Estimation of bending characteristics of creased paperboard using 45° tapered groove against unbalanced punch indentation

Shigeru NAGASAWA*, Tetsuya YAMAMOTO*, Kazuki UMEMOTO*, Shigekazu SUZUKI**, Akira HINE*** and Daishiro YAMAGUCHI***

*Department of Mechanical Engineering, Nagaoka University of Technology
1603-1 Kamitomioka, Nagaoka-Shi, Niigata 940-2188, Japan
E-mail: snaga@mech.nagaokaut.ac.jp

**Department of Mechanical System Engineering, National Institute of Technology Fukushima College
30 Nagao, Taira-Kamiarakawa, Iwaki-Shi, Fukushima 970-8034, Japan

***Tokyo Office, Katayama Steel Rule Die Inc.,
3-7 Higashi-Gokencho, Shinjuku-ku, Tokyo 162-0813, Japan

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Abstract

In a creased line processing of paperboard, deviation error between a groove of counter plate and a creasing knife is important for assuring the quality of creasing profile. It seems that a tapered (biased) groove of counter plate makes an unbalanced punching position of creasing knife well-adjusted in a certain range. In this work, the effect of a 45° tapered groove of a 1.5mm counter face plate on the eccentricity of crease bulging of a 0.43mm white-coated paperboard was compared with that of a rectangular groove counter plate (0° tapered). After scoring the paperboard across the fiber grain direction, using the rule deviation of $e = 0.0~0.4$mm and the indentation depth of creasing knife $d = 0.3~0.6$mm, the surface profile of scored zone was observed and folding tests and in-plane tensile test were carried out. Through the experiments, it was found that (i) a certain extent of asymmetric profile of scored surface was improved when observing the surface profile before folding, (ii) the changing range of bending moment resistance at the 90° bending test was reduced, (iii) the crease deviation at 180° folding test was reduced, and (iv) the in-plane tensile strength of 180° folded specimen was relatively large, compared to that of the rectangular groove.

Keywords: Folding, Shear, Bending, Creasing, Eccentricity, Deviation, Paperboard

1. Introduction

White-clay-coated paperboard is a fundamental raw material for various printed-decorated packaging and transport packaging industries due to its advantages such as high strength-to-weight ratio, high surface smoothness, printability, sustainability, recyclability (Kirwan, 2013). If any cracks occur on the outside of the 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. Actual creasing range was investigated based on the relationship between the crease depth and crease width (Hine, 1959), Carey (1992) and Carlson et al. (1983) explained about the bending behavior of creased part as composed of two parallel beams. There are several reports for estimating the anisotropic properties of paperboard and the delamination based folding resistance in a crease making process (Stenberg et al., 2001). Nagasawa et al. (2003, 2004a, 2004b, 2008, 2011) reported about the quasi-static folding stiffness and bulging profile with respect to the indentation depth of the creaser and also discussed about the fundamental crease deviation effect on the folding deformation characteristics by the use of CST J-1 (Katayama Steel Rule Die Inc., 2013). Beex et al. (2009), Nygards et al. (2009), Giampieri et al. (2011) and Jina et al. (2018) reported numerical models with respect to the de-lamination mechanism and bulging deformation. However, there are not almost any academic discussion or simulated estimation about the misalignment of creasing rule against the groove of counter face plate, except for reports of Nagasawa et al.
In the creased line processing of paperboard, deviation error between a groove of counter plate and a creasing knife is not negligible. Consequently, expert’s checkup examination of deviation error is necessary, and it takes a long time to adjust this misalignment. Regarding its countermeasure, it seems that a tapered (biased) groove of counter plate makes the unbalanced punching position of creasing knife well-adjusted, automatically in a certain range. In this study, therefore, in order to reveal the usefulness of tapered groove, the effects of a 45° tapered groove on the eccentricity of crease bulging was experimentally investigated, and also the bending characteristics of creased specimen by the 45° tapered groove counter plate was compared with that of rectangular groove counter plate (0° tapered). The side views of creased zone were analyzed using a digital camera when varying the eccentricity of creasing knife against the groove position, and the bending moment response with the folding angle was investigated up to the right angle, by using the creaser stiffness tester CST J-1.

2. Experimental condition and method

2.1 Pre-processing of specimen

A (white-clay-coated) paperboard is composed of a pulp fiber structure matrix and clay structured coated layer. The fiber layer consisted of multiple plies, while the coated layer was a mixture of ground calcium carbonate, kaolin and binder (Reinhard et al. 2013). The prepared paperboard (nominal basis weight \( \rho = 350 \text{ g} \cdot \text{m}^{-2} \)) had a thickness of \( t = 0.43 \) (0.42–0.44) mm. Table 1 shows the analysis results of fiber size and pulp combination ratio (Jina, et al., 2017). The in-plane tensile test properties in the fiber grain direction (Machine Direction of paper making, MD), based on JIS-P8113 (a gauge/clamped length of 180mm, a width of 15mm, a feed velocity of 0.33 mm/s\(^{-1}\)), were shown in Table 2. The specimens were kept in a room which had a temperature of 296 K and a humidity of 50 %RH. The test pieces were prepared as 5 pieces of rectangle-shaped paperboard, which had a width of 15 mm, a length of 60 mm, for each condition.

Table 1 Size of fiber and pulp combination ratio of white-coated paperboard 350 (measured by Kajaani-FS300)  

| Item       | Projected length of fiber / mm | Size / \( \mu \)m | Section area / \( \mu \)m\(^2\) |
|------------|--------------------------------|------------------|-------------------------------|
| Value      | L-BKP  | N-BKP | N-TMP | Width | CWT | CSA |
| Projected length of fiber / mm | 0.56 | 0.99 | 1.52 | 18.2 | 4.8 | 256.6 |
| Size / \( \mu \)m | | | | | |
| Section area / \( \mu \)m\(^2\) | | | | | |

Table 2 In-Plane tensile properties of white-coated paperboard in machine direction (MD). Tensile feed velocity was 0.33 mm/s\(^{-1}\) (strain rate: 0.00183 s\(^{-1}\)). Based on the procedure of JIS-P8113.

| Item | Young’s modulus \( E / \text{GPa} \) | Yield strength \( \sigma_t / \text{MPa} \) | Tensile strength \( \sigma_b / \text{MPa} \) | Breaking strain \( \epsilon_b \) |
|------|----------------------------------|------------------|------------------|------------------|
| Value | 5.22 (4.9–5.49) | 28.5 (27.7–29.2) | 42.5 (40–43.73) | 0.021 (0.018–0.023) |

Fig. 1 Layout of out-of-plane scoring by creaser.  

A paperboard specimen was scored using rubber blocks which had a hardness of 40 HS(A) as shown in Fig. 1. Figure 2 shows a scoring state (crease forming) of a specimen using a round-edge knife (a creaser with a radius of \( r = 0.355 \) mm, a thickness of \( b = 0.71 \) mm). In this work, firstly, the rule deviation (misalignment) \( \epsilon \) was carefully adjusted to zero. When the creaser is indented to the paperboard specimen, the expression: \( \tan \delta = \frac{2d}{B} = \gamma \) is the normalized indented depth. This quantity \( \gamma \) is understood as the nominal shear strain when \( d/B < 0.5 \) (Nagasawa et al., 2001). Using the paperboard...
thickness \( t \) and the thickness of creaser \( b \), the groove width \( B \) was empirically chosen as \( 2t+b \approx 1.5 \) mm, the height of groove \( H \) was 1.5mm in a case of the rectangle groove and the indentation of creasing knife \( d \) was chosen as \( d<H \). After scoring the paperboard, the upper layer was permanently dent as \( d_\text{max} \) which was less than the indentation depth \( d \), due to the spring back effect. Considering the rule deviation \( e>0 \), since the left clearance of creaser knife and the groove edge of the face plate was wider than the right clearance as shown in Fig.2, these scored parts were named as the wide and narrow side, respectively. Figure 3 shows the configuration of a creasing knife against a rectangular-grooved counter face plate (a): \( \alpha=0^\circ \) and a tapered-grooved counter face plate (b): \( \alpha=45^\circ \). When adding the rule deviation \( e>0 \), the lower surface of a paperboard seems to be strongly damaged on the narrow side in case of the rectangular groove, while that damage is relatively reduced by moving of creasing knife due to the reaction force from the inclined bottom in case of the tapered groove. Here, the lateral deflection \( d_L \) of the creasing knife by the applied lateral force \( Q \) N (Fig.3 (a)) was measured by a handy load meter and evaluated as 0.96 \( \mu \)m-N\(^{-1}\). If the indentation of the creasing knife was too deep, since the strong-compressed zone of the worksheet might be damaged due to the bottoming/crushing of the creasing knife, the in-plane tensile testing of 180° folded specimen was examined here.

![Configuration of creasing knife against grooved counter plate and conception of countermeasure for reducing the rule deviation](image)

Fig. 3 Configuration of creasing knife against grooved counter plate and conception of countermeasure for reducing the rule deviation

![Model of crease mechanism in case of \( e=0 \).](image)

(a) Concave shape after scoring

(b) Behavior of crease in folding process

![Model of crease mechanism in case of \( e=0 \).](image)

Referring the state of null adjustment (\( e=0.0 \)mm), the misalignment of creasing knife with the groove was set up as \( e=0.1, 0.2, 0.3 \) and 0.4mm, using shimming sheets as shown in Fig. 1. The creaser direction angle \( \phi \) was chosen as 90° with respect to the MD of the paperboard specimen. The normalized indentation depth \( \gamma \) was chosen as 0.4, 0.6 and 0.8 \( (d = 0.3, 0.45 \) and 0.6mm, respectively). The feed velocity of creaser was chosen as \( 0.0167 \) mm\( \cdot \)s\(^{-1}\) for scoring. The experiment was carried out under the following conditions; room temperature: 297K, room humidity: 50%, number of samples: 3~5 pieces for each condition.

2.2 Measurement method of scored profile, bending stiffness and crease deviation

Figure 4 illustrates a conceptual mechanism of crease folding when choosing \( e=0 \) mm. When the paperboard is scored by a creasing knife, the intermediate layers are damaged as shown in Fig.4 (a). Since the paperboard consisted of laminated plies (e.g. 8 layers), a certain extent of de-lamination damage is generated in the scored zone. When the paperboard is folded at this scored position, the damaged layers are further de-laminated and its inside (lower) layers are bulged as shown in Fig. 4 (b) (Nagasawa, 2004c). The bending moment resistance of the creased zone appeared to consist of three mechanisms: (i) a tensile resistance of the outside (upper) layers, (ii) a compressive resistance of the inside
(lower) layers, and (iii) a detaching (peeling) resistance of the middle layers (Nagasawa et al., 2011). The third item (detaching) affects only the transient folding resistance in the early stage, while the first (tensile of outside) and second (compression of bulged layers) items behave as the bending moment resistance in the full stage of folding test. Figure 5 shows a general view of bending test apparatus (CST J-I, 2013). Figure 6 shows a conceptual illustration of the folding process and rotating method used in the bending test.

After making the scored state onto the paperboard by varying the rule deviation $e$ and the indentation depth $d$ against the rectangular groove or the tapered groove, the following four items were investigated: (1) Measurement of displacement profile of scored zone before folding. A laser microscope was used for recording the surface dent profile. (2) Bending moment response of Narrow/Wide side scored zone clamped by the fixture of the bending tester with the rotation velocity of $\omega=0.2$ rps (revolutions per second). The specimen was bent up to $\theta=90^\circ$. The support point of the specimen was at 10mm from the rotation center, as shown in Fig. 6. (3) To estimate the eccentricity (caused by the tool deviation $c$) of scored part, the creased specimen was folded with $180^\circ$ at the root hinge by using a rolling device made by two hard rubber rollers which had the diameter of 20mm (Fig.7 (a)). The pressing force 14.8 N of each spring was previously applied to the folding rollers (the length of the rubber roller was 170mm). The specimen was folded by hand so as to form a hinge loosely. By letting the folded specimen pass through the folding rollers, the crushed hinge was completely formed. Using a digital microscope, the crease deviation $c_b = |e_1 - e_2|$ was evaluated from a side view of the crushed hinge as shown in Fig. 7 (b). If the scored position moves on the surface with an arc length $\Delta$, assumed to be sufficiently small, since $e_1 = A + \Delta$, $e_2 = A - \Delta$, $c_b$ becomes $2\Delta$. Here, $2\Delta (>2t)$ is the total height of a $180^\circ$ folded specimen. Principally, the crease deviation $c_b$ is twice the rule deviation $e$, if $\Delta = e$. This definition of $c_b$ was a little different from the crease deviation at the right angle reported by Nagasawa et al. (2003). (4) In order to conform the strength of creased part, the $180^\circ$ folded specimen (pressed by the rubber roller system) was reversely unfolded in a straight state and used for investigating the in-plane tensile strength. This method was known by Nagasawa et al. (2004a). The experiment was carried out in the same environment as that of the pre-process (scoring) experiment.

### 3. Results and discussion

#### 3.1 Profile of scored zone before folding

In order to confirm the deformation state of specimens after scoring by the creasing knife, the side views of scored zone were recorded by a camera of digital microscope and the surface profile of the scored upper layer was measured by a laser microscope. Figure 8 and Fig. 9 show photographs of side views of scored zone in cases of the rectangular groove ($\alpha=0^\circ$) and the tapered groove ($\alpha=45^\circ$) respectively, when $\phi=90^\circ$.
Figure 10 shows the cross sectional profile $D_{as}$ (permanent depth profile) of the upper surface of scored paperboard measured by a laser microscope when choosing $\phi = 90^\circ$ and $e = 0.0$–0.4 mm with two kinds of grooved face plate ($\alpha = 0$, $45^\circ$). Seeing these photographs and the profile diagrams, a large asymmetric deformation was detected in the scored profile when choosing $e > 0.2$ mm and $\gamma = 0.8$ in case of the rectangular groove, whereas a certain extent of asymmetry of scored profile with the tapered groove reduced in the range of $e < 0.3$ mm. In the case of rectangular groove processing, the lower surface of narrow side was sharply dented by the edge of grooved face plate and the upper surface of wide side was extremely raised (otherwise, the upper surface of narrow side was largely sunk). So far, it was found that the effect of rule deviation on the asymmetry of scored profile was remarkably reduced.
when using the tapered groove.

Figure 11 shows the relationship between the average permanent depth \( d_{as} \) (= the average difference of the \( D_{as} \) at the minimum peak from the \( D_{as} \) at a far position saturated) and the indented depth \( d \) when \( e = 0.0 \). Regarding the spring back effect, the ratio of \( d_{as}/d \) was about 0.41 when \( \gamma = 0.8 \) (\( d = 0.6 \)mm) and \( e = 0 \)mm. When the rule deviation \( e \) increased, this ratio appeared to increase a little with \( e \). As for the effect of rule deviation \( e = 0.1 \sim 0.4 \)mm on the permanent depth \( d_{as} \), the variation of \( d_{as} \) was less than 20\( \mu \)m when choosing \( \gamma = 0.4, 0.6 \), while the variation of \( d_{as} \) was about 50\( \mu \)m when \( \gamma = 0.8 \) for \( e > 0.3 \)mm. The gradient \( k_s \) and the intercept \( d_0 \) used in Eq. (1) were shown in Table 3 and they were derived as the linear approximation from the relationship between \( d_{as} \) and \( d \) when choosing \( e = 0, 0.2 \) and 0.4mm. Seeing Table 3, the variations of \( k_s \) and \( d_0 \) in the case of tapered groove were relatively smaller than that of rectangular groove. Therefore, the spring back of the creased zone in the case of tapered groove was stable and not so much changed, compared with the case of rectangular groove.

\[
d_{as} = k_s (d - d_0) \quad (1)
\]

Table 3 Parameters of the normal equation of Eq. (1). The expected relationship between the indented depth \( d \) and the permanent depth \( d_{as} \) was arranged with five samples when choosing \( e = 0.0, 0.2, 0.4 \)mm with the two grooves.

| Deviation of creasing knife | Rectangle groove, \( \alpha = 0^\circ \) | Tapered groove, \( \alpha = 45^\circ \) |
|-----------------------------|------------------------------------------|-----------------------------------|
| \( e \) (mm) | \( k_s \) (-) | \( d_0 \) (mm) | \( k_s \) (-) | \( d_0 \) (mm) |
| 0.0 | 0.549 | 0.160 | 0.501 | 0.149 |
| 0.2 | 0.571 | 0.157 | 0.542 | 0.168 |
| 0.4 | 0.730 | 0.193 | 0.555 | 0.156 |

Fig. 13 Side views of folded specimen when choosing \( \gamma = 0.8 \), \( e = 0.4 \)mm and clamping Wide side for two kinds of groove type \((\alpha = 0, 45^\circ)\).

Fig. 14 Side views of folded specimen when choosing \( \gamma = 0.8 \), \( e = 0.4 \)mm and clamping Narrow side for two kinds of groove type \((\alpha = 0, 45^\circ)\).

Figure 12 shows the scoring line force in a range of \( d = 0 \sim 0.6 \)mm with the two cases of groove type. It was confirmed that the interference of rule deviation against the narrow side of groove edge was negligible when \( e < 0.2 \)mm. The scoring force of the tapered groove was a little larger than that of the rectangular groove in the condition of \( e = 0.4 \)mm and \( d = 0.6 \)mm in Fig. 12, whereas the scored force of the rectangular groove was almost the same as that of the tapered groove when \( \gamma < 0.67 \) (\( d < 0.5 \)mm). So far, the crushing pressure on the paperboard seemed to be similar order in two cases of groove type when choosing a shallow indentation \((\gamma < 0.67)\).
3.2 Bulge shape and bending moment of scored zone at the narrow/wide side

Figure 13 shows a folding process of scored specimen when choosing \( \gamma=0.8 \) \((d=0.6\text{mm})\), \( e=0.4\text{mm} \) against the two types of grooved face plate and clamping the wide side, while Fig. 14 shows that of the narrow side clamped. Since the narrow side was strongly damaged and its bending stiffness was weakened, compared with the wide side, the primary bending was observed at the narrow side, when choosing \( e=0.4\text{mm} \). This tendency was seen in a certain extent when \( e<0.4\text{mm} \). At the same time, when using the CST J-1, as the bending is principally a cantilever type, the clamped side (the right side) is apt to be largely folded. However, comparing the groove and the tapered groove processing, the eccentric effect of the latter seemed to be reduced. Namely, the asymmetric bulging appeared to be reduced in the case of the tapered groove processing.

Figure 15, Fig.16, Fig.17 and Fig.18 show the relationship between the bending moment resistance per unit width \( M \) \(\text{N\cdot mm/mm}^2\) and the folding angle \( \theta^\circ \) in both cases: (a) the narrow side clamped and (b) the wide side clamped conditions. In Fig.15 and Fig.16, the rule deviation \( e \) was chosen as 0.0, 0.2, 0.3, and 0.4mm against the rectangular groove face plate, while the rule deviation \( e \) was chosen similarly against the tapered groove face plate in Fig.17 and Fig.18. Here, the normalized indentation depth was chosen as \( \gamma=0.6 \) in Fig.15 and Fig.17, while that was \( \gamma=0.8 \) in Fig.16 and Fig.18. Seeing the bending moment response and the video motion of folding process, the following features (1)~(4) were revealed: (1) When the rule deviation \( e \) increased from 0 up to 0.3mm, the bending moment \( M \) tended to be slightly increased, while its tendency was extremely changed when choosing \( e=0.4\text{mm} \). Since the critical deviation (tool interference with eccentricity) of the creaser side line against the groove edge was estimated as \((B-b)/2=0.395\text{mm}\), the deformation at \( e=0.4\text{mm} \) seems to be different from others (at \( e=0.0\text{~}0.3\text{mm}\)). Using this difference of bending moment response at \( e=0.4\text{mm} \), a sort of diagnosis of creasing stiffness caused by a large rule deviation is possible. (2) In Fig.15(a) at \( \gamma=0.6 \) \((d=0.45\text{mm})\), when the narrow side was clamped, the primary bending position occurred at the narrow side in the early-stage \((\theta<40^\circ)\) and that position moved to the wide side in the late-stage \((\theta>40^\circ)\). Principally, since the clearance of the narrow side was smaller than that of the wide side, the bending stiffness of the former (narrow side) is apt to be smaller than that of the latter (wide side). At the same time, since the distribution of bending moment with the longitudinal direction is determined as a simple cantilever beam theory, the gripped position (right side) is the most severe state (the bending stress is the largest). On the contrary, seeing Fig. 15(b), when the wide side was clamped, the narrow side seems to be primarily bent state in the last-stage and the wide side was apt to be primarily bent state in the early-stage. (3) Seeing Fig. 13(a)(b), Fig. 14(a)(b) and Fig. 16(a)(b) at \( \gamma=0.8 \), although the overshoot response was disappeared at the early-stage, the tendency of primary bending position was similarly observed, compared with the case of \( \gamma=0.6 \). (4) In the case of 45° tapered groove as shown in Fig. 17 and Fig. 18, comparing with the rectangular groove, the followings (i) and (ii) were detected: (i) A change of bending moment response was relatively small. When the rule deviation \( e \) increased from 0 up to 0.4mm, \( M \) tended to be decreased in the early-stage \((\theta<60^\circ)\), while it was apt to be increased in the last-stage \((\theta>60^\circ)\), when the narrow side was clamped. (ii) \( M \) was apt to be large in the early-stage \((\theta<60^\circ)\) when the case of the wide side was clamped. These tendency was the similar to that of rectangular groove face plate.

![Fig. 15 Response of bending moment resistance with folding angle. Here, the rotational velocity was \( \omega=0.2 \text{ rps} \), the normalized indentation depth was \( \gamma=0.6 \), the crease direction was \( \phi=90^\circ \), and the rectangle groove of face plate was chosen.](image-url)
Fig. 16 Response of bending moment resistance with folding angle. Here, the rotational velocity was $\omega=0.2 \text{ rps}$, the normalized indentation depth was $\gamma=0.8$, the crease direction was $\phi=90^\circ$, and the rectangle groove of face plate was chosen.

Fig. 17 Response of bending moment resistance with folding angle. Here, the rotational velocity was $\omega=0.2 \text{ rps}$, the normalized indentation depth was $\gamma=0.6$, the crease direction was $\phi=90^\circ$, and the 45° tapered groove of face plate was chosen.

Fig. 18 Response of bending moment resistance with folding angle. Here, the rotational velocity was $\omega=0.2 \text{ rps}$, the normalized indentation depth was $\gamma=0.8$, the crease direction was $\phi=90^\circ$, and the 45° tapered groove of face plate was chosen.

In the case of rectangular groove, although the change of bending moment resistance tended to increase with the rule deviation, this tendency seems to be limited in the special case of a certain length of a straight knife. Namely, the increasing of bending moment resistance seemed to be caused by the lateral deflection of creasing knife (increasing of clearance) against the interference of rectangular groove edge. In the case of tapered groove, the lateral deflection of creasing knife does not contribute to increase the total clearance due to the vertical compression of tapered surface.

### 3.3 Crease deviation of scored zone

Figure 19 shows examples of 180° folded specimens which were observed from the side view, using a digital microscope, when the normalized indentation depth was $\gamma=0.8$ against the rectangular groove and the rule deviation $e=0.0$, $e=0.1$, $e=0.2$, $e=0.3$, and $e=0.4 \text{ mm}$. The figures illustrate the difference in crease deviation depending on the clamping location.
0.4mm. Here, the crease direction was $\phi = 90^\circ$. Watching the scored position in the side view photographs, the crease deviation $c_b = |e_1 - e_2|$ was estimated for each case.

Figure 20 shows the relationship between the rule deviation $e$ and the crease deviation $c_b$ when choosing $\gamma = 0.4$, $0.6$ and $0.8$. As a general tendency in this experiment, the crease deviation $c_b$ tended to decrease with $\gamma$. It was found that the crease deviation with $45^\circ$ tapered groove was certainly less than that of rectangular groove. When $e \leq 0.1$mm, the difference of these two grooves on the crease deviation seems to be negligible, but it becomes remarkable for $e > 0.2$mm.

As mentioned in the section 2.4, assuming that the scored position moves on the surface with an arc length $\Delta$, if $\Delta = e$, $c_b$ becomes $2\Delta$. However, seeing Fig.20, it seemed that $c_b > 2e$ at $\gamma = 0.4$, $c_b \approx 2e$ at $\gamma = 0.6$ and $c_b < 2e$ at $\gamma = 0.8$. The ratio of crease deviation by the rule deviation $c_b/e$ was appeared to be varied with the nominal indentation depth $\gamma$ and the inclined angle of groove $\alpha$, when considering $e > 0$.

3.4 In-plane tensile strength of unfolded zone

As mentioned in the section 2.1 by referring Fig. 3(b), when a paperboard is subjected to a scoring force by the use of tapered groove, an inspection of bottoming damage is required for confirming the performance of creased part. The in-plane tensile testing based on JIS-P8113 was applied to the creased paperboard which was folded once in $180^\circ$ using the rubber roller and secondly unfolded in open-flat state.
Figure 21 shows the tensile strength as the nominal maximum stress of creased and 180° unfolded paperboard in the MD. Two types of the groove of counter face plate were compared when choosing the indentation depth of \(d=0.3\), 0.45 and 0.6mm. It was found that the tensile strength of creased zone using the 45° tapered groove was a little higher than that of the rectangle groove, especially for \(e<0.2\)mm.

### 3.5 Discussions for possible variety of groove design

Since the indentation depth \(d\) is usually considered as the order of the thickness of paperboard, \(\gamma=2d/B\) is normally expected to be about 2\(r/B=0.57\), when assuming the groove width \(B=1.5\) mm, the knife thickness \(b=0.71\) mm, the edge radius of knife \(r=B/2=0.355\) mm and the thickness of paperboard \(t=0.43\) mm. Prohibiting the excessive rule deviation against the groove edge in a scoring process, the rule deviation \(e\) ought to be less than \((B-b)/2=0.395\) mm. As the expected rule deviation is empirically about \(e=0.2\) mm, a combination of the round edge knife and the rectangle groove \((\alpha=0°)\) seems to be critically suitable for scoring the 0.43mm thickness paperboard, but there is not sufficient allowance when the rule deviation exceeds this condition \((e>0.2)\) mm. Keeping the top side width of \(B=1.5\) mm, and adding appropriate chamfer at the corner of groove, the results of this work seems to widely applicable to other similar worksheet. The inspected 45° groove had a 45° chamfer of depth \(B/(2\tan45°) = 1.06\) mm, whereas the rectangular groove had empirically a small chamfer less than 0.2mm. Considering a continuity of geometrical analogy, a combination of middle size chamfer plus a square groove is expected to a candidate of desirable profile of groove. Otherwise, an intermediate single angle of \(0°<\alpha<45°\) or appropriate multi-line profile such as a combination of 45° inclination (upper) and 30° inclination (lower) seems to be a candidate of groove profile. The performance of groove must be carefully considered when the indentation depth overruns due to any mis-operation. Since the rectangular groove normally has a certain depth less than the thickness of counter plate (e.g. 1mm depth), this limitation against mis-operation of overrunning is a common problem.

### 4. Conclusions

In order to verify the effects of tapered groove against arbitrary unbalanced creasing knife (punch) indentation on the scored state of a 0.43mm thickness white-clay-coated paperboard, the bending characteristics of creased part as a distributed change of the bending stiffness was experimentally investigated, and also the crease deviation of folded form was experimentally measured using a rubber roller passing method. As the tapered shape of groove, a rectangular type of \(\alpha=0°\) and \(\alpha=45°\) tapered type were prepared, and as for the unbalanced state between the creasing knife and the groove, the rule deviation \(e\) was varied from 0.0mm up to 0.4mm, which was geometrically limited to a half of the difference of the groove width \(B\) and the knife thickness \(b\), when keeping the indentation depth of creasing knife. The results were summarized as follows:

1. The scored surface profile of the paperboard subjected to the creasing knife indentation against the 45° tapered groove was superior for the rule deviation, compared to the rectangular groove. Namely, the extent of asymmetric profile was reduced by using the tapered groove.
2. The extent of change of bending moment resistance with the tapered groove was relatively smaller than that of the rectangular groove, when the rule deviation was changed under keeping the normalized indentation depth. Namely, a sort of stability of bending stiffness with the tapered groove was superior for the rule deviation, compared to the rectangular groove.
3. The crease deviation after passing the 180° folding test with the tapered groove was relatively small, compared to the rectangular groove.

### Nomenclature

- \(d\) : indentation depth of creasing knife
- \(d_{sn}\) : scored depth, permanent depth after scoring
- \(t\) : thickness of work sheet (paperboard)
- \(B\) : width of groove on counter face plate, 1.5mm
- \(\gamma=2d/B\) : normalized indentation depth
- \(e\) : rule deviation
- \(b\) : thickness of creasing knife, 0.71mm
- \(c_b\) : crease deviation, \(c_b = |e_1 – e_2|\) as shown in Fig. 7 (b).
- \(M\) : bending line moment against folding (N·mm/mm)
- \(\theta\) : folding angle of fixture (°)
- \(\omega\) : rotational velocity (revolutions per second (rps), s\(^{-1}\)), 0.2 rps

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