Bending Moment Characteristics on Repeated Folding Motion of Coated Paperboard Scored by Round-Edge Knife*

Shigeru NAGASAWA**, Mohd NASRUDDIN BIN M.** and Yoshiaki SHIGA**
**Department of mechanical engineering, Nagaoka University of Technology
1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan
E-mail: snaga@mech.nagaokaut.ac.jp

Abstract
This work deals the creasing characteristics of coated paperboard. It was not clarified to estimate the deformation behavior of creased line from the first peak bending moment $M_{p1}$ and the initial gradient $C_1$ of bending moment. In this study, a new prototype testing apparatus has been developed for seeking the bending moment and the side view picture of creased part during repeated folding motion. The permanent (residual) deformation angles, the variance of residual stiffness and the hysteresis characteristics of bending moment were analyzed for the nominal shear strain (the scoring depth) $\gamma$. The obtained results were as follows: (1) $C_1$ was characterized with $\gamma$, while the second term gradient $C_2$ was characterized with $\gamma$ and the inverse of tracking angle $\Theta^{-1}$. (2) By introducing the area of closed curve of second term hysteresis $A_{CC}$, it is revealed that the gradient of $A_{CC}$ was remarkably varied with $\Theta$ at near the peak point $M_{p1}$.

Key words: Shear, Score, Crease, Hysteresis, De-Lamination, Friction, Paper

1. Introduction
A wedge indentation processing is widely used for cutting off and creasing a complicated-formed pattern from a sheet material such as carton boxes, labels, insulation films and similar metal thin sheets (1,2). If any cracks occur at the outside of folded parts of paperboard, which is used for making a cabinet, the mechanical strength of the cabinet is weakened and also the folded parts are inferior in decorative aspects. A few reports for in-plane elongation of paperboard during indentation of creaser were shown by Halladay and Ulm (3). Actual creasing range was investigated as the relationship between the crease depth and crease width by Hine (4).

Nagasawa et al. (5,6,7) reported about the folding stiffness with respect to the indentation depth of the creaser and also discussed with the crease deviation effect on the folding deformation characteristics. Over here, the bending moment response with the folding motion was measured by using a bending-strength tester (BST-150M (8)). This testing device was evaluated by hand motion, and the relationship between bending moment and rotation angle was only one time investigated for each specimen. The correlation between the bending strength (resistance) and several primary problems on the actual processing phenomenon was not sufficiently discussed in the past. To know the reaction force acting on a hinge, which is folded with a creased line, is important for adjusting the mechanical condition in the boxing stage by automatic folder gluer machine.

However, it was not clarified to estimate the deformation behavior of creased line from the initial strength of creased part, such as the maximum bending moment and the initial gradient of bending moment which are evaluated by one way motion. Furthermore, as the transient
deformation of creased part subjected to the bending moment was not observed by any camera during the bending test, the relationship between de-lamination and reduction of bending stiffness could not be verified in direct when the initial indentation depth of creasing rule was varied. In this study, therefore, a new prototype testing apparatus has been developed for seeking the bending moment and the side view picture of creased part during repeated folding motion. In order to reveal the hysteresis characteristics of bending resistance during the repeated folding motion from the initial position up to 60 °, and also to investigate the residual behavior of bending moment, a white-coated paperboard of 0.3 mm thickness was scored with a round-edge knife (creasing rule) and a grooved counter plate under a specified feed velocity, and then the repeated bending test was carried out by varying the tracking angle.

2. Experimental condition and method

2.1 Pre-processing of specimen

Figure 1 shows the scoring state of a paperboard using a round-edge knife (creasing rule). Since the paperboard consists of multiple-plies, the in-plane sliding and de-lamination occur at the scored zone when the creasing rule moves downward with the indentation depth d. Fig.1 (b) illustrates the out-of-plane shearing deformation by drawing stepped virtual lattice. When the creasing rule is indented to the paperboard, the expression: \( \tan \delta = \frac{2d}{B} = \gamma \) is the average shearing strain with the specified three points as shown in Fig.1 (a). This quantity \( \gamma \) is defined here as the nominal shear strain \( \gamma^{(30)} \). Empirically, a special value of \( \gamma \) is referred as a representative state when the indentation depth is equal to the thickness of paperboard \( d=t \). Here, using the paperboard thickness \( t \) and the thickness of creasing rule \( b \), the groove width \( B \) was also empirically chosen as \( 2t+b = 1.3 \) mm.

![Fig.1 Schematics of out-of-plane scoring process by round-edge knife](image)

(a) Definition of nominal shear strain     (b) Shear by de-lamination

Figure 2 shows experimental apparatus in making the test pieces of paperboard scored by the creasing rule with radius of \( r=0.45 \) mm and the face plate with the groove width of \( B=1.3 \) mm. The creaser direction angle \( \phi \) was chosen as 90 ° with respect to the machine direction (MD). The nominal shear strains \( \gamma=2d/B \) were chosen as 0.0, 0.2, 0.3, 0.4, 0.6, 0.8, 1.0, while

![Fig.2 Experimental apparatus for scoring](image)

(a) Scoring apparatus     (b) Top view of face plate
the feed velocity was chosen as \( V = 0.0167 \text{ mm/s} \). The range of \( \gamma \) was empirically considered from 0.0 up to \( 4t/B \). Any rubber fixtures were not implemented here.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>In-plane tensile properties of white-coated paperboard in machine direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate TS ( \sigma_b )</td>
<td>41.1 (40.2–42.7) MPa</td>
</tr>
<tr>
<td>Proof S. 0.2% strain ( \sigma_b )</td>
<td>11.1 (11.4–10.9) MPa</td>
</tr>
<tr>
<td>Breaking true strain ( \varepsilon_b )</td>
<td>1.71 (1.81–1.62) %</td>
</tr>
<tr>
<td>Young’s mod. ( E )</td>
<td>5.72 (5.91–5.53) GPa</td>
</tr>
</tbody>
</table>

The test pieces were prepared as 10 pieces of the rectangle-formed white-coated paperboard (the basis weight \( \rho = 228–237 \text{ g/m}^2 \), which had width of 40 mm, length of 60 mm, and thickness of 0.3 (0.297–0.303) mm, for each condition of chosen nominal shear strain. The chosen paperboard was popular for a certain carton box in the worldwide packaging market. The width 40 mm of test piece was chosen so as to be larger than 10 times of thickness 0.3 mm, but less than the space restriction of 50 mm. If the width is too large, the misalignment of creaser gap in the longitudinal direction of creasing rule appears to increase and also the area of specimen becomes large. From the aspect of easiness for handling the test pieces, the width ought to be larger than 10 mm, but less than 50 mm. The span of load cell 10 mm was also chosen (designed) owing to the easiness for handling. As the creased zone has a size of 2.0–2.5 mm, it was noticed that the rest span of load cell was 7.5–8.0 mm.

The in-plane tensile test properties in MD, based on JIS-P8113 (gauge length: 180 mm, width: 15 mm, feed velocity: \( V = 0.33 \text{ mm/s} \)), were shown in Table 1. All paper boards were kept in a room which had the temperature of 296 K and the humidity of 50 %RH.

2.2 Measurement of bending moment during repeated folding motion

Figure 3 shows a schematic diagram and a general view of experimental apparatus for repeated folding motion test. Figure 4 is an example of relationship between a folding angle \( \theta \) and a bending line moment (resistance for the unit width) \( M \). The sampling time of \( M, \theta \) was chosen as 2 ms. Since the paperboard has viscous elasticity and creep characteristics during the folding process, rotation velocity of fixture \( \omega \) was set to 0.2 rps and stopping time for returning back was set to zero at a tracking position of \( \Theta \) and a second starting position of \( \theta_2' \). The rotation velocity of \( \omega = 0.2 \text{ rps} \) was empirically chosen for simulating a hand operation of BST-150M \(^8\).

The tracking angle (position) \( \Theta \) was varied from 0 up to 60 °. As the accelerated duration (transient time) was set to 0.1 s for each starting/Stopping, the rotation velocity \( \omega \) reached to 0.2 rps for \( \Theta > 7.2 \text{ °} \).
In case of $\theta=10^\circ$, therefore, it is estimated that the stationary state of $\omega=0.2$ rps is kept for 2.8° (28%). The initial (first term) gradient of bending line moment $C_1 (=G_i)$ (5), the second term gradient $C_2$, the released angle of $\theta_2$ and the area of closed curve $A_{CC}$ were investigated with respect to $\gamma$. $C_1$ is the bending resistance which includes the propagation of de-lamination caused by the first term folding, while $C_2$ is the residual bending resistance which includes the de-lamination caused by the tracking angle (same as the maximum folding angle) $\Theta$.

3. Results and discussion

3.1 Permanent deformation

Figure 5 shows a representative example of the relationship between a folding angle $\theta$ (up to the tracking angle $\Theta$) and a bending line moment $M$ by varying the nominal shear strain $\gamma$. The first starting position of $\theta_1$ was varied with $\gamma$ while the second starting position of $\theta_2$ was varied with the tracking angle $\Theta$.

Figure 6 shows the angle of starting position $\theta_1$ which corresponds to the residual camber derived from blade indentation without rubberring. Figure 7 shows the released angle $\theta_2$ with the tracking angle $\Theta$ by varying the nominal shear strain $\gamma$.

Equation (1) shows an approximation of $\theta_1$ with $\gamma$ while Eq. (2) is an approximation of $\theta_2$ with $\gamma$ and $\Theta$, respectively.

$$\theta_1 = -8.50\gamma^2 - 2.84\gamma \quad (0 < \gamma < 1)$$  \hspace{1cm} (1)

$$\theta_2 = a_1\Theta + a_0 \quad (0 < \Theta < 60^\circ)$$  \hspace{1cm} (2)

$$a_1 = 0.434\gamma^2 - 0.533\gamma + 0.75 \quad (0 < \gamma < 1)$$

$$a_0 = -9.492\gamma^2 + 11.32\gamma - 7.742$$

Fig. 5 Relationship between bending line moment and rotation angle by varying nominal shear strain, in case of tracking angle of 60°.
It was found that $\theta_2$ was linearly varied with $\Theta$ and about a half of $\Theta$ for $60^\circ > \Theta > 30^\circ$, it was less than 1.5° for $\Theta < 10^\circ$. Namely, when $\Theta$ was less than 10°, the permanent deformation of angle was remarkably small.

### 3.2 Relationship between second term hysteresis area and first peak point of bending moment

Figure 8 shows examples of the relationship between the folding angle $\theta$ and the bending line moment $M$ by varying the tracking angle $\Theta$ for the nominal shear strain of $\gamma = 0.4$, the rotation speed of $\omega = 0.2$ rps. From this response, the integration of closed curve $A_{CC}$ (hysteresis area for the second term loop) was calculated using the trapezoidal rule of numerical integration method. Figure 9 shows $A_{CC}$ with respect to $\Theta$ by varying $\gamma$. From Fig.5 and Fig.9, following features were detected:

1. When $\gamma > 0.6$, the overshoot of $M$ disappeared and $A_{CC}$ was almost linear with $\Theta$.
2. The peak position (angle) $\theta_1p$ of overshoot of $M$ appeared to match with transition limit $\Theta_T$ of gradient of $A_{CC}$ ($\frac{\partial A_{CC}}{\partial \Theta}$); For an example, when $\gamma = 0.2$, $\theta_1p \approx 20^\circ$ and it corresponds to the transition limit $\Theta_T$ of $\frac{\partial A_{CC}}{\partial \Theta}$.

![Graph showing relationship between bending line moment and rotation angle by varying tracking angle](image1)

**Fig.9** Relationship between bending line moment and rotation angle by varying tracking angle, in case of nominal shear strain of $\gamma=0.4$. 

![Graph showing relationship between angle of starting position and nominal shear strain](image2)

**Fig.6** Relationship between angle of starting position and nominal shear strain (indentation depth of blade).
Fig. 9 Relationship between second term hysteresis area and tracking angle.

Fig. 10 CCD Side views of scored paperboard during folding process in case of \( \phi = 90^\circ, \gamma = 0.2 \).

Figure 10 shows CCD photographs of side views of scored paperboard during the bending test. In this picture, a case of \( \gamma = 0.2 \) was shown. From Fig. 10 (b), the initial damage of score and the shallow buckling were detected, while the bulging was promoted with the scored corners (nodes) in Fig. 10 (c), (d).

Fig. 11 Transition model of creasing process.

The transition model was illustrated in Fig. 11 in order to exaggerate the transition of creasing process. At the peak position of overshoot, since a certain level of long-parallel de-laminations occur in the scored zone, the in-plane bending stiffness is remarkably decreased and then it appears that variance of hysteresis area increases in this process. When the folding angle \( \theta \) passes through the peak point \( \theta_{1p} \) of overshoot, the inner bulging is promoted (increased) but the deformation of de-laminated zone is restricted with the immobile nodes as shown in Fig. 11 (b).

So far, it is revealed that the creasing deformation at the peak point of overshoot is different from that after passing through the peak point of overshoot. The gradient \( \partial A_{CC} / \partial \Theta \) in the range of pre-stage of overshooting (\( \theta < \theta_{1p} \)) tends to be larger than that for the post-stage of overshooting (\( \theta > \theta_{1p} \)). When the inner de-lamination of scored paperboard is
insufficient by the specified $\gamma$, $A_{CC}$ remarkably increased in the pre-stage and the peak of overshooting.

Figure 12 shows the representative examples of angle of the peak position $\theta_p$ and angle of the transition limit $\Theta_T$, which were derived from Fig.5 and Fig.9. From this graph, it is confirmed that $\theta_p$ is approximately equal to $\Theta_T$.

Fig.12 Angles of peak position and transition limit (representative examples).

### 3.3 Gradient of line moment as stiffness with folding angle

Regarding the material properties of coated paperboard, the first peak of bending line moment $M_{p1}$ and the first term gradient of bending line moment $C_1$ are fundamental properties when nominal shear strain $\gamma$ is zero. Comparing the current paperboard shown in Table 1 with referred specimen of C (6), the thickness and the basis weight are fairly different with each other. In order to know the stiffness per unit thickness of those specimens, $M_{p1}$ was normalized as $M_{p1}t^{-2}$ and $C_1$ was also normalized as $C_1t^{-2}$.

The calculated values were shown in Table 2. From this result, the current specimen has a little higher stiffness while the breaking strength is a little smaller.

Table 2 Normalized peak bending moment and first gradient of paperboard w/o scoring.

<table>
<thead>
<tr>
<th></th>
<th>U.T Stress $\sigma_B$ MPa</th>
<th>Thickness $t$ mm</th>
<th>N.P. Peak M. $M_{p1}$ MPa</th>
<th>N.F. Gradi. $C_1t^{-2}$ MPa-deg$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current specimen</td>
<td>41.1</td>
<td>0.30</td>
<td>6.33</td>
<td>0.61</td>
</tr>
<tr>
<td>Referred specimen</td>
<td>45.8</td>
<td>0.46</td>
<td>8.03</td>
<td>0.47</td>
</tr>
</tbody>
</table>

Fig.13 Dependency of first gradient of bending line moment on nominal shear strain.
Figure 13 shows the first term gradient $C_1 = \frac{\partial M}{\partial \gamma}$ with respect to $\gamma$. The first term gradient $C_1$ $\text{Ndeg}^{-1}$ was approximated with the second order power rule for $0 < \gamma < 0.6$, and approximated with a linear rule for $0.6 < \gamma < 1.0$ as shown in Eq. (3) and Eq. (4), respectively.

$$100C_1 = -6.3\gamma^2 - 2.3\gamma + 5.5 \quad (0 < \gamma < 0.6) \quad (3)$$

$$100C_1 = -2.8\gamma + 3.7 \quad (0.6 < \gamma < 1.0) \quad (4)$$

It is found that $C_1$ is remarkably decreased up to the limit condition ($\gamma \approx 0.6$) of disappearance of overshoot response of bending line moment, while it is linearly varied with $\gamma$ after passing through the limit condition of disappearance ($\gamma > 0.6$).

Figure 14 shows the second term gradient $C_2$ with respect to tracking angle $\Theta$, where $\gamma$ was varied from 0.0 to 1.0. From this graph, followings are revealed: (1) $C_2$ is decreased with $\gamma$ as similar to the variance of $C_1$ with $\gamma$, while $C_2$ is also decreased with $\Theta$. It appears linearly with $\Theta$ for $\gamma < 0.6$; (2) $C_2$ is decreased and almost linear with $\gamma$ for $\gamma < 0.6$ under keeping $\Theta$ constant; (3) When $\gamma > 0.6$, $C_2$ is not so large in the range of $\Theta = 10$–30 °, while $C_2$ is remarkably large in the same range for $\gamma < 0.6$. This variance appears from the mechanism of Fig.10 (a). (4) The stiffness ratio of $C_2/C_1$ was 0.6–1.1 for $\Theta < 20$ °, while it was 0.4–0.6 in case of $40$ ° $> \Theta > 60$ °. To be less than 1.0 is equivalent to reduce the elastic bending stiffness of crease.

It is found that $C_2/C_1$ is roughly reduced to a half of virgin state for $\Theta > 40$ °. This reduction of $C_2/C_1$ seems to depend on the structural-material properties such as de-lamination resistance, inner friction characteristic. In order to decide the required stiffness of $C_2$ at a specified tracking angle, the nominal shear strain $\gamma$ must be chosen appropriately from the aspect of production design needs.

### 3.4 Relationship between variance of $A_{CC}$ and $C_1$

Assuming that the area of closed curve $A_{CC}$ is linearly approximated with $\Theta$ by using Eq. (5), coefficients $a_{01}$ and $a_{00}$ were estimated from Fig.9. Here, the range of $\Theta$ was considered as $\Theta_1 < \Theta < 60$ °.
\[ A_{CC} = a_{k1} \Theta + a_{k0} \]  \hspace{1cm} (5)

**Figure 15** (a) shows the coefficients of \( a_{k1}, a_{k0} \) with respect to \( \gamma \), while Fig.15 (b) shows relationship between \( a_{k1} \) and \( C_1 \). It is revealed that the intercept of \( a_{k0} \) is positive when the first peak of bending line moment appeared for \( \gamma < 0.6 \). For \( \gamma > 0.6 \), \( a_{k0} \) can be relatively negligible owing to a high density of de-lamination.

Observing the correlation between \( a_{k1} \) and \( C_1 \), they have the similar tendency with respect to \( \gamma \), and following expression (6) is derived:

\[ a_{k1} = 0.41 C_1 + 0.024 \]  \hspace{1cm} (6)

It was found that \( a_{k1} \) had strongly related to \( C_1 \) when \( \gamma \) was varied. So far, it is possible to predict the inside-frictional behavior of creased part from the value of \( C_1 \).

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### 4. Conclusions

Twice-repeated bending characteristic of creased white-coated paperboard of 0.3 mm thickness was investigated by varying nominal shear strain \( \gamma \) and tracking angle \( \Theta \), using a prototype crease strength tester under rotation angle velocity of 0.2 rps. The obtained results were as follows:

1. The initial (first term) gradient \( C_1 \) was characterized with \( \gamma \), while the second term gradient \( C_2 \) was characterized with \( \gamma \) and the inverse of tracking angle \( \Theta^{-1} \).
2. The first term starting position (angle) \( \theta_1 \) was approximately expressed with second order power rule of \( \gamma \), while the second term starting position (angle) \( \theta_2 \) was expressed with the first order of \( \Theta \) and the second order power rule of \( \gamma \).
3. By introducing the area of closed curve of second term hysteresis \( A_{CC} \), it was found that the gradient \( \partial A_{CC}/\partial \Theta \) is remarkably varied with \( \Theta \) at near the first term peak point \( (M_{p1}, \theta_{1p}) \) of bending line moment. Here, \( M_{p1} \) is the maximum bending line moment and \( \theta_{1p} \) is the corresponded folding angle position of the first term peak point.
4. When the first term peak point of bending line moment appears for \( \gamma < 0.6 \), (i) many parallel de-laminations occur at the scored zone for \( \Theta < \theta_{1p} \), while (ii) a bulging of inner layers and rotary opening of de-laminated zone appear at two immobile nodes for \( \Theta > \theta_{1p} \). Namely, it is revealed that there is a transition state from (i) to (ii) at near the first term peak point.
5. It is confirmed that the developed measurement system is useful for detecting the relationship between the second term hysteresis area and the bending stiffness parameters.
Acknowledgement

This work was supported by the JSPS Grants-in-Aid for Scientific Research, Creative and Pioneering Research (C) of Grant Number 22560106.

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