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Application Note

No. 58

Composite material

Verification and Validation (V&V) of Uniaxial Tensile Test Simulation Results of Composite Materials: Fusion of Actual Measurement and Homogenization Analysis

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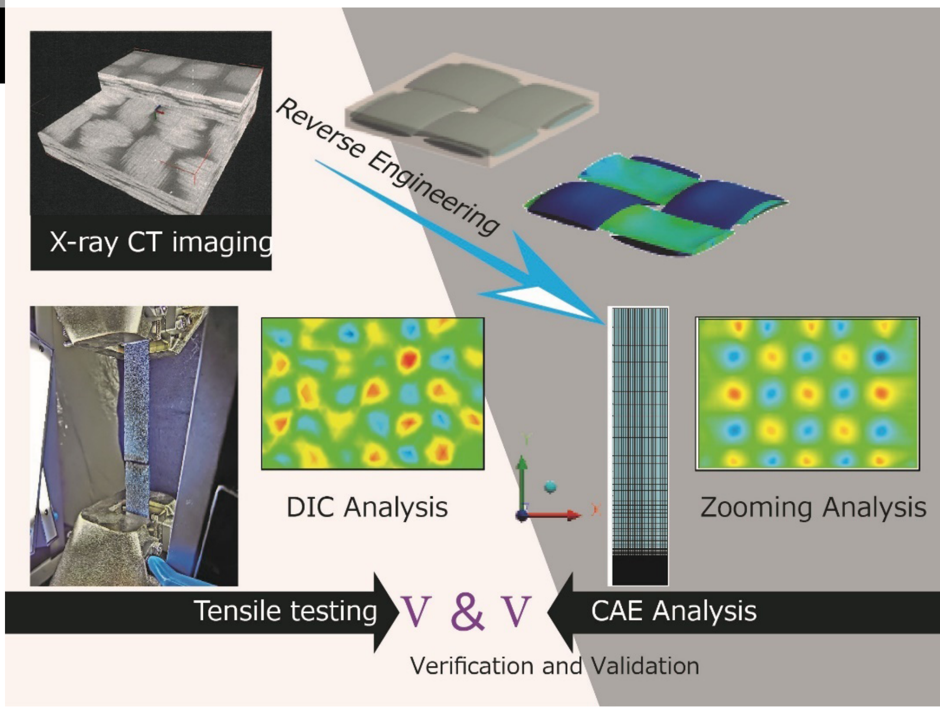

Composite material

1. Introduction

1-1. Verification and Validation (V&V) Testing of CAE Analysis Results

Use of Carbon Fiber Reinforced Plastics (CFRP) and other composite materials in transportation equipment, beginning with automobiles, has begun in response to calls for reduction of body weight to reduce environmental impacts. Unlike metal materials, composite materials have a complex internal structure and display complex fracture behavior, depending on the principal axis of applied stress, and this has made it difficult to establish highly accurate structural analysis models. Structural analysis simulation techniques such as CAE (Computer Aided Engineering) are widely used in design development of transportation equipment. Improved reproducibility of CAE analysis is expected to increase efficiency and reduce costs in development work, and to improve the reliability of the designs of complex structures and large-scale structures, which is difficult to assess by actual measurement.

In conventional product design development, there was a time when design work was considered complete with only CAE analysis. Today, however, actual measurement under the same conditions as the CAE analysis model and verification by comparison of those results and the CAE analysis results to validate the appropriateness of the simulation results (V&V: Verification and Validation) is considered important. As a result, product design utilizing both actual measurement and CAE analysis is becoming a general social requirement.

This article presents an outline of the distinctive features of composite materials related to CAE analysis, and based thereon, introduces examples of V&V by comparison of the CAE analysis results with the results of actual measurements of a Carbon Fiber Reinforced Thermo Plastics (CFRTP) fabric material.

1-2. Features of Composite Materials

As mentioned above, CAE analysis of product parts and structures produced from composite materials includes a number of difficulties that limit good repeatability. Table 1 summarizes the differences between metal materials and composite materials, focusing on material behavior. An outline of these features is introduced below.

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(1) Controllability of material physical properties

The physical properties of composite materials can be controlled as desired by changing the type and blending ratio of the materials used in the composite. While this is an important advantage from the viewpoint of increased freedom in product design, the flow of product design tends to become more complex due to a corresponding increase in the number of items that require study.

(2) Anisotropy of material behavior

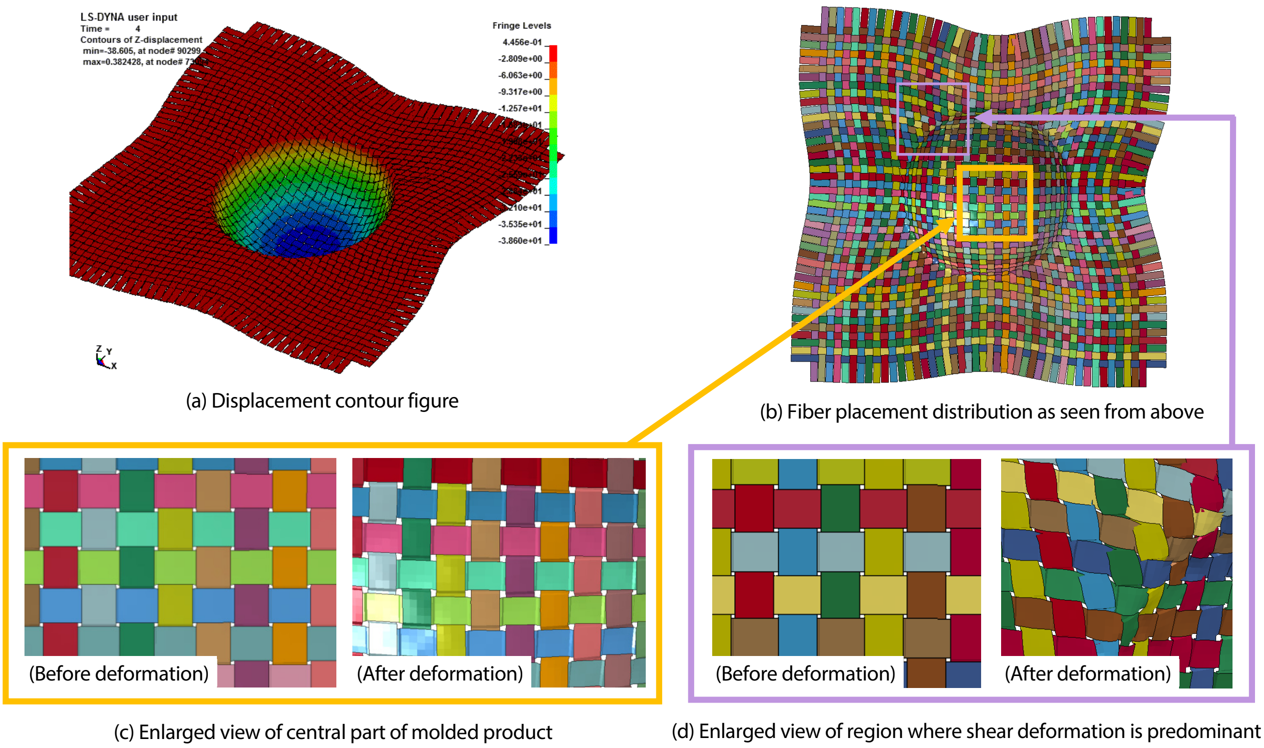
Anisotropy is a distinctive feature of fiber-based composites, as these materials display different material behavior depending on the principal axis of applied stress. In contrast, with the exception of single crystal metals and certain other special cases, metal materials are generally assumed to be isotropic, meaning their behavior does not depend on the principal axis of stress. When a material behavior is isotropic, its elastic behavior is determined solely by its elastic modulus and Poisson's ratio, and both of these physical properties can be identified by a uniaxial tensile test. However, when materials display anisotropy, a total of nine properties must be known in order to conduct an analysis, as the elastic behavior of these materials depends on the modulus of longitudinal elasticity, Poisson's ratio, and the shear elastic modulus in the three perpendicular directions defined by 3-dimensional space, and it goes without saying that tests must be conducted in a variety of deformation modes in order to identify the values of these physical properties.

(3) Molding history dependency of material behavior

Irrespective of the combination of materials, the behavior of a material also displays dependency on its molding history. Simultaneous production and molding of the materials is a distinctive feature of composites, and various molding methods are applied. Fig. 1 shows an example of a CAE analysis of press-forming for a fabric material of CFRP. A spherical punch is arranged in the center of the material, which has a sheet-like shape, and the material is press-formed by forced out-of-plane displacement. Because composite materials are anisotropic, as mentioned above, they exhibit complex deformation behaviors even with a simple test sample and die. Fig. 1(c) and (d) show the enlarged views of the region where uniaxial tensile strain in the fiber direction is predominant and where shear strain is predominant, respectively. During press-forming, the relative fineness of the fibers changes in the uniaxial tensile strain region, while the intersection angle of the fibers changes in the shear strain region. Since these types of deformation have an obvious effect on rigidity and strength, highly accurate analysis is not possible using only the property values evaluated at the test specimen level. This is particularly a problem in molded products with curved shapes.

Table 1 Differences in Material Behaviors of Metal Materials and Composite Materials

Feature	Metal materials	Composite materials
Controllability of physical properties	Low	High
Molding history dependency	Small	Large
Anisotropic behavior	Isotropic	Anisotropic
Material database	Abundant	Few
Fracture mode	Single	Multiple



(a) Displacement contour figure

(b) Fiber placement distribution as seen from above

(c) Enlarged view of central part of molded product

(d) Enlarged view of region where shear deformation is predominant

Fig. 1 Example of Analysis of Press-Forming of Fiber-Based Composite Material

(4) Multiple fracture modes

The fracture modes of composites are extremely complex. Fracture of metal materials is generally controlled by the nucleation and migration of dislocations, which are atomic defects, and nucleation can be predicted based on a single index called von Mises equivalent stress *3. However, composite materials exhibit diverse fracture modes, including material interfacial peeling (between the resin and fiber), delamination (between layers), and crack propagation. Local stress concentrations with a small scale (on the order of several μm to mm) relative to the total product size are also a factor in fracture. For all these problems, it is essential to acquire the material physical property values necessary for analysis, namely, the elastic modulus and strength. On the other hand, highlighting the importance of this issue, the international association for engineering design and analysis NAFEMS (1) actually conducted a questionnaire survey of CAE analysts and reported that acquisition of material physical property values was the No. 1 problem in analysis of composite materials by an overwhelmingly large margin in comparison with the No. 2 problem (2).

This article introduces an example in which a CAE analysis model was created by using data on the internal structure of a CFRTP fabric material acquired with a microfocus X-ray CT system, and its material physical properties were identified by using a multiscale analysis technology (3)-(5) based on the homogenization technique, and fracture behavior was captured by reproducing strain distribution at the microscopic scale as one technique to solve the above-mentioned problems. Specifically, in capturing the fracture behavior, an analysis was evaluated by comparing the measured results obtained with a testing system combining a precision universal testing machine and digital image correlation (DIC) analysis software and the results of a CAE analysis.

2. Evaluation Method

2-1. Outline of CAE Analysis

In order to predict material physical property values by the homogenization technique, the shape of the microstructure to be used in the analysis model must be given as a known quantity. Multiscale.Sim™ (8), which is a multiscale analysis add-in simulation tool of the general-purpose CAE analysis tool ANSYS® (7), provides a function that automatically generates models simply by setting the shape parameters of the microstructure, and supports a variety of microstructures as illustrated in Fig. 2. For the analysis, virtual material testing (hereinafter, numerical material testing or NMT) was conducted for the default structural data (Model 1) generated automatically by Multiscale.Sim™ and for the structural data (Model 2) generated by using data acquired by a microfocus X-ray CT system, as described below.

For Model 2, DICOM (Digital Imaging and Communications in Medicine) data that were output by the microfocus X-ray CT system were read into the image processing software Simpleware™ Software (6), and the cross-sectional shape of the fiber bundles and the pitch and volume fraction of the fiber bundles were identified. Following this, all subsequent analysis work was done using the general-purpose CAE tool ANSYS® (7) and the multiscale simulation add-in tool Multiscale.Sim™ (8).

*3 Equivalent stress (von Mises stress) is a stress index obtained by converting the information on a multiaxial stress field obtained by analysis to a value that can be compared with the response of a uniaxial tensile test.

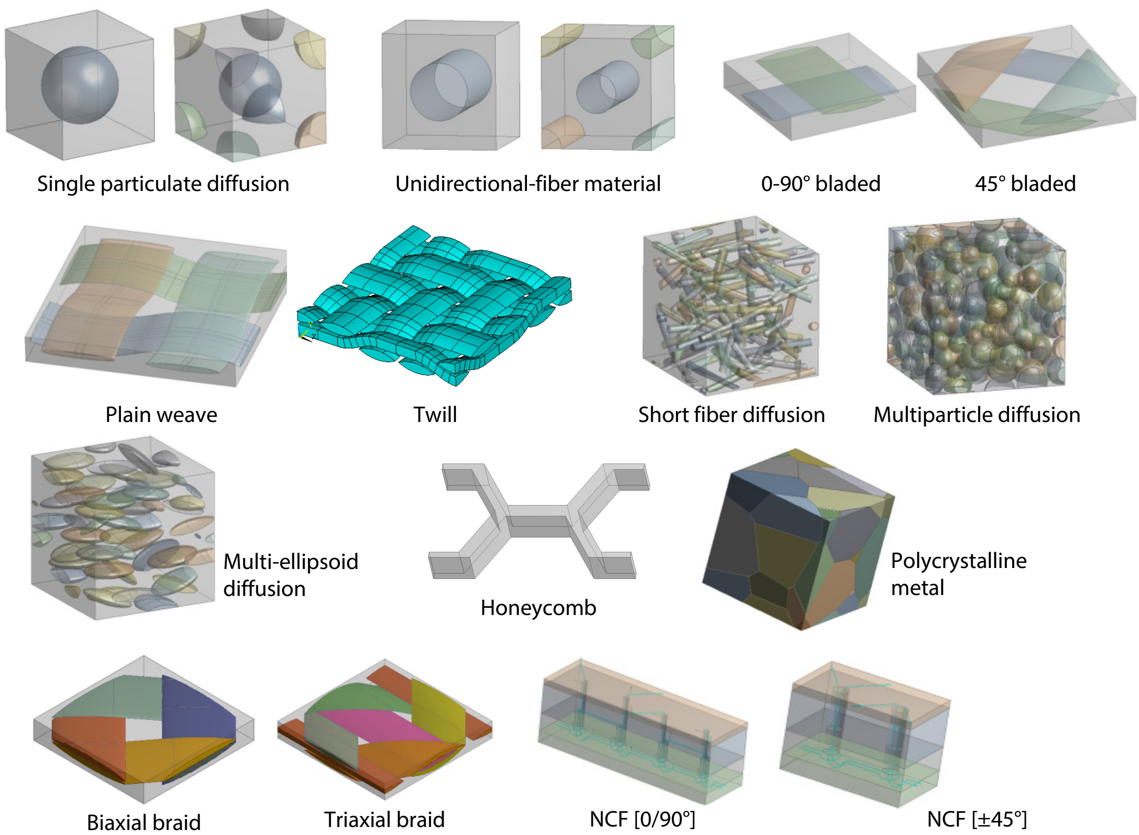


Fig. 2 Automatic Model Creation Templates of Multiscale.Sim™

As a feature of CAE analysis, since setting the ideal boundary conditions is simple, numerical material testing can be performed easily even for deformation modes that are considered difficult to realize in actual measurements, such as pure shear, biaxial testing, and volume testing. Moreover, as boundary conditions, cyclic symmetry can be assumed in all directions. This means the analysis can be conducted using only one unit cell in which cyclic symmetry is found, without modeling the entire test specimen used in the actual measurement. In this experiment, NMT was conducted using a unit cell for six deformation modes, representing the total of uniaxial tension and pure shear in three directions each in order to acquire the nine types of material physical properties necessary to express the elastic anisotropic behavior of a composite material, as mentioned previously. Here, all material physical property values were identified from the macro stress-strain characteristics obtained by NMT in each deformation mode. In parallel with the CAE analysis, an actual measurement was also conducted with a rectangular test specimen. Because only the uniaxial tensile test was carried out in that measurement, validation was done by comparison with the results of a CAE analysis limited to the modulus of longitudinal elasticity (Young's modulus). In addition, the distribution of the strain in each component direction in the specimen observation image obtained from the noncontact-type digital video extensometer used during material testing was also observed by using the DIC (Digital Image Correlation) technique. In NMT, the same strain distribution can be evaluated by applying the technique called zooming analysis. Validation of the results was conducted by comparing the results of zooming analysis with the results of measurement in the same manner as with the elastic modulus. Fig. 3 shows the flow of this analysis.

2-2. Acquisition of Test Piece Shape Data by X-ray CT

Fig. 4 shows the photograph of condition of the inspeXio™ SMX™-225CT FPD HR microfocus X-ray CT system and the test specimen. Fig. 5 shows the geometry of the test specimen for the uniaxial tensile test. The specimen has the dimensions provided for the JIS K7165 B type test piece. Tabs are glued to the specimen to avoid damage by stress concentration in the jig gripped parts during the material testing and ensure that fracture occurs in the parallel part. The X-ray detection system of this test system has a built-in 16-inch flat-panel detector. The maximum field of view in CT imaging is approximately φ400 × 300 mm, and internal observation of the large-sized test piece was also possible in this experiment.

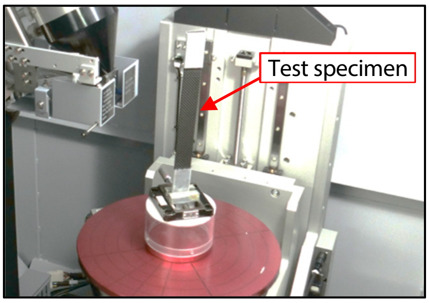


Fig. 4 Scene of X-ray CT Imaging

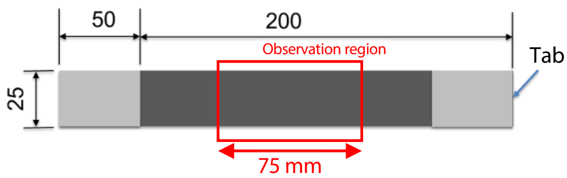


Fig. 5 Geometry of Uniaxial Tensile Test Specimen for X-ray CT Imaging

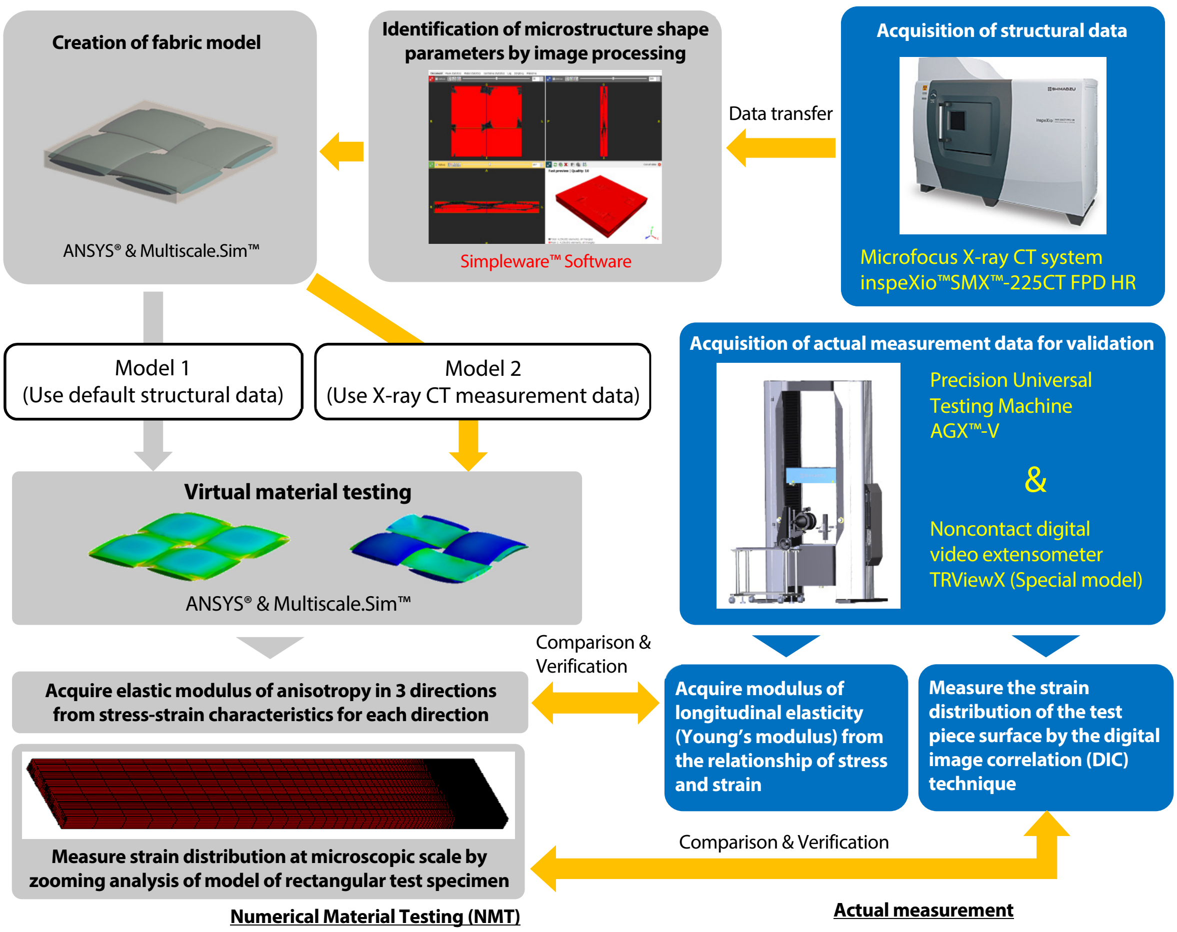


Fig. 3 Flow of Analysis

2-3. Acquisition of Uniaxial Tensile Test (Actual Measurement) Data

Fig. 6 shows a scene of the test. In the uniaxial tensile test (actual measurement), image data synchronized to loading were obtained by using a Shimadzu AGX™-V Precision Universal Testing Machine and TRViewX (SP.1.0.0) noncontact digital video extensometer. A DIC analysis was carried out with the DIC analysis software GOM Correlate 2016 (GOM GmbH) to obtain contour figures of the strain measurements and the strain of each component direction in the microscopic region. DIC analysis is a technique in which the amount of deformation of the analysis object are investigated by comparing random patterns of the object surface before and after deformation of the object. Measurement of displacement from the images and analysis of the strain distribution are possible. As features of this technique, it is not necessary to place a sensor in contact with the test object, and a complicated optical system is not required. Considering these advantages, DIC analysis is used in a wide range of fields, as application is possible under conditions where measurement was difficult to conventional technologies, for example, in strain distribution analysis of large-scale structures, targets in high temperature environments, and small measurement objects under a microscope. The test conditions were set to a test speed of 1 mm/min and a distance between grips of 136 mm, referring to JIS K7165. In strain measurements for measurement of the elastic modulus, the standard virtual strain gauge function of the DIC analysis software was used, and strain was obtained by calculation based on the reference points for a gauge length of 50 mm. The elastic modulus was calculated from the stress-strain relationship in the 0.05% to 0.25% strain region.

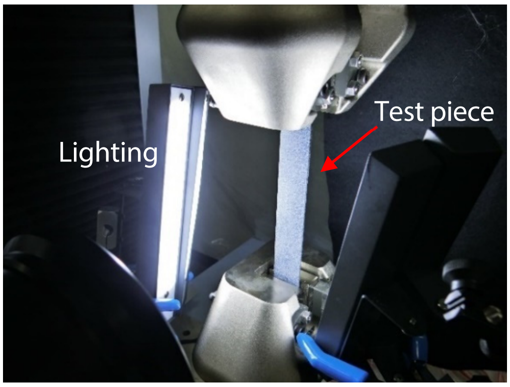


Fig. 6 Scene of Uniaxial Tensile Test

3. Evaluation Results

3-1. Identification of Material Constants

Fig. 7 shows MPR (Multi Planar Reconstruction) images of the test specimen. MPR imaging is a function that arranges recorded CT images in virtual space and shows images of any desired cross section. It is possible to display cross-sectional images (②, ③) which mutually intersect with a CT image ① at right angles, and it is also possible to show cross sections from arbitrary angles. Enlarged views of the necessary cross-sectional images can be displayed, enabling detailed confirmation and observation. concretely, in these MPR images, ① shows a cross section near the center of the specimen, and ② and ③ show cross sections that intersect from cross section ① in the vertical and horizontal directions, respectively. Cross section ④ is an arbitrary cross-sectional image that was extracted from ② at an angle where the method of arrangement and interfaces of the carbon fibers can be observed easily. Fig. 8 is a VR (Volume Rendering) display of an image captured by CT imaging of the specimen showing a partial enlarged view. VR displays can be created by using the 3D software VGSTUDIO MAX and enable three-dimensional observation of the condition of the fibers and resin in a form closer to the real object.

With the Shimadzu inspeXio SMX-225CT FPD HR microfocus X-ray CT system, it is possible to output observation data in the DICOM and STL (Standard Triangulated Language) formats and as other types of image and video data.

Fig. 9 shows a photograph of a specimen after fracture. A satisfactory uniaxial tensile test was possible, as fracture of the test specimen occurred in the parallel part, and no fracture or other abnormalities occurred in the tab ends or tabs.

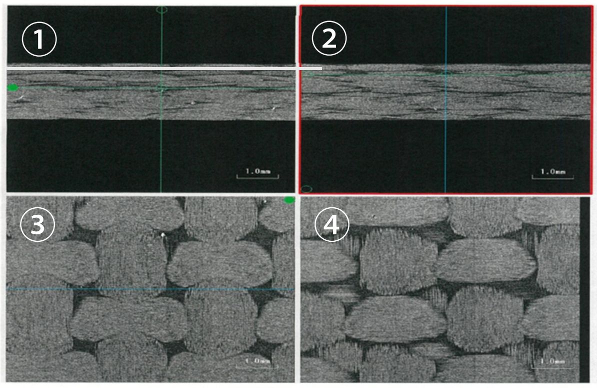


Fig. 7 MPR Images of Specimen

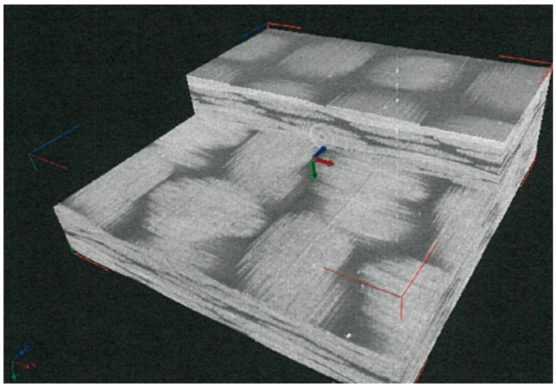


Fig. 8 VR Image of Specimen

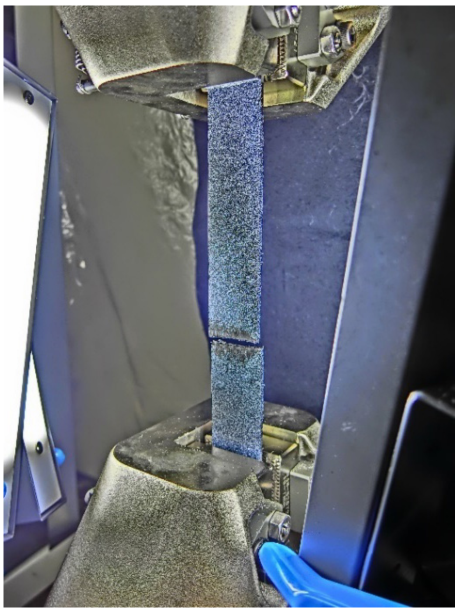
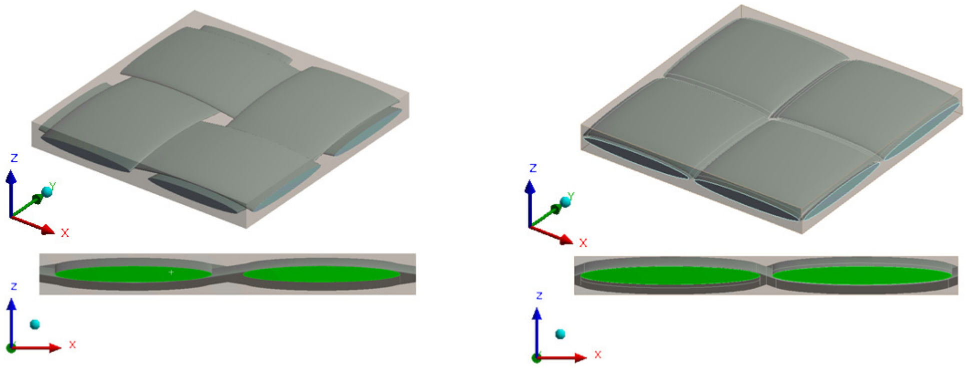


Fig. 9 Photograph of Specimen after Fracture

In NMT, the two models (Model 1 and Model 2) shown in Fig. 10 were used. In Model 1, the default structural data registered in the software are used. The cross-sectional shape is uniform for fiber bundles, and the fiber bundle shape displays sinewave-like undulations. The model was created so that the largest volume fraction of fibers is in the region where pairs of fiber bundles are not in contact. Model 2, on the other hand, was created based on the shape identified from the structural data acquired by the aforementioned microfocus X-ray CT system. In this model, the cross-sectional shape of the fiber bundles is not uniform, and the undulations deviate from the sinewave form and follow the cross-sectional shape of the fibers.

Table 2 summarizes the results of a comparison of the elastic modulus identified by NMT and the elastic modulus obtained in the uniaxial tensile test (actual measurement). Fig. 11(a) shows the nominal stress-nominal strain curves obtained in the uniaxial tensile test (actual measurement) and numerical material testing (NMT). The elastic modulus in the direction of uniaxial tension was 55.46 [GPa] in the uniaxial tensile test (actual measurement), but was 32.56 [GPa] with Model 1, showing a large error in the simulation result. In contrast, the modulus of longitudinal elasticity with Model 2 was 51.75 [GPa], which was close to the measured value. Use of the default structural data, as in Model 1, is convenient, since a simple analysis is possible, but in some cases the results differ greatly from the actual structure, as shown here. With Model 2, relative error was reduced by reflecting the structural data obtained with the microfocus X-ray CT system in the analysis model. These results indicate that material testing is required to validate CAE results. Since the material physical property values of the CFRTP fabric material in this evaluation depend on the microstructural shape, it is essential to identify that shape based on observation of the internal structure with the microfocus X-ray CT system.

Fig. 11(b) shows the contour figure of the y-component strain generated in the specimen surface layer at point A in the nominal stress-nominal strain curve of the uniaxial tensile test (actual measurement), together with a photograph of the specimen immediately after fracture. In the contour figure, areas with low strain are indicated by cool colors and areas with high strain by warm colors. Immediately before fracture, a stress concentration of y-component strain can be recognized in the bottom of the specimen. The position of this stress coincides with the point of fracture. In NMT that considers plasticity and damage, it is important to verify the strain that contributes to fracture in each component direction. For more detailed NMT, DIC analysis of the actual measured data and consideration of the contribution of strain by each component to fracture is effective.



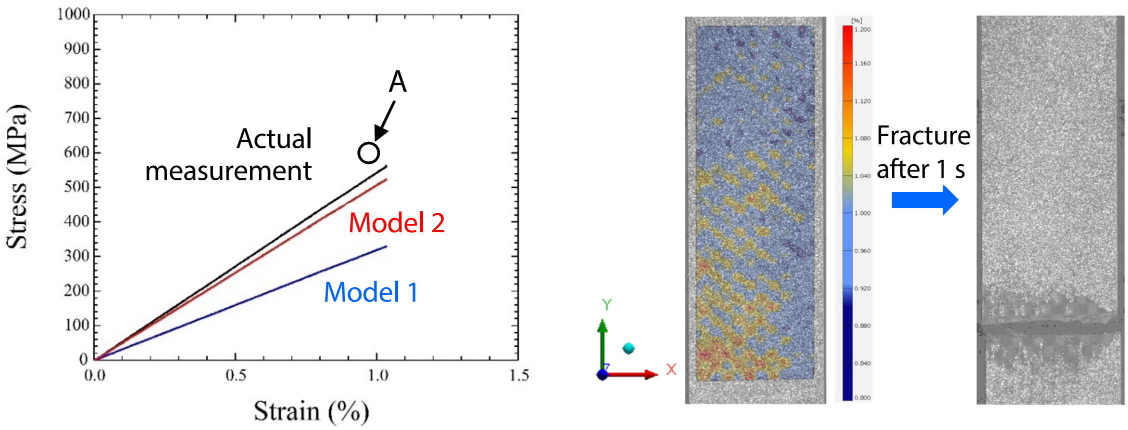
(a) Homogenization model expressing undulation of fibers by ideal sine curve (Model 1)

(b) Strict model using structural data obtained by X-ray CT (Model 2)

Fig. 10 Two Analysis Models Examined in V&V

Table 2 Comparison of Modulus of Longitudinal Elasticity Obtained by Homogenization Analysis and Actual Measurement Results

Material	Homogenization analysis (Model 1)		Homogenization analysis (Model 2)		Uniaxial tensile test (Actual measurement)
	Modulus of longitudinal elasticity (GPa)	Rate of agreement with actual measurement (%)	Modulus of longitudinal elasticity (GPa)	Rate of agreement with actual measurement (%)	Modulus of longitudinal elasticity (GPa)
CFRP	32.555	58.7	51.751	93.3	55.46



(a) Comparison of results of nominal stress-nominal strain curves in actual measurement and NMT

(b) Contour figure of y-component strain at point A and photograph of specimen after fracture

Fig. 11 Comparison of Nominal Stress-Nominal Strain Curves and Condition of Specimen Fracture

3-2. Evaluation of Strain Distribution in Microscopic Region

The elastic modulus evaluated in 3-1 reflects the apparent response measured with a strain gauge several times larger than pitch of the fabric of specimen. In internal structures of actual composite materials, resin and fibers with greatly different rigidity are mixed heterogeneously, and as a result, strain and stress naturally show local distributions, even supposing a simple uniaxial tensile test. Because fracture of composite materials originates from a stress concentration in a heterogeneous structure, this is a phenomenon that cannot be ignored.

Fig. 12(b) shows the heterogenous strain distribution around the center of a test specimen obtained by NMT. In combination with this, Fig. 12(c) shows the results of a DIC analysis focusing on a region of the same scale obtained from the results of the uniaxial tensile test (actual measurement). Here, a 1/4 size rectangular model of the test specimen that was used in the uniaxial tensile test (actual measurement) was used as the CAE analysis model to minimize the cost of the calculation. Furthermore, only the shape of the fiber bundles in the center of the specimen was modeled, and NMT was done assuming a homogeneous substance in the other regions. Concerning the pitch of fibers in the fiber bundles, the condition of alternating low strain and high strain states was qualitatively consistent in the analysis and the test. Unfortunately, however, a quantitative comparison of the strain values is still not possible at this time. This is an issue for future research.

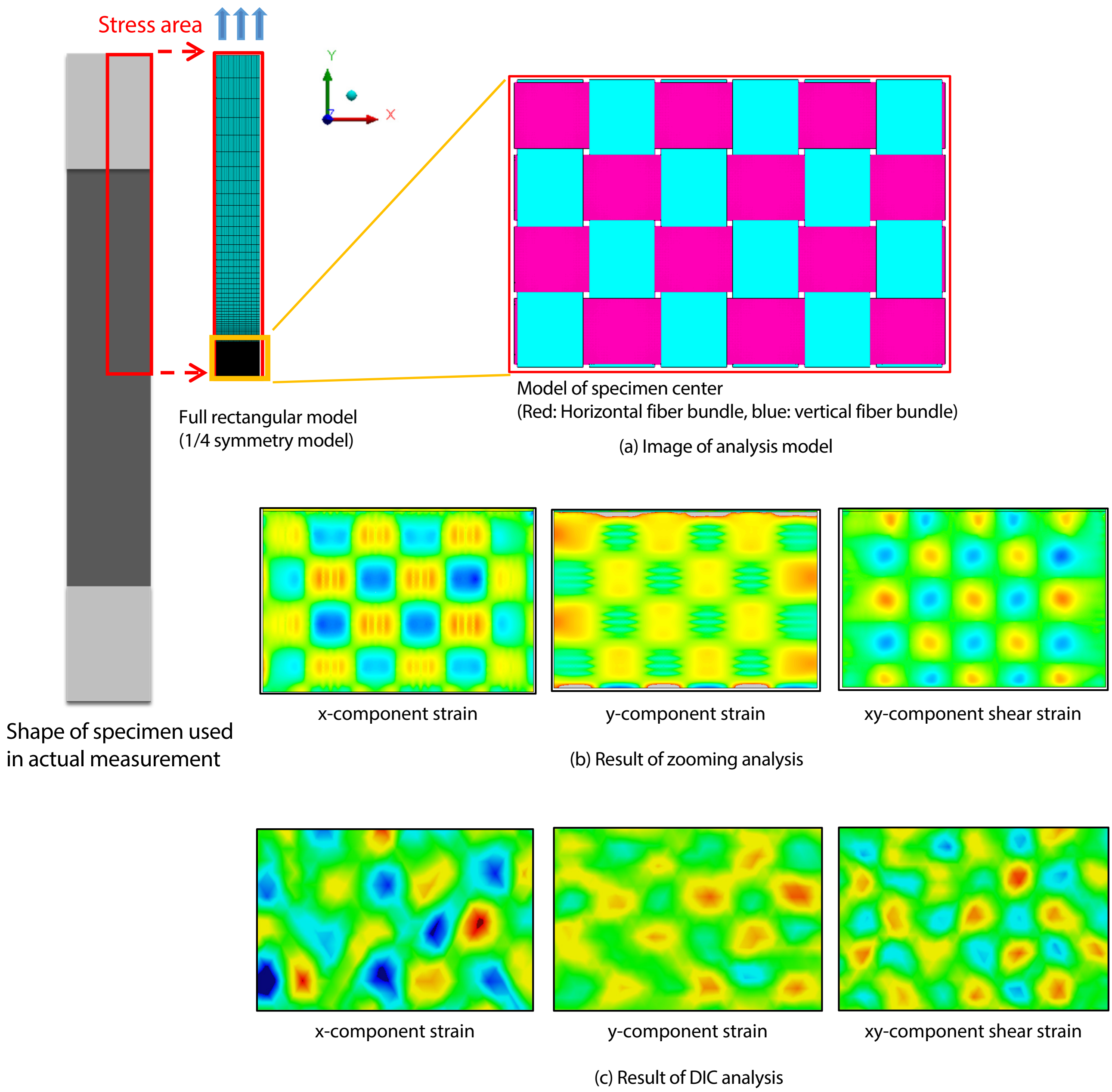


Fig. 12 Strain Distribution in Center of Specimen in NMT and Uniaxial Tensile Test (Actual Measurement)

4. Conclusion

This article has described an analytical technique for predicting the behavior of anisotropic materials, using the CFRTP fabric of a typical composite material by way of example. An example of verification of the internal structural model used in that analysis and an example of actual measurement for validation of the analytical results were introduced. In this study, it became clear that use of data modeled referring to structural data for the fabric acquired with a microfocus X-ray CT system is effective for enhancing the accuracy of numerical material testing (NMT). Moreover, this study also clearly demonstrated that accurate numerical data, such as stress and strain, obtained in a uniaxial tensile test (actual measurement) and evaluation of the component strain distribution in the microscopic region obtained by a DIC analysis are effective for detailed validation.

In the past, analytical techniques were perceived as tools for eliminating the need for trial production by actual equipment, but the current understanding is different. As the functions of analytical tools have continued to evolve, it has now become possible to predict even complex physical phenomena. However, accompanying these functional improvements, the applications of analysis have also expanded, and with the increasing complexity of these applications, a new concern has arisen, namely, securing the quality of analysis programs and their results. To address this issue, the Japan Society for Computational Engineering and Science [9] organized a Study Group on HQC (High Quality Computing) to establish a methodology for securing the quality of analysis, and a JSCES standard procedure titled "A Model Procedure for Engineering Simulation" has already been completed [10]-[12]. Those standards stress the importance of conducting actual measurements under the same conditions as those of the analytical model, and verification by comparison with the simulation results, for validation of the appropriateness of results obtained by analysis. Similar efforts are also being made internationally. The concept of analogy has been proposed by the American Society of Mechanical Engineers [13], and product design based on the twin-approaches of analysis and actual measurement is increasingly considered a general social requirement.

Particularly in the field of composite materials, it is difficult to adequately grasp all the material behaviors necessary for product design by measurement alone because composites, unlike metal materials, display complex anisotropic behaviors. We hope that the integrated approach using both measurement technologies and analysis techniques for prediction of the physical properties of materials introduced here will provide useful hints for more efficient material design and product design.

The data introduced in the article were the result of joint verification and validation of actual measurement results and CAE analysis results by Shimadzu Corporation and Cybernet Systems Co., Ltd.

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