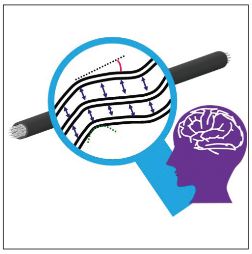

Characterizing the Shapes of Optical Communication Cables at Room Temperature and at Low Temperature

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The increased transmission loss of optical communication cables in low-temperature environments has been a longstanding issue. However, the mechanism of the loss is still largely unknown. We have developed a technique for evaluating the shape of actual optical cable samples in a low-temperature environment, which was one of the biggest obstacles to elucidating the mechanism. The proprietary technologies include the method to perform low-temperature observation with a simple retrofit mechanism for existing general x-ray computed tomography (XCT) systems and the method for accurately extracting the shape of individual fibers from an indistinct XCT image and quantifying them three-dimensionally. In particular, the latter technology applies not only to optical cables but also to a wide range of cable products, contributing in many ways to the digital transformation promotion of cable product design using big data. This paper introduces an effort to conduct cable evaluation from the viewpoints of both actual measurement and computer-aided engineering, using the shape evaluation of multi-core optical cables in a low-temperature environment as an example.

Keywords: optical communication cables, low temperature, XCT, wire tracking, CAE

1. Introduction

The optical communication cables that form the backbone of today's sophisticated information and communication technologies typically consist of optical fibers bundled together in extremely large numbers—as many as tens of thousands in some cases (Fig. 1). The role of these optical fibers is to transmit light, and the detailed shapes of individual fibers have a major impact on transmission losses in the cable. It is also known that optical communication cables typically exhibit greater transmission losses at low temperature such as -40°C. Although a variety of explanations have been proposed to explain this phenomenon, it has not been possible to test these hypotheses, and to use them as a basis for quality-improvement strategies, due to the difficulty of directly characterizing the shapes of actual optical cables in low-temperature environments.

Our research group is working to understand the mechanisms responsible for increasing of cable losses at low-temperature. Our tools for this effort include the sophisticated experimental methods and high-level computer-aided engineering (CAE) models used in previous studies—together with a powerful new proprietary data-analysis technique we have recently developed that establishes a bridge between experiment and CAE.

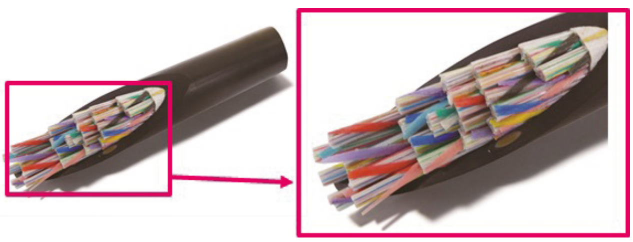

Fig. 1. Structure of modern optical communication cables

In designing this approach, we have made advances both in observation methods—developing a new approach for observing realistic samples in low-temperature environments—and in data-analysis methods, where we have developed a new technique of *wire tracking* that can extract accurate shapes for individual fibers from x-ray computed tomography (XCT)*1 image data. In what follows we discuss each of these developments.

2. Techniques for XCT Observations in Low-Temperature Environments

We first discuss observation techniques. This research project requires that we assess the shape of each fiber in an optical communication cable. For samples with realistic sizes (a few centimeters × a few centimeters × a few tens of centimeters), the only observation technique capable of achieving this is XCT. Although XCT itself is a mature technology, in this paper we present new techniques that we have developed for low-temperature observations of optical cables.

2-1 Strategy for low-temperature observations

The novel observation system we have developed is shown in Fig. 2. The basic idea is to embed the sample in a cooling vessel—which will eventually be mounted in the observation system—and conduct XCT observations of the entire cooling vessel. It should not be made from metals or other X-ray-absorbing materials and should use only components consisting of light elements with low density. For our vessel, we chose a mesh cylinder made from resin, filled with a liquid coolant (a blend of dry ice and ethanol). The sample is placed in the vessel and fixed in position. The mesh cylinder is wrapped in foamed styrol for thermal insulation. The temperature can be varied by adjusting the blending ratio of dry ice and ethanol in the coolant liquid. Thus, a sample mounted in the cooling vessel is separated from the outside by three material layers: ethanol, the mesh cylinder, and foamed styrol. All of these materials have low X-ray absorption coefficients, and thus we can perform entire XCT observations for multiple cooling vessels. The cooling vessel does not require a power source because the liquid coolant is prepared in advance outside the apparatus.

For XCT observations we use an SMX-225CT. This is a general-purpose, commercially available instrument not equipped with specialized cooling vessels. Nonetheless, our method as outlined above allows our cooling vessels to be used with standard XCT systems like this almost as an accessory, with no modifications whatsoever required to the instrument. Our approach makes it easy to perform XCT observations of samples uniformly cooled to low temperature even for samples of realistic sizes, which are difficult to handle via other methods. This represents a major step toward a thorough understanding of low-temperature loss mechanisms.

In this study, we used the system in Fig. 2 to perform three sets of XCT observations of an 864-core optical cable: first at room temperature, then at -40°C, and finally after warming back up to room temperature. In the graphs below, these results are respectively labeled ”RT”, “Low”, and “Low ⇒ RT”.

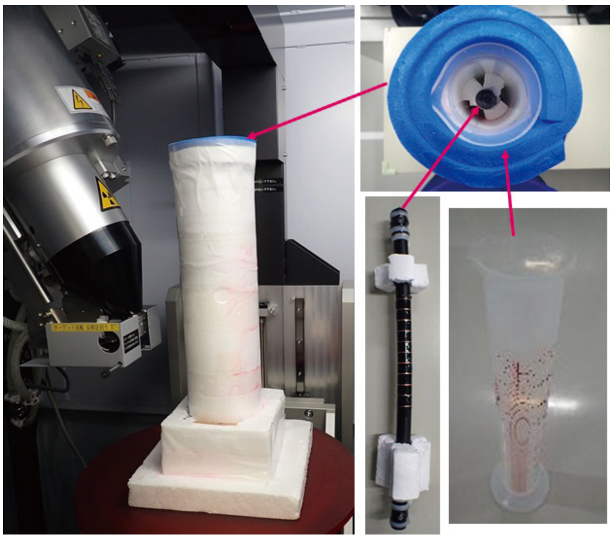

Fig. 2. Components of novel low-temperature XCT system for characterizing optical communication cables

2-2 Images captured in low-temperature XCT observations

The simplicity and convenience of our low-temperature observation method bring one problem. The XCT images obtained by our method are of inferior quality compared to typical XCT images. There are two reasons for this. The first involves observation time. The cooling vessel shown in Fig. 2 does not receive a steady supply of cooling power from the outside; instead, it is entirely dependent on the pre-cooled coolant medium to maintain the desired temperature. If the observation time exceeds the limit, the sample will gradually return to room temperature during the observation. To avoid this, observation times must be kept short—often shorter than the minimal time generally considered necessary for accurate observations—thus yielding images of lower quality than XCT images captured under typical conditions. The second reason involves the structure of our setup. In the simple cooling vessel in Fig. 2, the sample (in this case, an optical cable with a diameter of about 1 cm) is surrounded by a layer of liquid coolant (a few centimeters in diameter) and then by foamed styrol (around 10 cm in diameter). Although these are light-element materials, at thicknesses of 10 cm or more they do absorb X-rays to some extent, and thus the quality with which optical cables at the center of the cooling vessel can be imaged is inferior to that for images captured for isolated cables. Due to these factors, the XCT images obtained by low-temperature observations of optical cables are rather noisy, with optical fibers visible but quite blurry (Fig. 3).

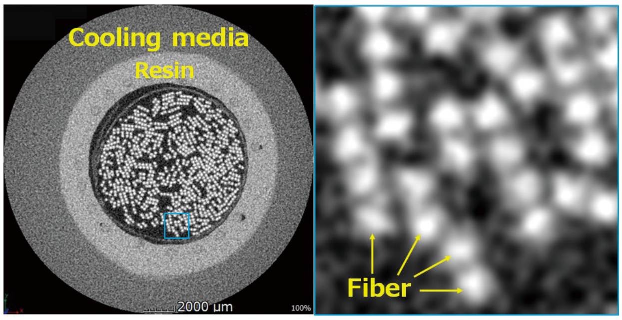

Fig. 3. Sample images captured by our low-temperature XCT observation system

3. Wire Tracking Technique for Extracting Trajectories from XCT Images

In this section we discuss a data-analysis technique that establishes a bridge between the observation methods in the previous section and the CAE methods described in the following section. Our goal is to extract, from XCT images, accurate quantitative shape information for all individual fibers in an optical cable. To achieve this, we have developed a proprietary technique of *wire tracking*.

3-1 Overview

The image data obtained from XCT observations of an optical cable consists of a set of cross-sectional images such as that shown in Fig. 3. Typically, this set contains a few thousand of these cross-sectional images, captured at various points along the cable length, constituting a three-dimensional brightness dataset (Fig. 4). Our objective is to extract a new digital dataset representing the trajectories traced by the centers of all fibers in the cable.

To extract such a trajectory, positions for each fiber in each XCT image must be determined. However, when working with images as unclear as Fig. 3, the application of simple binary quantization and other common image-processing techniques will serve poor accuracy of the extraction process. Instead, we have developed a novel image-processing technique that combines machine-learning techniques which automatically extracts features from datasets and classical image-processing methods following a rulebase furnished by the knowledge accumulated by Sumitomo Electric Group regarding optical cables.

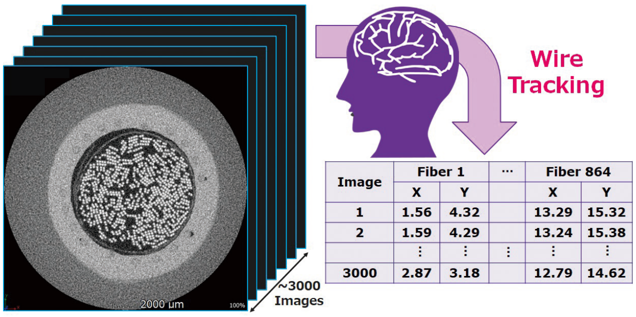

Fig. 4. Inputs and outputs of wire tracking algorithm

3-2 Creation of training data

In common with all general-purpose AI approaches to object detection, our wire tracking algorithm is based in part on the paradigm of supervised machine learning*[2], in which the preparation of high-quality training data is essential for successful implementation. The creation of the training data was made possible by extensive assistance from Sumiden Friend, Ltd., a special subsidiary of Sumitomo Electric that aims to increase employment opportunities for people with disabilities. Figure 5 shows an example of the type of training data for the low-temperature optical cable evaluation algorithm. Here the task of object detection is accompanied by an *annotation* step, i.e. "Draw a circle at the position of the fiber." (In this example, the circles are blue.) Then, each annotated image (Fig. 5 (b)) is paired with its original, non-annotated version (Fig. 5 (a)) and used as training data for the AI engine. The resulting algorithm, when combined with a custom-designed classical

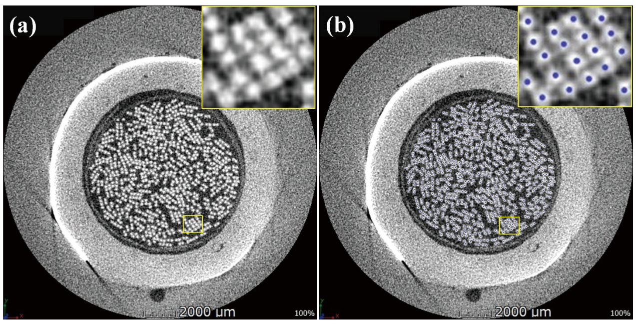

Fig. 5. Training data example created by Sumiden Friend

image processing technique, allows the position coordinates of fibers to be automatically extracted from blurry XCT images with high precision.

The creation of training data for machine learning projects is typically an extremely lengthy process, and this work was no exception, with the creation of training data serving as a longstanding bottleneck. The assistance we received from Sumiden Friend allowed us to establish a framework capable of analyzing large quantities of cable data.

3-3 Results: Trajectories of optical cable fibers

We apply our wire tracking technique to XCT data for our 864-core optical cable under three temperature conditions. Figure 6 shows the results of our analysis of the room-temperature data. Figures 6 (a) and 6 (b) show the first and last cross-sectional image slices, and indicate how the numerical indices assigned to fibers correspond to the trajectory data. As these images demonstrate, we assigned indices to all 864 fibers visible in the XCT images and tracked the position of each fiber along the full length of the cable sample to yield trajectories for all fibers. A subset of these trajectories is plotted in Fig. 6 (c). Plotting the full set of 864 trajectories would yield too dense a graph, so we have instead plotted only every 20th trajectory. Nonetheless, our analysis successfully extracted numerical X- and Y-coordinates for all 864 fibers.

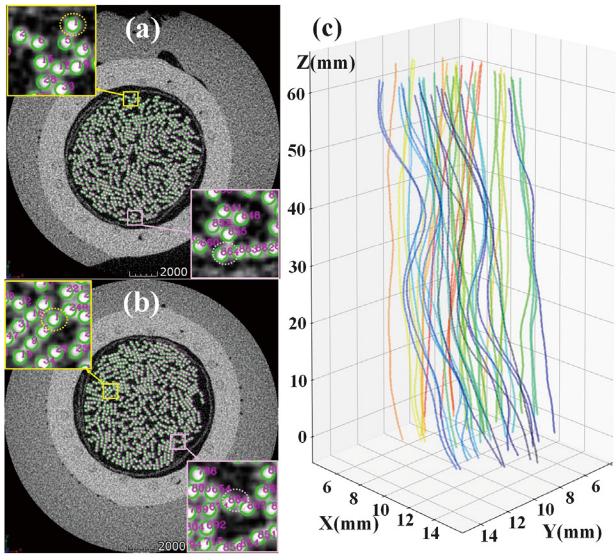

Fig. 6. Application of wire tracking analysis to optical communication cable

The trajectory dataset obtained in this way can be used to compute a variety of quantitative properties. As just one example, we consider an evaluation of the curvature radius of optical fibers. Figure 7 shows, for each of the 864 fibers, the minimum radius of curvature for that fiber at any point along its trajectory, i.e., the radius of curvature at the most sharply curved section of the fiber. The three curves in Fig. 7 correspond to the three temperature conditions. In each case, we have sorted and plotted the minimum-curvature data in descending order. As is clear from this figure, cooling from room temperature to -40°C induces a uniform reduction in the minimal curvature radius of the fibers (i.e., causes fibers to curve more sharply). Upon returning to room temperature, the fiber curvature profile reproduces the results of the original room-temperature measurements, indicating that the shift observed at low temperature is reversible. We will revisit this point in our discussion of cable-length contractions below.

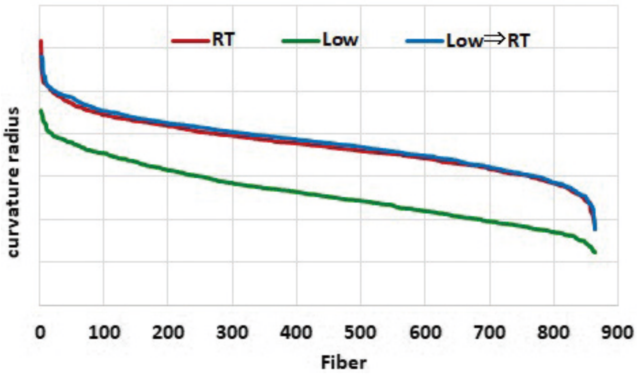

Fig. 7. Minimal curvature radius computed for optical fibers

In addition to mapping the trajectories of individual fibers, we also investigated temperature-induced variations in overall cable length. As shown in Fig. 8 (a), we first applied copper-foil tape at 10-mm intervals to our optical cable sample, and then proceeded with XCT observations under the three temperature conditions. Because the atomic number for Cu is much higher than that for any other material in our system, the copper strips appear white in XCT images (Fig. 8 (b)). By automatically detecting the Cu tape strips in every XCT image (Fig. 8 (c)) and plotting their area versus cable length on the horizontal axis, shrinkage of cables can be evaluated.

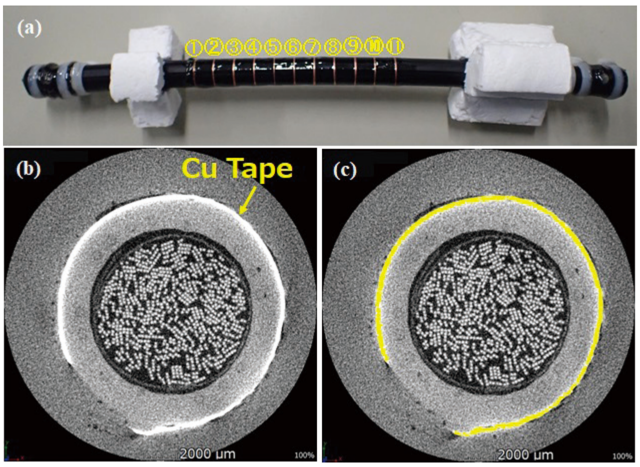

Fig. 8. Technique for analyzing contraction in cable length

Figure 9 plots the positions of the Cu tape strips, aligned so that the first tape strip is at Z=0, as observed under the three temperature conditions. We see that the pitch of the Cu tape strips shrinks slightly at low temperature, then returns to its original value when the sample is restored to room temperature. Thus, as we found with the fiber curvature radius, the temperature-induced contraction in cable length is a reversible effect.

These results demonstrate that our novel approach to low-temperature XCT observations, in combination with our image-analysis techniques, allows accurate measurement of fiber curvature radius and cable-length contractions for actual realistic samples. We expect that these techniques will prove to be powerful tools for identifying, characterizing, and counteracting the mechanisms responsible for increasing cable losses at low temperature.

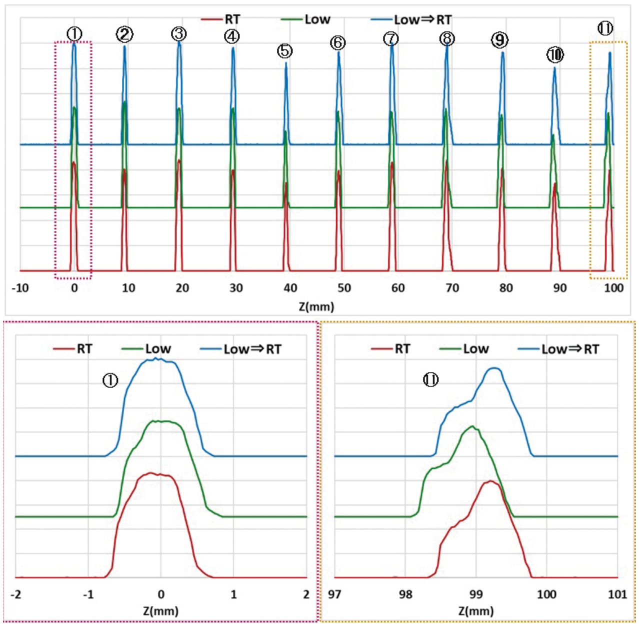

Fig. 9. Results of cable-length contraction analysis

4. Using CAE Techniques to Characterize Cable Properties

It is difficult to determine the lateral loading experienced by individual fibers when the cable contracts as a whole. With the goal of understanding the detailed behavior of cables during contraction, we used the fiber trajectories obtained with our wire tracking method to construct the CAE model shown in Fig. 10. This model reproduces not only the outer sheath of the cable, but also each of the 864 fibers, thus providing insights into contact phenomena between fibers at the level of individual fibers and ultimately yielding shape deformation information for each fiber.

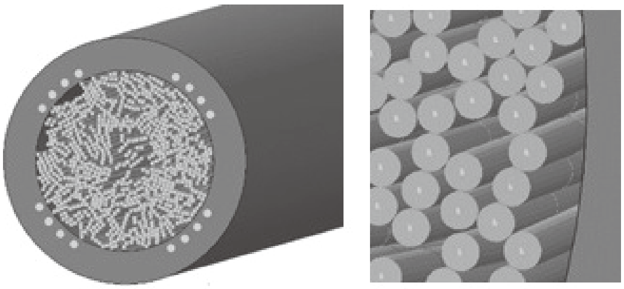

Fig. 10. CAE model for optical communication cable

4-1 Predicting cable contraction and fiber curvature

The following mechanism has been proposed as a possible cause of increased losses in optical cables at low temperature. First, the outer sheaths of cables that have large linear expansion coefficients will contract at low temperature. On the other hand, optical fibers have small linear expansion coefficients and may become too long to fit inside shrunken sheathes. This forces the fibers to bend, resulting in higher losses. Consequently, two low-temperature phenomena discussed in Section 3—the contraction in overall cable length and the increase in fiber curvature—may prove to be important benchmarks for understanding the mechanism for increased losses. To confirm the accuracy of our measurements of these phenomena, we used our CAE model to analyze deformation behavior in low-temperature environments, and compared the predictions of the model to our experimental findings.

The results are shown in Fig. 11, where we have plotted the quantity (experimental value)/(CAE model value) (i.e., the ratio of our experimental results to the CAE model prediction) for two quantities: the contraction in overall cable length (Cable Shrink) and the curvature of individual fibers (Curvature Radius), both at low temperature. As can be seen, the agreement is excellent for both quantities. This simultaneously confirms the validity of our experimental technique and demonstrates that our CAE model is capable of predicting accurate values for these properties.

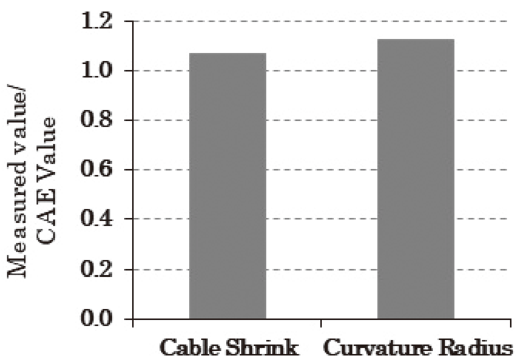

Fig. 11. Comparison of measured data and CAE results

5. Conclusions

We have developed a technique for characterizing the shapes of realistic cable samples in low-temperature environments, thus addressing a problem that had long posed one of the most formidable obstacles to understanding the mechanisms responsible for increasing transmission losses in optical communication cables at low temperature. By combining our proprietary new approach to low-temperature observations with our new *wire tracking* technique for processing XCT image data, we successfully characterized two quantities believed to contribute to low-temperature losses—namely, the contraction in cable length and the reduction in fiber curvature radius—and confirmed that our experimental results matched the predictions of CAE models.

The advances reported in this paper allow the true character of optical communication cables at low temperature—which, in the past, could not be directly observed—to be accurately characterized both experimentally and computationally, offering a variety of opportunities for quality improvements. The application of our new techniques to optical communication cables and other entries in Sumitomo Electric Group's broad catalog of cable products will enable high-level digital design optimization and advance the development of revolutionary new cable products.

Technical Terms

*1 X-ray computed tomography: A computer-assisted tomography technique involving x-rays. This technique allows non-destructive imaging of the internal structure of objects, and—when combined with data-analysis techniques such as those discussed in this paper—can yield quantitative information regarding sample morphology.

*2 (Supervised) Machine learning: An algorithm-design procedure that—in contrast to typical computer programming—does not involve explicit human-specified procedures for processing data. Instead, the computer is given (typically) a large number of 'example' input-output pairs, and uses these to 'learn' an algorithm that reproduces them as closely as possible. In the example discussed in this paper, each input-output pair consisted of one raw XCT image paired with an annotated version of that image prepared by Sumiden Friend. The AI engine used this training data to construct an algorithm for reproducing CT image annotations as accurately as possible—or, as one might say, for imitating the work of Sumiden Friend.

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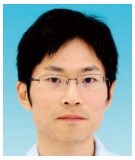

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