A NUMERICAL SIMULATION OF DAMAGE DEVELOPMENT FOR LAMINATED WOVEN FABRIC COMPOSITES

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ABSTRACT

Laminated woven fabric composites may induce better resin impregnation and mechanical properties than the conventional uni-directional laminates. However, cross sections and shapes of fiber bundles change at the cross-over parts of bundles, and the effects of a change of geometry of fiber bundles on the damage development had not been investigated. Therefore, we have developed the simulation program of mechanical behaviors for woven composites based on damage mechanics. A FE mesh generator and the simulation technique of mechanical behaviors of laminated woven fabric FRP considering the changes of shape of fiber bundles and volume fractions caused by nesting have been developed. As the numerical results, the initial stiffness showed same tendency at each numerical model, however, the location of damage and the propagation is quite different due to the effect of shape and scale of fiber bundles. From these results, the mechanical behaviors of laminated woven composites can be estimated with the proposed method.

KEYWORDS: woven fabric composite, finite element modelling, damage development, numerical simulation, damage mechanics

1. INTRODUCTION

Woven fabric reinforced plastics have been applied widely to many structures, because they have some advantages like easy handling, high lateral strength, etc. Woven fabric laminate consist of a pile of woven layers with a resin. It is difficult to control the layout of each lamina, so, the relative position of crimped yarns in layers is disordered. However, an effect of the disorder on the mechanical properties of woven fabric composites has not been completely investigated. Furthermore, woven composites have many design parameters such as volume fraction of fiber, architecture of reinforced fibers, the mechanical properties, etc. There are some problems as cost and protracted development period for airplanes and vehicles that must perform reliability evaluation by experiments with a real scale. And, the practical modelling technique and the systematization considering the complicated non-homogeneity of woven composites have not been developed completely.

Furthermore, the estimation of damage development is very difficult, because matrix cracks and delamination at the crossover parts of fiber bundle may occur leading to complicated fracture modes in comparison with uni-directional fiber reinforced composites. If damages can be estimated with numerical simulation, it will become very useful tool for the estimation of mechanical properties of woven fabric composites.

To solve the above difficulty, we have developed a numerical simulation program on damage development of woven composites based on damage mechanics [1]. A tensile test and a fatigue test for a lamina of woven fabric composites with In-site observation had been carried out [2]. Though the effect of a disorder of pile-up for woven

composites laminate on damage development had been investigated, the effects of a cross section and shape of fiber bundles on the damages had not been considered [3].
In this paper, we have developed the simulation program of mechanical behaviors for woven composites. The proposed numerical method consists of three parts, which are FEM modelling, numerical method, and damage states for the safety evaluation, respectively. The numerical procedure and results are described.

2. FLOW OF NUMERICAL SIMULARION OF WOVEN COMPOSITES

It is not easy to illustrate the geometry of textiles from the weave diagram or mechanical property of a yarn. In order to solve this problem, Lomov has developed 'WiseTex' program [4]. The topology of a weave architecture is determined by the input data like a filament diameter, the architecture of strand, etc. based on WiseTex program. The structural model of internal geometry of the fabrics is generated by *WiseTex* software. By using the data obtained by WiseTEX, FE model with yarns and matrix by the hexahedron element is generated by the developed numerical modelling program 'MeshTEX'[5]. The deformation and stress distribution can be evaluated by the generated mesh model and FEM software (SACOM). Figure 1 shows the scheme of the structure analysis of woven composites by the proposed numerical simulation method.

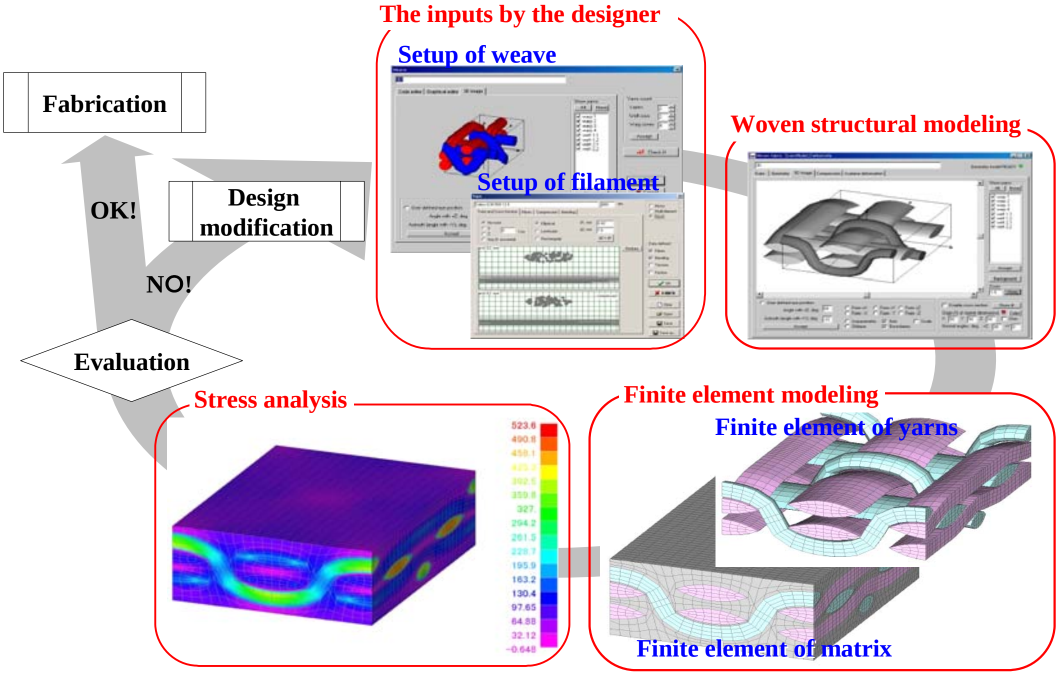
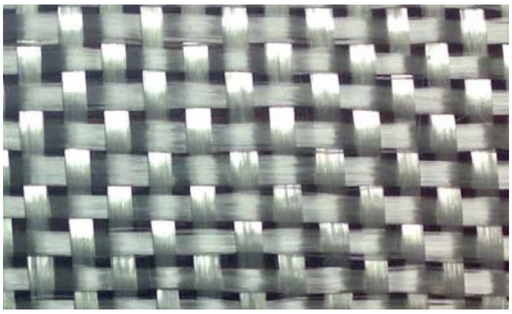


Fig.1 Scheme of numerical procedure for mechanical behaviors of woven composites

3. OBSERVATION OF CROSS SECTION OF FIBER BUNDLES

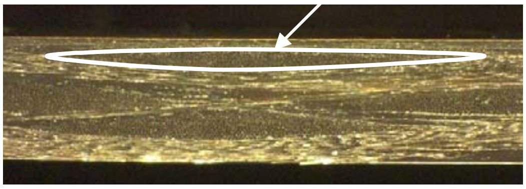
Before the simulation, we had checked the geometry of each layer for woven composites. Test specimens are cut out of laminate of woven GFRP, and the shape of specimen is rectangular. The laminate is fabricated by the hand-lay up method, using polyester resin reinforced by E-glass woven cloth fabric in Fig.2(a) with three layers. The width of a fiber bundle is 2mm, and the pitch between bundles is 3.5mm. In order to estimate effects of nesting on the damage development, the three layers are laminated with disorder as shown in Fig.2(b). The weft bundles have shifted to half-pitch, and the warp has not shifted.



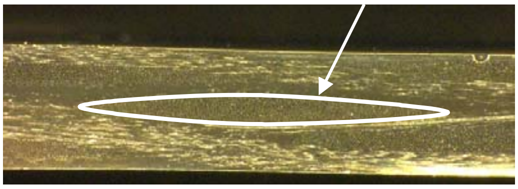
(a) E-glass woven fabric

(b) Cross section of specimen with nested structure

Fig.2 Test specimens of Woven GFRP



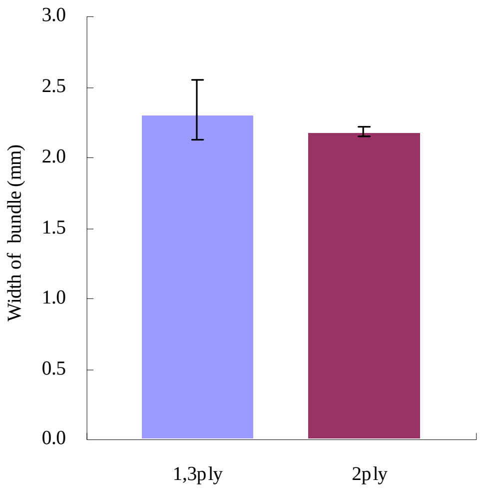
(a) Fiber bundle in outer layer



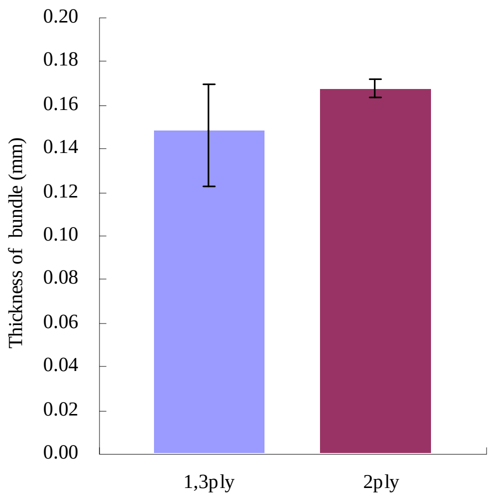
(b) Fiber bundle in central layer

Fig.3 Cross section of laminated woven composites

Figure 3 shows the observational results of test specimen for laminated woven composites with disorder fabricated by E-glass and polyester resin. The fiber bundles approximately indicated the shape of ellipse. There is a difference of the width and thickness of the ellipse in outer and central layers as shown in Fig.3. The major axis of a fiber bundle in outer layer is larger than that of central layer. On the other hand, the minor axis in outer layer tends to be smaller than that of central layer. Figure 4 shows the observational results of width and thickness of a bundle. The difference of width between outer and central layer is about 18%, and the difference of thickness is about 17%. We consider that this deference can not be ignored to estimate the mechanical behaviors of woven FRP.



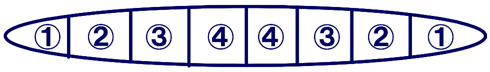
(a) Width of a bundle



(b) Thickness of a bundle

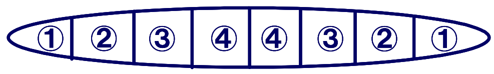
Fig.4 Observational results of width and thickness of bundles

Furthermore, the volume fraction in a fiber bundle has been measured by the digital image processing based on observational results. Figure 5 shows a cross section of the fiber bundle by SEM. From the image data of a cross section of fiber bundles in Fig.3, the volume fraction inside a fiber bundle can be evaluated with an image process. In case of a woven FRP, volume fraction is distributed in a fiber bundle. The center part in it has the highest volume fraction and edge parts have lower value. The tendency is same as the results of previous paper.



①	Vf=60.85%
②	Vf=63.10%
③	Vf=65.26%
④	Vf=74.87%

(a) Fiber bundle in outer layer



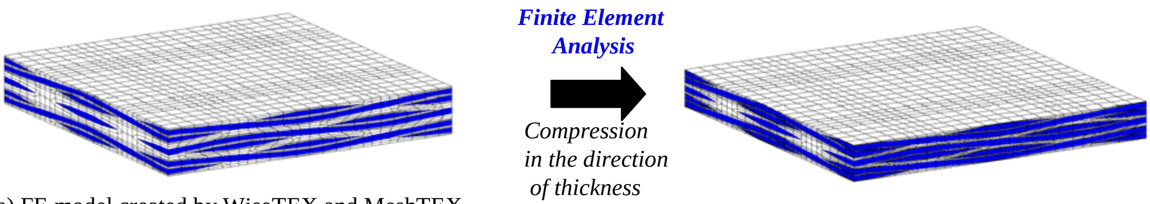
①	Vf=60.78%
②	Vf=63.24%
③	Vf=65.36%
④	Vf=72.40%

(b) Fiber bundle in central leyer

Fig.5 Distribution of volume fraction of fiber

4. FEM MODELING OF LAMINATED WOVEN COMPOSITES

To estimate the real shape and scale of fiber bundles in woven architecture on the damage development, the numerical model are generated. The procedure is as follows. Firstly, the structural model of internal geometry of the fabrics is generated by *WiseTex* software. By using the data obtained by WiseTEX, FE model with yarns and matrix by the hexahedron element is generated by MeshTEX program. Finally, we can get the laminated FE models by FE analysis of compressive deformation as shown in Fig.6.



(a) FE model created by WiseTEX and MeshTEX

(b) Unit mesh model

Fig.6 Finite element model for laminated woven composites

We have prepared three numerical models. One is a model (A) which means the real-scale structure for test specimen in Fig.7. As the comparison, a model (B), which the topology of fiber bundles at every layer is same with outer layer of model (A), was created. Furthermore, a model (C) was also prepared, which layer is same with central layer in model (A). The mechanical properties at each divided part of a bundle in Fig.5 were calculated. A fiber bundle is treated as uni-directional fiber reinforced composites, and the mechanical properties can be calculated by the rule of mixture based on the obtained volume fractions. Figure 8 shows the FE mesh for laminated woven composites with boundary condition.

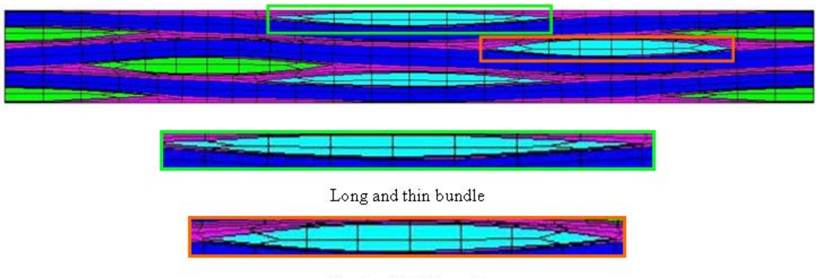


Fig.7 A cross section of numerical model (A)

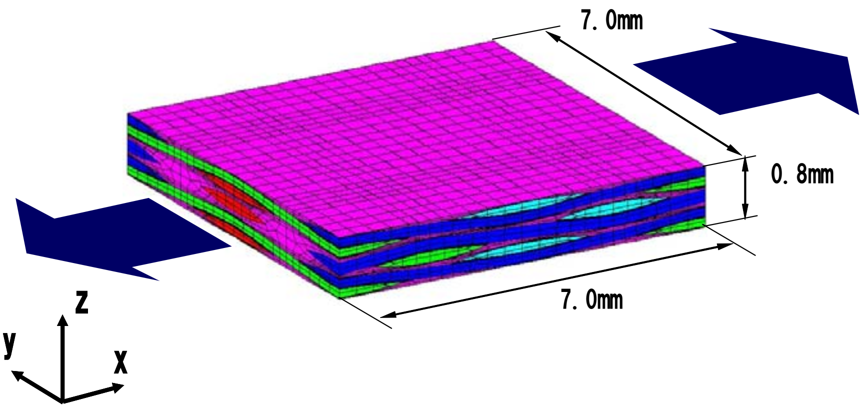


Fig.8 Finite element model of laminated woven composites with boundary consdition

5. NUMERICAL RESULTS OF DAMAGE DEVELOPMENT

To estimate the damage development of woven composites, woven composites are treated as heterogeneous bodies with anisotropy for fiber bundles and with isotropy for matrix, respectively. The occurrence of damage in fiber bundles can be predicted by Hoffman's criterion.

Figures 9 and 10 show the numerical results of damage development for each model, and the stress-strain diagram is shown in Fig.11. The effect of width and length of fiber bundles on Young's modulus does not appear in the elastic region. However, the location of damage and the propagation is quite different due to the effect of nesting.

Numerical results of initial damage are also shown in Fig.9. To make clear the damage in the strand, the only strand parts are also indicated. The black parts represent the damaged elements judged by Hoffman's criterion.

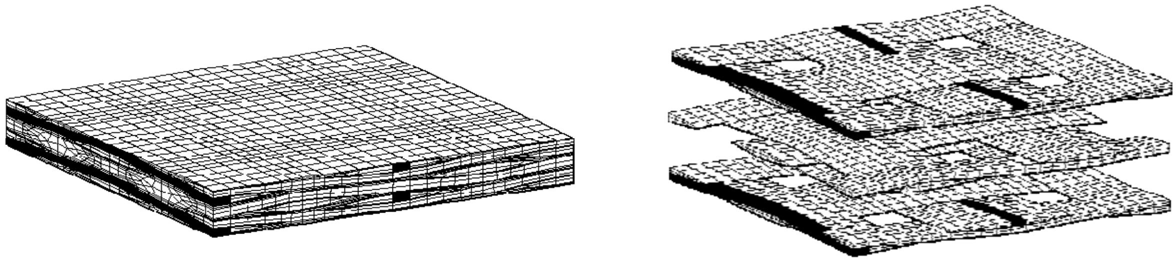
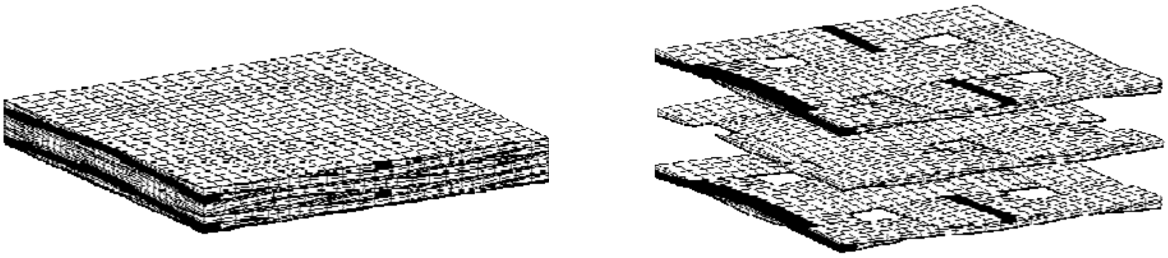
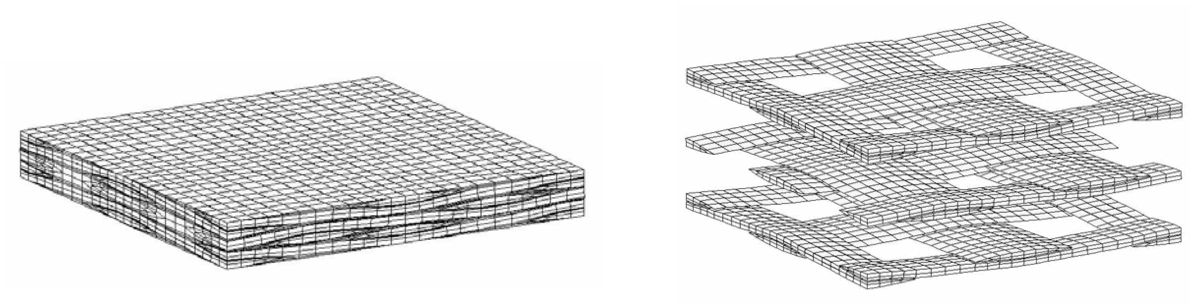

(a) Case of model (A)

Fig.9 Initial damage state of laminated woven composites (strain $\varepsilon = 0.34\%$)



(b) Case of model (B)



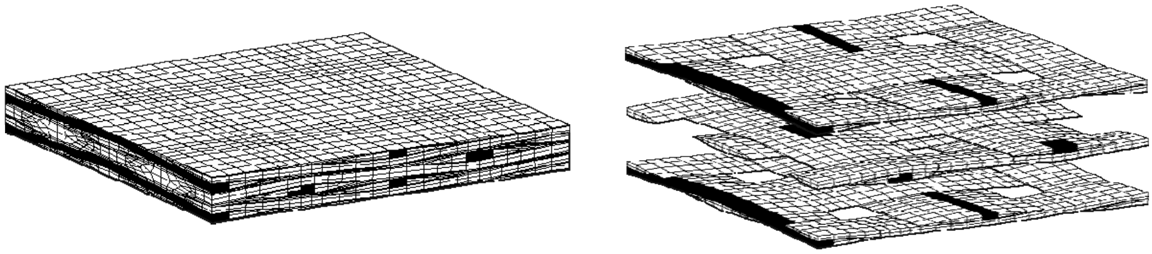
(c) Case of model (C)

Fig.9 Continued

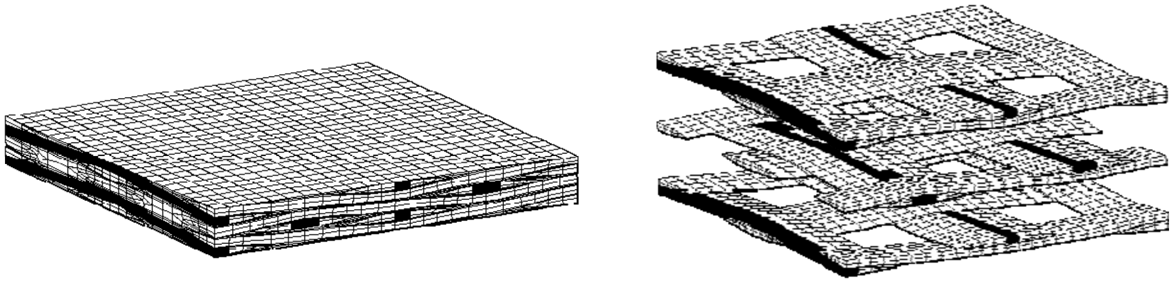
In case of model (A), which means real structures of test specimens, the initial damage of transverse cracks appears at the central parts of weft bundles in outer layers. And, no cracks occur at the edge part in Fig.9(a). Furthermore, there are no damages in central layer in model (A). This tendency is almost same with the numerical results of model (B) in Fig.9(b), however, there are no damages in outer and central layer in case of model (C) in Fig.9(c).

Figure 10 shows the damage development at strain $\varepsilon = 0.46\%$. In case of model (A) and (B), the damages develop in central parts of weft bundles in central layer. Furthermore, in case of model (C), the initial damage appears and develops in each layer.

From these results, the location of damage and the propagation is quite different due to the effect of shape and scale of fiber bundles. The cross-sectional shapes of fiber bundles and the changes of volume fractions have influenced the strain value of initial damage. The numerical results show that an effect of the distribution of volume fraction and local deformation of fiber bundles can not be neglected for the estimation of damage development of woven fabric composites.



(a) Case of model (A)



(b) Case of model (C)

Fig.10 Damage development of laminated woven composites (strain $\varepsilon = 0.46\%$)

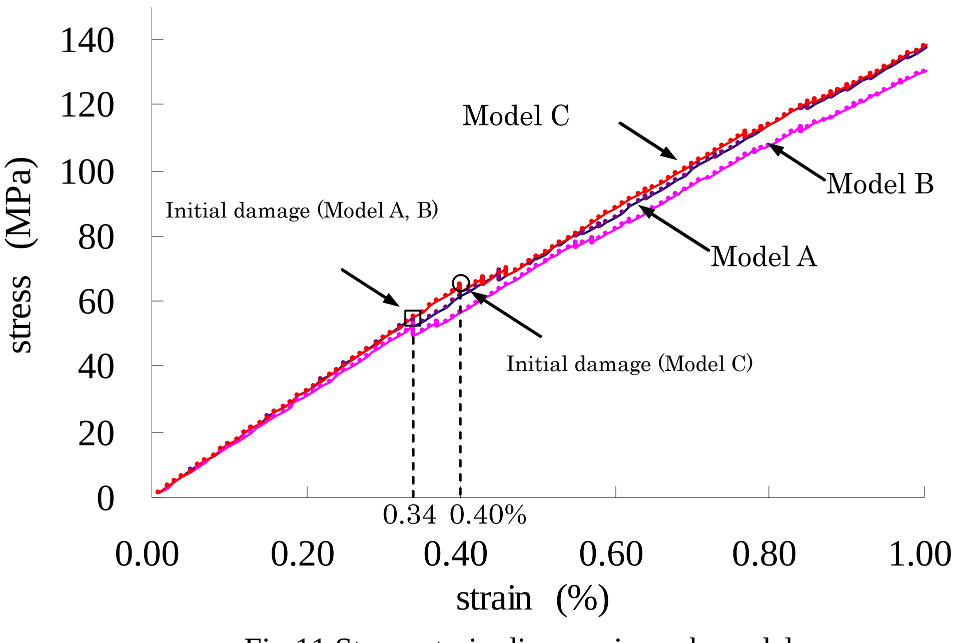


Fig.11 Stress-strain diagram in each model

6. CONCLUSION

A FE mesh generator and the simulation technique of mechanical behaviors of laminated woven fabric FRP considering the change of width and length of fiber bundles and volume fractions caused by nesting have been developed. FE models of laminated woven fabric composites can be obtained conveniently.

From the observational results of laminated woven composites, the width and thickness of weft bundles and volume fractions are quite different and distributed. By using the observational results, the finite element model of laminated woven composites have generated, and the damage development was estimated. As the numerical results, the initial stiffness showed same tendency at each numerical model, however, the location of damage and the propagation is quite different due to the effect of shape and scale of fiber bundles. Therefore, an effect of the distribution of volume fraction and local deformation of fiber bundles can not be neglected for the estimation of damage development of woven fabric composites.
From these results, the mechanical behaviors of laminated woven composites can be estimated with the proposed method. Though it is difficult to detect the strain level of the initial failure by the experiments, the strain of initial damage can be also evaluated conveniently with the proposed numerical simulation.

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