Deformation behavior analysis based on matrix/yarn sliding friction model of woven fabric green composite under simple tension

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Abstract. Finite element (FE) model of woven fabric green composites considering matrix/yarn sliding friction is adopted to simulate deformation behavior under simple tension in this study. In this model, certain gap were created on the interface between yarn and matrix, wrap and weft yarns. Each interface could contact and interact each other through deformation process. The interaction can be generated by the sliding friction contact surface. The deformation simulation under simple tension was carried out using a commercial explicit dynamic FE code, LS-DYNA. To clarify the obvious deformation behavior and a surface unevenness configuration on the composite, tensile deformation behavior was simulated for woven fabric green composite with fiber orientation $\theta=45^\circ$ to tensile direction. The validation of the FE model with a gap was confirmed compared with the FE models having a gap and non-gap at the interface.

1. Introduction

Natural fiber composite materials are expected as substitutes for glass fiber reinforced composite materials to establish a sustainable society from a viewpoint of a global environmental problem [1]. For over the past two decades, research and development of various green composites, which consist of natural fiber reinforcement and biodegradable resin, have been progressed.

In previous studies on macro and meso/micro analysis modeling of woven fabric composites, a number of researches adopted kinematic model of braid, the so-called “trellis effect” mechanism, and finite element analysis using integral modeling with yarn and matrix and meso/microscopic deformation analysis using homogenization method. However, these modeling methods cannot simulate slippage phenomena between yarn intersections, which were frequently observed in the experiments.

The authors first considered the slippage by FE modeling of the fabric only for braided thermoplastic composite tubes, on the basis of the assumption that the matrix does not affect the deformation of the braid during thermoforming process, since the flow stress of the matrix decreases markedly under elevated temperature. A yarn was modelled as shell element with constant thickness. As a result, it was clarified the bulging deformation behavior [2] and the pipe fittings forming behavior [3] of the braided composite tubes including slippage of only the braid subjected to axial penetration and/or internal pressure. Although these studies could predict to some extent the kinematic behavior of the yarn without considering the matrix, it is still necessary to consider the matrix at the same time in the analytical model to improve the analysis accuracy.
For woven fabric green composite sheets, the authors recently proposed a new model considering not only yarn but also matrix material to predict and evaluate accurately the deformation behaviour and the characteristics in thermoforming. The so-called gap model engaging with sliding friction allows a clearance on the interface between yarns and matrix to represent slippage and sliding phenomenon observed in the experiment [4]. The validity of model for deep drawing process of green textile composite sheets was validated.

In this study, we focused attention on the surface unevenness behavior of woven fabric green composite sheet using the above gap model, and investigated numerically on tensile deformation behavior and yarn mobility of the green textile composite sheet under simple tension.

2. Finite element modeling
A commercial dynamic explicit finite element code, LS-Dyna 970, was used in this study.

2.1. Three dimensional FE model considering matrix and yarns
Figure 1 shows a unit cell model for woven fabric green composite sheet. The reinforcing yarn was made into a plain weave structure, and the width of the yarn, the interval between the yarns were measured by an optical microscope and modeled based on the data of produced green composite. The fiber orientation of yarns with the loading direction is 45°. This is because high elongation and large shape change of the sheet can be obtained when a tensile load is applied. Both yarn and matrix were one point integral tetrahedral solid elements in the model. Total number of nodes is 505, total number of elements is 1,232 and the tensile specimen model was a single layer. A tensile specimen model consists of 9 unit cells vertically and 5 unit cells transversely as shown in figure 2. The volume fraction of fiber is about 18 percent.

2.2. Gap model
A number of FE analyses for woven fabric composite model with both yarns and matrix have been carried out aiming at elucidating fracture mechanism [5] and crack propagation behavior [6] of the composites. However, most of them are targeting the elastic deformation behavior at room temperature. In these studies, the yarns and the matrix are fixed on their respective interfaces and the yarn does not move in the matrix due to less strain deformation. Thus, for this elastic problem, there is not much problem without considering the interface state on the model.

For thermoforming process, however, the matrix softens and its interface strength decreases markedly at forming temperature. Despite of easy slippage phenomenon of yarn at severe straining part in thermoforming, the mesoscopic model with shared nodes cannot represent mobility of yarn. In order to solve this problem, we created a gap model in the green composite as shown in figure 3. The maximum clearance between nodes at the interface was set in 0.2 mm in this model. Also conventional mesoscopic model without gap (non-gap model) was created to confirm the validity of the gap model.
2.3. Material model

Bamboo rayon was used as a reinforcement material and wonder starch as a matrix. The mechanical properties of each constituent material are listed in Table 1. Material model is an elastic-plastic body with two-linear approximation. Figure 4 shows a schematic illustration of FE model showing the tensile direction and boundary conditions for analysis. The end face of the specimen was fixed except for the z direction rotational component ($\theta_z$), fixed at the other end except the x direction translational component and the z direction rotational component at the other end, and displaced by 50 mm in 0.4 seconds in the x direction. The yarns and the matrix were taken into consideration of the contact between both faces, and the reaction force was calculated by the penalty method. The coefficient of friction was assumed to be $\mu=0.1$ for all contact surfaces for both static friction coefficient and dynamic friction coefficient.

### Table 1. Material properties of textile green composites used in FEM.

| Material model                        | Matrix      | Yarn       |
|---------------------------------------|-------------|------------|
|                                       | Elasto-plastic body | Elasto-plastic body |
| Young’s modulus $E$ (MPa)             | 10.0        | 790        |
| Mass density $\rho$ (g/cm$^3$)        | 1.12        | 1.51       |
| Poisson ratio $\nu$                   | 0.35        | 0.30       |
| Yield stress $\sigma_y$ (MPa)         | 0.1         | 13.4       |
| Plastic hardening modulus $F$ (MPa)   | 2.0         | 226        |

(\sigma = \sigma_y + F\varepsilon)
3. Results and discussion

3.1. Deformation shape and surface unevenness configuration

Figure 5 shows the change in deformation shape and surface unevenness configuration of the woven fabric green composite sheet with increase in straining under simple tension for the gap model and the non-gap model. In the case of non-gap model, except restraint regions adjacent to both ends, uniform deformation area is widely seen from the beginning and the surface unevenness phenomenon appears in a regular pattern. On the other hand, for the gap model, the width shrinkage behavior at the central region of sheet appears and grows as tensile elongation increases, simultaneously the surface unevenness is also enhanced significantly and distributed irregularly than those of the non-gap model. These simulation results for the gap model agree well with the experimental results for bamboo woven fabric green composites [7].

3.2. Kinematic behavior of yarns inside composite sheet

To clarify the cause and mechanism of the above deformation behavior, kinematic behavior of yarns in the composite is taken notice.

Figure 6 shows the kinematic behavior of yarns inside the composite sheet under simple tension, which is extracted from figure 5. In the case of the non-gap model (a), all of the contact faces shares together in the model, and the yarn and the matrix can behave in the same manner as the consolidated composite sheet. As a result, it is seen from the figure that the kinematic behaviour of yarn shows in a regularly patterns. For the gap model (b), the yarn moves freely and the slipping behavior appears remarkably from early deformation stage because of no restraint by the matrix. In particular, the yarns at the central area of sheet become loose dominantly. In addition, density of yarn becomes different between side and middle parts. The yarn alignment becomes coarse at both sides area, and dense at central area. These phenomena obviously comes from the gap model.

According to the above discussion, it is supposed that the kinematic of yarns may affect surface unevenness behavior.

3.3. Variation in thickness of composite sheet

When a single layer textile composite sheet is deformed, the thickness of all matrix part without yarns may be squeezed or extended by fiber reorientation (the trellis effect mechanism). Through this mechanism, thickness distribution comes out in the sheet, and the thickness depends on the presence or absence of yarn. Accordingly this behavior is largely related to the change in surface unevenness configuration and roughness described in 3.1.

Figure 7 shows the comparison of variation in thickness at midpoint of the composite sheet (the center of matrix among yarns) in each of the two models. In the case of the gap model, the thickness of matrix part increases with increasing straining owing to squeezing by the movement of the yarn (including yarn’s translation) [7] and then reaches a peak. On the other hand, for the non-gap model with the shared contact faces, it is seen that the sheet thickness is rather gradually decreased, which is in agreement with experimental results with no slipping and/or sliding yarns [4]. In this calculation, we used mechanical properties of bamboo rayon as a yarn, whose Young’s modulus is extremely smaller (at least, about triple-digit smaller) than that of high specific modulus and strength material, carbon fiber. This implies that the yarn of bamboo rayon elongates during process and further deformation of matrix resin proceeds integrally with the yarn. Thereby it is supposed that the thickening of matrix does not appear and the sheet does become even thinner than the thickened value obtained by fiber reorientation mechanism.

Figure 8 shows the magnified kinematic deformation and distortion of the yarn at the total strain of 74% in the tensile direction. From the non-gap model (a), it can be understood well that almost the deformation is based on fiber reorientation effect mechanism since the yarn alignment is in a regular pattern. From the gap model (b), it is found that slipping and sliding behaviour of yarns are predicted.
Total elongation (x direction) = 0%

Total elongation (x direction) = 37%

Total elongation (x direction) = 74%

Total elongation (x direction) = 100%

(a) Non-gap model  (b) Gap model

**Figure 5.** Comparison of tensile deformation behavior of woven fabric composite model.

Total elongation (x direction) = 0%

Total elongation (x direction) = 37%

Total elongation (x direction) = 74%

Total elongation (x direction) = 100%

(a) Non-gap model  (b) Gap model

**Figure 6.** Comparison of kinematic behavior of yarns at each tensile elongation.

**Figure 7.** Relation between thickness at midpoint of composite sheet (the center of matrix among yarns) and tensile total elongation for two types of FE models.
Consequently, it is concluded that the gap model is valid to simulate deformation behavior and fiber reorientation of woven fabric green composite material occurring slipping and sliding behavior of yarns.

### 4. Conclusion

For the woven fabric green composite, FE analysis under simple tension test was conducted using a gap model considering the matrix and yarn all together. From the FE analysis results, the following conclusion is obtained. By considering the gap at the interface between the matrix and the yarn, it is possible to predict the change in the deformation shape and thickness distribution and surface unevenness behavior of the composite sheet, which cannot be realistically simulated by conventional consolidated matrix and yarns model. Adjusting the coefficient of friction and gap clearance value used in the model should be required for improving the prediction accuracy.

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