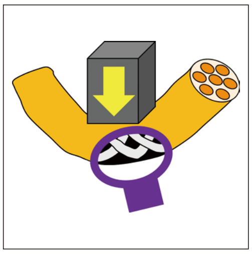

Cable Evaluation Using Dynamic X-ray Computed Tomography

Yutaka HOSHINA*, Shigeaki UEMURA, and Takuma YAMAMOTO

Evaluating the performance of electric cable products under external forces, such as bending, is crucial for assessing their behavior in real-world environments. We utilize a cutting-edge X-ray computed tomography (XCT) system to observe the effects of external forces and employ various data analysis techniques to enhance our understanding of how cable products respond dynamically to these forces. The first part of this paper introduces XCT observation results of some samples, including a bent cable and a large 1-meter sample, which were previously difficult to evaluate with former XCT systems. The latter part focuses on image analysis techniques for bent cable products, highlighting our unique technology. Through a combination of advancements in hardware and software, we can improve design processes and solve quality issues by clarifying the dynamic behavior of various cable products under external forces.

Keywords: X-ray CT (XCT), *in-situ* XCT observation, cable, Curve-Track-Slicing

1. Introduction

Industrial products need to pass various durability tests that replicate their real-world usage scenarios. Accurately knowing the state of a product not only before and after the test, but also during the test, is extremely important for developing new products and solving quality issues with existing products. For example, electric cables (one of our company's main products) are frequently subjected to bending stress in actual use environments, and are subject to numerous bending tests. Electric cables are composed of hundreds or thousands of thin metal wires and insulators which cover them. Each wire does not exist independently. Wires are generally twisted together. The phenomena that occur in bent cables are very complicated, reflecting the twist. Figure 1 is a schematic diagram of a bent electric cable. On the inside of the curve (① in Fig. 1), the wires are crowded and rub against each other. On the outside of the curve (② in Fig. 1), the wires tend to move away from each other. It is known that many properties such as bending rigidity, which is one of the most important characteristics of electric cables, are greatly influenced by the interaction between the wires. Accurate understanding of the actual shapes of the wires is therefore extremely important for the design of electric cables.

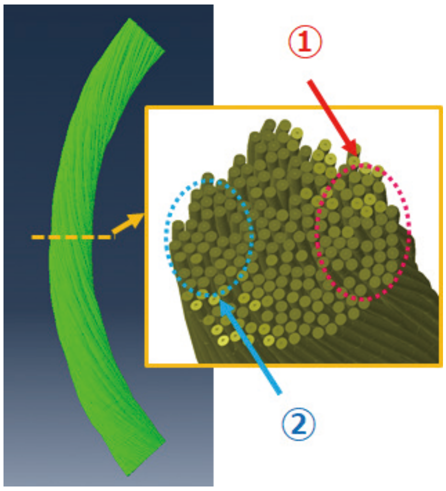

Fig. 1. Schematic diagram of wire status in a bent electric cable

Analysis Technology Research Center (ATRC) of Sumitomo Electric Industries, Ltd. (Sumitomo Electric) is developing the technology to visualize and quantify the internal state of electric cables under bending stress, from both a hardware and software perspective. In Chapter 2, we will discuss X-ray computed tomography (XCT)*[1] observation as a hardware technology. XCT observation of a sample which is subjected to an external force such as bending is hereafter referred to as "*in-situ* XCT observation" (*IS*XCTO). After that, Chapter 3 introduces the latest data analysis technology for XCT images obtained by *IS*XCTO as software technology.

2. XCT Observation Examples Using Dynamic XCT

ATRC of Sumitomo Electric launched a new type of XCT system in 2023 and is developing various observation techniques in order to meet the demand for *IS*XCTO of various products including electric cables. In this paper, the new XCT system is referred to as "dynamic XCT" to emphasize that it enables us to conduct *IS*XCTO. This chapter introduces some examples of *IS*XCTO using the dynamic XCT.

2-1 Dynamic XCT system

Figure 2 shows the appearance of the dynamic XCT system. This model is the UniTOM XL manufactured by TESCAN. Sumitomo Electric is the first to utilize this model in Japan. The maximum tube voltage and tube current is 230 kV and 1300 μA, respectively, which is one of the largest outputs among XCT systems with a 3 µm microfocus source. This observation capability enables us to effectively manage various evaluations previously conducted with earlier XCT systems. On the other hand, the biggest feature of the dynamic XCT is the sample stage which can hold a sample measuring ϕ600 mm, H1150 mm weighing up to 45 kg. This allows us to observe samples and testing machines at the same time, as demonstrated in 2-2 and 3-1, and a large sample as shown in 2-3. It is also equipped with a system that can apply external force to samples while controlling the load, as introduced in 2-2.

Fig. 2. Picture of Dynamic XCT System

2-2 Evaluation of bent cable using small testing machine

In the dynamic XCT shown in Fig. 2, a small testing machine (CT5000 manufactured by DEBEN, Fig. 3(A)) attached to the system allows us to conduct *IS*XCTO under pressure (100–5000 N), temperature (-20–160°C), and displacement (maximum 10 mm). Here, we show an example of *IS*XCTO using the displacement control mechanism of this small test machine.

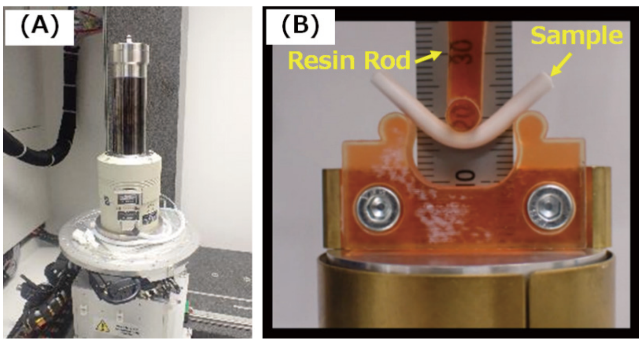

Fig. 3. (A) Small Testing Unit
(B) Bending Stress Application

In the testing machine, an external force can be applied to the cable while controlling the stroke to bend the cable as shown in Fig. 3 (B). Using this system, it is possible to perform *IS*XCTO with various strength of the bend, as shown in Figs. 4 (A)–(C). By performing "Wire-Tracking"*2 using the obtained data, we can extract the actual shape of each wire under various bending stresses, as shown in Fig. 4 (D). By performing Wire-Tracking for a group of XCT image data observed with different stroke conditions, it is possible to capture the behavior of each wire under bending stress. This knowledge can be utilized in design and for solving quality issues.

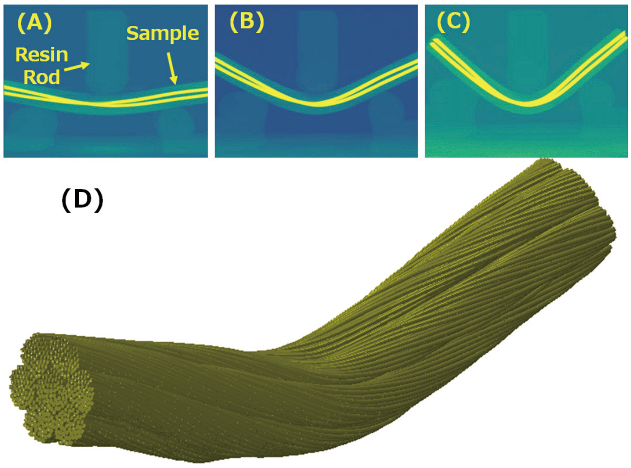

Fig. 4. Observation example of bent cable using the system shown in Fig. 3

2-3 Evaluation of power cables

Although this case is not in the category of *IS*XCTO, it is introduced to show that the dynamic XCT can observe large samples, which is one of its important features. The power cable sample shown in Fig. 5 (A) (about 1 m in

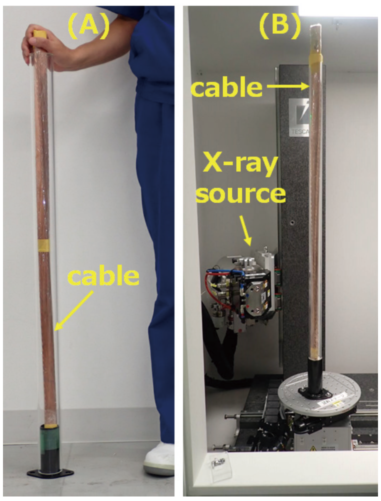

Fig. 5. (A) Power cable sample
(B) XCT observation setup

length) was fixed with a circular resin to prevent it from moving during XCT observation, and was placed on a dynamic XCT sample stage to be observed as shown in Fig. 5 (B). This sample includes 61 copper wires that are twisted together. Cross-sectional XCT images as shown in Fig. 6 (A) can be obtained over about 1 m in the length direction of the sample. When Wire-Tracking is performed for these image data as in 2-2, indexes are assigned to all 61 wires over the entire length as shown in Fig. 6 (B).

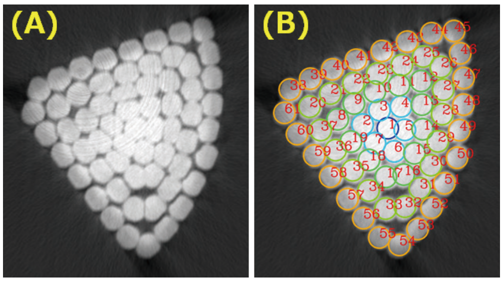

Fig. 6. Examples of (A) XCT image and (B) Wire-Tracking results

Figure 7 shows the obtained trajectory data displayed as graphs of Z (length direction) -X (horizontal direction of the image) and Z-Y (vertical direction of the image) coordinates. The 61 wires are arranged in layers (1, 6, 12, 18, and 24 wires) starting from the center, and each of these five layers is shown in different colors. Notice that the horizontal axis is just under 1 m (1000 mm). Using these graphs, quantitative indicators such as twist pitch can be calculated for each layer, which can be used to evaluate sample performance and discuss other aspects of quality. Electric cable products range in scale from thin (2-2) to thick (2-3). The dynamic XCT can be used to evaluate a wide variety of products.

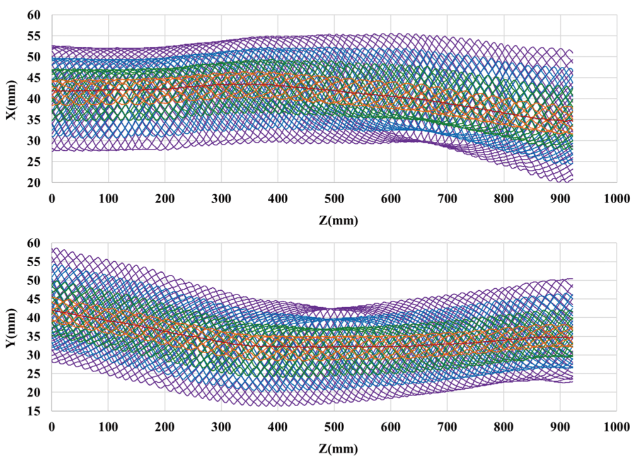

Fig. 7. Wire-Tracking results of X (upper) and Y (lower) coordinates

2-4 Other *in-situ* XCT observation

Although not included in this paper due to space constraints, our *IS*XCTO cover a wide variety of products other than those shown above. We are creating unique equipments that apply desired external forces to imitate actual usage environments. The samples and the equipments are observed simultaneously using the dynamic XCT. We are trying to understand the behavior of various products under external forces through quantification using various image analysis techniques including Wire-Tracking. This knowledge will be utilized for design improvement.

3. Wire-Tracking of Bent Electric Cable Using Curve-Track-Slicing

As introduced in 2-2 and 2-3, Wire-Tracking for cables is used as a standard quantification tool. Although this is a useful tool, it was difficult to apply Wire-Tracking to significantly bent cable samples which is becoming the main target of *IS*XCTO because Wire-Tracking was originally developed for straight cables. In this section, our new technology "Curve-Track Slicing" (CTS) for such significantly bent cables is demonstrated.

3-1 Bent cable observation

In this paper, we will take up a XCT observation of a sample shown in Fig. 8 as an example. There are durability tests related to such "U-shaped bending" in actual cable products. Evaluating each wire under such bending stress is therefore important. This cable sample consists of 399 wires in total, consisting of 19 bundles of 21 wires twisted together.

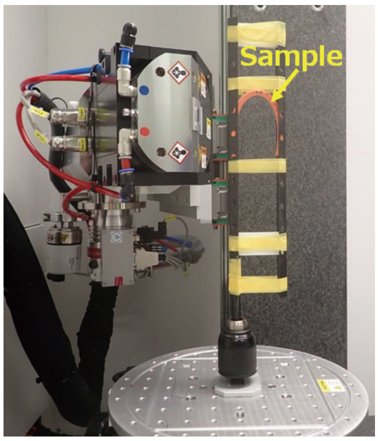

Fig. 8. Observation of U-shaped bent cable

Generally, XCT systems output cross-sectional images along a certain direction in space (in this example, the vertical direction), as shown in Fig. 9. In these images, the cross section of the cable and the shape of the wires change drastically among images, which makes it difficult to extract the coordinates of the wires. We have developed CTS that constructs a cross section along the length of the cable (curve-track-sliced image; CTSI). The cable is recognized as a three-dimensional object from the original image data in Fig. 9. A local bent coordinate system is determined along the trajectory of its center of gravity. By cutting the original 3D image data along these local bent coordinates, it is possible to construct a cross section perpendicular to the length direction of the cable. This CTS can be applied to cables of any shape other than the U-shape shown in Fig. 8, and is an essential technology to promote *IS*XCTO of cables.

3-2 Curve-Track-Slicing

Figure 10 shows an example of CTSIs. It can be clearly seen that the cable is deformed at the center of the U-shaped bend (②) compared to the cable ends (locations far from the U-shaped bend area, ① and ③). In this example, 2666 CTSIs along the length of the cable were constructed from the original 1129 slice images in Fig. 9. CTS corresponds to a kind of coordinate transformation. It enables us to treat a significantly bent cable as a virtually straight cable by representing data in a curved coordinate system.

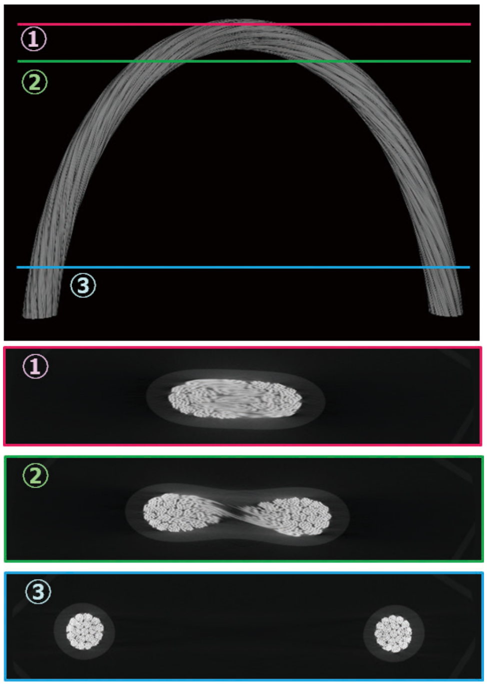

Fig. 9. Typical slice images of XCT system

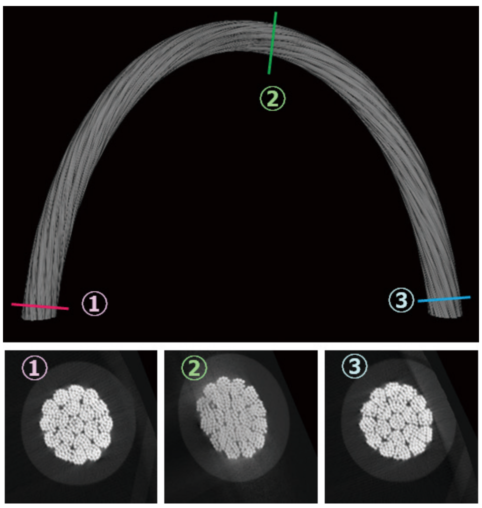

Fig. 10. CTSIs constructed by the data of Fig. 9

3-3 Results of Wire-Tracking

Figure 11 shows the results of Wire-Tracking using the CTSIs in Fig. 10. Wire-tracking is performed for all 2666 CTSIs. Here, we show the results of image ① ("Cable End") and ② ("Center of U-shape"). "Input" is the CTSIs and "Output" is the coordinates of the wires superimposed on the CTSIs using colored circles. The colors of the circles are used to indicate separate twisted bundles. By applying clustering to the trajectory data, it is possible to automatically separate each twisted bundle of cables. It becomes possible to calculate various indicators such as twist pitch for all twisted bundles. Indexes are given to all wires by Wire-Tracking. Figure 11 also includes an enlarged view of the vicinity of the wires numbered 1 and 399.

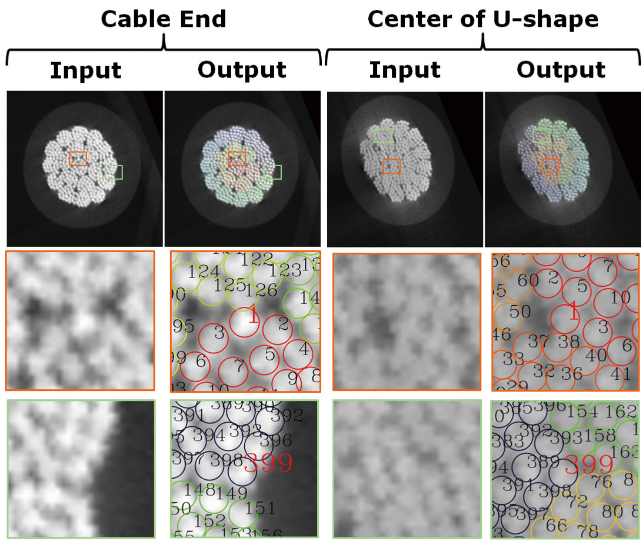

Fig. 11. Examples of Wire-Tracking results

In the XCT observation, we had to observe the entire U-shaped cable, which made it impossible to use a higher magnification than that used for a straight cable. Furthermore, as the object sample is bent, the volume of the object that the X-rays must pass through increases compared to when the object is not bent. Although the wires are somewhat unclear in the input image (Input) due to these effects, our image analysis technology can capture the coordinates of all 399 wires (Output). In general, XCT images obtained by *IS*XCTO when the cable is bent are less clear than images when the cable is not bent. Advances in image analysis technology including the CTS described here have made it possible to quantify various deformed samples.

Using the above process, it is possible to obtain the trajectory of virtually straight cables. Finally, by applying a coordinate transformation equivalent to the inverse of CTS to the trajectory, the true curved trajectory of the cable can be obtained. Figure 12 shows the results. Here too, each of the 19 twisted bundles is displayed in different colors.

In this way, it is possible to clarify the actual shape of the entire cable and each wire under bending stress. This understanding contributes to quality improvements and product design.

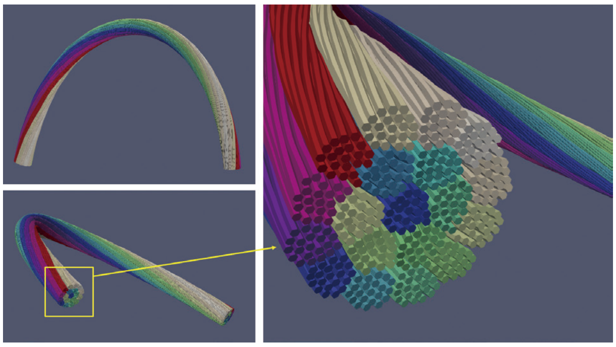

Fig. 12. Final track data of bent cable

4. Conclusion

XCT observation under external loads that simulates the actual usage environment of various products and various quantification techniques of the data are important for product design and quality improvement. In this paper, we focused on electric cables and introduced "Curve-Track-Slicing," which is an important technology to conduct Wire-Tracking of significantly bent cables. Utilizing these unique technologies, we will strengthen digital transformation of product design, shorten development periods, and further differentiate our products.

Technical Terms

*1 X-ray computed tomography (XCT): A computer-assisted tomography technique involving x-rays. A sample is photographed using X-rays from various directions, and a computer estimates the spatial distribution of the X-ray absorption coefficient in the target space based on the information in the many "shadow pictures" and displays it as a black-and-white contrast. Using this technology, it is possible to nondestructively know the internal structure of a sample. By combining XCT with the external force application mechanism and data analysis technology described in this paper, it is possible to investigate various changes in the shape of a sample due to external force.

*2 Wire-Tracking: Sumitomo Electric's unique technology that extracts the actual shape of all wires that make up cable products. Using data analysis techniques such as deep learning, the coordinates of wires are extracted from XCT image data of cable samples and the coordinates are connected between images. Examples have been reported regarding straight cables (Refs. 1 and 2) and slightly bent cables (which do not require CTS described in this paper) (Ref. 3).
In addition, the Sumitomo Electric Group promotes InAID (Inclusive Artificial Intelligence Development), in which the entire process of Wire-Tracking is carried out by people with disabilities who belong to a special subsidiary, Sumiden Friend Co., Ltd. (Ref. 4). This is a multifaceted effort that aims to improve the competitiveness of cable products based on unique technology while building an inclusive organization.
This initiative (specifically the paper of (2)) has been selected for the 2023 Incentive Award by the Japan Society for Artificial Intelligence (JSAI).

(JSAI website; in Japanese)
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