

# FACESHEET DENT FORMATION AND RELAXATION ON INDENTED FOAM-CORE SANDWICH BEAMS

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## 1 Introduction

Foam core sandwich structures are integral constructions consisting of two composite facesheets and a lightweight foam core. Since they have high mechanical characteristics, the application of the foam core sandwich structures to primary aircraft structures is expected [1,2]. However, since the composite facesheet is very thin and the lightweight foam core is weak, they can be easily damaged when an impact or indentation load is applied [3]. As illustrated in Fig. 1, the sandwich structure is deformed globally under localized transverse loading, and the upper facesheets, to which the load is applied, locally deflects against the lower facesheet, followed by through-thickness deformation of the core. As a result, the core is crushed and a residual facesheet dent remains after unloading. The dent causes a significant deterioration in the mechanical properties of the structure, even when it is small and barely visible [4-6]. Furthermore, the dent depth determines the detectability of the damage by visual inspection. Thus the residual dent formation is a key phenomenon under the localized loading condition. However, underlying mechanism of the dent formation on foam core sandwich structures is not

sufficiently clarified.

This study investigates static indentation loading-unloading behavior of foam core sandwich beams by focusing on interaction between the local facesheet deformation and the core crushing. First, the indentation response is evaluated using quasi-static indentation tests. The indentation behavior is then predicted by extending a “segment-wise model”, which was formulated for honeycomb sandwich structures in a previous study [7,8].

## 2 Quasi-static Indentation Test

### 2.1 Materials and Methods

Figure 2 depicts the experimental setup. The specimens consisted of carbon fiber reinforced plastic (CFRP) facesheets (T700/2500S, Toray Industries, Inc., [0<sub>8</sub>], thickness 1.15 mm), foam core (PMI Rohacell WF-51, Evonik Rohm GmbH, thickness 35 mm), and thermosetting adhesive films (AF-163-2K, 3M Co.). The CFRP laminates were manufactured in advance. The laminates and the foam core were then secondarily bonded to form a sandwich panel. The beam specimens (width 25

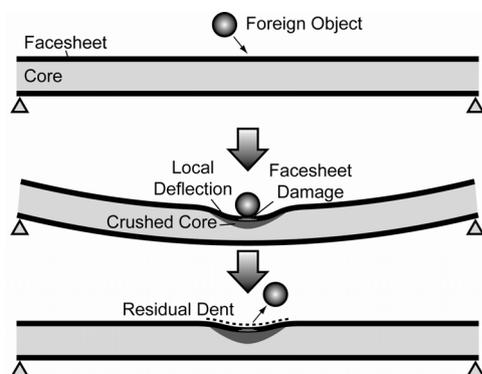


Fig.1. Sandwich structures under transverse loading.

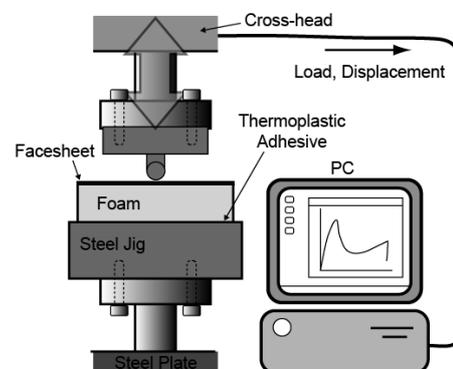


Fig.2. Setup of quasi-static indentation tests.

mm) were carefully cut out from the panel using a diamond blade saw. The specimen was bonded to a flat steel plate with an adhesive, eliminating overall bending. A 10 mm-diameter steel cylinder was attached to a material testing system (AG-50kNI, Shimazu Co.), and a concentrated line-load was applied to the center of the specimen. Constant displacement rates of 5 mm/min were used. After the maximum indentation displacement of 5 or 2.5 mm was reached, the specimens were unloaded.

## 2.2 Results

Indentation load-displacement curves obtained in the experiments are presented in Fig. 3. The curves started to bend rapidly after initial elastic

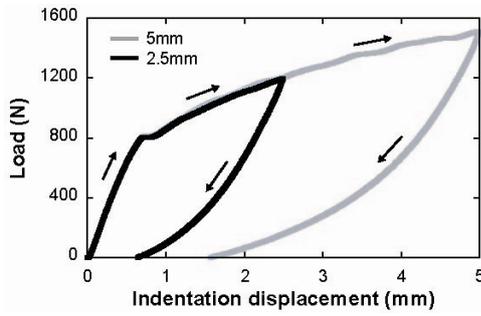


Fig.3. Measured load-displacement curves.

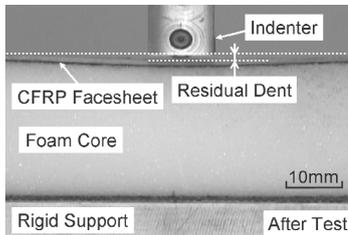


Fig.4. Specimen just after unloading (5 mm loading).

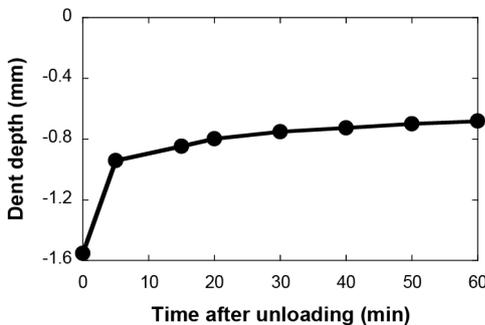


Fig.5. Time change of dent depth right under loading point.

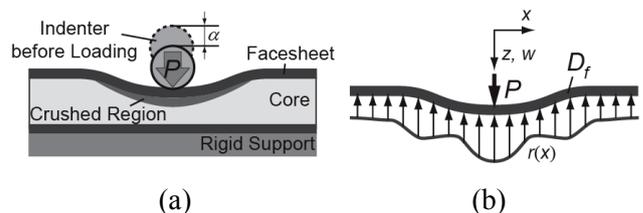
deformation. They increased in an approximately constant ratio while the core crushing evolved. Meanwhile, during the unloading process, the load rapidly decreased and the residual deformation remained depending on the applied maximum indentation displacement. Figure 4 presents a photograph of the specimen just after unloading (maximum indentation displacement: 5 mm). A gentle dent is remaining on the facesheet.

Figure 5 shows the time change of the dent depth right under the loading point after unloading (applied maximum indentation displacement: 5mm). The measurement was conducted by using a laser displacement meter (LK-030, Keyence Co., Ltd.). The dent depth, which was about 1.55 mm immediately after the unloading, rapidly changed to 0.95mm five minutes later. Afterward, the facesheet shape was gradually restored and, 1 hour later, the dent depth became less than half compared to the original one. The final dent shape not only affects the residual strength of the structures but also determines the detectability of the damage under visual inspection in structural maintenance. Hence the relaxation behavior after unloading is crucially important.

In the following sessions, the indentation loading-unloading behavior is predicted by an extended “segment-wise model.”

## 3 Extension of Segment-wise Model

The segment-wise model formulated for honeycomb sandwich beams is based on a deformation theory of an Euler beam on an elastic Winkler foundation [7]. As depicted in Fig. 6 (a), an indentation load  $P$  is applied to a sandwich beam and a consequent indentation displacement  $\alpha$  is induced. With the back facesheet supported by a rigid facing, the upper facesheet of unit width can be considered as a beam



(a) Specimen under indentation loading.  
(b) Model for upper facesheet.

of rigidity  $D_f$  supported by a foundation that provides a reaction  $r(x)$  per unit length. The equilibrium of the beam is governed by the generalized equation

$$D_f \frac{d^4 w(x)}{dx^4} + r(x) = 0 \quad (1)$$

where  $w(x)$  is a transverse deflection of the facesheet as seen in Fig. 6 (b). In the segment-wise model, it is assumed that through-thickness stress field of the core is governed by the transformation of adjacent intersection lines, defined as line joints between honeycomb cell walls. The honeycomb sandwich beam is divided into many segments centering around the intersection lines and each segment has a material property determined from the through-thickness deformation of the intersection line within it [7]. The model can theoretically calculate indentation loading-unloading response of honeycomb sandwich beams. In order to extend the segment-wise model, two modifications were made.

First, complex crushing-stretching properties of the foam core were integrated in the model. We comprehensively conducted modified flatwise compression tests of the foam [7] to obtain compressive stress-displacement curves, i.e. the reaction stress  $r(x)$  depending on the deformation of the foam (Fig. 7 (a)). Then we focused on the strong relationship between the bending of the stress-displacement curves and the crushing-stretching behavior of the foam core (Fig. 8). The compressive stress-displacement curves were approximated as a set of lines based on the crushing-stretching behavior observed during the test (Fig. 7 (b)). The reaction function  $r(x)$  was determined as a combination of the following linear equations,

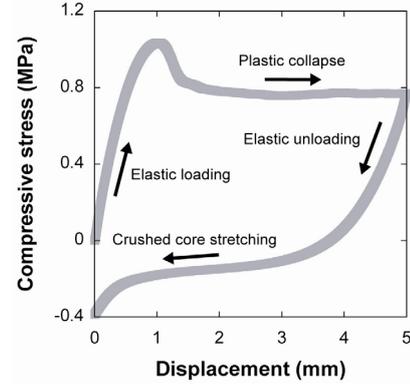
$$r_i(x) = k_i w(x) + q_i \quad (2)$$

where  $k_i$  is the gradient of the line and  $q_i$  is the intercept of the line as indicated in Fig. 7 (b).

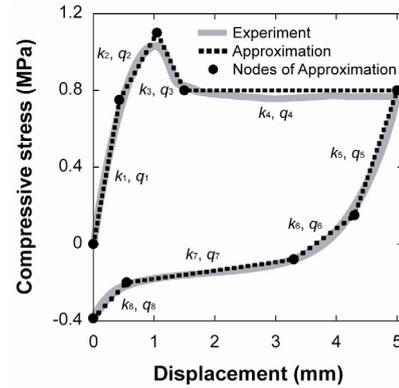
Next, the segmentation method was modified. In the segment-wise model for honeycomb sandwich beams, the beams were divided into segments based on the periodic shape of the honeycomb. However, the foam core does not have such a periodic shape. Thus, the foam core sandwich beam was divided into segments based on the physical property, not on the geometrical property, of the foam and the facesheet. The length of the segment  $a$  was

determined, based on the oscillation property of the solution (Eq. (1)), as

$$a < \frac{1}{3} \sqrt{\frac{4D_f}{k_1}} \quad (3)$$



(a) Compressive stress-displacement curve obtained in modified flatwise test.



(b) Approximation of stress-displacement curve.

Fig.7. Crushing-stretching property of foam integrated in model.

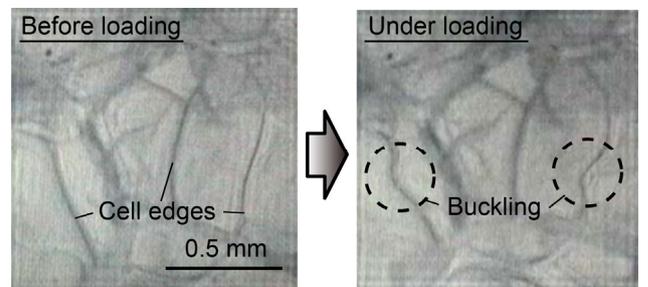


Fig.8. Micrographs of unit cell during flat-wise compression test.

where  $k_1$  is the elastic foundation coefficient found in Fig. 7 (b). This segmentation makes it possible to accurately reproduce the actual facesheet deformation, regardless of facesheet and core types. The indentation response for a given indentation displacement  $\alpha$  can be calculated by determining  $P$  and all the integral constants included in general solutions obtained from Eq. (1), using boundary conditions between the segments. And we can conduct indentation loading-unloading simulation by renewing the foundation parameters as  $\alpha$  increases. The detailed procedure of the simulation is presented in Ref. [7].

#### 4 Analysis of Indentation Behavior

Figure 9 compares indentation load-displacement curves obtained in the analysis and experiment. The segment-wise model, which takes into consideration the complicated crushing-stretching characteristics and physical property of the foam core, successfully reproduced the nonlinear load-displacement curves obtained in the experiment. Judging from calculated reaction stress distribution from the core to the facesheet, severely damaged core near the loading point generated “pull-down” force, inducing the residual facesheet dent.

Furthermore, the relaxation behavior of the facesheet dent was predicted. Under indentation unloading, the facesheet deflects upward as the indentation load decreases, and the crushed core, whose height in the stress-free state is lower than its uncrushed height, pulls the facesheet down. Finally, the facesheet stops at the position where the deflection of the facesheet and the deformation of the crushed core are in equilibrium. Thus, it was expected that the time change of the facesheet dent (Fig. 5) was attributed

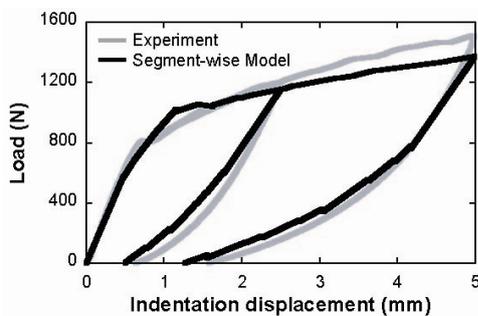


Fig.9. Comparison of stress-displacement curves.

to the relaxation of the pull-down force of the crushed core (Fig. 10). Hence, in order to predict the relaxation behavior of the facesheet dent, the stress relaxation effect of the crushed core during the stretching process was investigated by modified flatwise compression tests and the updated compressive stress-strain curves (Fig. 11) were then implemented in the simulation model. Residual dent profiles (1 hour after unloading, maximum indentation displacement: 5mm) obtained

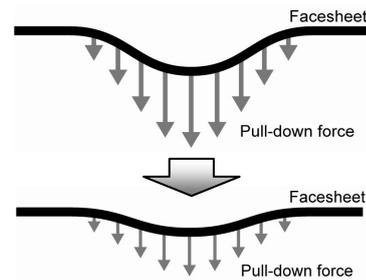


Fig.10. Time change of pull-down force inducing facesheet dent.

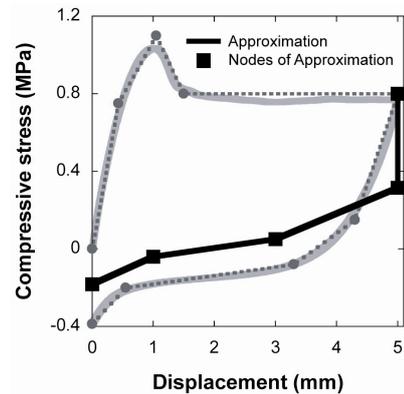


Fig.11. Time change of pull-down force inducing facesheet dent.

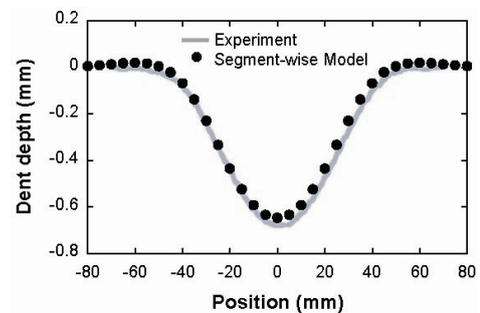


Fig.12. Comparison of residual dent profiles after relaxation.

in the calculation and the experiment are compared in Fig. 12. The predicted residual dent shape was in good agreement with the experiment data, confirming that the relaxation behavior of the facesheet dent can be predicted by considering the stress relaxation of the crushed foam core.

## 5 Conclusions

This paper investigated the indentation loading-unloading behavior of foam core sandwich beams by focusing on the interaction of the local facesheet deformation and the core crushing. First, the indentation response was evaluated using quasi-static indentation tests. The extended segment-wise model was then established to theoretically analyze the behavior. It was shown that the reaction force from the core to the facesheet controls the residual dent formation phenomenon and that relaxation behavior of the facesheet dent can be predicted by considering the stress relaxation of the crushed foam core.

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