend diameter when it was subjected to thermal influence. Even if this resembles how the cable would act in a real fire scenario, it made it difficult to fully control and analyse how different bend diameters affected the cables' functionality. Further disadvantages could be found with the data loss measurements. First, the measurements were made in the so-called user space. This means that the measurement can be affected by other applications taking control over the processing capabilities of the computer. The second one is that it was not possible to maximise the bandwidth for the fibre optic cable. To get around these issues, further knowledge, equipment and software would be required. This was not available for this master thesis.

Further, the cables used in the tests were all from the same manufacturer and of the same type. By analysing cables made with other materials in protective jacket and strength member it would create a wider base for conclusions about fibre optic cables as a whole. This has been done for copper cables, but it requires time and resources beyond what was available for this thesis. For example, the cables used in these tests had a protective jacket made of halogen free and flame resistance polyolefin. Other cables use plastics such as PVC, which could lead to other effects while heated. Also, for this study SM cables were used, with the argument that these will phase out MM cables, this being said there are still MM cables used. Thus, the experimental setup could have been broader by using a variety of cables both when it comes to what protection and what type of fibre that makes up the cable.

The initial sample holder setup had some flaws and was therefore, after a few tests, changed to the final sample holder setup that can be seen in section 3.1. In the same section, the two main changes to the sample holder were briefly discussed and will be further discussed in this section. The first change was the fibre cement board that was placed below the cable. In the initial tests, it was observed that the temperature around the cable was low and it was concluded that this most likely had to do with the heat flux from the cone calorimeter not hitting the cable and escaping at the sides. The fibre cement board creates re-radiation of some of the lost heat and resulted in a more realistic setup regarding the temperatures around the cable. However, in some of the main tests it was observed that, when the aramid fibre broke, the cable laid down on the board steadily. Thus, giving the cable support and reducing the tensions in the fibre. In future work, this board might have to be moved down a bit further from the cable, if that can be done without affecting the temperature around the cable too much.

The second change to the sample holder setup was the pendulum that struck the sample holder every 10 minutes. In a real fire scenario, it is possible that debris from the ceiling or from the interior of a room could hit the surroundings of a cable and therefore create mechanical stresses on the cable. This change was also motivated with the standard SS-EN 50200:2006, where a pendulum is used in a similar manner to strike the board where the cable is mounted (SEK, 2006). The results did however not show any signs that the pendulum affected the cables' functionality. This could either be because the cable is not affected by the pendulum, or because the pendulum was not effective enough. As there is no weight on the pendulum in the standard, only dimensions, it might be possible that the pendulum used in the tests in this report does not produce enough force to impact the cable. For future work, this might be an interesting point to investigate further.

An aspect of the experimental setup that is hard to define as good or bad is the choice of heat flux. In these tests the heat flux was increased in steps. To vary this, some tests were made where the heat flux was set at 50 kW/m^2. In these tests it was noted that the cable did not have time to move in a way so that tension was created before the protective plastic and strength member became combusted. However, it would be interesting to look at how other heat flux increases could affect the build up of tension in the different materials. For example, a linear increase could give more information on this. The heat flux model chosen was deemed as best in these tests as the increase was made manually. A linear increase would require more personnel for the tests as the cable needed to be observed continuously, and the sample holder needed to be struck every 10 minutes. One final remark on the heat flux model, in section 5.2 it is stated that the cables broke during the larger step from 35 to 50 kW/m^2. This could be examined further by dividing this step into a series of smaller steps. However, due to time and material limitations of this report it was not possible, and the damage criteria was evaluated with temperature instead of heat flux.

5.8 Previous experiments

In section 2.5, several previous conducted experiments, that was found through the literature study, were summarized. Out of the five experiments that could be found on cables' behaviour during fire conditions, three of them were made on fibre optic cables and two of them were made on regular copper cables. This section aims to compare the results from this report to the results from the previous experiments, to see if these results can validate previous results or give new information in the area.

Both Rosenqvist (2014) and Ritz, et. al., (2012) measured attenuation in the fibre optic cables when they were subjected to fire conditions in their experiments. This attenuation was most likely caused by mechanical stresses on the cable that arose due to thermal influences. From the tests in this report, it could also be seen that thermal influences caused the cable to twist and turn, thus creating mechanical stresses that in most of the tests lead to the cable breaking. However, no data loss was measured even though the cables were exposed to mechanical stresses. The lack of data loss could mean that the stresses on the cable did not disturb the light going through the cable enough to cause data loss. However, it is important to keep in mind that the cable's bandwidth was not maximized, and a higher bandwidth could possibly show an amount of data loss corresponding to the increase in attenuation seen from Rosenqvist (2014) and Ritz, et. al., (2012).

Similar to the experiments conducted by Andersson & Van Hees (2000) and Andersson & Persson (2001), the tests in this report showed no data loss before the cable broke and stopped working completely. Therefore, it is not possible to get an indication of when a cable is about to break. As discussed in the previous paragraph, it could be possible that a higher bandwidth would show data loss before the cable breaks and therefore give an indication of that. However, as a high-speed bandwidth was used in these tests it is not reasonable to believe that an early warning system based on an even higher bandwidth would be useful, but this needs to be analysed further. Another conclusion drawn from the experiments conducted by Andersson & Persson (2001) and Bertrand, et. al., (2001) was that a critical temperature could be found for when the cables stopped working. Similar analysis was attempted with the result from this study, resulting in a probabilistic distribution of the lowest allowable temperature. However, this result can be further refined by analysis of the relationship between temperature and strain.

5.9 Research questions

In section 1.3, three research questions were presented. The answers to these questions have continuously been discussed through the work on this report and will be summarized in this section.

How is the transferred data through fibre optic cables affected by fire?
From the measurements made in this report the heat and radiation did not affect the transferred data before the cable broke off. It has also been discussed that a higher bandwidth could give measurable data loss. However, the bandwidth used for sensitive control equipment is not public information and therefore difficult to define.

What is the risk that data becomes corrupted or lost when fibre optic cables are exposed to fire conditions?
From the above answer, no data loss was measured until the cable broke off. This in turn means that data would not be corrupted before complete loss. However, a probabilistic distribution was fitted for allowable temperatures of the cable in a fire risk analysis. This type of damage criteria could be used for fire risk assessment together with the THIEF model. However, analysis is recommended before usage of the THIEF model.

Can this risk be tied to a critical temperature or radiation?
As discussed in section 5.2, the cable broke when the heat flux was increased from 35 to 50 kW/m^2 but before the heat flux had time to stabilise at 50 kW/m^2. Since it was not possible to log the heat flux for each test, the temperature measurements can be seen as more detailed. Therefore, it is more reasonable to base the damage criteria on temperature rather than radiation. On the same time, it was also seen that the relationship between bend diameter and temperature was more important than just temperature alone. The tests and data analysis in this report showed that the 5th percentile of the critical temperature was 336 ºC for a correctly installed cable. The tests also showed that when a bend with a diameter smaller than 4.5 cm was created by thermal influences it became more vulnerable to elevated temperatures. Thus, for any temperatures below 336 ºC and for any bend diameters larger than 4.5 cm, the cable should function without any data being lost or corrupted. For practical use, due to the small sample size, and the fact that only one cable type is examined in this study a conservative value of 300 ºC would be recommended until a larger study has been conducted. The value of 300 ºC is chosen as it is also lower than the lowest measured temperature of 322 ºC in the tests.

6 Conclusions

From this report a few conclusions can be drawn based on the tests and data analysis. First, the optical signal in a SM fibre is resilient to the effects of a fire. The extent of this resilience needs further studying by looking at a variety of bandwidths and cable constructions. Second, for risk assessment of fibre optic cables it seems possible to derive a probabilistic damage criterion based on temperature. From these tests the 5th percentile is calculated to 336 ºC, but due to the limitations and sample size this is an estimated value. Third, the thermal properties of the different materials in the cable creates tensions as it is heated. This tension can make bends even smaller and compromise the functionality of the cable, even if the cable is installed according to the manufacturer's recommendations. Lastly, fibre optic cables have properties that makes them useful in sensitive equipment, such as inherent electrical isolation, and this study shows that there is a possibility to use fibre optic cables in a wider extent. However, there are some areas that needs further studying such as the relationship between mechanical strain from bend diameter and temperature.

Below these conclusions are summarized as a bullet list.

- The signal in a single-mode fibre shows resilience to fire exposure.
- Based on this study a probabilistic distribution of the critical temperature resulted in a 5th percentile of 336 ºC, i.e., 95% of the cables have a critical temperature above 336 ºC.
- Even if installed according to the manufacturer's recommendations, bends that lead to break can be formed on the cable due to thermal stresses.
- Fibre optic cables have inherent properties such as electrical isolation which makes them useful for critical safety systems in, for example, high reliability facilities.

7 Suggestions for future work

Due to limitations for this thesis some areas remain unexplored and would be suggested to study further. First, the cables used in this thesis were all from the same manufacturer and of the same type. It would be useful to test other types of cables, meaning other materials in both jacket and strength member to see if this leads to different results, much like what has been done for copper cables.

Second, it was found in the literature that aging cables are subjected to moisture penetrating the fibre making it less refractive as well as lowering the tensile strength. In some of the literature it was discussed that the aging due to radiation from other processes, for example in a power plant, could have an impact on the fibre. This would make it interesting to conduct similar experiment on cables that have been operating for some time to see whether there is a difference in function during fire due to these aging processes.

Third, one of the limitations of this report is that the measurements of data loss were made in the user space. It would be interesting to further develop the data loss measurements and perhaps even test data loss in a laboratory environment with the same type of packets that would be used for critical control equipment. However, this would require further knowledge of computer science and access to the critical equipment.

Fourth, in the same way as there are many standards there needs to be a variety of tests. In some standards propane burners are used to directly impact the cable and in other the cables are tested in a heated environment. With this future work could preferably include other sources of heat and other ways to mount the cable.

Finally, with further study of the relationship between mechanical strain from bends and temperature, it is possible that a more detailed damage criterion could be derived. It is also possible that this could verify that fibre optic cables can handle higher temperatures before failure than copper cables. For example, the distributions for average or maximum temperature could be used instead of the minimum.

8 References

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Appendix A

A.1 Dimensions

The dimensions for the sample holders will be displayed below. The dimensions for the initial setup can be seen in Figure A-1.

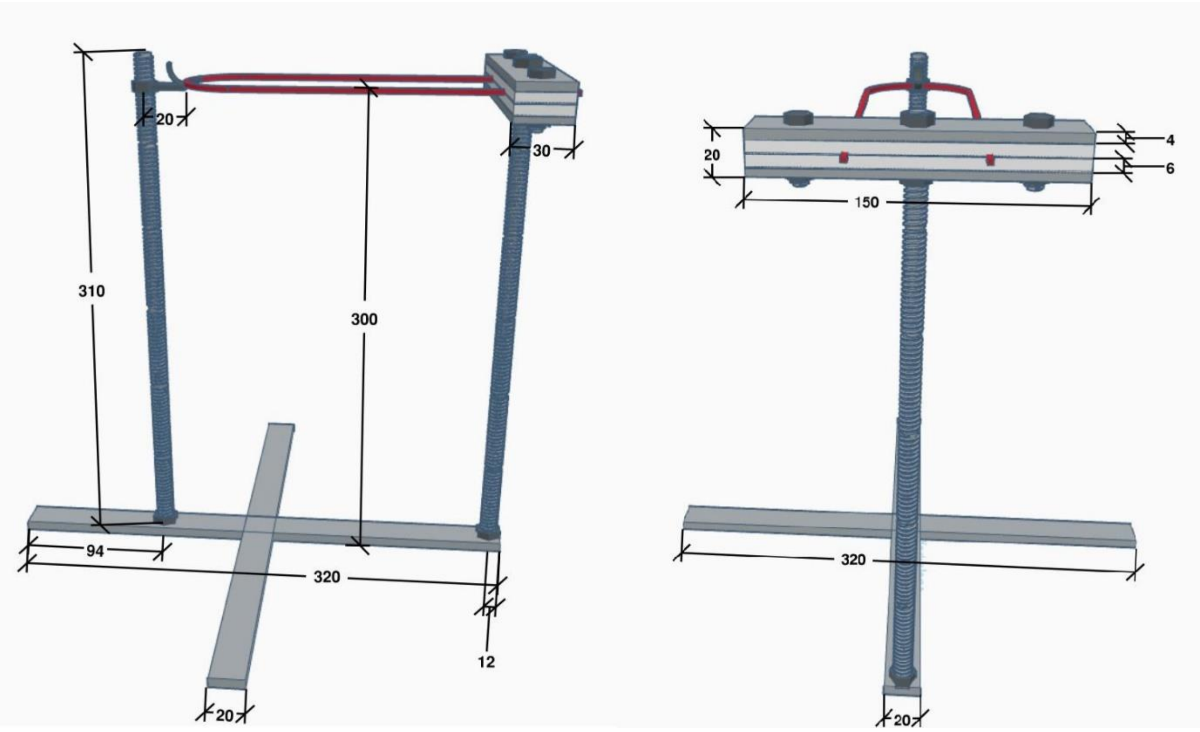

Figure A-1. Dimensions [mm] for the initial setup.

The initial setup was then modified to the final setup. The dimensions for the final setup can be seen in Figure A-2 and Figure A-3.

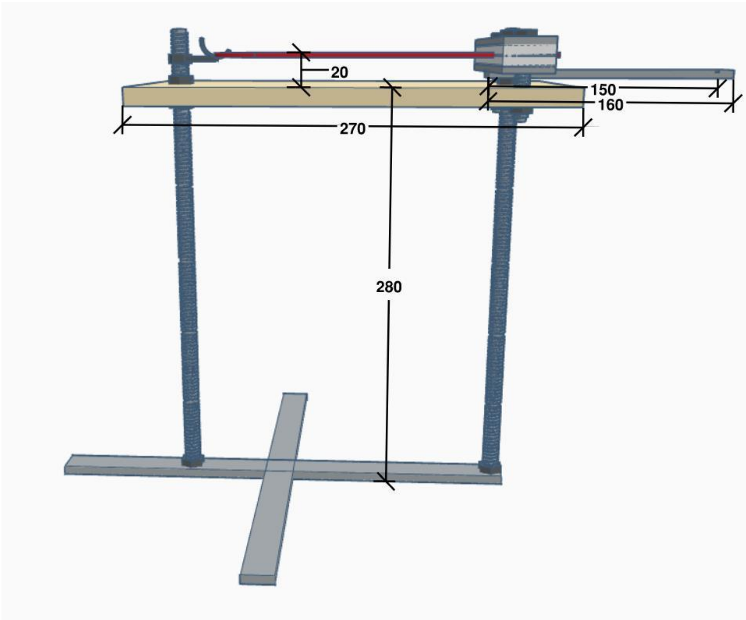

Figure A-2. Dimensions [mm] for the final setup (view from side).

On the right-hand side in the figure above, the length of 150 mm is from the fasteners to the point where the pendulum hit the sample holder.

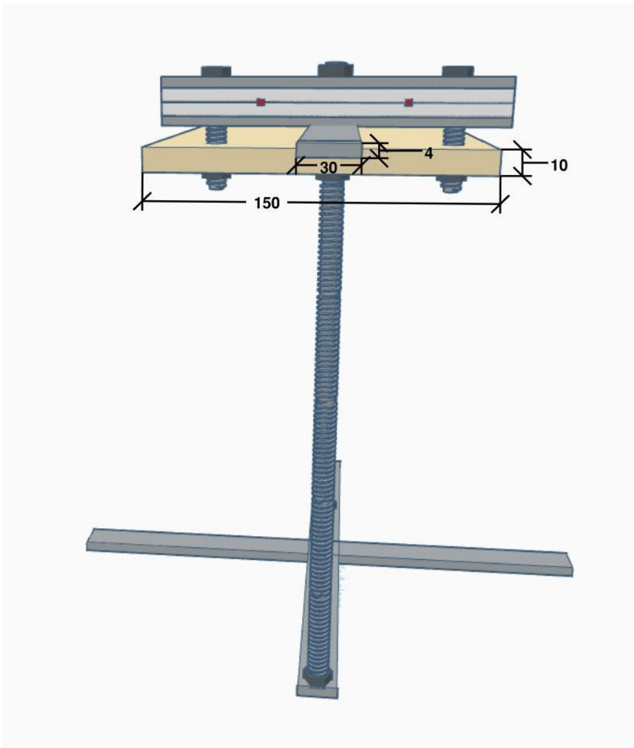

Figure A-3. Dimensions [mm] for the final setup (view from back).

The pendulum used in the final setup struck the holder with its own weight from an angle of 60º from the horizontal plane. The weight of the pendulum used was 106.5 g. The pendulum had a rectangular shape with dimensions 215 x 30 x 6 mm (length x width x thickness). Lastly, the dimensions for the propane test are presented in Figure A-4. Observe that the measurements not included in this figure are unchanged from the initial setup.

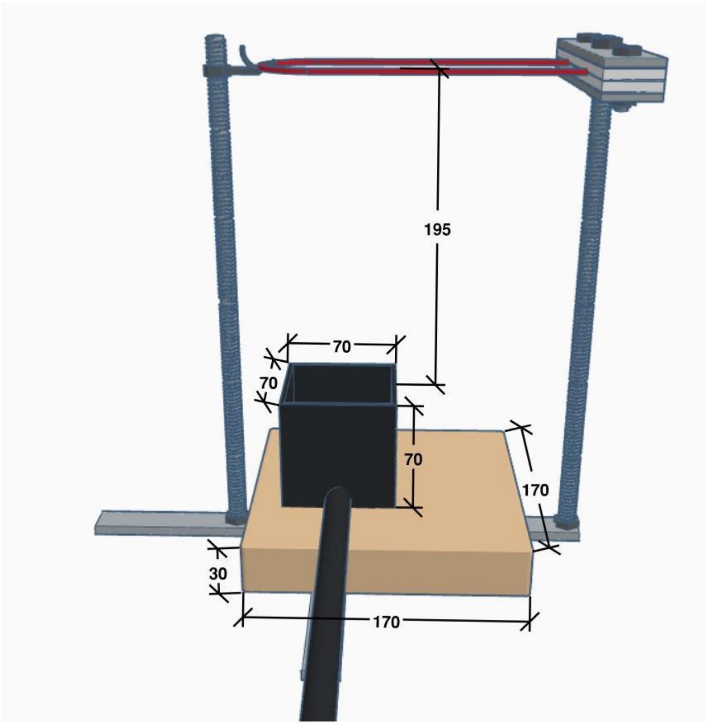

Figure A-4. Dimensions [mm] for the propane burner setup.

A.2 Test protocol

1. Turn off the fire alarm.
2. Turn on the smoke evacuation system for the cone calorimeter, panel on the left (around 30 – 35 Hz). If smoke still makes it out into the room, speed up the fan and/or open additional ventilation.
3. Bring out heat resistant gloves, safety glasses and overalls, together with other safety equipment if deemed necessary.
4. Remove cone calorimeter equipment that will not be used for this experiment, such as the scale.
5. Turn on the cone calorimeter, cone calorimeter fan and the program ConeCalc on the associated computer.
6. Calibrate the cone calorimeter for the heat fluxes needed for the experiment (15, 25, 35 and 50 kW/m^2) using the heat flux meter (HFM).
    a. Turn on main- and HFM-valve under the sink. Make sure that enough water is flowing through, but not too much as the equipment is sensitive to pressure. If needed, empty the cannister of excess flow in order to avoid leakage.

   b. Place the HFM under the cone at a 25 mm distance from the edge of the heater.
   c. Using ConeCalc, enter the last temperature of the heater that corresponds with a heat flux of 15 kW/m^2.
   d. When ConeCalc show a heat flux of 14.5 – 15.5 kW/m^2 let it stabilize for 10 minutes.
   e. Repeat step c-d for each of the heat fluxes.
   f. Turn of the valves under the sink.
   g. Empty the cannister of excess flow water and remove the HFM device from the cone.
7. Reset the cone calorimeter temperature corresponding with a heat flux of 15 kW/m^2.
8. Set up the LAN.
   a. Place the switches and computers on a safe distance from the heater, but not too far away.
   b. Connect the switches and computers in accordance with the flow chart in Figure A-5.

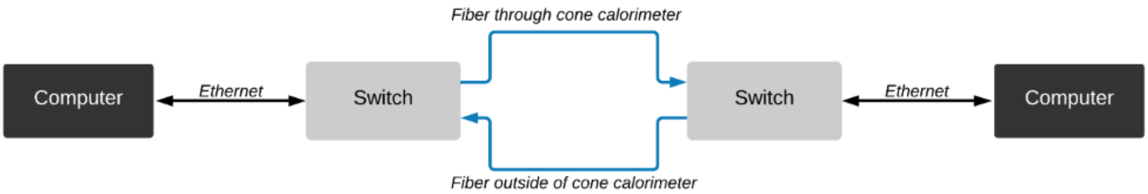

Figure A-5. Flowchart of data transfer setup.

   c. Run a test of iPerf (version 2.0.9) to make sure that the communication between the computers is working.
9. Mount the test sample and thermocouples in the sample holder, according to the sketch in Figure A-5.

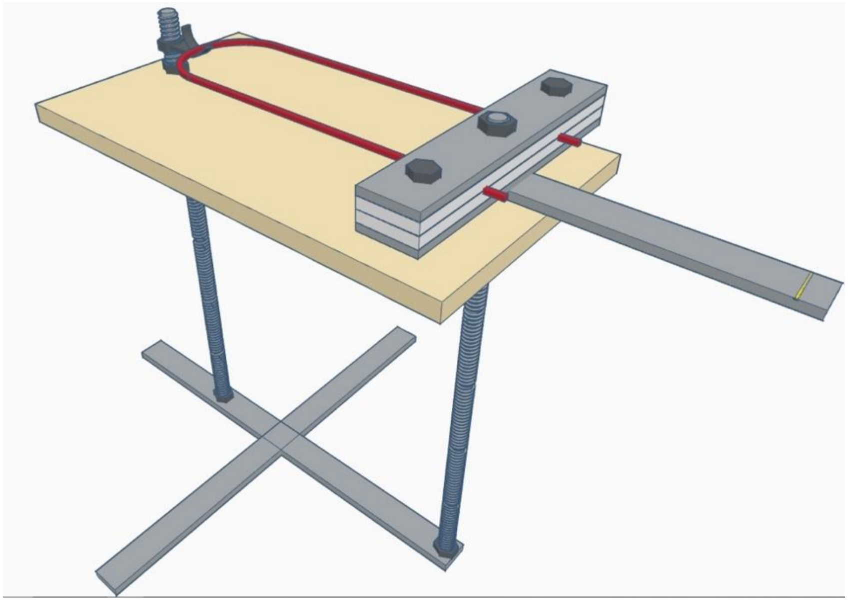

Figure A-6. Final sample holder setup.

10. Control that the communication over the LAN was not affected by placing the cable in the sample holder by running a 100 s test in iPerf.
11. Set up a test in ConeCalc to log the temperature of the thermocouples.
    a. Set weight and thickness to 0 (zero) and enter the temperature and humidity of surrounding air.
    b. Start baseline test.
    c. After the baseline, press “start test”.
12. Close the shutters for the heater.
13. Place the sample holder with the mounted sample under the cone.
14. Start the data transfer using the following lines in windows PowerShell:
    a. Client:

       [folder location for iPerf] \iperf.exe -c 192.168.1.106 -u -b 1000M -t 5410 -i 1 -p 62000 -l 63k -w 128

    b. Server:

       [folder location for iPerf] \iperf.exe -s -u -i 0.1 -p 62000 -l 63k -y csv | tee [file location]\[filename].csv

15. After 10 seconds of data transfer, open the shutters and note the time on ConeCalc test.
16. Observe and note the following phenomenon’s during the test:
    a. Protective plastic started to soften
    b. Aramid fibre was tightened
    c. Aramid fibre broke
    d. Protective plastic was completely melted
    e. Protective plastic started to turn black

f. All protective plastic has become black
g. Protective plastic started to glow
h. Protective plastic was completely combusted
i. Cable broke

17. After five minutes strike the sample holder with the pendulum device, continue striking the sample holder every 10 minutes.
18. After 10 minutes (610 seconds in iPerf) raise the temperature on the heater to correspond with 25 kW/m^2.
19. After 20 minutes (1210 seconds in iPerf) raise the temperature on the heater to correspond with 35 kW/m^2.
20. After 30 minutes (1810 seconds in iPerf) raise the temperature on the heater to correspond with 50 kW/m^2.
21. The test ends if data communication stops, or after 90 minutes (5410 seconds in iPerf).
22. Close the shutters for the heater.
23. Lower the temperature on the cone calorimeter to 0 ºC.
24. Move the sample holder to a heat resistant surface.
25. Remove the sample from the holder and place in a heat resistant cannister where the test will lay for 24 hours before recycling.
26. Monitor the cone calorimeter until cool (at least below 100 ºC). Restore the cone calorimeter as it was before the test.
27. When cooled, place the sample holder in appropriate storage.
28. Turn off the cone calorimeter, associated computer and (if no other experiments are running) the smoke evacuation system.
29. Reset the fire alarm if no other experiments are running.

Appendix B

B.1 Events

Here pictures from the observed events in Table 3 are presented. The cable and thermocouples mounted in the sample holder (left) together with the cable initially softening in the cone (right) can be seen in Figure B-1.

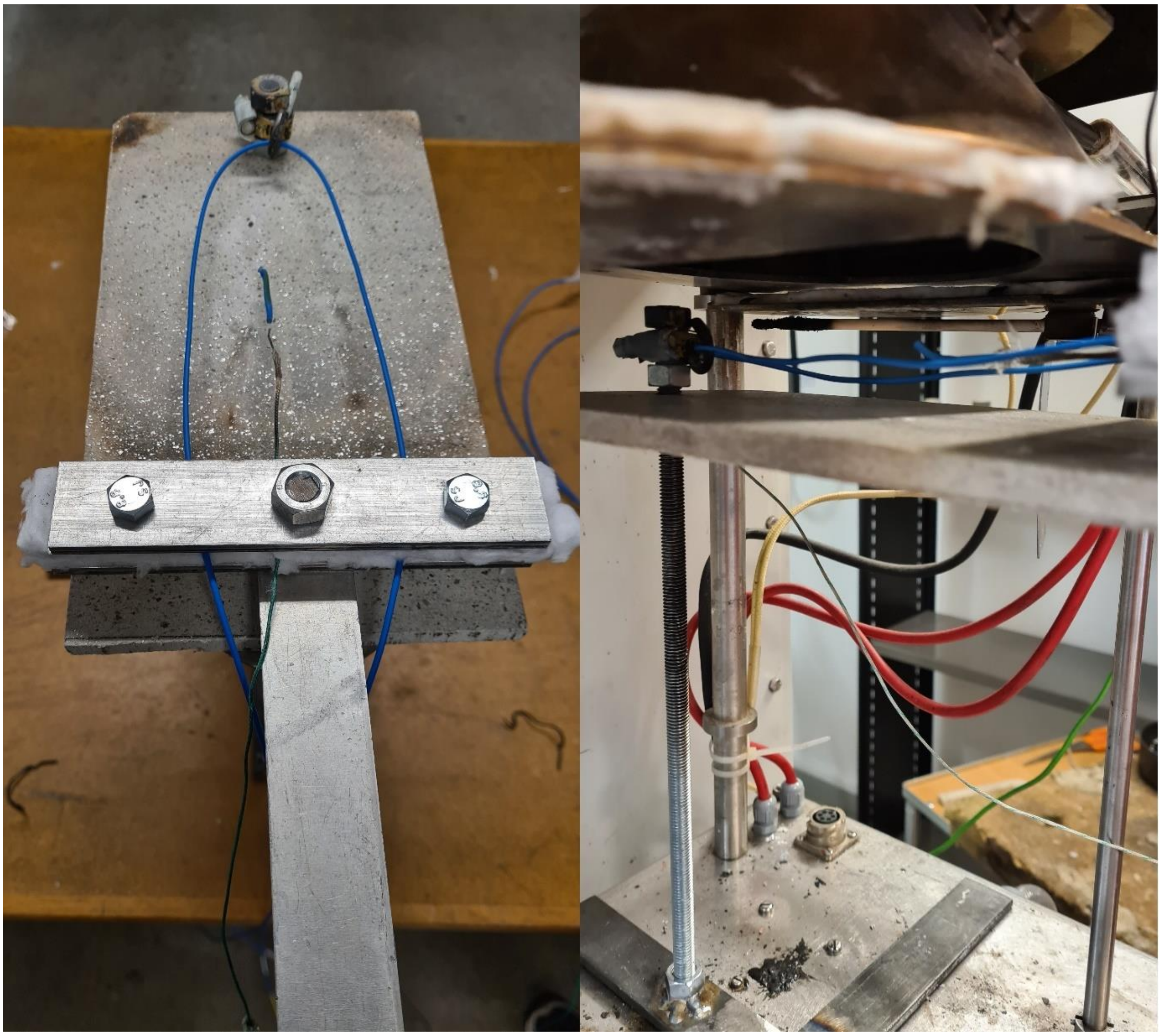

Figure B-1. Mounted cable before tests (left) and softening of cable (right).

In Figure B-2 the tightening (left) and break (right) of the aramid fibre are shown.

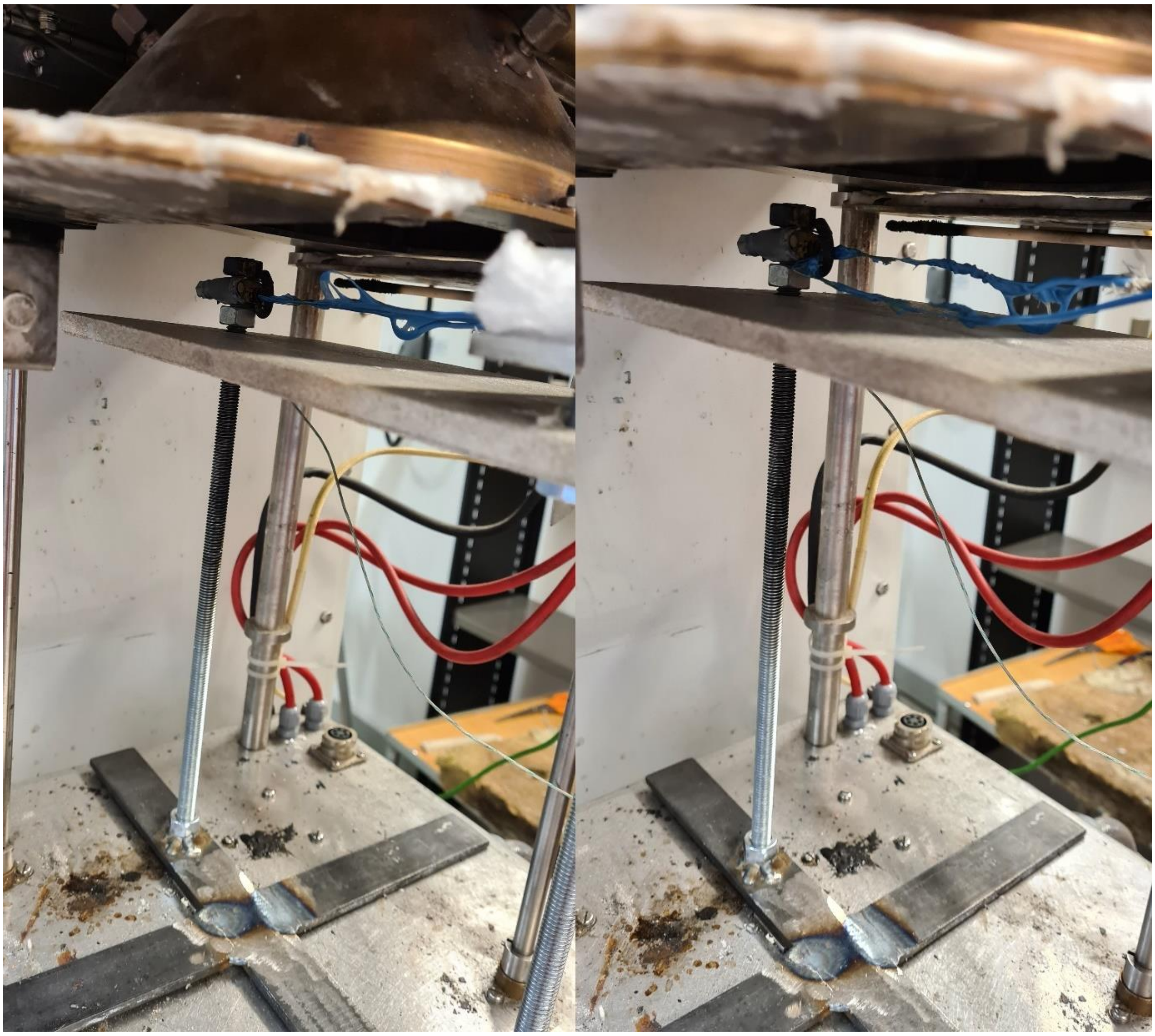

Figure B-2. Tightening of aramid fibre (left) and breaking of aramid fibre (right).

The complete melting of the protective plastic (left) and the cable turned black (right) can be seen in Figure B-3. The cable turning black was observed at two times during the tests, once when it began to turn black and once when it was completely black. Both are represented by the same picture.

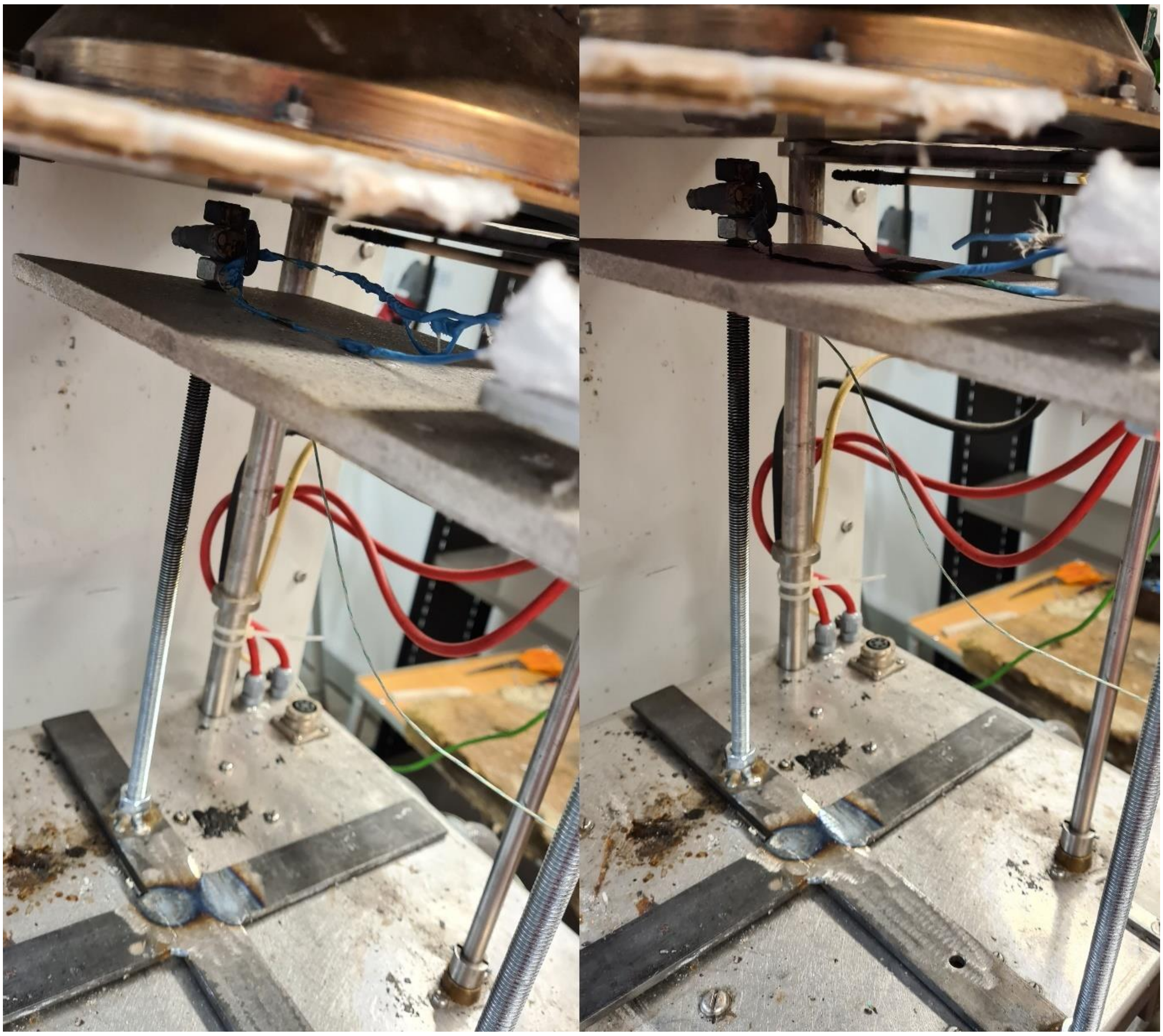

Figure B-3. Cable completely melted (left) and cable turning black (right).

After the cable turned black it started to glow somewhere on the cable (left) and finally the entire cable had become charred (right) which often occurred around the time of the break. These events can be seen in Figure B-4.

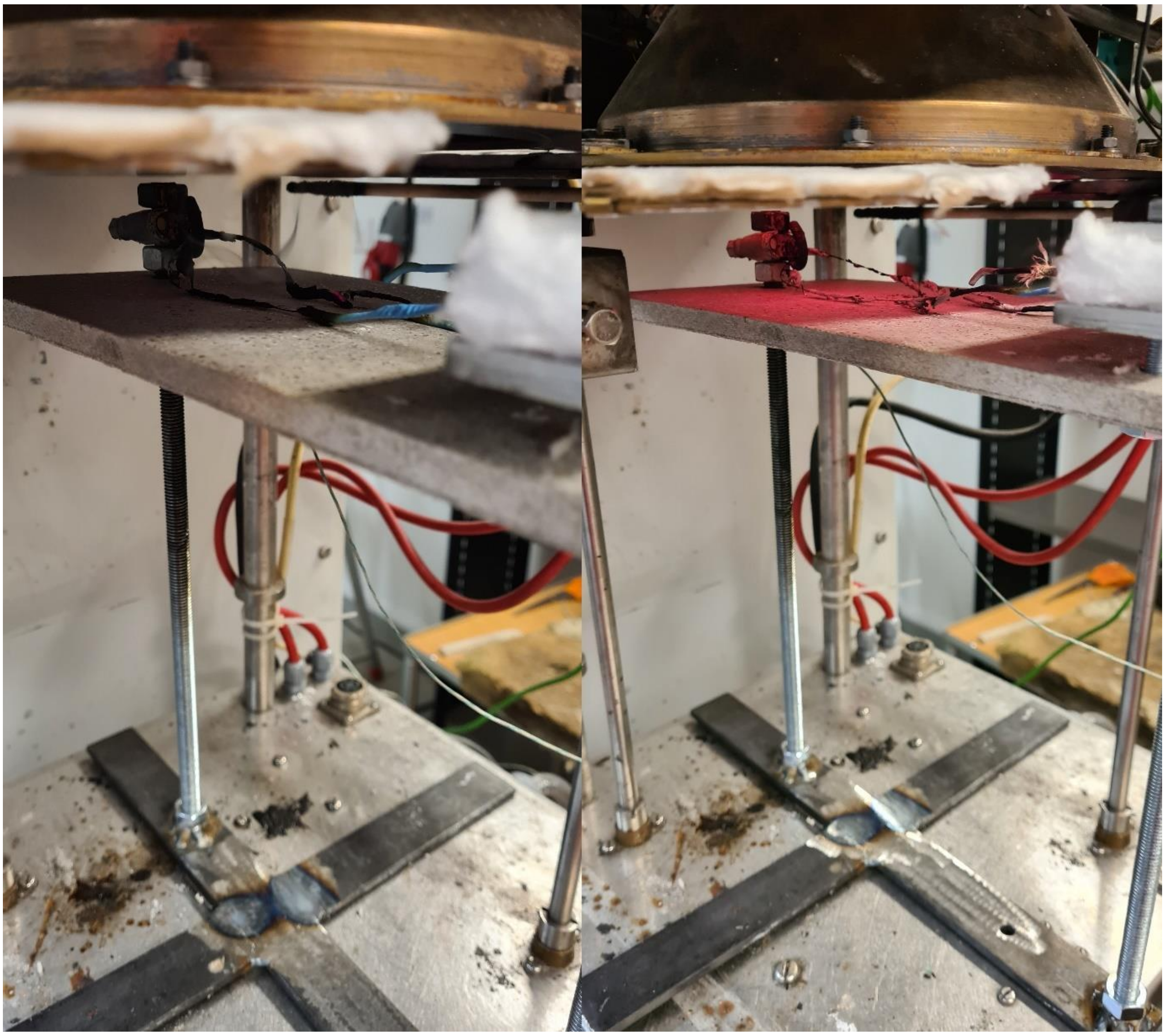

Figure B-4. Cable starting to glow (left) and cable completely charred (right).

The cable usually broke around the small ring, as seen on the left in Figure B-5. To the right in the same figure another type of break is shown. Here the fibre twisted more than the other tests resulting in break away from the small ring. The two points of break are marked in the figure as well.

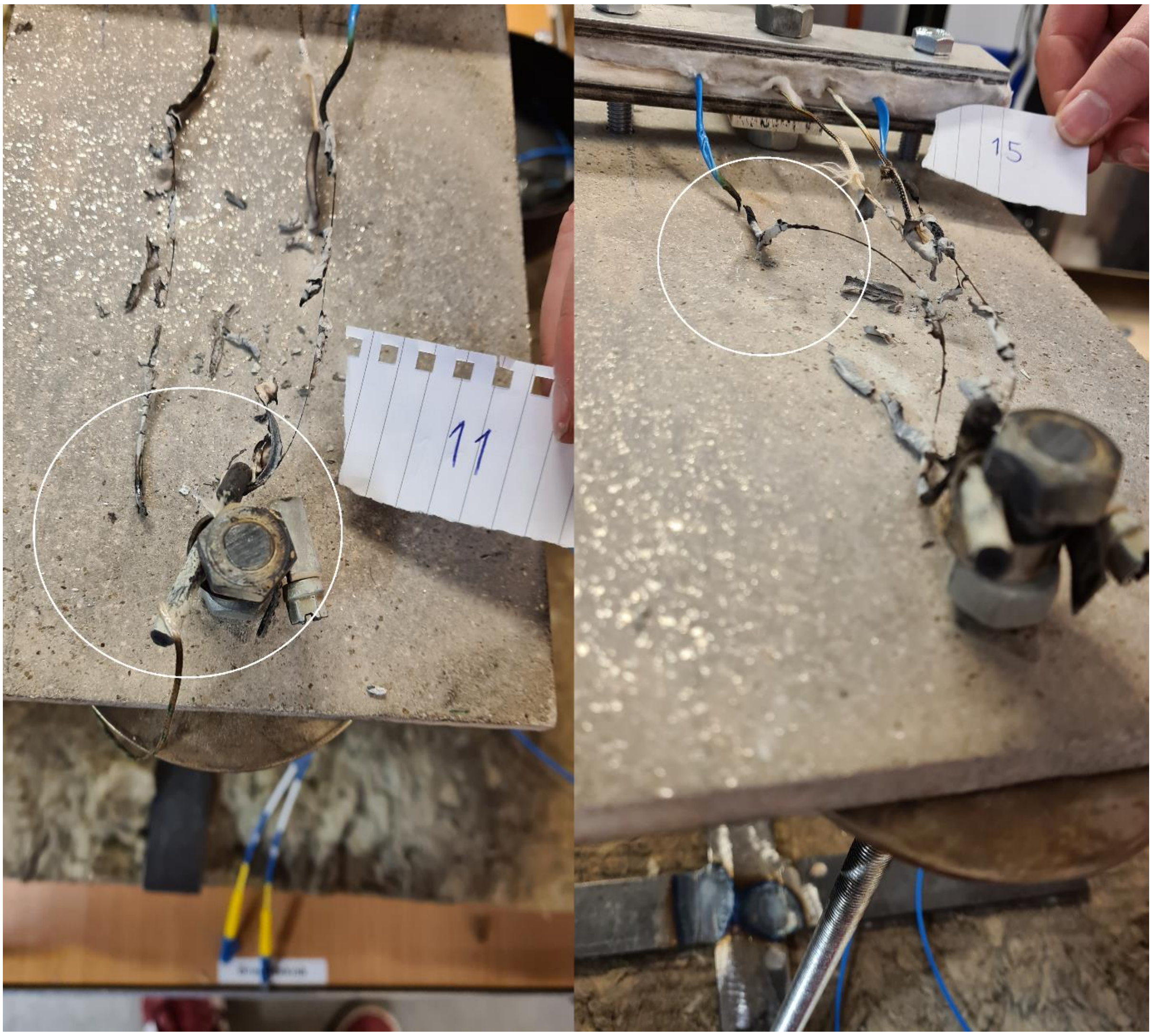

Figure B-5. Two places where the cable broke.

In Figure B-6 the different flows of propane are shown. On the left the cable is in the intermediate flame region and on the right the gas flow is set so that the cable is in the continuous flame region.

Figure B-6. Two different flows of propane in the propane burner test.

B.2 Data

Here more detailed temperature graphs from the main experiments will be presented. The centre temperature from each of the main tests are presented in Figure B-7. Note that the temperature measurement was added at test 10 and at test 15 two thermocouples were placed in the centre. Test 15 was a successful validation test for the thermocouples, as both thermocouples showed roughly the same temperatures.

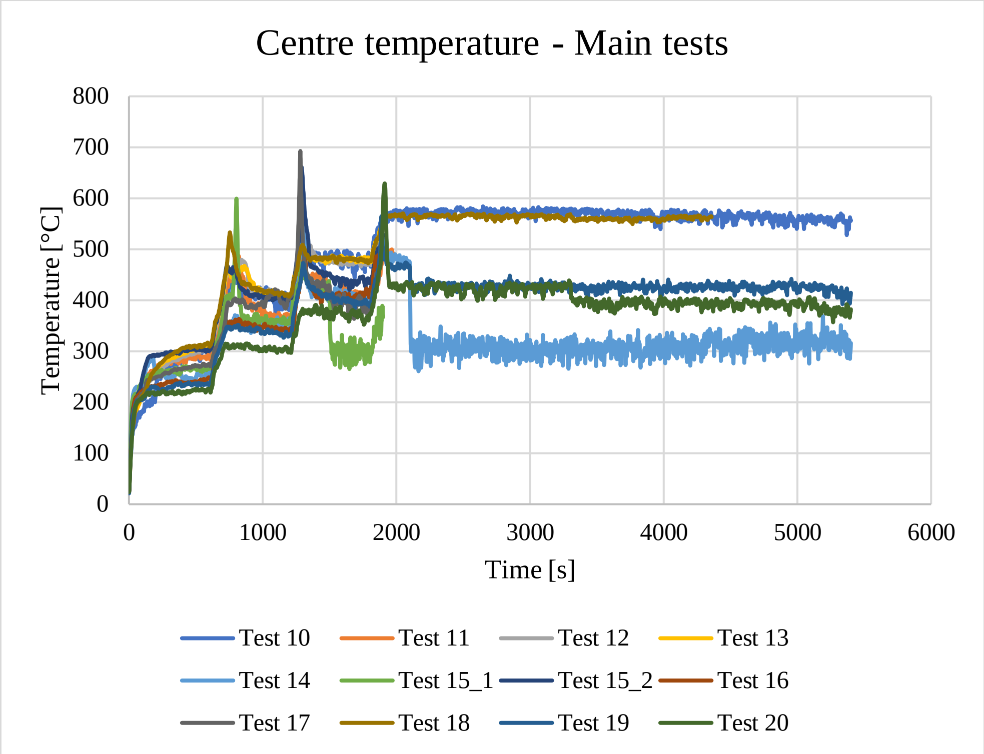

Figure B-7. Centre temperature for every main test.

In Figure B-8 the main test measurements from the small ring are presented. Since the temperature varied less at the small ring, they lie on top of each other.

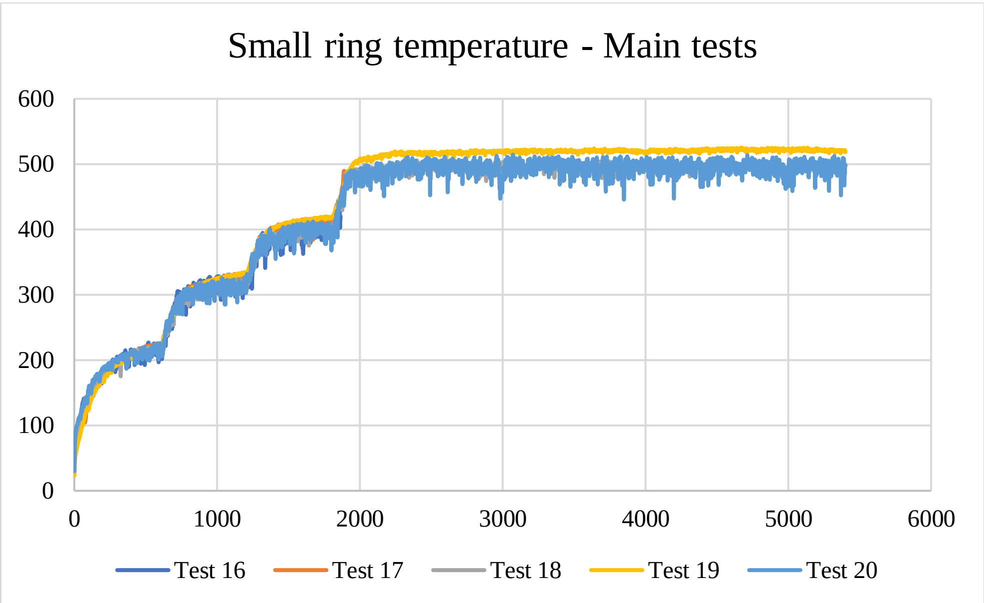

Figure B-8. Small ring temperature for every main test.

B.3 Test 22

After test 22 the bend diameter was undeterminable since the cable broke while removing it from the cone calorimeter. Figure B-9 shows how the cable looked after being removed from the cone calorimeter. The cable had fallen from the small ring due to multiple breaks, thus making it difficult to determine the bend diameter at the end of the test.

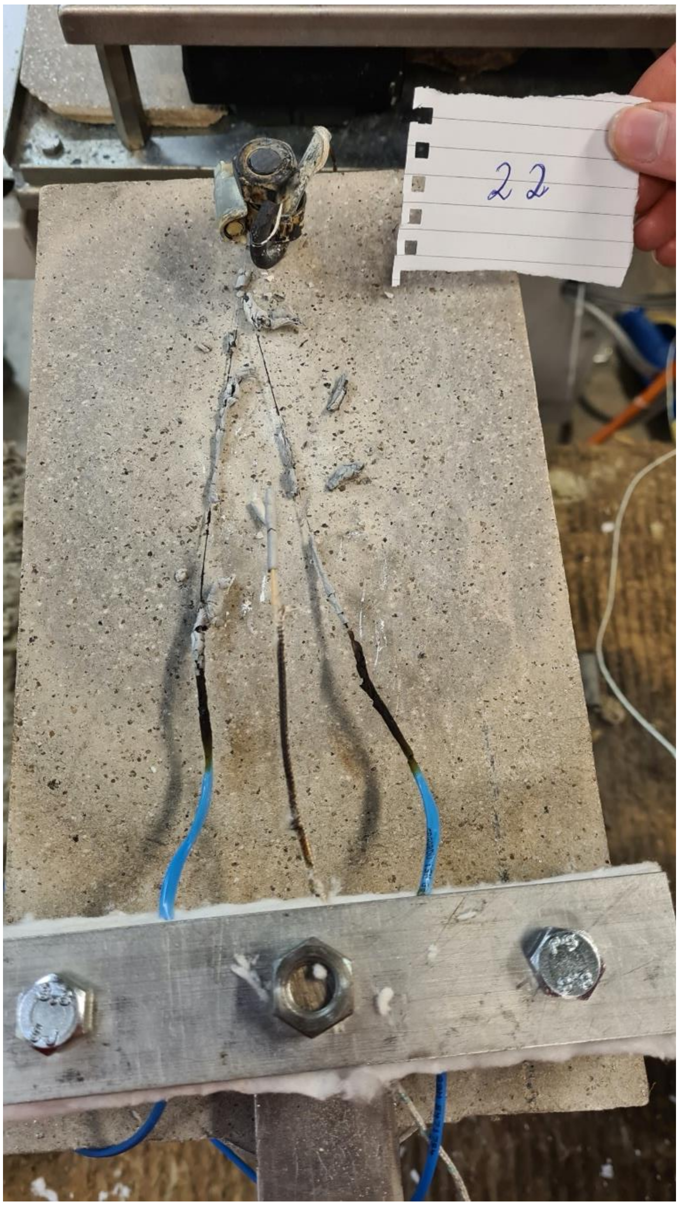

Figure B-9. The cable after test 22 was finished.