Analyses of press formability of CFRP sheet considering the fiber kinking and the ductile behavior of resin

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Abstract. Establishment of a press forming method of carbon fiber reinforced plastic (CFRP) is desired. However, fundamental research on a ductility improving mechanism of CFRP is still insufficient. Since unidirectional CFRP shows different characteristics in compression and tensile deformation, accurate expression in both characteristics is necessary to investigate factors that affect formability. To express fiber kinking and ductile behavior of resin, a microscale model that separated fiber and resin was made. The fiber part in FEM model was tilted as initial misalignment and Gurson-Tvergaard-Needleman (GTN) model was applied to the resin part. To investigate the influence of design parameters such as temperature and initial void fraction on formability, this study performed tensile, compression and bending analyses by changing the resin temperature and initial void fraction. Results of compression analysis showed that the higher the temperature and initial void fraction, the earlier fiber kinking occurrence. Bending analysis showed a similar tendency. These results are physically reasonable. Therefore, these numerical experiments confirmed that the model used in this research is valid for studying factors that affect formability.

1. Introduction
The concern over carbon fiber reinforced plastics (CFRP) has risen. It is a composite material of carbon fiber and thermosetting resin and has high specific strength, specific rigidity and heat resistance. For that reason, its demand is increasing in industry fields requiring weight reduction of bodies such as automobiles and aircraft. However, high production cost hinders CFRP from spreading to more common products. The disadvantage of high production cost is caused by poor productivity of CFRP. An efficient forming procedure such as press forming has not been established because of the poor ductility of CFRP.

Although research on failure strength after processing of CFRP has been actively conducted, there has been little study done concerning formability of CFRP. In recent research, it has been experimentally confirmed that the formability of CFRP sheets is improved by the processing conditions[1][2] and the laminated structure[3]. This result shows that the press forming possibility of CFRP exists. However, the problem seems to lie in the fact that the fundamental research of the mechanism including the plastic deformation is insufficient. Therefore, trying to clarify how the phenomena occurring inside the material during deformation improve the formability seems important.
Figure 1. Stress versus strain curves of thermosetting resin at different temperatures[1].

Because the influence on deformation of CFRP due to temperature has been confirmed[4], considering the mechanism of deformation under warm condition is necessary. The thermosetting resin has a crosslinked bonding in its molecular structure. In tensile deformation, breaking of molecular chains, generation and coalescence of microvoids are repeated, leading to macroscopic failure. To express this characteristic, Yoshioka et al.[5] applied a model that can consider the damage due to voids to the thermosetting resin. In press forming, failure at the compressive part in the fiber direction becomes a problem. It is difficult to capture the internal deformation behavior from macroscale analysis due to characteristics of each material and the interaction between resin and fiber such as fiber kinking. Therefore, analysis based on a microscale model which can accurately express internal deformation has been studied[6].

Therefore, the present study was undertaken in order to reveal influence of temperature, microvoid and fiber kinking on deformation of CFRP. By FEM analyses using microscale model, the influence of the interaction between resin and fiber within a CFRP during plastic deformation was evaluated. These results showed that the proposed model is suitable for appropriately expressing the complicated deformation characteristics of CFRP.

2. Factors influencing the deformation characteristics of CFRP

2.1. Temperature characteristics of thermosetting resin

Resin plays a major part of the deformability of the fiber composite material. CFRTP composed of carbon fiber and thermoplastic resin is easily formed because thermoplastic resin can soften again by heating even if it is cured once. On the other hand, thermosetting resin used in CFRP does not soften once cured. This property lowers the formability of CFRP. However, thermosetting resin does not melt even when heated, but previous research[7] has confirmed that the stress-strain curve of resin changes with temperature. Fig. 1 shows how the stress-strain curve changes with temperature. This study used curves shown in Fig.1 to conduct analyses considering temperature.

2.2. Ductile behavior of thermosetting resin

Thermosetting resin has molecular chains connected with three-dimensional cross-linking. In tensile deformation, tensions of molecular chains cause plastic deformation. Molecular chains break from the short one and microvoids are generated at the break points. Generation and coalescence of microvoids are repeated, then void volume fraction increase, which leads to the ultimate fracture of the entire material. This fracture mechanism can be assumed the same process as ductile fracture mechanism of metal due to void damage. So, in this research, Gurson-Tvergaard-Needleman (GTN) model[8] was applied to the material model of the thermosetting resin. The yield function of the GTN model is given as follows,
\[
\phi = \frac{\sigma_M^2}{\sigma_Y^2} + 2q_1 f^* \cosh \left( \frac{3q_2 \sigma_H}{2\sigma_Y} \right) - 1 - (q_1 f^*)^2, \tag{1}
\]

where \(\sigma_M\) and \(\sigma_H\) are the effective stress and hydrostatic stresses, respectively, \(q_1\) and \(q_2\) are adjustment parameters, \(\sigma_Y\) is yield stress and \(f^*\) is the modified void volume fraction. Volume fraction \(f^*\) is defined as below,

\[
f^*(f) = \begin{cases} 
  f & (f \leq f_c) \\
  f_c + \frac{1}{q_1} - f_c & (f > f_c) \\
  f_F - f_c f - f_c & (f > f_c) 
\end{cases}
\tag{2}
\]

where \(f_c\) is the critical void volume fraction, and when the void fraction exceeds this value, coalescence of the voids start. \(f_F\) is failure void volume fraction.

Table 1 shows patterns of parameter. Parameters of pattern 1 were obtained by inverse analysis from experiments. In pattern 2 and 3, initial void fraction \(f_0\) were changed to investigate the influence due to the difference in initial void fraction.

| Pattern     | \(f_0\) | \(f_c\) | \(q_1\) | \(q_2\) | \(f_F\) |
|-------------|---------|---------|---------|---------|---------|
| Pattern 1   | 0.1     | 0.123   | 1.5     | 1.0     | 0.15    |
| Pattern 2   | 0.001   | 0.123   | 1.5     | 1.0     | 0.15    |
| Pattern 3   | 0.05    | 0.123   | 1.5     | 1.0     | 0.15    |

2.3. Fiber kinking

Under longitudinal compression, various patterns exist in fracture of the unidirectional laminate, but among them, it is widely known that the shear fracture mode generated by the formation of the kink band is dominant. Fiber kinking is caused by initial fiber misalignment generated at the production process of sheets. In previous researches, various kind of microscale model considering fiber kinking are used. Some used two-dimensional models like Gutkin et al. [9]. Others used three-dimensional models like Naya et al. [10] and Bishara et al. [11]. The present study adopted two-dimensional model. To express the occurrence of fiber kinking due to the initial misalignment of the fiber, the fiber model in the FEM model is tilted at 1 degree from the 0 degree direction. Fig. 2 shows the load displacement curve and the appearance of fiber kinking when the UD material is compressed in the fiber direction.

3. Tensile and compression analysis

3.1. Overview of model

Analysis was carried out using finite element analysis software LS-DYNA. Figure 3 shows overview of analysis model. A constraint condition as shown in Fig. 3 is given to the node on the left side, and a forced displacement that gives tension or compression is given to the node on the right side. The gray area in Fig. 3 represents fibers on which a material model of orthotropic elasticity is applied. To express initial misalignment, they are tilted at 1 degree from \(x\) axis. And the diameter of the fiber is 5 \(\mu m\), the length is 0.5 \(mm\), and the volume fraction of the fiber is 50%. The black area in Fig. 3 represents thermosetting resin on which a material model of GTN model or simple elastoplastic model is applied.
Figure 2. Load versus displacement curve and fiber kinking under longitudinal compression.

Figure 3. FEM model used for tensile and compression analysis.

Figure 4. Stress versus strain curves of thermosetting resin at different temperatures.

3.2. Analysis results for investigating the influence of temperature
Compression analysis was carried out using simple elastoplastic model to the resin and a stress-strain curve for each temperature. Fig.4 shows these results. This result shows that the higher the temperature rises, the smaller the displacement the load suddenly decreases. In other words, it can be said that kink generation is accelerating as the temperature rises. Although the formability should improve as the temperature rises, the timing of occurrence of fiber kinking is earlier. From these results, it was found that formability can not be evaluated only by the occurrence timing of fiber kinking. Therefore, to evaluate formability, a method to evaluate in combination with other factors is necessary.

3.3. Analysis results to investigate the influence of initial void
Tensile and compression analysis were carried out using GTN model to resin. Fig.5(a) and (b) shows load-displacement curve in tensile and compression analysis, respectively. These results represent that the initial void fraction has an influence on both tensile analysis and compression analysis. In the case of tensile deformation, void coalescence is less likely to occur as the initial voids are smaller, and resin damage is less likely to occur. In the case of compression analysis, because the small value of initial void fraction slowed the attainment to the critical void fraction, the initiation of kink band was delayed. The initial void fraction can be varied by the manufacturing process. Therefore, in realizing efficient press molding, it is necessary to be
Figure 5. Load versus displacement curves when initial void fraction is different.

able to optimize the initial void fraction at a process design. It can be said that the model used in this study is a suitable model considering the influence of void.

4. 4 points bending analysis
This model was applied to 4 points bending deformation which is closer to actual forming than tensile and compression deformation, and investigate fiber kinking in the state of displacement gradient. By applying the GTN model to the resin and analyzing with the initial void fraction changed, the relation between the initial void fraction and the occurrence of kink in bending deformation was investigated.

4.1. Analytical method
Since the model used in the tensile analysis was a microscale model, if it is tried to extend it to an analysis model simulating an actual 4-point bending test, the calculation cost becomes very large. So, in this analysis, firstly, the displacement history of the center part of the specimen was obtained by macroscale analysis, and by applying it as a boundary condition to the microscale model, the portion subjected to pure bending deformation was analyzed. Figure 6 shows macroscale and microscale model.

Figure 6. Macroscale model and microscale model.
Figure 7. The deformation state of the microscale model using parameters of pattern 1. It is the state when the stroke is 0 mm, 0.3 mm, 0.45 mm, 0.6 mm in order from the left.

4.2. Result of 4 points bending analysis
Analysis was performed with three patterns of GTN parameters shown in Table 2. Figure 7 shows the deformation state of the microscale model using parameters of pattern 1. It was confirmed that failure of resin and fiber kinking gradually occurred in compression part as the stroke of the punch increased. As failure of resin and fiber kinking occur, the load of node on compression part decreases. In the case of pattern 2, failure of resin and fiber kinking did not occur in the analyzed stroke range. In the case of pattern 3, failure of resin and fiber kinking occurred, but it is later than in pattern 1. The comparison of the results when changing the initial void fraction concludes that a load reduction is less likely to occur as the initial void fraction is smaller.

5. Conclusions
From the compression analysis conducted with changing the temperature, it was confirmed that the kink occurred earlier as the temperature was higher.

The analyses made by changing the initial void fraction using the GTN model confirmed that the initial void fraction has a large influence on deformation, and that it can be properly expressed in this model. In the 4 points bending analysis, exhibiting the same tendency regarding the influence of void and fiber kinking is physical reasonable.

Therefore, the model constructed in this research is efficient to investigate factors that affect formability of CFRP.

References
[1] Uriya Y, Ikeuchi K and Yanagimoto J 2015 Int. J. Mater. Form. 8 415-21
[2] Uriya Y and Yanagimoto J 2017 Int. J. Mater. Form. 10 527-34
[3] Uriya Y and Yanagimoto J 2015 Int. J. Mater. Form. 9 243-52
[4] Cao S, Zhis WU and Wang X 2009 J. Compos. Mater. 43 315-30
[5] Yoshioka K, Kumagai Y, Higuchi R, Lee D and Okabe T 2016 Materials system (Japan: Materials System Research Laboratory, Kanazawa Institute of Technology) 34 7-13
[6] Prabhakar P and Wass A 2013 Compos. Struct. 98 85-92
[7] Hobbiebrunken T, Fiedler B, Hojo M, Ochiai S and Schulte K 2005 Compos. Sci. Technol. 65 1626
[8] Tvergaard V and Needleman A 1984 Acta Metall. 1 157
[9] Gutkin R, Pinho S, Robinson P and Curtis P 2010 Compos. Sci. Technol. 70 1214-22
[10] Naya F, Herráez M, Lopes C, González C, Veen S and Pons F 2017 Compos. Sci. Technol. 144 26-35
[11] Bishara M, Rolles R and Allix O 2017 Compos. Sci. Technol. 169 105-15