

Quantitative assessment of fiber alignment in CFRP using Persistent Homology

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The lightweight features and unique mechanical properties of carbon-fiber reinforced plastic (CFRP) are attributed to their multi-component structure. However, the composite structure also imposes performance limitations. The failure behavior of CFRP is influenced by the properties of matrix resin, fibers, fiber-resin interfaces, and the relative geometric alignment of fibers. Despite extensive research, a gap remains in understanding how the spatial distribution of composite constituents affects crack initiation and propagation. In this paper, we established an innovative scoring method to assess fiber alignment in CFRP using persistent homology, providing a fundamental understanding of the crack propagation mechanism.

Persistent homology-based topological data analysis (TDA) is an advanced analytical method derived from the field of topology, designed to quantify the "holes" in discrete datasets, such as point clouds and pixel images. [1-3] X-ray computed tomography (X-ray CT) has become a widely adopted method for analyzing fiber alignment in CFRP. [4,5] In our previous work, we effectively applied persistent homology to identify carbon fibers from X-ray CT images of CFRP, as illustrated in Figs. 1a and 1b. [6] In the present study, the detected fiber positions were saved as point cloud data, and persistent homology-based TDA was re-applied to assess the fiber alignment within CFRP. By calculating the first-degree persistence diagram (PD1), we characterized the ring structures formed by fibers, with focusing on the triangles and quadrangles that are emerged. We regarded the regular triangle and square formed by close-packed fibers as fundamental units. In assessing the triangles and quadrangles, the scoring method incorporated deviations in both shape and size relative to the fundamental units. Figs. 1c and 1d display the triangles and quadrangles detected in Fig. 1b, with the gray spots corresponding to the crack regions shown in Fig. 1a. The color represents scoring results, with darker colors indicating closer resemblance to the fundamental units. We analyzed a sequence of X-ray CT images taken along the depth of the specimen, each capturing the endpoint of crack propagation. Fig. 1a is one image from this sequence. Fig. 2 illustrates the other three images from the sequence, with each triangle and quadrangle represented as a colored dot. The color reflects the scoring results, enabling a quantitative visualization of fiber alignment around cracks. It was observed that the fiber alignment in Figs. 2a and 2b are more ordered than in Fig. 2c. Additionally, the cracks in Figs. 2a and 2b are shorter than those in Fig. 2c, indicating that a higher degree of ordered alignment effectively suppresses crack propagation.

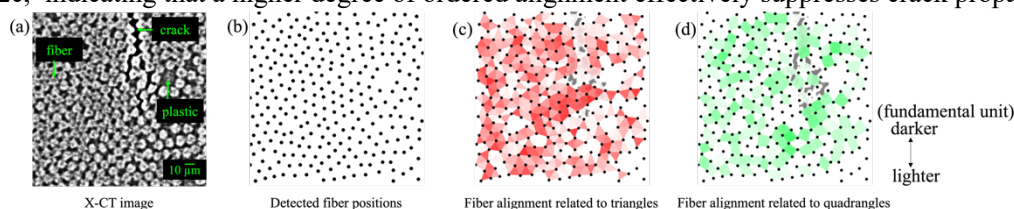


Fig. 1. Identification of fiber positions and evaluation of fiber alignment in CFRP.

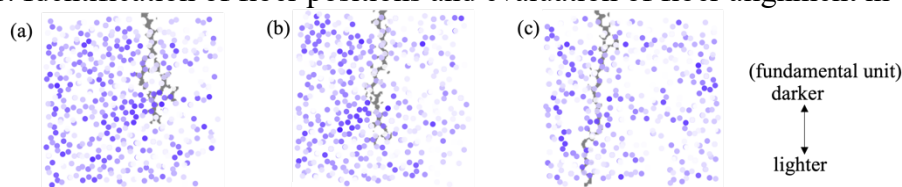


Fig. 2. The fiber alignment (purple) around cracks (gray) in CFRP.

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- This study was supported by JSPS KAKENHI 22H05109 and 19H00834, and JST-MIRAI JPMJMI22C1.