FRACTURE BEHAVIOR AND FACE SHEET BUCKLING ANALYSIS
OF CFRP/HONEYCOMB SANDWICH PANELS
SUBJECTED TO BENDING LOAD

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ABSTRACT

In our previous work, the fracture behavior of the carbon fiber reinforced plastic (CFRP) / Nomex honeycomb sandwich panels simulating aircraft interior materials under four-point bending load was observed using high-speed cameras. The observation results revealed that the debonding between the face sheet and the honeycomb core, which was induced by the buckling of the face sheet was dominant for the strength of the CFRP / honeycomb sandwich panel. The local buckling of the face sheet as fracture initiation was as follows: (1) local buckling of the face sheet at the specimen edge, or (2) local buckling of the face sheet at the middle of the specimen. However, there are few reports regarding the numerical analysis of failure mechanisms in CFRP / honeycomb sandwich panels based on detailed observation. In this study, in order to establish the bending strength prediction methodology of CFRP / honeycomb sandwich panels for aircraft interior, stress and buckling analyses using finite element method (FEM) were carried out. Honeycomb structures were modeled with shell elements in the middle part of the beam and solid elements were used for the other parts to reduce the calculation cost. The equivalent elastic properties used for the solid elements were obtained with the unit cell model of the honeycomb core by the key degrees of freedom method. The results of the stress analysis well agreed with the experimental results, therefore the effectiveness of the FE model and the equivalent elastic properties of the honeycomb core were shown. The buckling mode calculated by the buckling eigenvalue analysis corresponded to the experimentally observed local buckling behavior. In addition, the buckling load estimated by the FE analysis also agreed with the bending strength of the sandwich panels.

1 INTRODUCTION

Carbon fiber reinforced plastic (CFRP) is widely used for aircraft structural materials because of its lightweight and high stiffness. CFRP is used up to approximately 50 wt.% of the latest Boeing`s aircraft, B-787 [1]. CFRP / honeycomb sandwich panels are used for aircraft interior structures such as floor panels, galleys and lavatories. CFRP / honeycomb sandwich panels are manufactured by bonding thin CFRP face sheets to both sides of a honeycomb core with adhesives. Honeycomb sandwich structures have lightweight, high stiffness, impact absorption and thermal insulation. In order to improve the mechanical properties of sandwich panels, understanding of the damage and failure mechanism in detail is very important.

Several research works were carried out to clarify the fracture behavior of honeycomb sandwich panels [2-12]. The following failure modes are included in the honeycomb sandwich panels subjected to bending load; face sheet yielding, intra-cell buckling (or dimpling), face sheet wrinkling, debonding between face sheet and core, and core shear [2-5]. Petras and Sutcliffe [3] conducted three-point bending tests for CFRP / Nomex honeycomb sandwich panels to investigate the detail failure mode of the panels. They made a fracture mode map based on the dependence of the fracture mode on the face sheet thickness to the span length of the bending jig, and the relative density of the honeycomb core. According to this map, thin face sheet thickness to the span length of the bending jig results in the failure
of sandwich panel due to the face sheet wrinkling. Ley et al. studied the effects of the face sheet wrinkling on the buckling behavior [6]. They reported that sandwich panels with a thin face sheet and a low-density core tend to fail at lower load due to the face sheet wrinkling. Jen and Chang [7] conducted bending tests for the sandwich panel with aluminum face sheets and aluminum honeycomb cores. They reported that the main failure mode was the debonding between the face sheet and the adhesive layer. Hoff and Mauntner [8] established the theoretical expression that were widely used to predict the failure stress of the sandwich structure owing to the face sheet wrinkling. Yusuff [9-10] and Kassapoglou et al. [11] established the face sheet wrinkling expressions by considering the fracture of the face sheet and the core, that showed agreement with the experimental values. Stall et al. [12] improved these theoretical expressions [9-11] and compared to the experimental results of four-point bending tests for CFRP / Nomex honeycomb sandwich panel. The theoretical solution well agreed with the experimental values. They reported that the local core crushing due to the face sheet wrinkling led to the face sheet failure and the fracture of the panel.

Failure strength prediction by numerical analyses [13-17] has also been attempted as well as the observation of fracture behaviors in sandwich panels through bending tests. Koissin et al. [13] established the theoretical model of the local buckling due to the face sheet wrinkling and compared to the Finite element (FE) model. Sun et al. [14] conducted three-point bending tests and in-panel compression tests for the sandwich panels with aluminum face sheets and aluminum honeycomb cores. They carried out numerical analyses using the FE model of the sandwich panels and simulated the fracture behavior of the panels subjected to three-point bending load and in-panel bending load. Giglio et al. [15] conducted three-point bending tests and FE analyses for the aluminum / Nomex honeycomb sandwich panels and simulated the crush behavior of the honeycomb core in consideration of the friction between the panel and the jig. Sankar and Narayanan [16] carried out in-plane compression tests for CFRP / Nomex honeycomb sandwich panels and Gopalakrishnan et. al. [17] conducted bending tests for aluminum / aluminum honeycomb sandwich panels. In order to find out the buckling behavior, they simulated the debonding between the face sheet and the core using the FE model with cohesive elements.

The authors attempted to observe the buckling behavior of CFRP / Nomex honeycomb sandwich panels simulating aircraft interior materials under four-point bending using high-speed cameras [18]. Observation results revealed that the fracture process of the panels. The failure process was as follows; (1) the local buckling of the face sheet, (2) the debonding between the face sheet and the core, (3) crack propagation of the face sheet. In addition, the fracture process initiation was categorized into the following three types as shown in Figure 1.

1. Type I: outward local buckling of the face sheet at the specimen edge
2. Type II: outward local bucking of the face sheet at the middle of a specimen
3. Type III: inward local buckling of the face sheet at the specimen edge

There are few reports regarding the numerical analysis the failure mechanisms of CFRP / honeycomb sandwich panels based on the detailed observation of the fracture behavior. In this study, in order to establish the bending strength prediction methodology of CFRP / honeycomb sandwich panels for aircraft interior structures, stress analyses and buckling analyses using FE method (FEM) were conducted. The numerical results were compared with the observation results in the previous study [18].

2 EXPERIMENTAL METHOD AND RESULT

2.1 Material and specimen preparation

Figure 2 shows a bending specimen simulating aircraft interior materials. The dimensions of specimens were 610 mm (24 inches) in length and 76 mm (3 inches) in width. The face sheets (0.3 mm in thickness) were made of cross-ply CFRP laminates, [90°/0°]. The core (10.3 mm in height) was made of the Nomex honeycomb. The honeycomb cell size was 3.175 mm (1/2 inch). The face sheet and core were bonded with adhesive films. The longitudinal direction of the specimen was 0° and the lateral direction was 90°. The direction of the adhesive foil of the honeycomb was 0°.
2.2 Four point bending test

Four-point bending tests were conducted in accordance with ASTM-D7249 [19] using a screw-driven mechanical test rig (AG-250 kN X-plus; Shimadzu Corp., Japan) with a 50 kN load cell and a spherical seating four-point bending jig (558.8 mm in lower span, 101.6 mm in upper span). Number of specimens was three. During the bending test, the displacement of the center of the lower face sheet was measured with a laser displacement sensor (IL-S100; Keyence Corp., Japan). The loading rate was 8.0 mm/min.

2.3 Experimental result

Figure 3 shows load-displacement curves obtained by the experiments. The displacement increased almost linearly but slight nonlinearity was observed near the failure point because buckling of the face sheet or the core occurred before the panel failure.

According to the Bernoulli-Euler beam theory, displacement of a center of a beam subjected to four-point bending load can be expressed as the following equation.

\[
\delta_{\text{exp}} = \frac{PL_1}{12EI} \left[ \frac{3}{2} \left( \frac{l}{2} \right)^2 + 3l \left( \frac{l}{2} \right) - l_1^2 \right]
\]  

(1)
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Figure 3: Load-displacement diagram.

<table>
<thead>
<tr>
<th>Specimen number</th>
<th>Failure load [N]</th>
<th>Failure deflection [mm]</th>
<th>Bending rigidity [N m²]</th>
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<tr>
<td>1</td>
<td>659</td>
<td>28.7</td>
<td>79.7</td>
</tr>
<tr>
<td>2</td>
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<td>27.6</td>
<td>75.9</td>
</tr>
<tr>
<td>3</td>
<td>523</td>
<td>23.3</td>
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Table 1: Experimental results.

Where $P$ is a load, $l$ is the lower span length and $l_1$ is the distance between the supporting points, and $EI$ is a bending rigidity. Bending rigidity of each panel calculated by Equation (1) is shown in Table 1.

The failure load and the bending rigidity were scattered. This seems to be occurred because due to the difference in the adhesion condition and the dimensional error of the specimens.

Load-displacement diagram in Figure 3 showed nonlinearity near the failure point because buckling of the core and the face sheet occurred before the final failure as well as the geometric nonlinear effects. The failure load and the bending rigidity of each specimen agreed with the experimental results in the previous study [18]. The failure load and the failure deflection were obtained for confirming the validity of the equivalent stiffness of the honeycomb core.

3 NUMERICAL SIMULATION METHOD

3.1 Stress and buckling analysis model

Figure 4 shows the FE model used for both stress and buckling analyses. Detailed honeycomb structures were modeled in the middle part of a beam where the face sheet local buckling occurred, and solid elements were used for the other parts to reduce the calculation cost. Equivalent elastic properties of the honeycomb core presented in Section 3.2 were applied to the solid element. The face sheets were cross-ply CFRP laminates, [90°/0°], and the adhesive films were modeled between the face sheet and the core. The adhesive films were assumed to be isotropic, and the elastic properties were obtained by tensile tests. The dimensions of sandwich model were 610 mm in length, 76 mm in width and 11 mm in height. The face sheets and the honeycomb cores consist of 4-node shell element, and the solid core consist of 8-node solid element, respectively. Numbers of elements and nodes were 162816 and 180616,
3.2 Determination of equivalent stiffness of honeycomb core

The determination of equivalent elastic properties is required for the solid elements applied to the honeycomb core structure. However, experimental determination of elastic properties are difficult because of extremely low stiffness of the honeycomb core. In this study, equivalent elastic properties were determined by FEM. Periodic boundary conditions were applied to the unit cell model of the honeycomb core. The unit cell model is shown in Figure 5. Width, length and height of the model were, 3.175 mm, 5.499 mm, and 5.0 mm, respectively. The honeycomb core was modeled with 4-node shell elements. Numbers of elements and nodes were 336 and 405, respectively. Nomex paper was assumed to be isotropic, and elastic moduli were obtained by tensile tests.

In this analysis, the key degrees of freedom method proposed by Li, et al. [20] was employed to set the periodic boundary condition. Independent nodes were placed out-of-model to apply tensile strain ($\varepsilon_x^0$, $\varepsilon_y^0$, $\varepsilon_z^0$) and shear strain ($\gamma_{xy}^0$, $\gamma_{xz}^0$, $\gamma_{yz}^0$) to the unit cell model. Multi point constraint (MPC) was utilized for surfaces, edges and vertexes. The center of the FE model was fixed and unit tensile strain and shear was applied to each virtual node. ABAQUS Standard 2018 was used for the analyses.

Equivalent stiffness of the honeycomb core was calculated from compliance matrix obtained by the analyses. The compliance matrix was obtained by reaction forces of each virtual node. The estimated equivalent elastic moduli of the honeycomb core are presented in Table 2.

3.3 Stress analysis

Equivalent elastic moduli of the honeycomb core presented in Table 2 were used for the solid elements of the honeycomb core as shown in Figure 4. A translational displacement of 40 mm in the $z$ direction was applied to the upper loading points. The lower support points were simply supported. Linear stress analysis was conducted using ABAQUS/Standard 2018.

Figure 4: Analytical model for stress and buckling analysis.

Figure 5: Unit cell of honeycomb core.
Figure 6 shows load-displacement diagrams obtained by the stress analysis and bending tests in Section 2. The calculated bending stiffness showed good agreement with the experimental results, and the relative error was approximately 1.1%. Therefore, the effectiveness of the FE model and the equivalent stiffness of the honeycomb core were shown.

### 3.4 Buckling eigenvalue analysis

Buckling eigenvalue analysis using the FE model shown in Figure 4 was conducted under the same boundary conditions as the stress analysis. Figures 7(a)-(c) show the typical buckling mode calculated by the buckling eigenvalue analysis. Each buckling mode corresponded to the experimentally observed local buckling behavior shown in Figure 1.

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<tr>
<td>(E_1) [GPa]</td>
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<tr>
<td>(G_{23}) [GPa]</td>
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Table 2: Material properties of honeycomb core calculated by FE analysis.

![Figure 6: Experimentally and analytically obtained load-deflection curves of the sandwich panel.](image)
The calculated buckling load and the displacement are summarized in Table 3. The calculated buckling strength was about 660-665 N of local buckling of the face sheet at the specimen edge, and about 720 N of local buckling of the face sheet at the middle of the specimen, which also well agreed with the bending strength of the sandwich panels.

Therefore, this analysis model is useful for analysis using panels with various laminated face sheets.
4 CONCLUSIONS

In this study, in order to establish the bending strength prediction methodology of CFRP/honeycomb sandwich panels for aircraft interior structures, stress and buckling analyses using FEM were conducted. The following conclusions were obtained.

1. Load-displacement diagram obtained by four-point bending tests showed nonlinearity near the failure load. This seems to be because buckling of the core and the face sheet occurred before the failure point.

2. Load-displacement diagram calculated using the stress analysis well agreed with the experimental results. Therefore, the effectiveness of the FE model and the equivalent stiffness of the honeycomb core were demonstrated.

3. Buckling modes calculated by the buckling eigenvalue analysis corresponded to the experimentally observed local buckling behavior. In addition, the buckling load and the displacement at each eigenvalue also showed good agreement with the experimental results.

REFERENCES