Effect of Scoring Condition on Creasing Characteristics of Double-Wall Corrugated Board*

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Abstract
A prototype-rotary creaser was experimentally applied to an AB double-wall corrugated fiberboard to reveal creasing characteristics of the corrugated fiberboard and mechanical factors on failures of its height wise crease. Through this work, the followings were obtained. (1) There are appropriate combinations of pre-creaser gap and main-creaser gap for restricting the failure occurrences in the inside liner; (2) The pre-stage creasing for crushing corrugated medium was severely necessary for reducing the failures of the inside liner and performing the high-precision positionment for bending; (3) Dependency of water content and feed velocity on the failures of the inside liner was revealed.

Key words: Paper, Corrugated Board, Bending/Folding, Failure of Sheet, Double-Wall

1. Introduction
In the die cutting process of corrugated fiberboard (Cfb) that is used for packaging containers, creasing is a very important mechanical behavior. The following points are especially important for controlling the quality of packaging containers of Cfb: (1) adjustment of folding position and precise dimensions of container box; (2) restriction of occurrence of cracks on the liner sheet; (3) stabilization of bending resistance moment of the creased part. To produce precise box dimensions at the creasing positions and reducing any surface failures on the liner sheet, advanced technique for stabilizing the folding deformation is required. In the past, the bending characteristics of thin Cfb were investigated by Nagasawa et al. with respect to the precise dimensioning of the creased line (1), although the bending characteristic of a thin-fluted material was similar to that of a white-coated paperboard (2). Stress distribution during bending test, being perpendicular to the inner flute wave, was studied by Ishibuchi et al. (3) and the cutting characteristics of Cfb were reported by Hofer et al. (4),(5). Regarding the creasing process of a thick-fluted material, there is not any study on the deformation behaviors of the inner flute (medium), the outer liner and the inner liner sheet by using a rotary creaser, owing to the complicated structure of the creaser and to the difficulties of taking measurements while performing the process.

In 2008, Harryson et al. (6) and Thakkar et al. (7) reported about the anisotropic model analysis of Cfb subjected to creaser indentation. This is useful for knowing the crushing mechanism of a corrugated medium (CM), but there is not any discussion about the failure mechanism on the liner, neither about a double-wall Cfb.

As the prior investigation by Nagasawa et al. (8), A-flute Cfb’s, which were relatively thinner than AB-double-wall Cfb’s, were experimentally creased by using three
main-creasers in parallel with a driving shaft. Here, the frequency of failure occurrences on the inside liner was statistically investigated when the main creaser gap (or the indentation depth of creasing knives) was varied according the specified A-flute Cfb. From this experiment, half-breaking (failure) condition of the inside liner was confirmed with machining conditions, such as the creaser gap and the in-plane restraint for the three creasing knives.

However, since the wave phase between the A-flute layer and the B-flute layer of the AB-double-wall Cfb's appears to be randomly produced and the B-flute layer behaves as a flexible underlay, the frequency of failure occurrences on the inside liner of the AB-double-wall Cfb seems to be different from that of the A-flute Cfb.

In this work, in order to clarify the deformation behaviors of AB-double-wall Cfb in the creasing process using a rotary creaser, a proto-type creaser system has been used for scoring the heightwise Cfb. The deformation of AB-double-wall specimens was investigated with respect to the gap of the creaser roll, the feed speed and the room humidity. After the creasing process went through without any failures on the inside liner, a bending strength test was applied to the specimens to evaluate the bending moment resistance. When the surface of the inner liner was broken by the creasing roll, the surface failure state of the specimens was observed using a CCD camera. In this prototype creaser experiment, a critical breaking condition of the liner sheet was revealed.

2. Experimental condition and method

Figure 1 shows schematics of a prototype rotary ruler as an experimental apparatus, and illustrates the sectional views of the bite rolls for one scoring line. In this apparatus, there are three scoring lines in parallel. The figure illustrates the stream line of a Cfb (specimen) fed by a pair of pre-creaser rolls, which were set at the entry side, and a pair of creaser rolls, which were set at the finishing side. The pre-creaser consists of a round steel roll with a radius of \( R = 40 \) mm and a flat-trapezoidal steel roll with a width of 17 mm. The main creaser is composed of a biting roll, which has a wedge angle of 120° with a width of 3.2 mm, and a flat anvil roll embedded with urethane rubber which has a JIS-K-6253 based hardness of 90 degrees, 8 mm width and a depth (thickness) of 7 mm. Diameter of pre-creaser is 140 mm, and that of main creaser is 310 mm.

Figure 2 shows the relationship between the three scored lines and the primary dimensions of the specimen in the top view. In Fig.2, there are two scoring lines, which have a distance of 80 mm from the center scoring line. Those two scoring lines are dummy but necessary for keeping a stable center scoring line. The specimen, which had a width of 230 mm and a length of 320 mm, was fed from the left side of Fig.1 using an entry guide. After passing through the rotary ruler, the specimen was cut by hand cutter and several pieces of rectangle specimens were made with a length of 125 mm and a width of 50 mm.

**Fig.1** Schematics of creasing apparatus for each scoring line

**Fig.2** Dimensions of specimen
The primary dimensions of AB double-wall Cfb are shown in Fig.3. The nominal basis weights of the raw-materials, that were used for liners and inner flutes (corrugated medium, CM), were composed of 210(K6)-160 -160-180-210(K6) g·m⁻². Table 1 shows the material properties of the raw-materials of specimens, derived from the in-plane tensile testing. The thickness of the B-flute medium (160 g·m⁻²), the A-flute medium (180 g·m⁻²), and the outside/inside liners (210 g·m⁻²) were 0.22, 0.25, 0.24 mm, respectively. The total thickness $t_F$ of the five raw-material sheets: 210(K6)-160-160-180-210(K6) was 1.17 mm.

**Table 1** In-plane tensile properties of raw-materials of AB double-wall corrugated fiberboard (at 50%RH, 296K, strain rate: 0.002 s⁻¹).

<table>
<thead>
<tr>
<th>Raw-mat.</th>
<th>Cross direction</th>
<th>Machine direction</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Ult.Str. $\sigma_B$/MPa</td>
<td>Br.Strain $\varepsilon_B$/%</td>
</tr>
<tr>
<td>Liner 210</td>
<td>29.1 (28.5~30.0)</td>
<td>5.5 (5.2~5.8)</td>
</tr>
<tr>
<td>Medium 160</td>
<td>17.6 (16.9~18.3)</td>
<td>4.2 (3.7~4.7)</td>
</tr>
<tr>
<td>Medium 180</td>
<td>18.4 (17.5~19.1)</td>
<td>4.7 (4.2~5.0)</td>
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The Cfb specimen was scored in the longitudinal direction of CM by both the pre-creaser and the main creaser. The roll gap of the pre-creaser was denoted with $c_P$, and that of the main creaser was denoted with $c_C$, respectively. In the following, the normalized gaps $c_P/t$ and $c_C/t$ were considered as processing parameters. Here, $t (=7.91$ mm) is the measured height of Cfb. In Fig.3, the sum of the B-flute height of $t_B=3$ mm and the A-flute height of $t_A=5$ mm was not 8 mm as the result of measurement, due to the height loss in the production process and/or by the measuring pressure. Ten pieces of specimens were prepared for inspecting the failure occurrences, while ten pieces of the same specimens were used for the bending test for each condition of creaser gaps.

![Fig.3](image) Layout and primary dimensions of section across to the height wise corrugated board.

![Fig.4](image) Schematics of bending moment measurement using a prototype equipment for the crease stress test.
As a normal condition for scoring, the followings were chosen: the feed velocity \( V = 2.92 \text{ m/s} \), the gap of the pre-creaser \( c_p = 1.2 \sim 1.4 \text{ mm} \) \((c_p/t=0.15 \sim 0.18)\) and the gap of the main-creaser \( c_C = 0.7 \text{ mm} \) \((c_C/t=0.09)\). In this work, the following scoring conditions were considered in order to investigate the effect of \( V, c_p \) and \( c_C \) on the failures of Cfb:

(a) The feed velocity of Cfb: \( V=0.0162, 1.62, 2.92 \text{ m/s} \), \( c_p = 0.75 \sim 7.1 \text{ mm} \) \((c_p/t=0.09 \sim 0.90)\) while keeping \( c_C = 0.7 \text{ mm} \) \((c_C/t=0.09)\);
(b) \( V=2.92 \text{ m/s} \), \( c_C = 0.7 \sim 3.2 \text{ mm} \) \((c_C/t=0.09 \sim 0.40)\) while keeping \( c_p = 8.5 \text{ mm} \) \((c_p/t=1.08, \text{ no pre-creasing})\) for failure diagnose on the scored inner liner;
(c) \( V = 2.92 \text{ m/s} \), \( c_p = 0.75 \sim 7.1 \text{ mm} \) \((c_p/t=0.09 \sim 0.90)\) while keeping \( c_C = 8.5 \text{ mm} \) \((c_C/t=1.08, \text{ no creasing})\) for the sake of diagnosis of failure on the scored inner liner.

As a representative characteristic for the folding of the creased part, the relationship between the bending moment per unit width \( M \text{ Nm/m} \) and the bending angle \( \theta \) was measured by using proto type equipment used in the creasing stress test (CST)\(^9\)\(^{10}\). Figure 4 shows the measurement principle of the bending moment and its rotation angle.

The specimens of Cfb were prepared in a room with an average temperature 296 K and average humidity 50%RH for 24 hours.

3. Results and discussion

3.1 Occurrences of failure when varying the main creaser gap or the pre-creaser gap

In order to know the necessity of a combination scoring using the pre-creaser and main creaser rolls, the experiments under the scoring conditions (b) and (c) above mentioned were carried out. Figure 5 shows the frequency of failure occurrences \( q \) (the occurrences of failures) on the scored inside liner for the main creaser gap \( c_C \) in the case (b).

The frequency of failure occurrences \( q \) was counted when the length of the failure zone was totally longer than 5% length of a specimen, although the actually observed failure length was longer than a half of the specimen.

It was confirmed that \( q \) on the inside liner remarkably increased when \( c_C/t < 0.4 \), and it was almost 1.0 in the case of \( c.C/t < 0.09 \). When \( c_C/t=0.09 \), the indentation ratio of five layers of raw-material was estimated to be \( 1-0.7/1.17 = 0.4 \). Since the counter roller of the main creaser was made of urethane rubber, the actual roller gap of the main creaser was larger than the estimated one.

Under the scoring condition (c), the failure occurrences were detected for \( c_p/t < 0.09 \) \((c_p=0.75 \text{ mm})\). Therefore, the raw-materials of five layers with \( t=1.17 \text{ mm} \) are supposed to be broken when the indentation ratio reaches \( 1-0.75/1.17 = 0.36 \).

3.2 Effect of pre-creaser gap on failure occurrences while keeping \( c_C/t = 0.09 \)

In order to know the effect of the pre-creaser gap \( c_p \) on the frequency of failure
occurrences, the case of $V=2.92 \text{ m} \cdot \text{s}^{-1}$ was chosen from the scoring condition (a) and carried out. Figure 6 shows the frequency of failure occurrences $q$ on the scored inside liner by varying the pre-creaser gap $c_P$ while keeping $c_C=0.7 \text{ mm}$ ($c_C/t=0.09$). From this graph, it was found that $q$ was linear with $c_P/t$ of $0.2 < c_P/t < 0.4$ and there was a local-minimum zone near $c_P/t=0.15-0.25$. This local-minimum zone is an optimal condition for scoring the inside liner of AB double-wall Cfb. In the case of $c_P/t <0.09$, as mentioned in the previous section, $q$ tended to increase due to a surplus indentation of the roller onto the work sheet.

Figure 7 shows a representative example of a photograph of a central scored line in the case of $c_P/t=0.16$, $c_C/t=0.09$ and $V=2.92 \text{ m} \cdot \text{s}^{-1}$. The failure occurrences were partial. From this photograph, the following features are detected: (i) the scored line tends to meander with a height wise of corrugated mediums; (ii) a scored failure profile is clearly detected at the scored-center line, while it is not clearly detected on the two scored dummy lines. This seems to be caused by differences in the in-plane tensile state. (iii) the failure occurrences were remarkably detected near but not just on an apex position of corrugated mediums. So far, seeing Fig.6 and Fig.7, it seems that $q$ of the inside liner could be decreased due to work-softening of corrugated medium.

Fig.7 Top view of the scored inside liner of a specimen in case of $c_C/t=0.09$, $c_P/t=0.16$, $V=2.92 \text{ m} \cdot \text{s}^{-1}$.

3.3 Relationship between interference of inside liner and pre-creaser gap

Figure 8 shows sectional views of the creased part at right angle in cases of $c_P/t=0.16$, $0.38$ under $c_C/t=0.09$. Here, the chosen samples were successfully scored without showing any failure occurrences in Fig.6. When the indentation ratio of the pre-creaser was small, namely in the case of $c_P/t=0.38$, interference of the inside liner was detected from Fig.8 (c),(d). In the case of $c_P/t=0.16$, interference of the inside liner disappeared as shown in Fig.8 (a), (b).

Fig.8 CCD photographs of the creased part at right angle in case of $c_C/t=0.09$. 
It is confirmed from Fig.6 and Fig.8 that the pre-creaser gap remarkably affects the stress state of the creased part and the in-plane strength of the outside liner. Dispersion of folding position concerning an apex position of corrugated mediums seems to affect the interference of the creased part at a certain level from the aspects of variance of compressed-space density of fiberboard in the creased part.

### 3.4 Effect of dispersion of folding position on bending resistance

As mentioned in the section 3.3, there was meandering of the scored line and dispersion of folding position measured with an apex position of CMs. This seems to cause an additional dispersion of bending moment resistance.

**Figure 9** shows a representative bending moment diagram in the case of $c_C / t = 0.09$, $c_P / t = 0.38$, $V = 2.92 \text{ m}\cdot\text{s}^{-1}$. From the bending diagram, the difference $\Delta M_{\text{peak}}$ from the upper-bound peak point to the lower-bound peak point of bending moment was estimated for each case of $c_P / t$. At the same time, the deviation $\Delta X = e / \lambda$ of folding position from an apex position of corrugated mediums was measured from each specimen after bending with right angle. **Figure 10** shows the relationship between the peak bending moment $M_{\text{peak}}$ and its correspondent deviation of folding position $\Delta X = e / \lambda$, while **Fig. 11** shows the relationship between the maximum difference of peak bending moment $\Delta M_{\text{peak}}$ and $\Delta X = e / \lambda$ for each setup condition of $c_C$, $c_P$.

**Fig.9** Relationship between bending moment resistance and rotation angle (10 pieces from two specimens of 230x320).

**Fig.10** Relationship between deviation of creasing position and peak bending moment ($V = 2.92 \text{ m}\cdot\text{s}^{-1}$, $c_C / t = 0.09$)
Fig. 11 Correlation between deviation of creasing position and peak bending moment 

\[ V = 2.92 \text{ m/s}^{-1}, \quad c_{c}/t = 0.09 \]

From Fig.10, the average of \( M_{\text{peak}} \) appears to be increased along with the gap of \( c_{p}/t \). It seems that there is not any correlation between \( M_{\text{peak}} \) and \( \Delta X \), while it is found that there is a strongly positive correlation between \( \Delta M_{\text{peak}} \) and \( \Delta X \). Eq.(1) is the linear approximation with respect to Fig.11.

\[
\Delta M_{\text{peak}} = 2.21 \left( \frac{e}{\lambda} \right) + 0.34 \quad \text{Eq.(1)}
\]

Eq.(1) shows that the dispersion of \( M_{\text{peak}} \) is proportionally caused by the deviation of the folding position with reference to the apex position of CM.

3.5 Effect of water content on failure occurrences

Figure 12 shows the relationship between the frequency of failure occurrences \( q \) and the pre-creaser gap \( c_{p}/t \) under \( c_{c}/t = 0.09, V = 2.91 \text{ m/s}^{-1} \). When the water content (WC) increased with 1.6\%, the frequency of occurrences decreased by 20~40\%. It is confirmed that the water content of Cfb is a primary factor to determine the frequency of failure occurrences in the inside liner. Regarding the local-minimum zone of failure occurrences for \( c_{p}/t \), it was almost invariant with the WC. In actual production, since the failure occurrences on the inside liner must be zero, the pre-creaser gap zone of \( c_{p}/t = 0.11 \sim 0.25 \) is supposed to be an allowable and optimal condition for processing the AB-double-wall Cfb.

According to the in-plane tensile testing of a kraft linerboard\(^{(11)}\), the breaking strain tends to be increased, while the tensile strength tends to be decreased with the room humidity.
Namely in general, the stiffness of linerboard becomes reduced and the failure limit of strain is increased with the WC. The variance of breaking strain by the humidity seems to be coincident with the variance of failure occurrences of the scored inner liner.

3.6 Effect of feed velocity on failure occurrences

Figure 13 shows the relationship between the frequency \( q \) of failure occurrences and the pre-creaser gap \( c_p/t \) for the feed velocity \( V \) chosen from 0.016 up to 2.92 m/s\(^{-1} \). Here, \( c_c/t=0.09, c_p/t=0.09-0.5 \) were considered (a part of the case (a)). When \( V \) was decreased, the distribution of \( q \) by \( c_p/t \) was apt to be decreased, although the decreasing relation was not uniform for \( c_p/t=0.3-0.5 \). The local-minimum zone of \( q \) was almost invariant from the variance of feed velocity.

The non-uniformity of the decreasing of \( q \) seems to be caused by meandering of scoring and dispersion of deviation of the scored position from an apex position of the CMs. Therefore, it is found that there are two stable states: the upper bound probability of 1.0 and the lower bound probability of 0.5.

3.7 Stiffness effect of flat-roller on failure occurrences

In order to crush and soften the stiffness of CMs, the pre-creaser gap \( c_p/t \) is one primary factor. Wave numbers with the flat-roller contact width: 17/8=2.13 are also another primary factor. Adding those, the uniformity of crushed wave numbers and that of its reduced stiffness appear to be effective for restricting the failure occurrences of the inside liner. Therefore, here, the flat-roller made of SKD was modified and exchanged for a new flat-roller, which was bound with a 8.5mm-thickness ring of 90degree-urethane rubber.

Figure 14 shows the relationship between the frequency \( q \) of failure occurrences and the pre-creaser gap \( c_p/t \) by exchanging the flat-roller material.

By binding the urethane rubber layer on the flat-roller, a zero-value state of failure occurrences appeared in the range of \( c_p/t < 0.3 \). As a tendency, the frequency of failure occurrences \( q \) shifted to the right side with an offset of 0.05–0.15 due to elastic deforming (sinking by contact pressure) of the urethane rubber layer. This is clearly superior for creasing the AB double-wall Cfb. This result suggests that there is a suitable range of hardness of the rubber layer on the flat-roller, and also there is an appropriate range of the radius \( R \) of the round pre-creaser roll.

Regarding the details of the uniformity on crushing deformation of CMs, a certain numerical simulation is necessary for estimating the breaking stress state, furthermore.
3.8 Comparison of AB-double-wall with A-flute corrugated board

The relationship between the frequency of failure occurrences and the gap of main-crease was explained by using Fig.5. This diagram used the normalized gap of $c_C/t$, where the height of Cfb $t=7.91$ mm was assumed to be the sum of A-flute and B-flute layer. This situation seems to make difficult to compare the failure occurrences of AB-double-wall with that of A-flute Cfb \(^{(8)}\). Since the AB-double-wall Cfb is composed of an A-flute and a B-flute Cfb, this structure can be understood as an A-flute Cfb stacked on a flexible underlay which is same as the B-flute Cfb. Putting the parameters of $(c_C-t_0)/t_A$, $c_C/t_A$ as the equivalent main-crease gaps for the AB-double-wall and the A-flute Cfb, respectively, it is possible to compare the performance of both Cfb with each other, as shown in Fig. 15. Here, the dataset of AB-double-wall (ABF) was the same as that in Fig.5, while the diagram of AF was referred from the experimental result of A-flute Cfb \(^{(8)}\). Synthetically, the B-flute layer of AB-double-wall Cfb appears to make the A-flute layer sink with the equivalent gap of 0.2. To introduce the equivalent main-crease gap $(c_C-t_0)/t_A$ enables to compare the performance of failure occurrences for knowing the stiffness effect of the outer layer, when the specification of the outer layer (e.g., the B-flute layer) is changed.

4. Conclusions

A prototype rotary creaser, which was composed of three parallel lines with a pre-crease and a main creaser, was applied to score in the height wise a rectangle specimen of AB-double-wall corrugated board (Cfb) in order to investigate the folding performance of the creased part of the Cfb. Through this work, the followings were revealed.

1) Creasing mechanism and failure occurrences of the Cfb using the pre-crease and the main-crease was experimentally revealed. Namely, the out-of-plane crushing (stiffness softening) of the corrugated mediums (CMs) and thinning of the Cfb by upsetting with the pre-crease reduces the failure occurrences on the inside liner during a scoring process of the main creaser.

2) Frequency of failure occurrences on the inside liner was revealed for a single processing of the pre-crease and/or that of the main-crease. It is revealed that a combining process using those pre/main-creasers enables to reduce the failure occurrences. A suitable combination of pre-crease and main-crease gaps for restricting the failure occurrences was experimentally revealed in case of an AB-double-wall Cfb which was composed of 210(K6)-160-160-180-210(K6).

3) Regarding the height wise scoring, there was experimentally a dispersion of scoring position and meandering concerning the feed direction. A positive correlation between the offset of scoring position from an apex position of CMs and the variance of peak bending moment during the folding process was revealed. This is based on the principle that the peak bending moment is statistically decreased when softening the stiffness of the CMs.

4) During the folding process of the creased part, interference and deformed profile of the inside liner are remarkably affected by the pre-crease gap. The interference profile is almost independent of the offset of the height wise scoring position, while it depends on the pre-crease gap. Namely, to crush the Cfb with a certain range of $c_P/t$ (less than 0.2) under a certain wave number (e.g. larger than 2) contributes to avoid interference of the folded inside liner.

5) Effect of feed velocity on the failure occurrences of the inside liner was experimentally revealed. When the velocity is decreased, the failure occurrences were apt to be decreased, although its tendency was unstable with the variance of the pre-crease gap. Namely, there are the upper and lower bound levels concerning the frequency of failure occurrences for $c_P/t>0.3$.

6) Effect of water content of the Cfb on the failure occurrences was experimentally revealed.
7) A 8.5mm-thickness urethane rubber ring was applied to the flat-roller of pre-creaser. It is superior for restricting the failure occurrences at near its local-minimum zone (0.1<\frac{\rho}{\delta}<0.3).

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