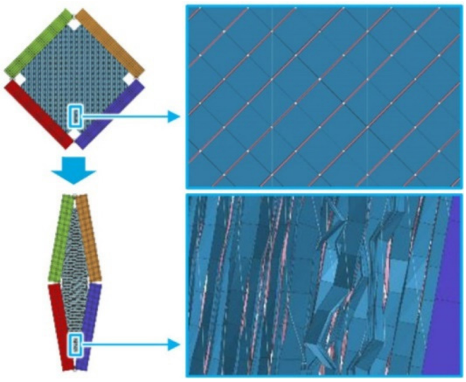
High-precision Forming Simulation for Composite Material Using Mesoscale Material Model



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Forming carbon fiber base materials such as Non-Crimp Fabrics (NCFs), which have been increasingly applied mainly to aircraft, into complex-shaped products causes defects such as fiber wrinkling. In general, quality can be improved by optimizing the forming conditions. However, for greater improvement of the quality, making the fiber base material itself more formable is effective. Mitsubishi Heavy Industries, Ltd. is developing a technology to predict mesoscopic deformation behavior of materials to optimize the material composition through forming simulation using a mesoscale material model. This report describes the results of evaluating the deformation behavior of fibers in shearing test by constructing a mesoscale material model of an NCF.

1. Introduction

As a low-cost forming method for composite material structures, research and development of forming technology using NCFs, which are composed of carbon fibers and have been increasingly applied to large structures such as aircraft, has been conducted mainly in Europe. As shown in **Figure 1**, an NCF is a sheet made of carbon fiber bundles arranged in different directions and stitched together in multiple layers to form a single structural material. Compared to woven fabrics, NCFs have superior strength properties because the straightness of the fibers is maintained.

Forming NCF sheets into complex-shaped products causes manufacturing defects such as fiber wrinkling, which affects the strength properties of structures. In general, quality can be improved by correcting the forming process and product shape, but one of the effective methods for quality improvement is to make the NCF itself more formable. Although forming simulation has been used as a method to study quality improvement measures, generally used macroscale simulation that models the material in units of sheets of composite material cannot predict microscopic deformation behavior of the material, such as fiber movement during forming and in-plane and out-of-plane wrinkles.

As such, we aimed to improve the prediction accuracy of in-plane and out-of-plane wrinkles during forming by using a mesoscale material model consisting of separate elements of fiber bundles and stitches, which are the constituent materials of an NCF. We expected that the prediction of microscopic deformation behavior of the material would enable the optimization of the material composition of an NCF and improve the forming quality. This report describes the construction of a mesoscale material model of an NCF and a comparative evaluation of the deformation behavior of the fibers in shearing test obtained by simulation and test.

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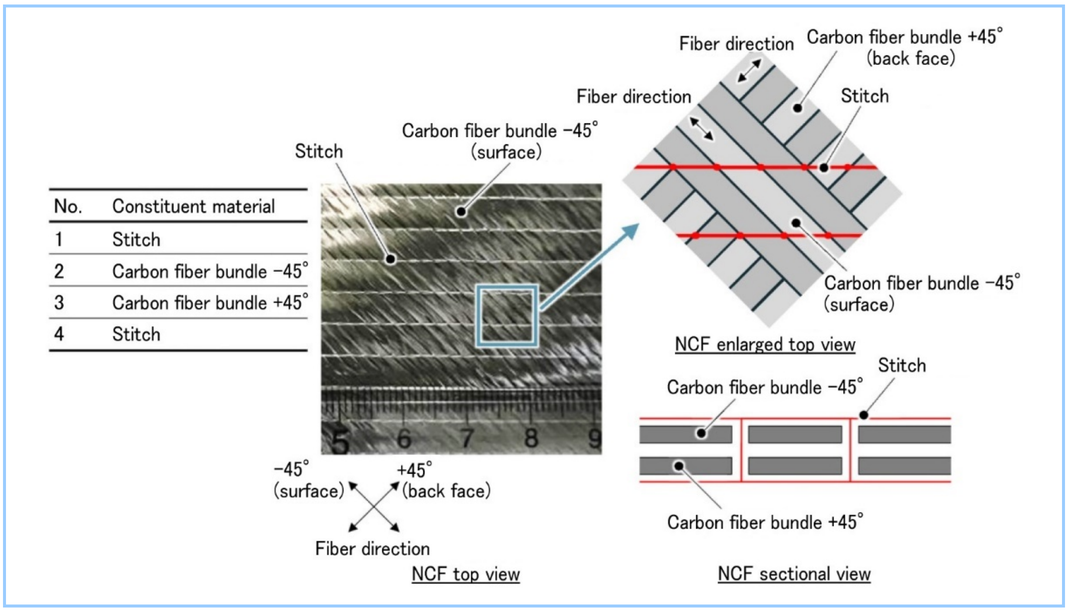

Figure 1 Targeted NCF configuration
The material (NCF) discussed in this report is composed of the constituent materials listed in the table above. Two layers of carbon fiber bundles arranged in the directions of -45° and +45° are stitched together.

2. Mesoscale material model

As shown in Figure 1, the targeted NCF consists of two layers of carbon fiber bundles arranged in the directions of +45° and -45° and stitches that stitch them together. The simulation software used was Virtual Performance Solution from ESI Group.

As shown in **Figure 2**, a model that can consider fiber bundle opening/closing and sliding phenomena was constructed by modeling all fiber bundles and stitches of the NCF, with the carbon fiber bundles modeled by three-dimensional solid elements and the stitches modeled by one-dimensional bar elements. The width and thickness of fiber bundles, gaps between fiber bundles, and distances between stitches were set according to the actual material. The gap between fiber bundles was set to 0.1 mm and the gap between two layers of fiber bundles in the out-of-plane direction was also set to 0.1 mm.

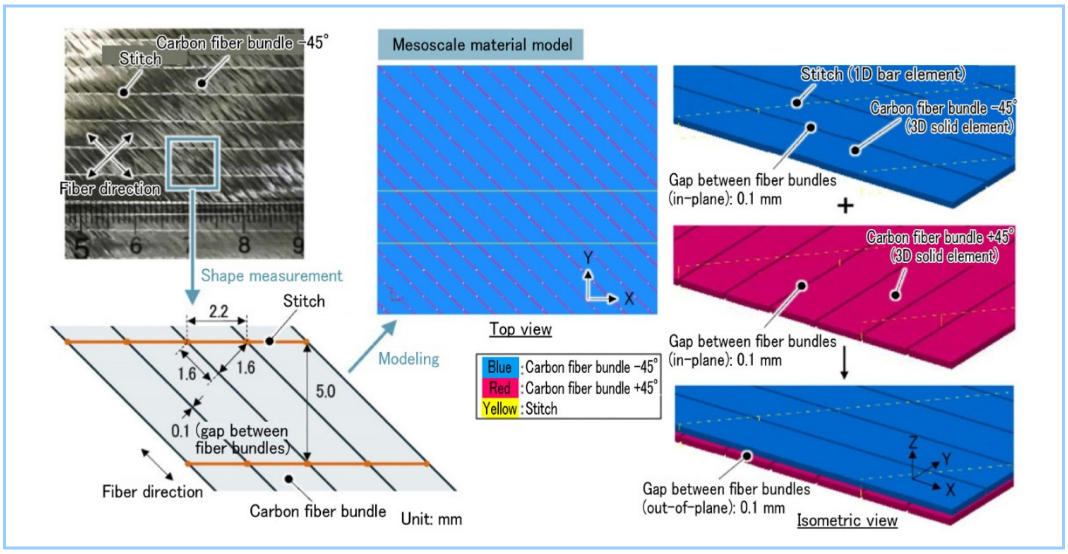

Figure 2 Mesoscale material model of NCF
We measured the shape of the actual NCF and created mesoscale material model to match the actual NCF. The fiber bundles in the -45° and +45° directions were modeled by three-dimensional solid elements, and the stitches were modeled by one-dimensional bar elements.

3. Reproduction of shearing test by simulation

We compared and evaluated the behavior of shear deformation of the NCF in a picture frame test obtained by simulation and test. **Figure 3** shows the analytical models of the NCF and picture frame test jigs. The NCF was made from a 220 mm by 220 mm sheet with cutouts at its corners where the test jig pins were placed, and the stitches arranged in the tensile direction.

Meshes were created for the arms to clamp and constrain the four sides of the NCF from the surface and back face and for the inner and outer pins that connect the arms together, and translational and rotational constraining conditions were set for each of the test jigs. The arm and inner pin were integrated, and the outer pin was placed outside the inner pin. The displacement of the lower outer pins of the test jigs was fully constrained according to the constraining conditions of the test, and the upper outer pins were pulled upward to analyze the shear behavior of the NCF.

Table 1 shows the material physical property values used for the simulation. For the simulation, it was necessary to input the physical properties for each of the modeled carbon fiber bundles and stitches, rather than for each NCF sheet. The young's modulus, shear modulus, and friction coefficient were input for the carbon fiber bundles. The young's modulus in the fiber direction, E1, was taken from a fiber catalog, while the other young's modulus, E2 and E3, shear modulus, and friction coefficient values were taken from a similar literature(1). The young's modulus for the stitches was adjusted so that the load-displacement curves input for the shearing test and the simulation would match.

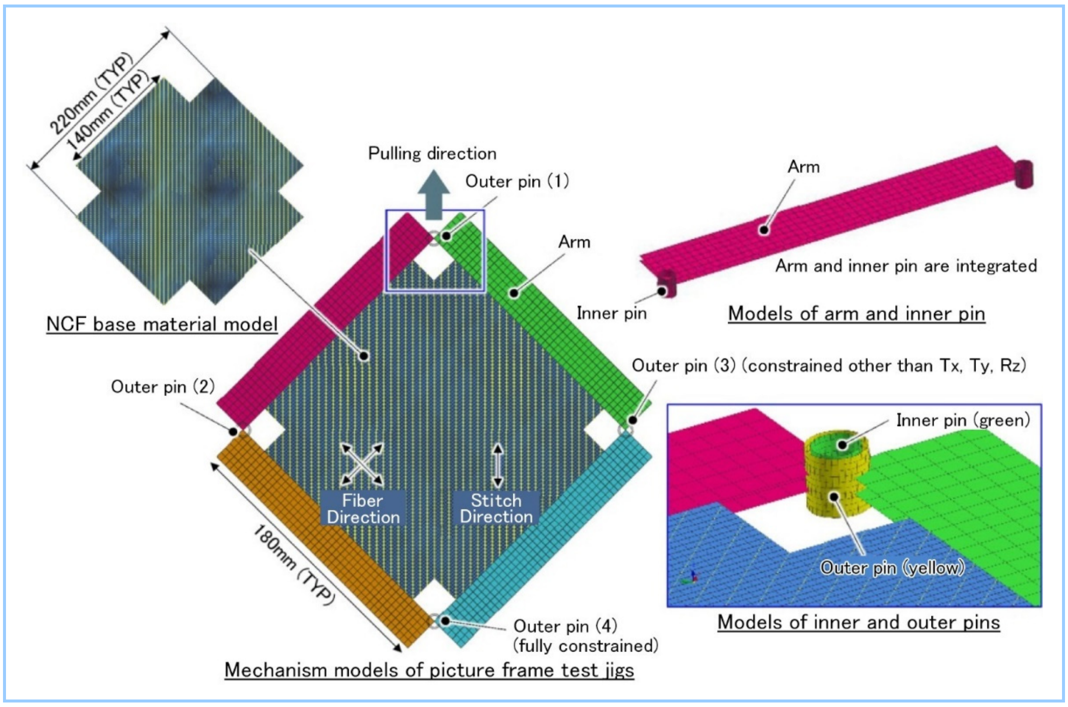

Figure 3 Analytical model of NCF and picture frame test jigs

Table 1 Material physical property values used for simulation

Constituent material	Material physical property		Input value
Carbon fiber bundle	Young's modulus	E1	150 GPa
		E2	Stress-strain curve
		E3	Stress-strain curve
	Shear modulus	G12	0.2 GPa
		G13	0.2 GPa
		G23	0.004 GPa
	Friction coefficient	Between fiber bundles (in-plane/out-of-plane)	0.2
		Between fiber bundle and stitch	0.2
		Between fiber bundle and test jig	0.2
Stitch	Young's modulus		Load-displacement curve

4. Verification of simulation accuracy by shearing test

4.1 Test conditions

Shearing test under the same conditions as in the simulation was conducted to verify the accuracy of the simulation. **Figure 4** shows the test setup. The four sides of the NCF test piece were clamped and constrained from the surface and back face using steel test jigs. The test was conducted at room temperature, and the stroke speed of the crosshead was 10 mm/min. To evaluate the displacement of the NCF by Digital Image Correlation (DIC), a DIC coating was applied to one side of the NCF. A test piece drawn with a 20 mm by 20 mm grid was also used in the test to evaluate the opening/closing, buckling, and other deformation behavior of the fiber bundles.

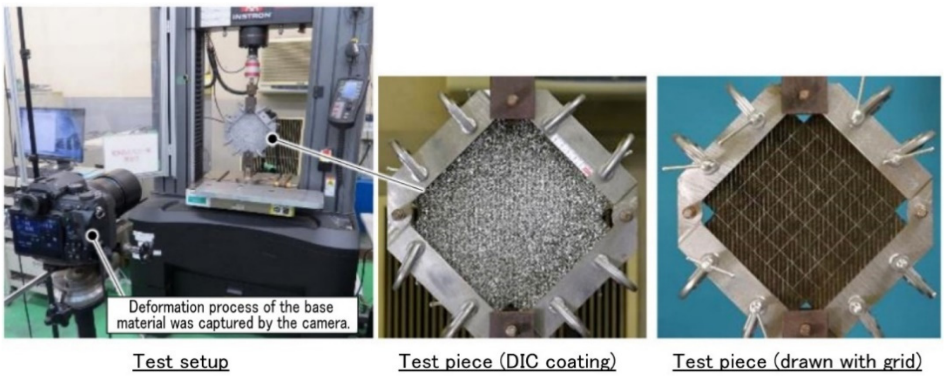

Figure 4 Shearing test

4.2 Evaluation of deformation behavior of NCF

Figure 5 shows the results of the comparison of NCF shapes between the simulation and the test. Over the entire stroke range, the simulation and test resulted in similar base material shapes, and the simulation also reproduced the situation of large deformation of the NCF in the region beyond pure shear at the stroke of 80 mm.

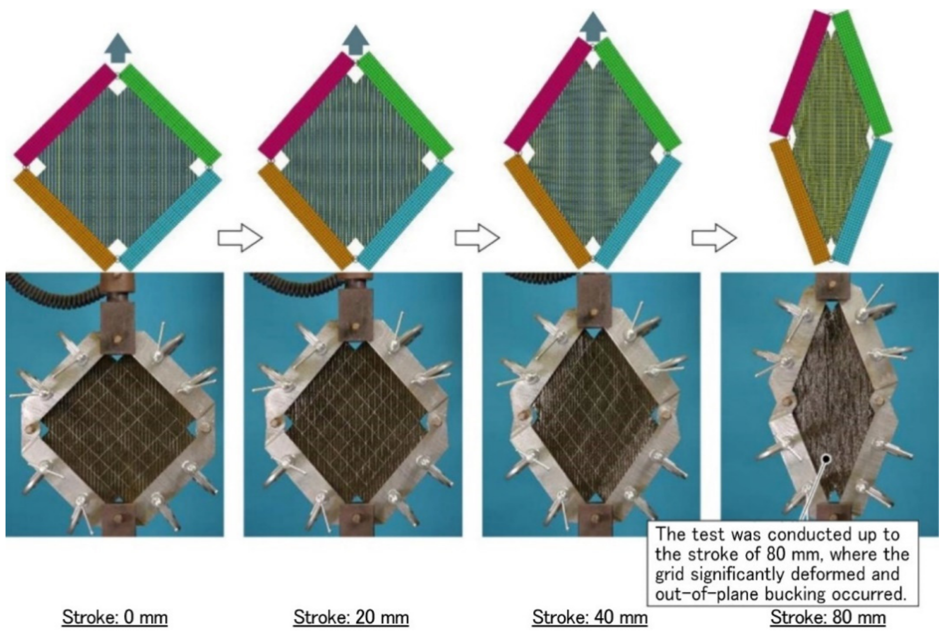

Figure 5 Result of comparison of NCF shapes between simulation and test

Figure 6 shows the results of comparison between the displacement of the NCF acquired by the DIC and the simulation. Although image simulation was not possible when the crosshead stroke was 40 mm or more due to collapse of the DIC coating, it was confirmed that the displacement in the X and Y directions of the five evaluation points acquired by the model simulation agreed with the test within an error range of ±20% in the range up to a stroke of 40 mm.

Figure 7 shows the reproduction of in-plane and out-of-plane wrinkles of the NCF at the stroke of 80 mm. At the initial phase of shear deformation, the fiber bundles were spaced at equal intervals, but as the deformation progressed, the significant opening/closing of fiber bundles and out-of-plane buckling observed in the test were reproduced. This behavior was not predictable by macroscale analytical models, demonstrating the superiority of the constructed mesoscale material model.

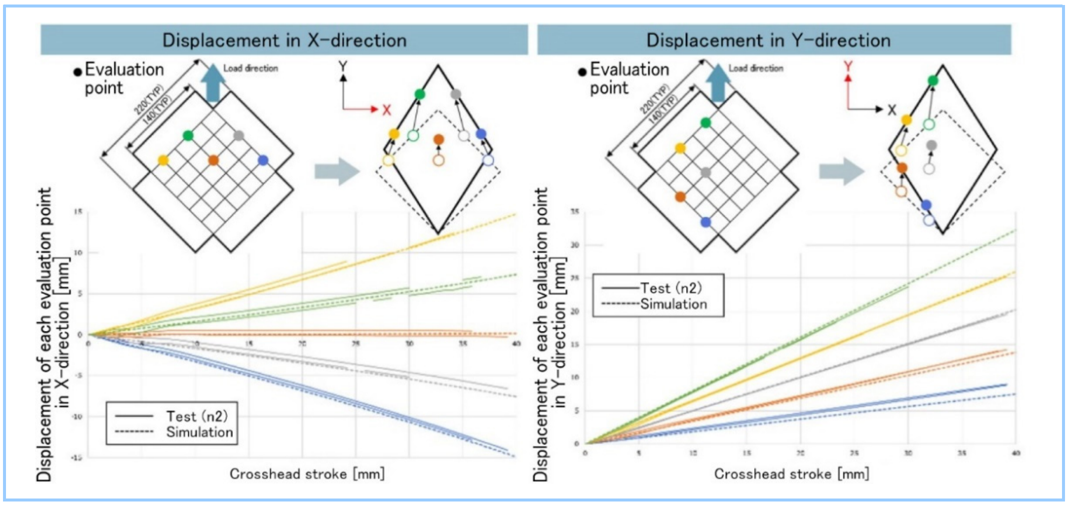

Figure 6 **Result of comparison of fiber bundle displacement between simulation and test**

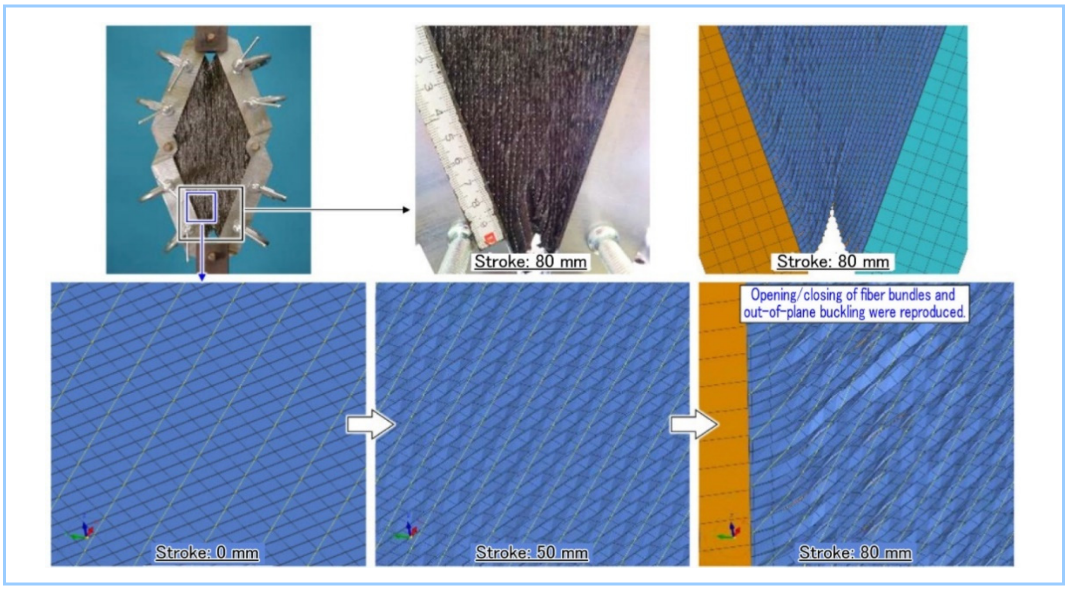

Figure 7 **Reproduction of in-plane and out-of-plane fiber wrinkles**

5. Conclusion

In the study presented in this report, we constructed a mesoscale material model consisting of three-dimensional solid elements for NCF fiber bundles and one-dimensional bar elements for stitch threads, and compared the results of picture frame test and analyses to verify the model. As a result, opening/closing of fiber bundles and out-of-plane buckling behavior were reproduced, and the applicability of the model to the prediction of formability of NCF materials was confirmed. In the future, after evaluating the accuracy of analysis and deriving material properties for deformation modes other than shear described in this report, such as for bending and compression, we will optimize the material configuration, including fiber bundle width, arrangement angle, and stitch positions, to improve the forming quality.

References

(1) J. Sirtautas et al., A mesoscopic model for coupled drape-infusion simulation of biaxial Non-Crimp Fabric, Composites: Part B, Vol.47 (2013), p.48-57