EFFECTS OF STITCHING PARAMETERS ON DAMAGE DEVELOPMENT FOR NON-CRIMP FABRIC COMPOSITES UNDER TENSILE LOADING

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Keywords: Non-crimp, Damage development, FEM, Stitching parameters

Abstract
In order to estimate stitching parameters on mechanical behaviors of NCF composites, test specimens had been prepared with changing the stitching parameters such as stitching pattern, pitch and direction. The static tensile test had been carried out and the data of acoustic emission and optical digital image with applied load have been accumulated. The small stitching pitch, stitching loop and narrow width of channel are effect to delay the occurrence of initial damage. We have also developed a simulation procedure of mechanical behaviours for NCF based on mesh superposition method and has been verified by the experiment data.

1 Introduction
Non-crimp fabric (NCF) composite is one of remarkable materials because it has some advantages such as the improvement of out-of-plane strength due to effects of stitching yarns. The stitching technology offers the potential for substantial weight and cost reduction in complex and highly loaded composite structures. On the other hand, several works have been reported in the literatures regarding FE-based model of NCF composites. Tserpes reported a meso-mechanical approach of NCF composite structural parts based on RVE (representative volume elements) and homogenized progressive failure analysis [1]. Himmel developed a FE based unit-cell model considering the thickness and fiber orientation of the layers and the shape and size of resin pockets [2]. Mikhaluk reported a multi-scale FE homogenization to obtain effective mechanical properties of NCF composites with account of resin-rich zones and various fiber volume fraction values [3]. However, there are few reports of the FE models of NCF with stitching yarns, because of the complicated geometry for stitching yarns and opening resin region. From these reasons, the effects of the stitching parameters on the damage development have not been investigated completely with numerical methods.
In order to estimate stitching parameters on mechanical behaviors of NCF composites, test specimens have been prepared with changing the stitching parameters such as stitching pattern, pitch, and direction. The tensile test has been carried out and the damage development has been investigated by the acoustic emission and the optical digital image.
Furthermore, the finite element model of NCF is generated and the numerical simulation has been carried out based on mesh superposition method which is one of the multi-scale analytical methods.

2 Static tensile test for glass NCF composites

2.1 Geometry of test specimens

The test specimen has been prepared as glass fiber / polyester composites. Figure 1 shows the stitching pattern and geometry of a specimen for NCF composites. The stitching pattern is a promat type, and the structure has the opening resin region due to the insertion of stitching yarns. It is clear that the shape is channel type by the observation of the specimens.

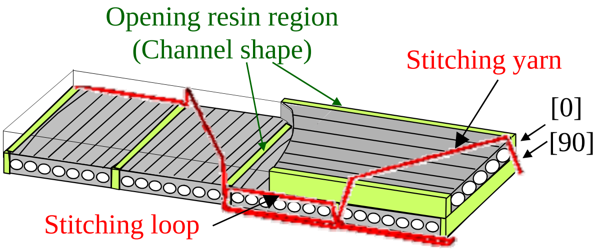


Figure 1. Geometry of NCF specimen with promat stitching

In order to estimate the stitching parameters on mechanical characteristics of NCF, the test specimens had been prepared with changing the several stitching parameters. The first parameter is a stitching pitch (2, 6 course) in Figure 2, the second is stacking sequence ([(0/90)s], [(90/0)s]) in Figure 3, and the last is the tensile direction (MD: machinery direction, CD: cross direction).

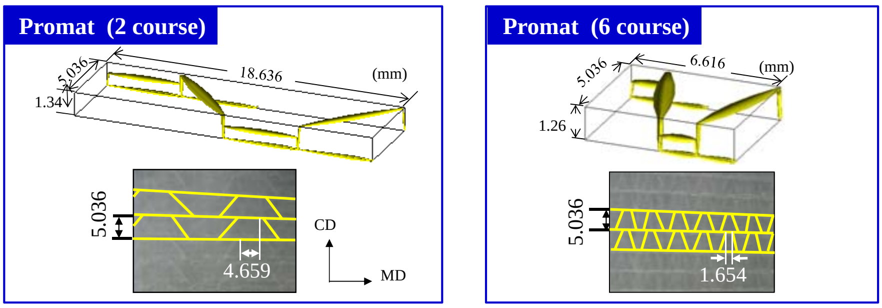


Figure 2. NCF composites with different stitching pitch

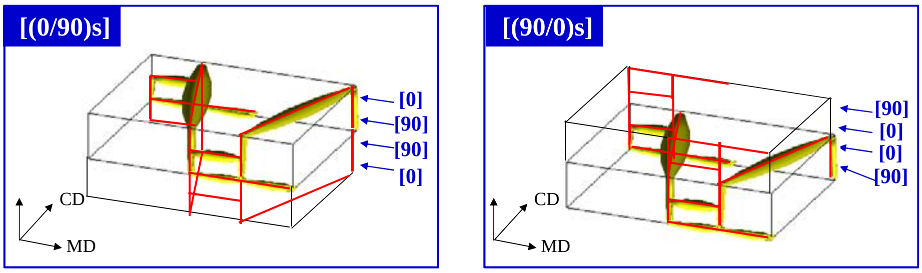
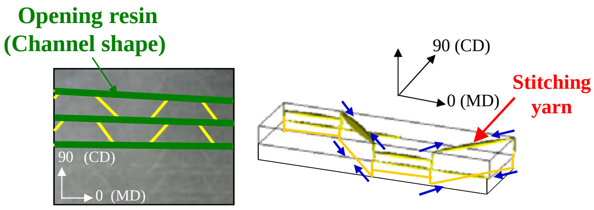


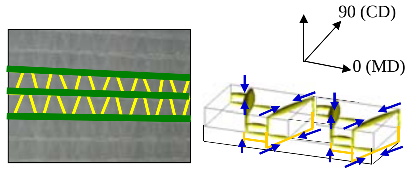
Figure 3. NCF composites with different stacking sequence

2.2 Geometry of opening resin region

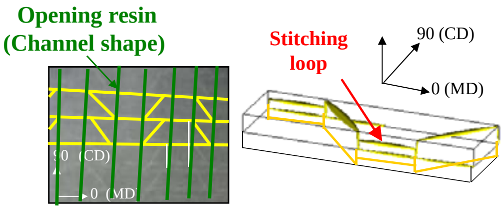
The geometry of opening resin region is measured by microscope. Figures 4, 5 show the observational results of geometry of opening resin region. The width of channel is quite different due to the stitching pitch. In [0] ply, the width in 6 course is wider than that of 2 course due to the tension force of stitching yarn as shown in Figure 4(b). On the other hand, the width of channel in 6 course is narrow due to the stitching pitch in the case of [90] ply. The volume fraction of fiber observed by microscope in each ply is shown in Figure 6. The volume fraction is almost 59%, however, there are high volume fraction in case of [0] ply (6 course) of [(0/90)s]MD and [90] ply (6 course) of [(90/0)s]CD due to the effect of opening resin region.



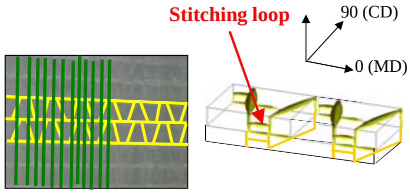
(a) [0] ply (2 course)



(b) [0] ply (6 course)



(c) [90] ply (2 course)



(d) [90] ply (6 course)

Figure 4. Geometry of opening resin region in [(0/90)s]MD

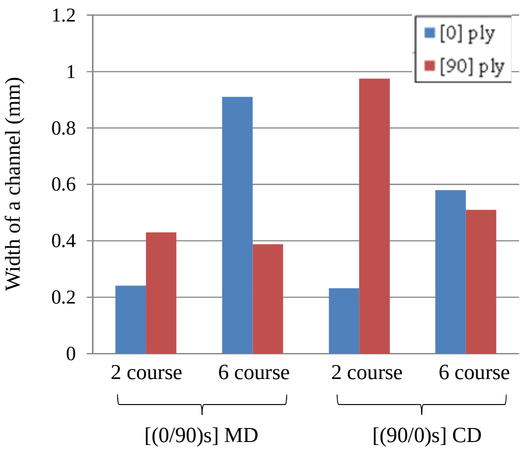


Figure 5. Width of channel resin

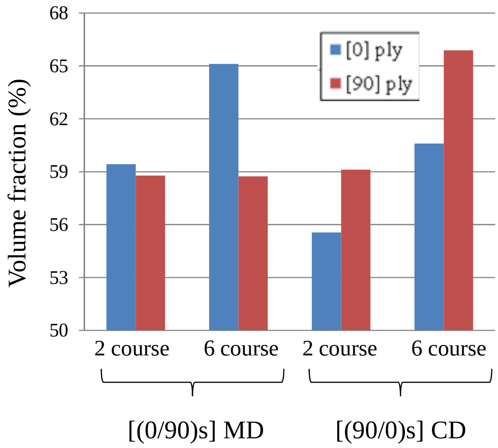
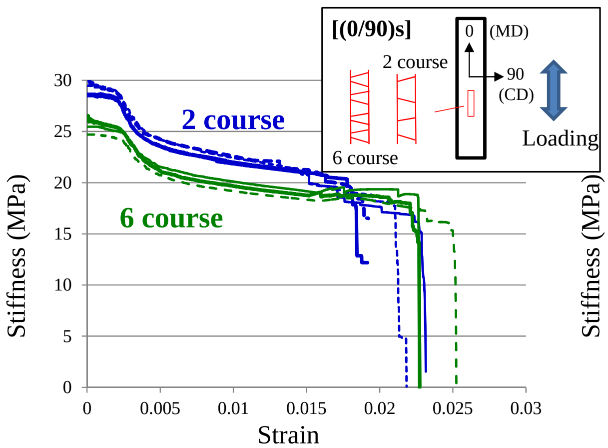
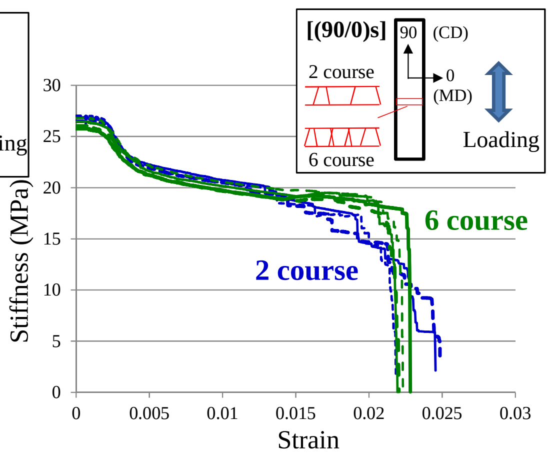


Figure 6. Volume fraction of fiber



(a) Case of [(0/90)s] MD



(b) Case of [(90/0)s] CD

Figure 7. Stiffness reduction

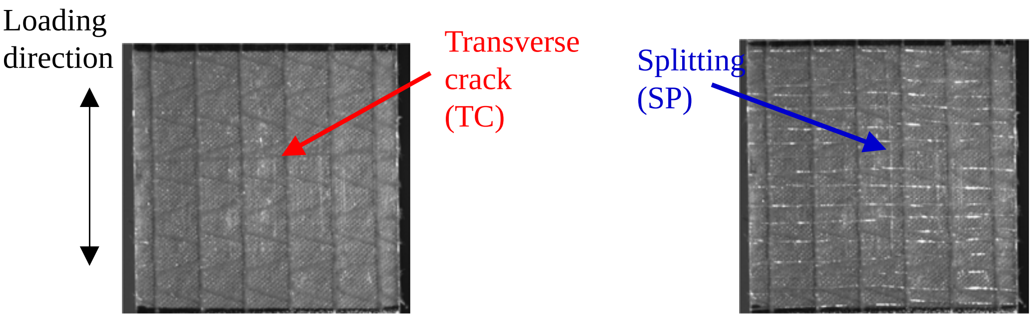
2.2 Stiffness reduction

Figure 7 shows the stiffness reduction with applied strain. In the case of [(0/90)s]MD, the initial stiffness and failure behaviors are quite different with the changing the stitching pitch.

In the case of [(90/0)s]CD, the initial stiffness with 2 and 6 course is same. But, the failure behaviors are different. To make clear the reason, the effects of geometry of opening resin region, stitching loop and volume fraction have to be taken into considered.

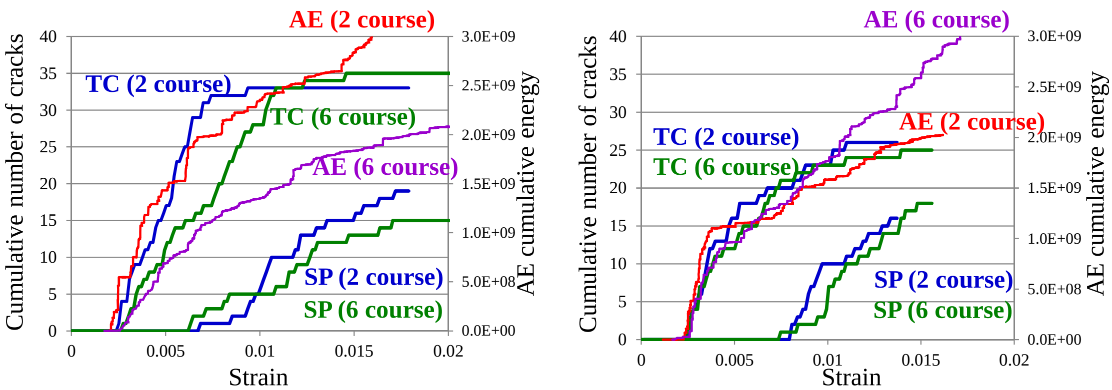
2.3 Damage development

The cracks had been counted with the images of In-situ observation. Figure 8 shows the images of damage development for [(0/90)s]MD (6 course). An initial damage of transverse crack has appeared under 0.275% strain, and sequential damage of splitting appeared toward to the loading direction under 0.687% strain. The relation between number of damages and strain is shown in Figure 9. The relation of cumulative energy of AE and strain is also shown in the figure. The tendency of the increase of transverse cracks and AE signals are almost same. In case of [(0/90)s] MD (6 course), the narrow width of channels in [90] play is generated the large strain of initial failure. Furthermore, the high density of stitching loop in perpendicular to the loading direction is effective to delay the occurrence of initial failure if the stitching pitch is small and the width of channel resin is narrow. And, the high density of stitching yarns and stitching loop are effective to the high strength.



(a) $\varepsilon = 0.275\%$ (b) $\varepsilon = 0.687\%$

Figure 8. Damage development by In-situ observation in case of [(0/90)s]MD (6 course)



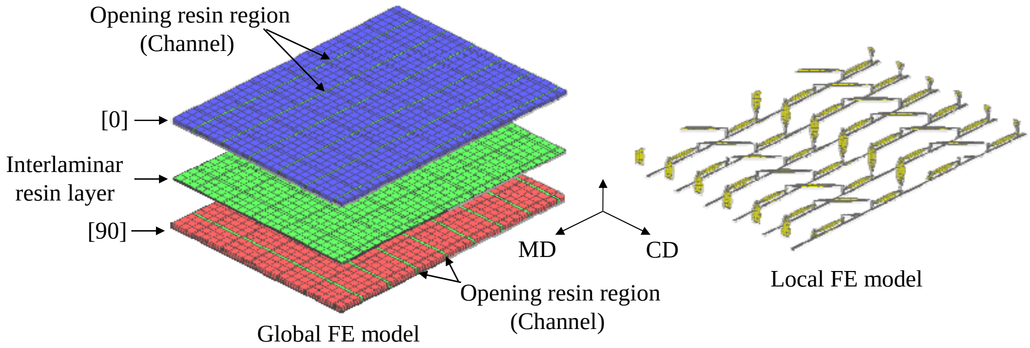
(a) Case of [(0/90)s] MD (b) Case of [(90/0)s] CD

Figure 9. Relation between number of cracks, AE energy and strain

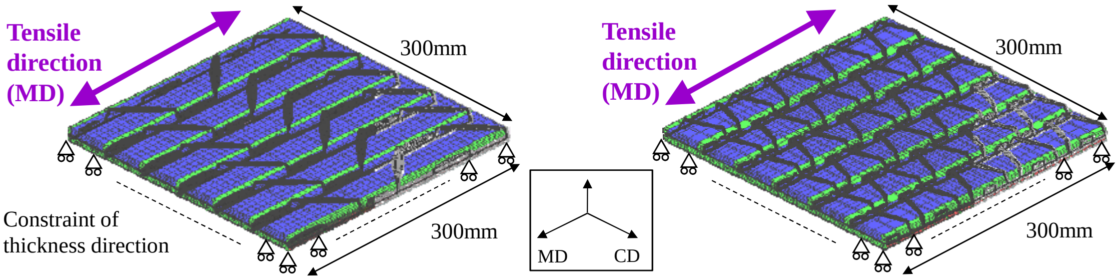
3 Numerical modeling and simulation for glass NCF composites

3.1 Numerical model based on Mesh superposition method

In order to estimate the effects of stitching parameters on mechanical properties of NCF, the geometrical data of NCF is generated by WiseTex[4]. FE mesh of NCF is implemented by MeshTex[5] which is the FE modeling software for fiber reinforced composites. Since geometry of NCF is complex, it is not easy to generate FE models integrally. Therefore, the stitching yarn part and laminates part are modeled individually. In order to consider the interaction of each part, the mesh superposition method is applied. Figure 10 shows the FE mesh of 2 and 6 course. NCF composites are treated as heterogeneous bodies with anisotropy for fiber bundles and with isotropy for matrix, respectively. The isotropic damage model is applied for matrix, and anisotropic damage model is applied for the fiber bundle, respectively [6]. The occurrence of damage can be predicted by Hoffman's criterion.

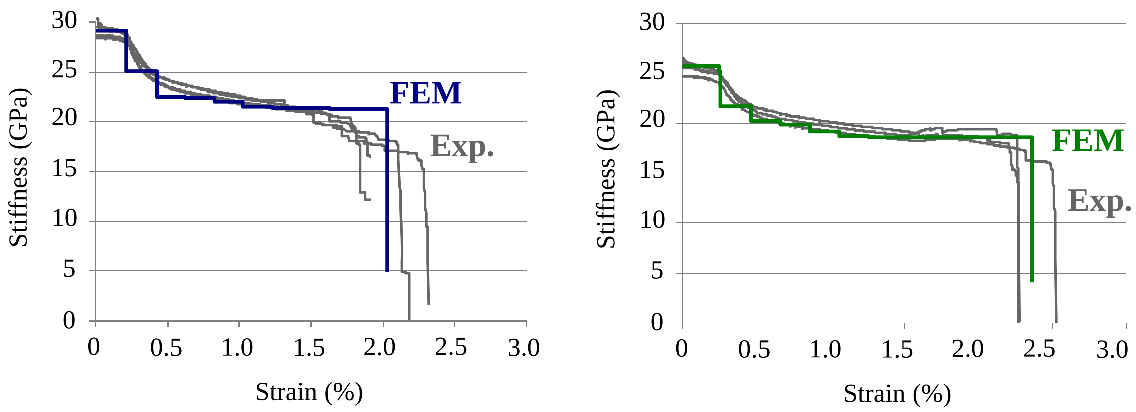


(a) Global and local FE model



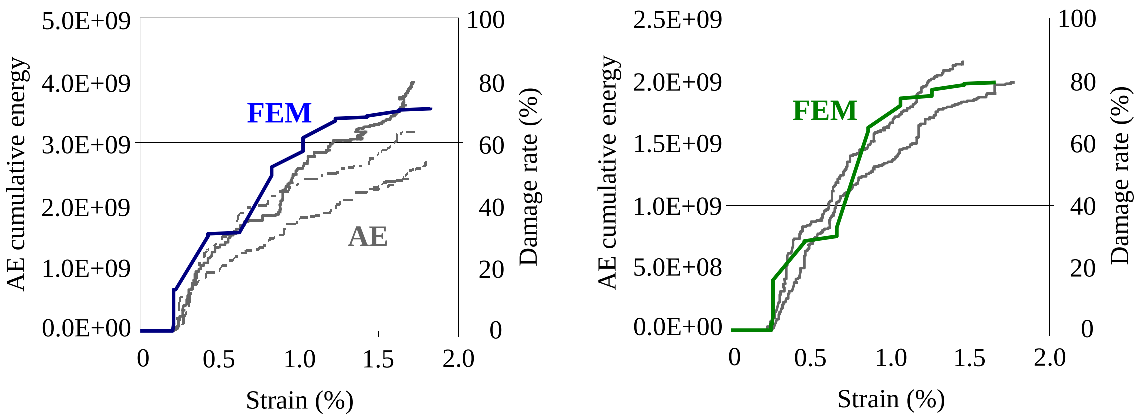
(b) 2 course (c) 6 course

Figure 10. FE mesh of NCF composites based on Mesh superposition method



(a) 2 course (b) 6 course

Figure 11. Comparison of stiffness reduction for numerical and experimental results in case of [(0/90)s]MD



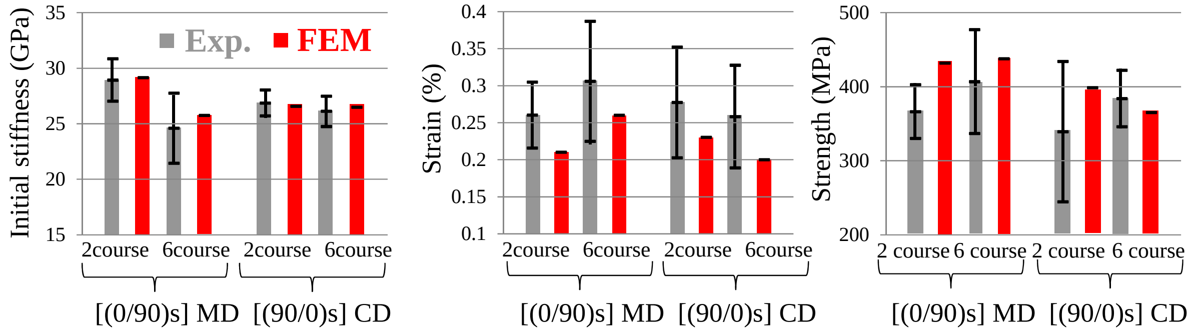
(a) 2 course (b) 6 course

Figure 12. Relation between AE cumulative energy and damage rate in [(0/90)s] MD

3.2 Numerical results

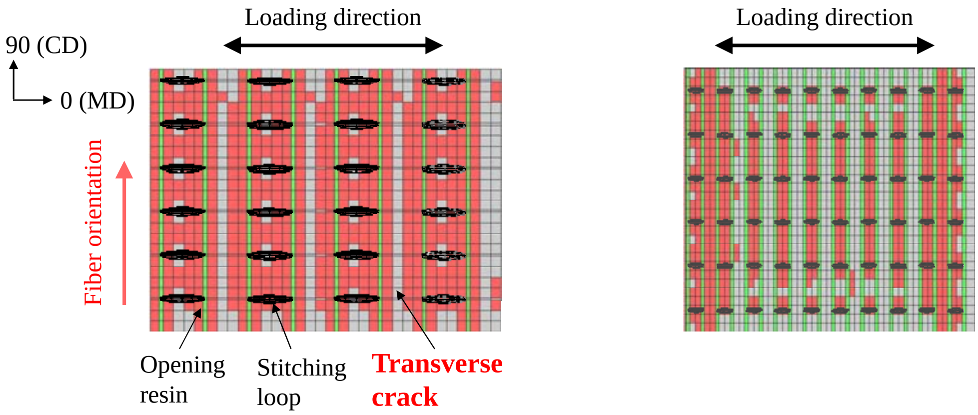
Figure 11 shows the comparison of stiffness reduction for numerical and experimental results in case of [(0/90)s] MD specimen. Both results are similar tendency. Figure 12 shows the relation between AE cumulative energy and damage rate. The damage rate means the volume ratio of damage elements to total elements obtained from FEM. The increase of damages with applied strain has similar tendency.

Figure 13 shows the numerical and experimental results of initial stiffness, strain of initial failure (transverse cracks), and strength. The scatter bar of experimental results means 95% confidence interval. The tendency of initial stiffness is almost same with numerical and experimental results.



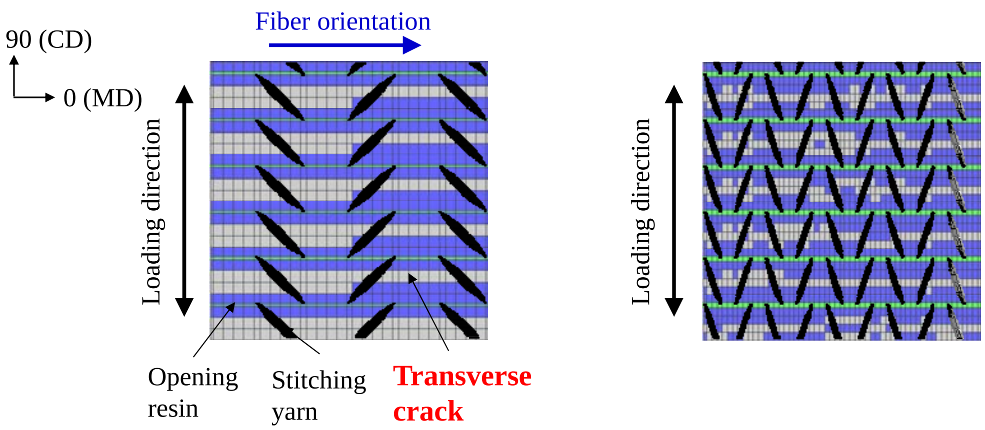
(a) Initial stiffness (b) Strain of initial transverse crack (c) Strength

Figure 13. Comparison of numerical and experimental results



(a) 2 course ($\varepsilon = 0.21\%$) (b) 6 course ($\varepsilon = 0.26\%$)

Figure 14. Damage development of initial transverse cracks for [90] ply in [(0/90)s] MD



(a) 2 course ($\varepsilon = 0.23\%$) (b) 6 course ($\varepsilon = 0.20\%$)

Figure 15. Damage development of initial transverse cracks for [0] ply in [(90/0)s] CD

As a comparison of 2 and 6 course, there is no large difference of final strength in Figure 13(c). But, the strain when initial transverse crack appeared is quite different in Figure 13(b). Figure 14 shows the initial damage state of [90] ply in [(0/90)s]MD model under tensile loading. The initial failure appeared from the outside of stitching loop in Figure 14(a)(b). And, high density of stitching loop in perpendicular to loading direction is effective to delay the occurrence of initial failure if the stitching pitch is small and width of channel resin is narrow as shown in Figure 14(b). Figure 15 shows initial damage states of [0] ply in [(90/0)s] CD model. If the width of channel resin is narrow as shown in Figure 15(a), the strain of initial transverse crack is large.

From these numerical results, the effects of the stitching parameters on the damage development can be estimated with FEM based on mesh superposition method.

4 Conclusions

In order to estimate stitching parameters on mechanical behaviors of NCF composites, experimental and numerical research had been carried out. The obtained remarks are as follows.

(1) Static Tensile Test for glass NCF composites

Stitching pitch and position of stitching loop affect the geometry of opening channel resin. The small stitching pitch, stitching loop and narrow width of a channel resin are effective to delay the occurrence of initial failure.

(2) Numerical modeling and simulation for glass NCF composites

The mesh superposition method is very effective for NCF with stitching yarns, because we can generate the FE meshes of stitching yarns, laminate and resin-rich region, individually. It has been revealed that the mesh superposition method can estimate the initial crack occurrence and the damage development with applied strain.

Acknowledgement

The authors would like to express our thanks to Fukui Fibertech Co., Ltd. (Japan) for their cooperation.

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