Effect of Defect on Mechanical and Failure Behavior of Plain Weave Textile Composites

Abebaw Abie Mekonnen[1] and Kyeongsik Woo[2*]

[1]Department of Civil Engineering, Chungbuk National University, Cheongju, Korea
[2]School of Civil Engineering, Chungbuk National University, Cheongju, Korea

*Corresponding author: kw3235@chungbuk.ac.kr

1. Introduction

Void defects are the most commonly encountered manufacturing defect in composite materials, and its formation and evolution depend on manufacturing techniques used such as resin transfer molding (RTM) and vacuum-assisted resin transfer molding (VARTM). Among the reasons that introduce voids, the major one is the air entrapment. It is mainly due to the non-uniform permeability of the fibers, which causes local variation in resin flow rate. The difference in the resin flow rate is triggered by the capillary effect. Manufacturing parameters such as applied pressure and curing temperature have also key control over void formation. Voids formed in composites may have different types: intra-tow, inter-tow, and dry spots. As their name indicate, the first types of void are formed in between fibers in the tow, the second type is formed in between the tows, and the last type is formed in a larger size as it can be seen by naked eye [1].

The effects of these voids in structural composites are the main interests of many literatures. Voids adversely affects the mechanical properties, specially matrix-dominated properties such as inter-laminar shear, axial compressive, and transverse tensile strengths. In contrary, longitudinal tensile strength in the fiber direction are insensitive [1, 2]. Their existence is not only affecting the mechanical properties, but also affects the failure behavior of the structure. The void defects have great influence on tensile strength of the composite. A carbon/carbon woven composite with void volume fraction of 2.66% had reduced the tensile strength by 12.7% [3].

The development of voids in woven textile composites are quite complex due to the nature of geometry complexity. However, literatures available on the effect of voids on elastic and failure behavior of textile composites are limited compared to unidirectional laminates. In the current study, the detrimental effects of void defects of plain weave textile composite on both elastic and failure behavior are studied. The study was performed considering different void volume fractions of voids incorporated in to the plain weave textile composite model and the change in the behavior from the pristine composite behavior are carefully investigated.

2. Analysis

A plain weave composite material is composed of the tows (fibers impregnated in resin) and the matrix pocket. The repeating pattern of interlacing tow structure of plain weave composite allows to represent the behavior of the entire structure by single unit cell with a periodic boundary conditions (PBC) that repeat the displacement conditions of opposite faces of the unit cell. For this study, a unit cell of plain weave textile composite with dimensions given in the Fig. 1 are considered [4].

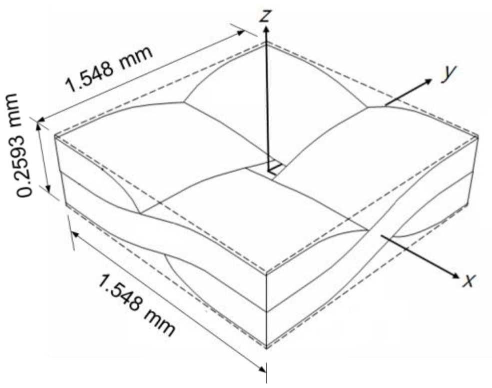

Fig.1 Tow structure of plain weave textile composite

The material properties of the tows calculated from homogenization of constituent material properties and the epoxy resin properties are shown in the Table 1.

Table 1 Material properties for tows and matrix

Material	Property
Tows (AS4/3501-6)	E_{11} = 156.6 GPa E_{22} = E_{33} = 10.4GPa v_{12} = v_{13} = 0.256, v_{23} = 0.439 G_{12} = G_{13} = 5.9 GPa G_{23} = 2.84 GPa
Matrix (3501-6)	E = 3.8 GPa, v = 0.34

The damage development of the material was simulated using cohesive zone modeling (CZM). The cohesive elements are inserted between bulk finite elements and when sufficient force to initiate and extend the failure developed, they progressively separate to simulate crack extension.

Two type of voids were considered: randomly distributed micro-voids and macro-void located at the center of the unit cell. Different quantities of void volume fractions were used to investigate their effect as per the variation of the quantity of void defects. The void volume fractions to quantify the amount of the defect are calculated as the ratio of the sum of voids in the matrix pocket and the tows to the total volume of the unit cell. The volume of void in the tows includes only the volume of resin in the tows, but not the volume of fibers in the tows. Fig. 2 shows the randomly distributed voids in the unit cell model when the void volume ratio is 2.37%.

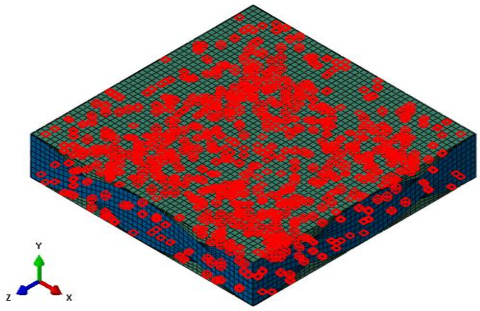

Fig.2 Random distributed voids (void volume fraction = 2.37%)

The property of void elements was given depending on the region where they belong. The properties of void elements in the matrix pocket were completely disregarded. And the properties of void elements in the tows were also disregarded but the tensile stiffness in the major material direction (tensile E_{11}) was given the fiber volume fraction in the tow times the pristine axial modulus. This is because the voids are purely due to the absence of resin and still the fibers in the tows can sustain tensile loads.

3. Results and Discussions

The numerically predicted elastic properties of the plain weave textile composite with various void volume fraction of randomly distributed voids are shown in Table 2. The elastic properties given are normalized by the respective elastic properties of pristine model.

Table 2 Normalized effective material properties with randomly distributed voids

	2.37%	4.62%	6.89%
E_{11}= E_{22}	0.974	0.948	0.919
E_{33}	0.927	0.855	0.781
ν_{12}	1.041	1.086	1.139
ν_{13}	0.995	0.990	0.984
ν_{23}	0.947	0.894	0.838
G_{12}	0.934	0.868	0.803
G_{13} = G_{23}	0.933	0.865	0.797

The random void in the matrix pocket has higher detrimental effect on the out-of-plane direction properties. A void volume ratio of 6.89% reduced the transverse modulus (E_{33}) by 21.9% and the shear moduli G_{12}, and G_{13} (=G_{23}) by 19.7%, and 20.3%, respectively. On the other hand, the effects on major material axes (E_{11} and E_{22}) were minimum (8.1%). The reduction of E_{11} and E_{22} was smaller than out-of-plane properties because the loads in these directions are mainly supported by the fiber tows.

The effects of void defects in the form of concentrated void are also showed similar behavior but in larger scale than distributed voids. The effects of void defects are also extended to the failure behavior. The presence of voids changed the development of failure from the wavy tow-pure matrix pocket interface to where preexisted voids located.

4. Conclusion

The effects of void defects (distributed micro-voids and concentrated voids) in the plain weave textile composite were studied. A larger reduction on the out-of-plane tensile modulus and all shear moduli was observed for both distributed and concentrated void defects, but there was relatively less reduction on the in-plane tensile moduli. The maximum failure stress of woven composite with defect reduced significantly depending on stacking sequence and the type of void defect considered.

References

[1] M. Mehdikhani, L. Gorbatikh, I. Verpoest, and S.V. Lomov, Voids in fiber-reinforced polymer composites: a review on their formation, characteristics, and effects on mechanical performance, *Journal of Composite Materials*, 53(12), (2019) 1579-1669.

[2] P. Wang, H. Lei, X. Zhu, H. Chen, C. Wang, and D. Fang, Effect of manufacturing defect on mechanical performance of plain weave carbon/epoxy composite based on 3D geometrical reconstruction. *Composite Structures*, 199, (2018) 38-52.

[3] A. Shigang, F. Daining, H. Rujie, and P. Yongmao, Effect of manufacturing defects on mechanical properties and failure features of 3D orthogonal woven C/C composites. *Composites Part B: Engineering*, 71, (2015) 113-121.

[4] K. Woo, Fracture analysis of woven textile composite using cohesive zone modeling, *Journal of Mechanical Science and Technology*, 31(4), (2017) 1629-1637.