Estimation of Mechanical Behavior of Non-crimp Fabric Composites With an Open Hole Based on Mesh Superposition Method

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Abstract

The stitching yarn of Non-crimp fabric (NCF) composites brings the improvement of out-of plane strength and intricate microscopic structure. In order to estimate the effect of position of a hole and opening resin region on damage development of NCF composites conveniently, a new modeling of NCF composites with a circular hole is proposed based on the mesh superposition method. The laminate parts and a hole part were modeled individually, and the mechanical behaviors under static tensile loading was estimated. As the numerical results, the effects of opening resin region and a hole on the damage had been estimated with the proposed mesh superposition method. And it is revealed that the proposed numerical modeling method is useful for design of the products composed of NCF composites.

1. Introduction

1.1 FE modeling of NCF composites

Non-crimp fabric (NCF) composites are made by molding reinforced fiber laminates which are stitched by stitching yarn. The NCF composite is one of remarkable materials because it has some advantages such as the improvement of out-of-plane strength and impact resistance due to the effects of stitching yarns. The stitching technology offers the potential for substantial weight and cost reduction in complex and highly loaded composite structures. Several works have been reported in the literatures regarding FE based model of NCF composites.

Tserpes et al. reported a meso-mechanical approach of NCF composite structural parts based on RVE (representative volume elements) and homogenized progressive failure analysis [1]. Himmel et al. developed a FE based unit-cell model considering the thickness and fiber orientation of the layers and the shape and size of opening resin region [2]. Mikhaluk et al. reported a multi scale FE homogenization to obtain effective mechanical properties of NCF composites with account of opening resin region and various fiber volume fraction values [3]. The previous research about mechanical characterization of woven fabric composites established theoretical and experimental investigations, which were based on mechanical behavior at macro scale as “composite part scale” [4,5,6]. In order to evaluate fiber cracking, resin failure, delamination which relate to meso and micro scale structures, recent studies have tried to generate more detailed FE models based on meso scale which means “fiber geometric scale” and micro scale which means “filament scale” [7]. However, NCF composites and woven composites have many design parameters such as stitching pattern, volume fraction, architecture of reinforced fibers, matrix properties, etc. Furthermore, it is very difficult to evaluate the mechanical behaviors because of the complicated geometrical shape like opening resin region.

1.2 Purpose and the proposed method

We propose a numerical analysis method for NCF composites which have an open hole. Many applications require a notch for joining of a NCF composite either to another NCF composite or to metal, which is often fastened by bolts. It is very difficult to evaluate the mechanical characterization of notched NCF composites not only their heterogeneous characteristics, complicated structures but also stress concentration around the hole. For evaluation of mechanical property of NCF composites with several parameters, FEM is one of the effective methods in order to reduce the development times and the costs, but it is laborious to make some FE models for evaluate interaction between a hole and opening resin region. A new modeling method is needed that can change the position of a hole conveniently.

Therefore we propose a numerical method by using mesh superposition method. In the proposed method, a laminate model and a hole model are generated individually. The continuous model of NCF GFRP with a hole as the conventional model, and the super imposed model which is consisted of global model (laminate with opening resin region) and local model (a hole part) are generated. By using two models, the mechanical behaviors under static tensile loading are estimated.

2. Verification of mesh superposition method

2.1 Mesh superposition method

Mesh superposition method has some advantages. The local mesh can be superimposed on a macro mesh without considering the matching of boundary for each mesh. In the mesh superposition method, the analytical area is divided into global area ($\Omega^G=\Omega-\Omega^L$) and local area (Ω^L) as shown in Figure 1. Ω^G is the area where only global mesh exists, and Ω^L is the area determined both global mesh and local mesh. The boundary between two meshes is defined as Γ^{GL}, and surface forces affect not Γ^{GL} but only the external boundary (Γ^S), because Ω^L is perfectly inside Ω. On the assumptions, the stiffness equation is represented as shown in Equation (1).

$$\begin{bmatrix} [K^G] & [K^{GL}] \\ [K^{LG}] & [K^L] \end{bmatrix} \begin{Bmatrix} \{d^G\} \\ \{d^L\} \end{Bmatrix} = \begin{Bmatrix} \{F^S\} \\ \{0\} \end{Bmatrix} \tag{1}$$

Each component in Equation (1) is indicated with the following equations.

$$[K^G] = \int_{\Omega^G} [B^G]^T [D^G][B^G] d\Omega + \int_{\Omega^L} [B^G]^T [D^L][B^G] d\Omega \tag{2}$$

$$[K^L] = \int_{\Omega^L} [B^L]^T [D^L][B^L] d\Omega \tag{3}$$

$$[K^{GL}] = \int_{\Omega^L} [B^G]^T [D^L][B^L] d\Omega \tag{4}$$

$$[K^{LG}] = \int_{\Omega^L} [B^G]^T [D^L][B^L] d\Omega = [K^{GL}]^T \tag{5}$$

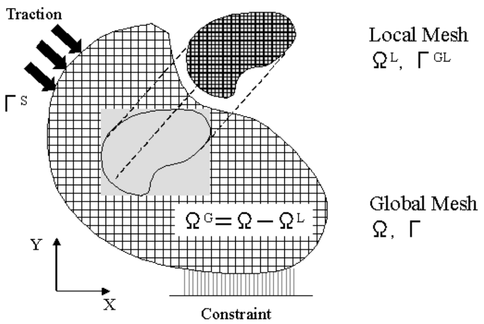
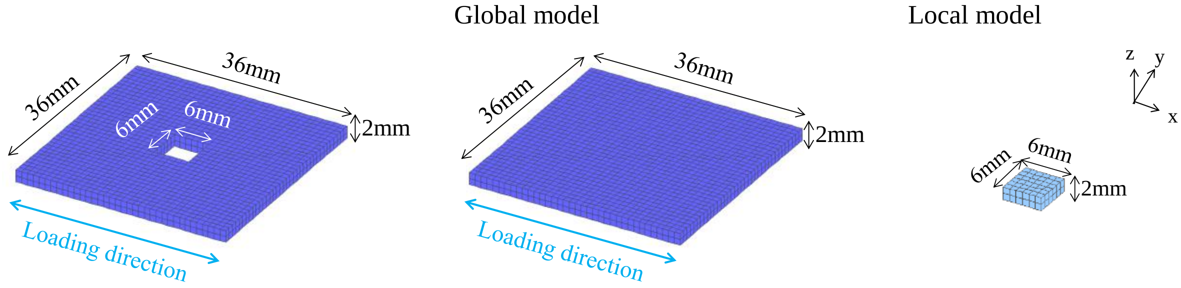


Figure 1. Definition of analytical area for mesh superposition method on structural analysis

2.2 Numerical model of resin plate with a hole

To verify the mesh superposition method with conventional FEA method, the numerical models of a resin plate with a hole are prepared. In the superposition method, the laminate part is treated as global mesh and a hole part is treated as local mesh. The hole part is regarded as a geometry of a column, and the elastic modulus of local mesh is extremely small. In the previous study, there is no verification of differences of elastic modulus between global mesh and local mesh. In this paper, the ratio of elastic modulus of local model (E_L) and that of global model (E_G) on the mechanical properties of the plate is investigated.

As the verification, an isotropy resin plate model which has a square hole was used. In Figure 2, two models are generated. One is the continuous model of resin plate with a square hole as the conventional FE model. The other is the superimposed model which is consisted of global model (resin plate without a hole) and local model (a square hole part). The properties of resin part is applied that of polyester. In the superimposed model, the local models are generated as $E_L/E_G=10^{-1}, 10^{-3}, 10^{-5}, 10^{-7}, 10^{-8}, 10^{-9}, 10^{-10}$. The mechanical behavior is estimated under tensile loading for x-axis direction.



(a) Continuous model (b) Superimposed model

Figure 2. The models of verification of mesh superposition method

2.3 Results of numerical analysis

Initial stiffness is evaluated by relative difference which uses the stiffness of continuous model (S_C) and that of proposed (superimposed) model (S_P) in Equation (6).

$$d = \frac{S_P - S_C}{S_c} \times 100\ (\%) \tag{6}$$

Figure 3 shows the results of relative difference. If E_L/E_G is more than 10^{-3}, the difference is too large. On the other hand, when if E_L/E_G is less than 10^{-8}, the analysis isn't finished because of numerical error. As the results, it is considered that the elastic modulus of local model could be selected in the range of $E_L/E_G=10^{-5}$~10^{-7}.

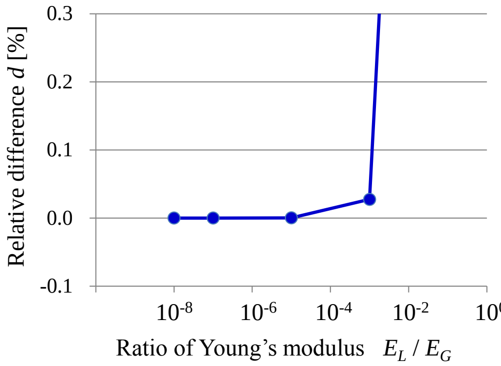


Figure 3. Relative difference of verification of mesh superposition method

Furthermore, stress distributions around a hole are measured as shown in Figure 4. Figure 5 shows the results of stress on A-B line and C-D line in Figure 4. As the results, the stress distributions of the proposed method is effective if E_L/E_G is in the range of 10^{-5} to 10^{-7}.

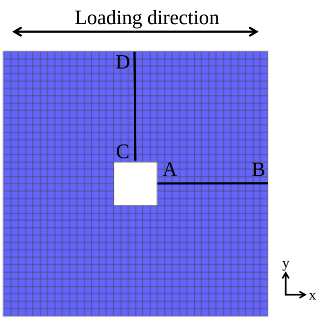
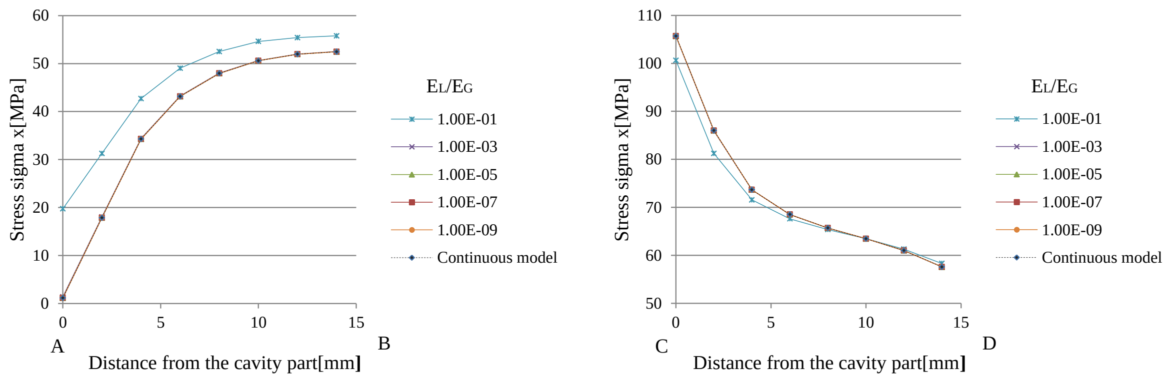


Figure 4. Measurement range of stress distribution



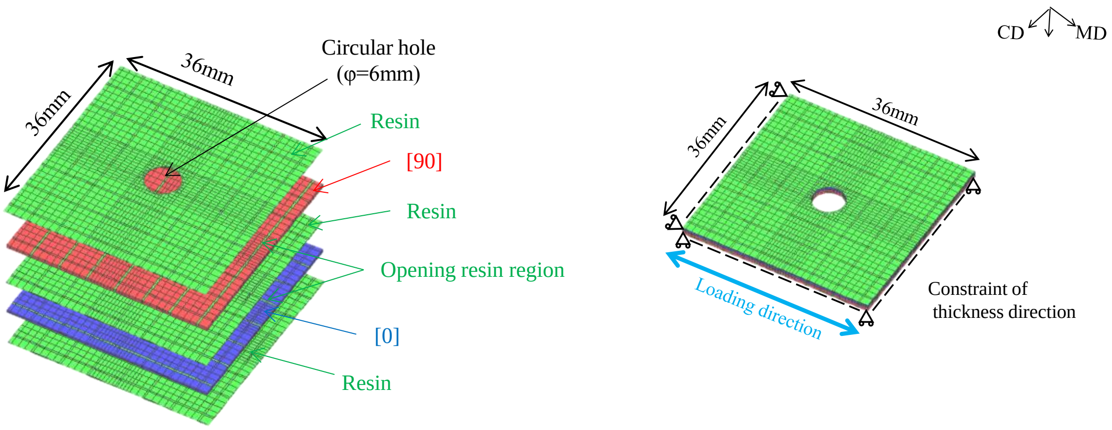
(a) A-B (b) C-D

Figure 5. Results of stress distribution

3. Evaluation of proposed method for laminate of NCF composite with a circler hole

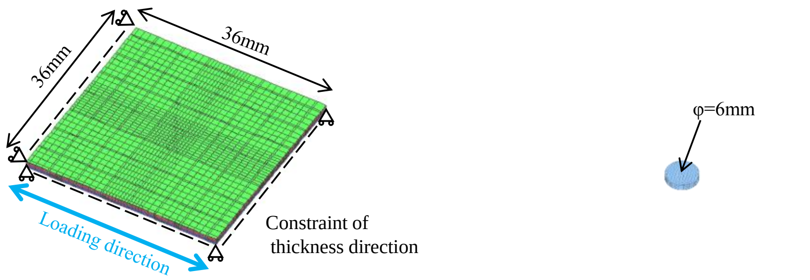
3.1 Numerical model

In order to evaluation of proposal method, two numerical model are generated. One is the continuous model as the conventional model which is NCF GFRP laminate with a hole. The other is super imposed model which is consisted of global model (laminate with opening resin region) and local model (a hole part). The geometry and boundary condition of the continuous model are shown in Figure 6. As the boundary condition, the model is laminated symmetrically by considering the constraint of thickness direction. This continuous model has been verified integrity between experiments. Figure 7 shows the super imposed model. The scale of the global model is the same with the continuous model. Material properties are shown in Table 1.



(a) Structure of laminate (b) Boundary conditions

Figure 6. FE model of continuous model



(a) Global model (b) Local model

Figure 7. Super imposed model

	Global			Local
	[0]ply	[90]ply	Resin	
Volume fraction of fiber[%]	65.40	60.30	-	-
Longit. Modulous[GPa]	56.19	49.17	6.40	1.00E-06
Transv.Modulous[GPa]	27.86	20.78		
Longit. Shear modulous[GPa]	11.89	9.19	2.37	3.7E-07
Ttansv. Shear modulous[GPa]	10.66	7.88		
Longit. Poisson's ratio	0.17	0.13	0.35	0.35
Transv. Poisson's ratio	0.13	0.11		
Longit. Tens. Strength[MPa]	1883.76	1619.30	88.26	1.00E+05
Transv. Tens. Strength[MPa]	44.88	48.05		
Longit. Comp. Strength[MPa]	7836.72	5914.04	117.70	1.00E+05
Transv. Comp. Strength[MPa]	59.85	64.08		
Shear strength[MPa]	29.92	32.04	88.26	1.00E+05

Table 1. Material properties

3.2 Results of numerical analysis

The numerical analysis of tension test is carried out based on enforced displacement in the direction of machinery direction (MD). Figure 8 shows numerical results of stiffness reduction for the continuous model, the super imposed model and results of experiments. It is confirmed that the stiffness reduction of the super imposed model is similar to that of the continuous model until ε=1.0%. As compared with the results of the analysis and the experiments, it can be regarded that the numerical results are in the variability of the experiments until ε=0.3% which means the occurrence of initial damage. As the results, the proposed method is effective to estimate the initial stiffness and the behavior of initial damage.

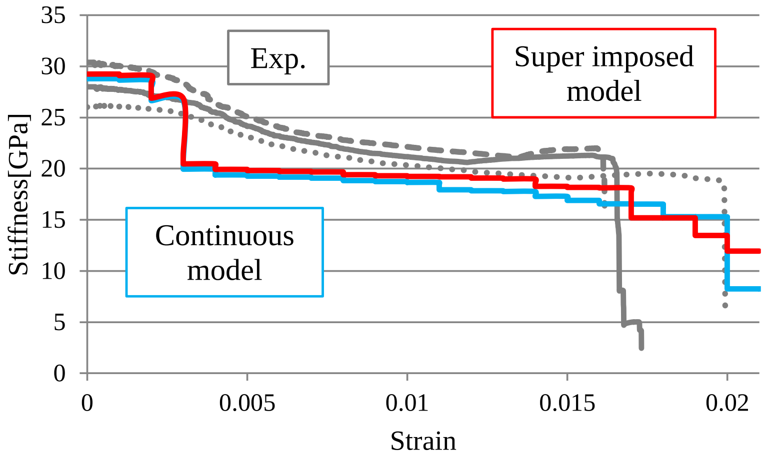
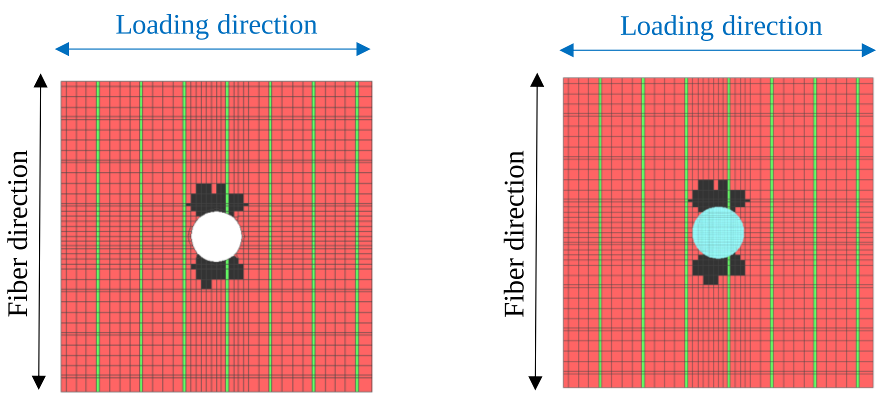


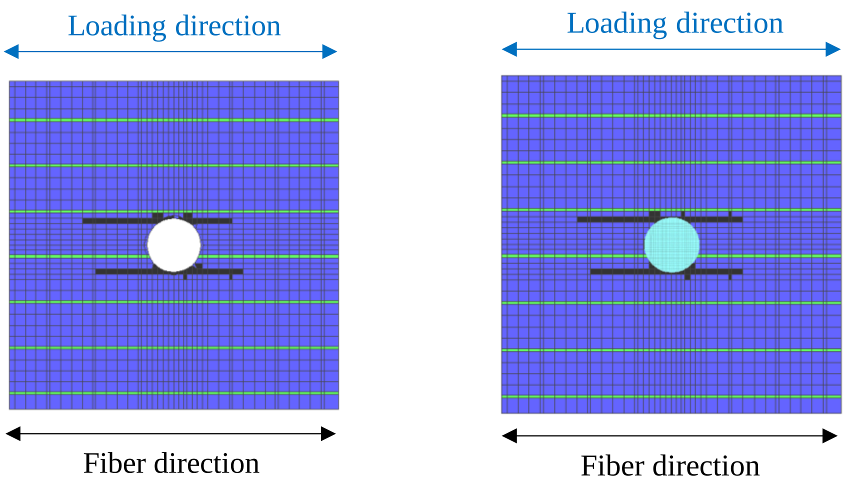
Figure 8. Results of stiffness reduction

Furthermore, in order to verify the correctness of proposed method, damaged elements of initial damage area are investigated. Figure 9 shows the damaged elements of the [90] ply at ε=0.2%, and Figure 10 shows the damaged elements of the [0] ply at ε=0.3%. The black color of Figure 9 means the transverse crack damage and that of Figure 10 means the splitting damage. As compared with the continuous model and the super imposed model, it is confirmed that distribution of damaged elements is same tendency on each model. It is verified that proposed method is effective for damage-tolerant design for NCF composites with a hole.



(a) Continuous model (b) Super imposed model

Figure 9. Damaged elements of the [90] ply at ε=0.2%



(a) Continuous model (b) Super imposed model

Figure 10. Damaged elements of the [0] ply at ε=0.3%

4. Conclusions

We proposed a new FE analytical method for NCF composites which have an open hole by modeling the laminate part and the hole part individually and using mesh superposition method. Firstly, the tolerance for elastic modulus ratio of global and local model (E_L/E_G) by using a isotropy resin plate model is verified. As the results, the elastic modulus of local model could be selected in the range of $E_L/E_G=10^{-5}$~10^{-7}. Secondly, the laminate model of NCF composite with a hole is used to verify this method. As the results, the proposed method is effective for damage-tolerant design of NCF composites with a hole. From the results, it has been revealed that the proposed numerical modeling method is useful for designing NCF composites.

References

[1] Tserpes, K.I., et al., Mesomechanical analysis of non-crimp fabric composite structural parts, Composite Structures, 87, (2009), 358-369.
[2] Himmel, N., et al., Elastic constants estimation of stitched NCF CFRP laminates based on a finite element unit-cell model, Composites Science and Technology, 67, (2007), 1081-1095.
[3] Milhaluk, D.S., et al., Experimental observations and finite element modelling of damage initiation and evolution in carbon/epoxy non-crimp fabric composites, Engineering Fracture Mechanics, 75, (2008), 2751-2766.
[4] U.A. Khashaba, M.A. Seif, Effect of different loading conditions on the mechanical behavior of [0/±45/90]s woven composites, Composite Structures, 74, (2006), 440–448.
[5] M. Khoshbakht, S.J. Chowdhury, M.A. Seif, U.A. Khashaba, Failure of woven composites under combined tension-bending loading, Composite Structures 90, (2009), 279–286.
[6] Jang-Kyo Kim, Man-Lung Sham, Impact and delamination failure of woven-fabric composites, Composites Science and Technology, 60, (2000), 745-761.
[7] Lomov, S.V., Textile composites: modelling strategies, Composites Part A: applied science and manufacturing, (2001), 1379-1394.