Effects of Stitching on Damage Development for Non-crimp Fabric Composites based on Multi-scale Analytical Method

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Abstract

In order to estimate stitching parameters on mechanical behaviors of non-crimp fabric (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 had been accumulated. The small stitching pitch, stitching loop and narrow width of channel were effective to delay the occurrence of initial damage. We had also developed a simulation procedure of mechanical behaviors for NCF based on mesh superposition method and had been verified by the experiment data.

Key Words: Mechanical property, Finite element analysis, Stitching, Polymer-matrix composite

1. Introduction

Non-crimp fabric (NCF) composites are remarkable materials because it has some advantages such as the improvement of delamination resistance, impact damage tolerance and out-of-plane stiffness of the laminate due to effects of stitching yarns [1, 2]. The need for an alternative to unidirectional pre-impregnated tape in high performance composites application led to the appearance of NCF composites [3]. The stitching technology offers the potential for substantial weight and cost reduction in complex and highly loaded composite structures.

Several research has been conducted concerning NCF and the composites, and the differences between their behavior and that of composites to those of UD prepregs or woven fabrics. Godbehere [4] compared the tensile properties of NCF composites to those of UD prepreg composites. Edgren [5] described the effect of the stitching parameters on the fatigue performance of several unidirectional NCF composites, and compared the results to the behavior of a UD prepreg laminate. Effects of stitching on mechanical response have been investigated, and the superior response is evident when stitched composites are subjected to out-of-plane loading such as impact and static loading [6-10]. The stiffness and strength of laminates loaded in quasi-static tension can be unaffected, increase or more common reduced by stitching [11, 12]. The characteristics of fatigue and post-fatigue behavior have been investigated [13], and the impact and post-impact properties for NCF composites have been estimated [14].

Several works have been reported in the literatures regarding FE-based model of NCF composites [15, 16]. Especially, Tserpes reported a meso-mechanical approach of NCF composite structural parts based on RVE (representative volume elements) and homogenized progressive failure analysis [17]. Heβ developed a FE based unit-cell model considering the thickness and fiber orientation of the layers and the shape and size of resin pockets [18]. 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 [19]. Moreover, some authors have developed 3D FE models of NCF composites with straight tows and with a rectangular cross-section [20-22].

As the knowledge of the results presented in literatures, textile composites have many parameters for design. In the case of NCF composites, there are many stitching parameters such as stitching pattern, stitching pitch, stacking sequence, kind of materials, loading direction and so on. Especially, the insertion of a stitching yarn leads to the generation of resin rich regions around the stitching yarn. The opening resin region may bring the stress concentration and initiation of damage, however, the estimation of damage development is difficult due to the effects of stitching.
yarns and opening resin region. Furthermore, it is also difficult to generate numerical models for NCF composites considering the geometry of opening resin region, stitching yarn, and laminates parts. From these reasons, the effects of the stitching on the damage development have not been investigated completely with numerical methods.

The present work aims to investigate effects of stitching parameters on damage development for glass NCF composites under static tensile loading. 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, we develop the numerical modeling and simulation for glass NCF composites based on mesh superposition method [23, 24] 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 E-glass fiber / polyester composites (Fukui Fibertech Corp.). Fig. 1 shows the stitching pattern and geometry of a specimen for NCF composites. The stitching pattern is a promat type which is one of the stiching types of tricot-chain, 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.

In order to estimate the stitching parameters on mechanical characteristics of NCF composites, the test specimens had been prepared with changing the several stitching parameters. The first parameter is a stitching pitch (2, 6 course) in Fig.2, the second is stacking sequence ([0/90]s), [(90/0)s]) in Fig.3, and the last is the tensile direction (MD: machinery direction, TD: transverse direction). The fiber bundles of several specimens were observed by a microscope. The average value of the width of the fiber bundle which means the stitching interval (TD) of both 2 and 6 courses was 5.00 (mm), and the stitiching intervals (MD) of 2, 6 courses were 5.00, 1.65 (mm) in Fig.2, respectively.

2.2 Geometry of opening resin region

The geometry of opening resin region is measured by microscope. Figs. 4, 5 show the observational results of geometry

![Fig. 1  Geometry of NCF specimen with promat stitching.](image)

![Fig. 2  NCF composites with different stitching pitch.](image)

![Fig. 3  NCF composites with different stacking sequence.](image)
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 Fig.4(b). On the other hand, the width of channel in 6 course is narrow due to the stitching pitch in [90] ply. The volume fraction of fiber in a bundle observed by microscope in each ply is shown in Fig.6. The volume fraction is almost 59%, however, there are high volume fraction in [0] ply (6 course) of [(0/90)s]MD and [90] ply (6 course) of [(90/0)s]TD due to effects of opening resin region.

2.3 Stiffness reduction

Fig. 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]TD, the initial stiffness with 2 and 6 course are 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. In the case of fine stitching (6 course), the width of channel resin in [0]ply is larger due to tension force of fine stitching yarns than that in [0] ply of coarse stitching (2 course) in Fig.4. Therefore, the volume of channel resin is larger, and the initial stiffness is lower as compared with the case of coarse stitching (2 course). On the other hand, in the case of transverse direction ([(90/0)s]TD), as the effect of width and number of channels on the volume of channel resin is small, there is little difference for the initial stiffness.

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![Diagram](image1)

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

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![Diagram](image2)

Fig. 5  Width of channel resin.

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![Diagram](image3)

Fig. 6  Volume fraction of fiber.
2.4 Damage development

The cracks had been counted with the images of In-situ observation. Fig. 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 Fig.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.

3. Numerical modeling and simulation for glass NCF composites

3.1 Numerical modeling 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 [25,26]. FE mesh of NCF is implemented by MeshTex [27] which is the FE modeling program for fiber reinforced composites. Since geometry of NCF is complex, it is difficult to generate FE models integrally. Therefore, the stitching yarn and laminate parts are modeled individually. In order to consider the interaction of each part, the mesh superposition method is applied in Fig.10.

### 3.2 Mesh superposition method

In the mesh superposition method, the stitching yarn is defined as local mesh, and laminate model is treated as the global mesh. The analytical area is divided into global area ($\Omega^G=\Omega^L\Omega^G$) and local area ($\Omega^L$) as shown in Fig.11. $\Omega^L$ is the area where only global mesh is exists, and $\Omega^L$ is the area determined both global mesh and local mesh. The boundary between two meshes is defined as $\Gamma_{GL}$, and surface forces affect the external boundary ($\Gamma^S$), because $\Omega^L$ is perfectly inside $\Omega^G$. On those assumptions, the stiffness equation is represented as shown in Eq.(1).

This method has some advantages. The local-mesh can be superimposed on a macro-mesh without considering the matching of boundary for each mesh.

$$\begin{bmatrix} [K^G] & [K^{GL}] \\ [K^{LG}] & [K^L] \end{bmatrix} \begin{bmatrix} [d^G] \\ [d^L] \end{bmatrix} = \begin{bmatrix} (F^G) \\ (F^L) \end{bmatrix}$$

(1)

Each argument in Eq.(1) is indicated with the following equations.

$$\begin{bmatrix} [K^G] = \int [B^G]'[D^G][B^G]d\Omega^G \\ [K^{GL}] = \int [B^L]'[D^L][B^G]d\Omega^G \\ [K^{LG}] = \int [B^G]'[D^L][B^L]d\Omega^G \\ [K^L] = \int [B^L]'[D^L][B^L]d\Omega^L \end{bmatrix}$$

(2)

Where, $[N]$ and $\{d\}$ have been shape function matrix and displacement respectively, and suffix G and L have represented the domain of global and local. $[B]$ is strain-displacement matrix, and $[D]$ is stress-strain matrix.

### 3.3 Numerical model

Fig. 12 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 [28]. The occurrence of damage can be predicted by Hoffman’s criterion.
3.4 Numerical results

Fig. 13 shows the comparison of stiffness reduction for numerical and experimental results in case of [(0/90)s] MD specimen. Both results are similar tendency. Fig. 14 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.

Fig. 15 shows the comparison of numerical and experimental results for 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.

As a comparison of 2 and 6 course, there is no large difference of final strength in Fig.15(c). However, the strain when initial transverse crack appeared is quite different in Fig.15(b). Fig. 16 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 Fig.16. 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 Fig.16(b). Fig. 17 shows initial damage states of [0] ply in [(90/0)s]TD model. If the width of channel resin is narrow as shown in Fig.17(a), the strain of initial transverse crack is large.

![Damage rate (FEM)](image)

**Fig. 14** Relation between AE cumulative energy and damage rate in [(0/90)s] MD.

![Comparison of numerical and experimental results](image)

**Fig. 15** Comparison of numerical and experimental results.

![Damage development of initial transverse cracks](image)

**Fig. 16** Damage development of initial transverse cracks for [90] ply in [(0/90)s] MD.
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 geometrical models of NCF composites are determined by WiseTex, and FE models are generated by MeshTex. FE meshes of stitching yarn and laminates with resin-rich region are modeled and the mesh superposition method is applied to FE analysis. The mesh superposition method is very effective for NCF with stitching yarns and opening resin region, 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.

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