Engineering estimation of time-dependent deformation characteristics as bending moment relaxation and released unfolding motion of creased paperboard

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Abstract. Paperboards are recognized to be important raw materials for packaging industry due to their advantages such as high strength-to-weight ratio, recyclability. Regarding the development of advanced packaging materials and the requirement of smart formed products, a study of sheet’s response behaviour is necessary for expanding the advanced converting industry. After introducing a couple of past research works concerned crease technologies, a fundamental mechanisms of crease deformation is reviewed using the scoring depth and the folding angle of a paperboard. Since one of important forming characteristics is a time-dependent stress relaxation or time-delayed strain during a fold/unfold process, the author's experimental approaches for estimating a short term (less than 10 seconds) dynamic deformation behaviour of creased paperboard are discussed.

1. Introduction
Paperboards are recognized to be important raw materials for packaging industry due to their advantages such as a high strength-to-weight ratio, printability, recyclability. The paperboards can be converted and used as carton boxes. In order to convert a raw paperboard into packaging containers, the boards are firstly printed with color inks. Next, they are subjected to cutting and creasing processes. The objectivity of these two processes is to convert such printed boards into designed blank forms. After that, the blanks are folded and glued to obtain the containers [1].

Since coated and printed paperboards are kinds of laminated composite materials which are made of multiple plies and composed of numerous fibers, they normally exhibit complicated mechanical properties and forming behaviors. In addition, the successful forming of the paperboards tends to be more difficult than that of other monolithic resin or metallic sheet materials. Regarding the continuous development of advanced packaging materials and the requirement of smart formed products, understanding of sheet’s response behaviors and their forming characteristics are necessary for the converting industry. They contribute to design suitable forming conditions and to develop smart forming technologies. A few reports for in-plane elongation of paperboard during indentation of creaser were shown by Hallady and Ulm [2]. Actual creasing range was investigated as the relationship between the depth and width by Hine [3]. Carlsson et al. [4] explained about the bending behavior of creased part as composed of two parallel beams. Beex et al., Nygards et al. and Sudo et al. [5-7] reported a sort of full model based on the through-thickness discretization of creased paperboard.

The author's group investigated various forming characteristics of a white-coated paperboard
subjected to a sort of cutting and/or creasing process. Nagasawa et al. [8-9] reported about the quasi-static folding stiffness with respect to the indentation depth of a creaser and also discussed with the crease deviation effect on the folding of creased part. However, since the paperboard is a sort of composite material made of laminated thin papers and numerous fibers, its crease-based forming or shaping behaviors are fairly complicated.

In this work, a couple of current research works concerned board forming processes are reviewed. One of important forming characteristics is a bending moment (which is composed of in-plane bending stress and out-of-plane delamination) relaxation and/or released (creep) behavior during a unfolding process. Before reviewing the time-dependent behavior of bending moment resistance and unfolded deformation, the in-plane loading behavior of paperboard is briefly reviewed.

Regarding the in-plane tensile deformation of paper, the stress relaxation by a specified forced displacement was known by several reports [10-11] and the stress was often characterized with the logarithmic reduction of elapsed time. When the elapsed time of relaxation process is sufficiently taken as long, it is known that the relaxation response tends to be non-linear [10]. Generally speaking, a generalized Maxwell model can be considered to describe the non-linear relaxation. However, when the response is primary composed of the logarithmic characteristic and a bit offset from the main part, a modified Maxwell model, called as KWW (Kholrausch-Williams-Watts) rule, is analyzed [12]. When considering a package box making, the scoring and folding of paperboard is empirically processed in a short time. The folding duration seems to be less than a few seconds. Therefore, we may focus here on the working time as shorter than 10 seconds. Apart from the in-plane uni-axial tensile deformation, the folding of creased part is complicated due to the structure of multiple plies. Recent author’s approach for estimating the time-dependent relaxation of bending moment resistance and released unfolded deformation of creased part is synthetically discussed [13-15].

2. Quasi-static deformation mechanism of crease of paperboard

Figure 1 illustrates a stripped carton development by a punching process and its box form. A stable folding of paperboard is enable by keeping a smart profile of scored crease line and its inner bulge. In this review paper, the crease deformation characteristics were investigated by varying the mechanical conditions of die set.

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Figure 1. A punching process of carton development and folding on crease lines

Figure 2. Layout of out-of-plane scoring by creaser

Figure 3. Schematic of scoring state and parameters
Figure 2 illustrates experimental apparatus in making the test pieces of paperboard scored by a round-edge creaser with radius of \( r = 0.355 \) mm and the rubber fixture of shore hardness 40A. 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. Figure 3 shows a detail of scored zone of paperboard when the creaser moves downward with the indentation depth \( d \). Since the paperboard consists of multiple-plies, the in-plane sliding and de-lamination occur at the scored zone. The normalized indentation depth \( y = \tan \varepsilon = 2d/B \) were chosen as 0.0—1.0, while the feed velocity was chosen as \( F = 0.0167 \) mm's\(^{-1}\). The creaser direction angle \( \phi \) was chosen as 90° with respect to the machine direction (MD).

The test pieces were prepared as 10 pieces of rectangle-formed white-coated paperboard (the basis weight \( p = 228–237 \) g·m\(^{-2}\)), which had a width of 15 mm, length of 60 mm, and thickness of \( t = 0.3 \) (0.297–0.303) mm, for each condition of chosen normalized indentation depth \( y \). The in-plane tensile test properties in MD, based on JIS-P-8113 (gauge length: 180 mm, width: 15 mm, feed velocity: \( F = 0.33 \) mm·s\(^{-1}\)), were shown in Table 1. All the paperboards were kept in a room which had the temperature of 296 K and the humidity of 50 %RH.

| Table 1. In-plane tensile properties of white-coated paperboard in machine direction |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Ultimate tensile strength \( \sigma_B \) MPa | 41.1 (40.2–42.7) |
| Proof stress at 0.2% strain \( \sigma_s \) MPa | 11.1 (11.4–10.9) |
| Breaking true strain \( \varepsilon_{B} \) % | 1.71 (1.81–1.62) |
| Young’s modulus \( E \) GPa | 5.72 (5.91–5.53) |

Figure 4 shows a general view of experimental apparatus CST-J-1 [9] for repeated folding motion test and a schematic diagram of folding process at the first round fold.

Figure 5 shows examples of relationship between a folding angle \( d \) and a bending line moment (resistance for the unit width) \( M \) when varying the tracking (maximum) angle \( \theta \), the normalized indentation depth \( y \) in the cases of fold repetition \( n = 2 \) and the rotation velocity \( w = 0.2 \) rps. When \( y > 0.6 \), the overshoot of \( M \) disappeared [8, 9]. The transition of this overshoot disappearance was illustrated in Fig.6 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. When the folding angle \( d \) passes through the peak point of overshoot, the inner bulging is promoted but the deformation of de-laminated zone is restricted with the immobile nodes.
Figure 5. Relationship between bending line moment and rotation angle in case of second round folding: n=2. (a) Left: Analysis parameters on folding resistance diagram ($\theta=90^\circ$, $\gamma=0.6$), (b) Right: Examples of bending moment responses by varying the tracking angles ($\theta=10^\circ$–$60^\circ$, $\gamma=0.4$).

Figure 6. Transition model of creasing process

Figure 7 shows the first term gradient $C_{1,1} = \partial M / \partial \theta|_{\theta=\theta_{1,1}}$ with respect to $\gamma$, while Fig. 8 shows the initial released angle $\theta_{2,1(0)}$ with the tracking angle $\theta$ when varying the normalized indentation depth $y$ at the first fold repetition $n=1$ [9]. Seeing Fig.7, the variation tendency of gradient $C_{1,1}$ with $y$ is obviously changed around $y=0.6$. This seems to be related to the disappearance of overshoot of bending moment. In Fig.8, the angle difference of $\theta - \theta_{2,1(0)}$ is a sort of spring back and $\theta_{2,1(0)}$ is the residual deformation, tentatively. This value $\theta_{2,1(0)}$ was roughly estimated as a half of tracking angle $\theta$ when varying $\gamma$ and $y$. Figure 9 shows a representative example of the relationship between the folding rotation angle $d$ (up to the tracking angle $\theta=90^\circ$ in 15 times) and the bending moment $M$ when choosing the nominal shear strain $\gamma = 0.3$, 0.8. Since the paperboard has viscous elasticity and creep characteristics during the folding process, the rotation velocity $\omega$ of the fixture was normally set to $\omega = 0.2$ rps and the elapsed time for returning back until the next folding (release time) was set to $t_{2ep}$, which was defined as the duration starting from a releasing position $\theta_{2,n}$ until reaching a restarting position $\theta_{1,n+1}$. Here, $n=1,2,3,...15$ is a dummy suffix used to count the number of folding repetitions. In every folding round, the stopping time before returning back (holding time) was set to $t_{1ep}$ = 10s at a tracking position $\theta$. The relationship between the first term gradient of bending moment $C_{1,n}$ and the number of folding repetitions $n$ is shown in Fig.10, while Fig.11 shows the bending moment $M_{\theta=90^\circ}$ at $t_{1ep}=0$s when choosing $\gamma=0$, 0.3, 0.8. It is revealed that $C_{1,n}$ and $M_{\theta=90^\circ}$ tend to be a little decreased but almost stable with respect to the folding number $n$, when watching the range of $5\leq n\leq 15$. 
Figure 7. Dependency of first gradient of bending line moment on normalized indentation depth

Figure 8. Dependency of initial released angle on tracking angle

Figure 9. Response of bending moment with respect to folding angle (Ref. [14] Nagasawa et al. (2015))

Figure 10. Effect of folding repetitions $n$ on first term gradient moment of bending moment $C_{1,n}$

Figure 11. Effect of folding number $n$ on bending $M_{00}$ at tracking position $90^\circ$

3. Relaxation of bending moment resistance at tracking position

Observing the time-dependent response of bending moment resistance $M_\Theta$ at the tracking position $\Theta$ in Fig.5 and Fig.9, the relaxation response of $M_\Theta$ with respect to the elapsed (holding) time $t_{lep}$ was revealed as shown in Fig.12. In order to characterize this relaxation, a linear approximation was introduced with the logarithmic term $\ln(t_{lep})$ using Eq.(1). Two relaxation coefficients $a_1$, $a_0$ are introduced by Eq.(1). Here, $a_0$ is defined as $M_\Theta(1)$ (at $t_{lep}=1s$).
Figure 12. Relaxation of bending moment resistance with elapsed (holding) time in case of $\Theta = 90^\circ$

Figure 13. Relationship between coefficients $a_1$ and $a_0$ for $0.2 < \gamma < 1.0$ and $30^\circ < \Theta < 120^\circ$ ($\eta = 1$)

Figure 14. Relaxation coefficients $a_1$ and $a_0$ with respect to $\gamma = 0, 0.3, 0.8$ for $n = 1$ to 15

Figure 15. Variance of exponent coefficient $p_1$ with number of folding repetitions $n$

Regarding the effect of rotary velocity $\omega$ on the bending moment resistance at the tracking position, it is known that the exponential coefficient $p_1$ tends to increase for $\omega < 0.1$ rps, while the value of $p_1$ is...
almost constant for 0.2<ω<0.6 rps. Namely, the relaxation of bending moment resistance basically depends on the preparation time of specified folding angle (tracking angle).

4. Released unfolding motion
When choosing the released time \( t_{2\omega} \) as a positive value in Fig.5, the angle of folded paperboard tends to be decreased (unfolded). This is a sort of creep deformation and residual stress released state under an unloading condition. This behaviour was investigated by the use of the released angle \( \Theta_{2,1} \) captured by a video camera. Figure 16 illustrates the released (unloading) process from the tracking position when the folding repetition number is \( n=1 \). The initial released angle is defined as \( \Theta_{2,1}(t_{2\omega}=0) \) when the reaction force of load cell becomes zero. From the previous research of relaxation at the tracking position, the time-dependent deformation of creased part seems to be characterized by the preparation duration or the rotation velocity \( \omega \) and the holding time \( t_{1\omega} \). Therefore, in this work, the relationship between \( \Theta_{2,1} \) and \( t_{2\omega} \) was investigated for \( \omega = 0.02~0.6 \) rps when \( \gamma = 0.6 \) and \( t_{1\omega} = 0s \).

Figure 17 shows the initial released angle \( \Theta_{2,1}(0) \) and Fig.18 shows the time-dependent released angle \( \Theta_{2,1}(t_{2\omega}) \) with respect to \( \omega \) [15].

Figure 16. Schematics of unloading and relationship between released angle and fixture angle (a) State of tracking angle of 90°; (b) State of initial released angle \( t_{2\omega}=0 \) when reaction force of load cell becomes zero; (c) In case of unfolded state when detaching the load cell (for \( t_{2\omega}>0 \)).

Figure 17. Dependency of initial released angle on folding velocity in case of \( \gamma = 0.6, \Theta = 90° \)

Figure 18. Released response of folding angle with respect to elapsed time after releasing in case of \( \gamma = 0.6, \Theta = 90° \)

The released angle \( \Theta_{2,1} \) was approximated with the logarithmic term \( \ln(t_{2\omega}) \) as shown in Eq.(3) and Eq.(4). Two released coefficients \( b_1, b_0 \) are introduced and investigated with respect to the rotary velocity \( \omega \). Figure 19 shows the relationship between the exponent number \( p_2 = b_1/b_0 \) and \( \omega \).

\[
\Theta_{2,1} = -b_1 \ln(t_{2\omega}) + b_0 \tag{3}
\]

\[
\Theta_{2,1}/b_0 = 1 + \ln(t_{2\omega})^p_2, \quad p_2 = b_1/b_0 \tag{4}
\]
When choosing the rotary velocity as $\omega > 0.2 \text{ rps (1.26 rad-s)}$, it is revealed that the recovered angle (by released) tends to be insensitive (stable) with the rotation velocity.

5. Conclusions and summary
Several folding processes of creased part of paperboard were investigated by using a creasing strength tester CST-J-1. Through this works, the followings are revealed.

(1) The relaxation of bending moment resistance at the tracking (maximum) angle $\Theta$ is characterised by a logarithmic function of holding time when varying the normalized indentation depth $y$ (which determines the scoring condition). The bending moment gradient $a_1$, the bending moment of intercept $a_0$ and the exponential coefficient $p_1 = a_1/a_0$ are the fundamental and essential quantities, which are almost independent to the mechanical condition (normalized indentation depth and tracking angle).

(2) The creep-recovery (release) response of folded angle during returning back is characterized and approximated by a logarithmic function of elapsed time. Here, the released angle gradient $b_1$, the released angle of intercept $b_0$ and the exponent number coefficient $p_2 = (b_1/b_0)^{-1}$ were introduced for characterizing the unfolding motion of creased paperboard.

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