Estimation of detaching resistance of a peeled in-plane layer of a white-coated paperboard using fluffing resistance and an isotropic elasticity model

Wecerayut JINA*, Shigeru NAGASAWA* and Seksan CHAIJIT**
*Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka 940-2188, Niigata, Japan
E-mail: snaga@mech.nagaokaut.ac.jp
**Department of Mechatronics Engineering, Pathumwan Institute of Technology 833 Rama 1 Rd, Pathumwan Bangkok, 10330 Thailand

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Abstract
This paper aims to describe an in-plane detaching resistance of a white-coated paperboard subjected to a peeling deformation. Since the paperboard is composed of fibrous plies, its detaching mechanism seems to be different from a crack propagation of a fragile material. In this work, an internal breaking criteria and transient de-lamination of a weak-bonded layer of paperboard was experimentally investigated through a peel cohesion test (PCT), and its detaching resistance was estimated with a fluffing model using a finite element method (FEM) code to characterize the peeling deformation of the weak-bonded layer. A white-coated paperboard of 0.45 mm thickness (basis weight of 350 g·m⁻²) was chosen for conducting a PCT and z-directional (out-of-plane) tensile test (ZDTT). The relationship between the pulling force and curvature of delaminated upper layer of the paperboard were discussed; moreover, the anaphase yielding resistance of detaching was analyzed through ZDTT. The peeled deformation of PCT was analyzed using the isotropic elasticity FEM model, which was developed through the ring crush test. The results were as follows: (1) The in-plane detaching resistance of white-coated paperboard by PCT is experimentally characterized for observing with the maximum peak at early stage and the stationary line force. These line forces are almost independent of the paper-making direction. (2) A fluffing profile of the de-laminated layer and the thickness of the peeled upper layer experimentally depend on the pulling velocity. (3) Regarding the detaching resistance of peeled layer, a fluffing model was proposed in the developed simulation model. Equivalent fibers based fluffing model that were derived from a ZDTT experiment (approximated as discretely distributed nonlinear springs) well explains the existence of the peak point of peeling force and saturated peel resistance.

Key words: Paperboard, Peel cohesion test, Delamination, FEM model, Fluffing

1. Introduction

When making a packaging box of a paperboard, a creasing process, which is composed of the first stage: scoring by a creasing knife and the second stage: folding, is widely used (Kirwan, 2013). Since the delamination occurs during the folding process of scored paperboard, a reasonable estimation of bending mechanism of a folded part under delaminating is necessary for performing a stable and smart folding and designing a suitable strength of inner delamination of paperboard. The delamination behavior is not only an essential feature of crease folding but also a primary factor of failure modes when tearing or shearing a laminated material. Regarding the estimation of detaching resistance, the peel cohesion test (PCT) or T-peel test (Koubaa, 1995; ASTM-D1876-01, 2001; Fellers et al., 2012; Pungo et al., 2012) and the z-directional (out-of-plane) tensile test (ZDTT) (Scandinavian Pulp, Paper and Board Testing Committee-SCAN-P,
1998) are well used for measuring the bonding strength of the delamination layer of paperboard and the bonding strength of peeled metallic foil stacked on adhesive mat.

There are several reports for estimating the anisotropic properties of paperboard and the delamination-based folding resistance in a crease making process. Material properties of a thickness direction were analyzed by several researchers (e.g., Stenberg, et al., 2001). Thakker et al. (2008) reported the nonlinear local buckling of folded raw sheet of corrugated fiberboard, using the orthotropic elasto-plasticity. Nagasawa et al. (2006) reported about the orthotropic elasticity of paperboard during a wedge cutting process, and the surface breaking behaviors was explained through FEM simulation and experiments. Sudo et al. (2005) showed a feasibility study about the effect of inner detachment behavior on creasing deformation of the paperboard using a distributed resistance model of nonlinear springs, which was described in the MARC subroutine: USPRNG (MSC software, 2003, 2010), although Sudo’s model was not considered with the shear resistance. The ink-tack delamination of a paperboard that comprised softly connected plies was investigated (Hallbäck et al., 2006) for assessing the effect of elastic moduli of each layer on the ink-tack delamination event. In order to simulate the delamination and folding resistance of creased paperboard, a cohesive damage model was considered for explaining the bulging of a creased part (Beex and Peerlings, 2009). The cohesive damage model seems to be convenient for adjusting the shear slide and normal detaching in a delaminated layer, but it is not based on the real fluffing behavior.

The delamination mechanism under fluffing of paper fibers is quite important to estimate the creasing deformation of paperboard. However, the detachment behavior on the creased paperboard was insufficiently discussed from the aspect of the internal bonding strength of the fluffing structure. Therefore, to reveal a deformation characteristic of a weak-bonded layer of paperboard, a new consideration of peeling resistance is proposed.

In this work, a white-coated paperboard was chosen for examining the PCT and ZD TT. In the PCT, the in-plane pulling (tensile) line force and the corresponding z-directional elongation of the upper layer peeled from the paperboard was observed during the peeling process to investigate the fluffing detachment of the weak-bonded layer. To develop a simplified mechanical model of detaching resistance of weak-bonded in-plane layer of a paperboard, an FEM model has been utilized with the MARC user’s subroutine USPRNG, which comprises anaphase yielding resistance derived from the z-direction tensile test in the FEM simulation. In this study, this model was known as the fluffing model, which was composed of distributed nonlinear spring joints. The fluffing model based on experimental data of ZD TT is our original method for solving an in-plane detaching behavior of multiple plies. The fluffing-based peeling model has been discussed for characterizing the experimental features.

2. Analysis condition and preliminary investigation

2.1 Specimens

For a peeling experiment, a commercially recycled white-coated paperboard that had a thickness \( t = 0.45 \text{ mm} \) and nominal basis weight of 350 g\( \cdot \text{m}^{-2} \) was chosen. Its fiber and pulp analysis was summarized in Table 1, while the in-plane tensile properties of the paperboard in the making machine direction (MD) were shown in Table 2. Figure 1 shows an example of in-plane tensile stress–strain diagram of the paperboard.

Table 1 Size of fiber and pulp combination ratio of white-coated paperboard 350 (measured by Kajaani-FS300) L-BKP. Broad-leaved lumber (hard wood), bleaching kraft pulp; N-BKP: Needle-leaved lumber (soft wood), bleaching kraft pulp; NTMP: Needle-leaved, thermal mechanical pulp; L(n): based on number of fibers in each fibrillation index class; L(l): based on length weighted number of fibers in each fibrillation index class; L(w): based on weight-weighted number of fibers in each fibrillation index class; CWT: Wall thickness of cell; Width: average width of fiber.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Pulp combination ratio/%</th>
<th>Projected length of fiber/\mu m</th>
<th>Size/\mu m</th>
<th>Width</th>
<th>CWT</th>
<th>CS A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>L-BKP</td>
<td>N-BKP</td>
<td>N-TMP</td>
<td>L(n)</td>
<td>L(l)</td>
<td>L(w)</td>
</tr>
<tr>
<td>Value</td>
<td>64.7</td>
<td>16.0</td>
<td>19.3</td>
<td>0.56</td>
<td>0.99</td>
<td>1.52</td>
</tr>
</tbody>
</table>
Table 2 In-plane tensile properties of a white-coated paperboard in MD. The tensile feed velocity was 0.33 mm s$^{-1}$ (strain rate: 0.00183 s$^{-1}$). The tensile procedure was based on JIS-P8113. The average (maximum–minimum) of ten samples was shown.

<table>
<thead>
<tr>
<th></th>
<th>Young’s modulus $E$/GPa</th>
<th>Yield strength $\sigma_Y$/MPa</th>
<th>Tensile strength $\sigma_B$/MPa</th>
<th>Breaking strain $\delta_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD</td>
<td>5.22 (4.9–5.49)</td>
<td>28.5 (27.7–29.2)</td>
<td>42.5 (40–43.73)</td>
<td>0.021 (0.018–0.023)</td>
</tr>
</tbody>
</table>

![Graph showing tensile stress–strain relationship](image)

Fig. 1 In-plane tensile stress–strain diagram (feed velocity $V = 0.33$ mm s$^{-1}$).

2.2 Estimation of elastic properties for compressive strength by ring crush test

Although some articles for deformation analysis of a paperboard or corrugated board using the orthotropic elastic model have been published (Nagasawa et al., 2006, 2013a, 2013b; Komiyama et al., 2013), a large deformation of orthotropic elastic model is generally unstable for numerical simulation. In this work, since the peeling resistance in the weak-bonded layer was macroscopically discussed with the pull-up force and the curvature of peeled layer, the peeled-off layer was assumed to be equivalently isotropic elastic, and the corresponded Young’s modulus was investigated for developing an FEM model. This equivalent Young’s modulus was examined using several evaluation tests: the in-plane tensile test (as shown in Table 2), an in-plane ring crush test (JIS-P8126, 2005), and an out-of-plane three points bending test (ASTM-D790-2, 2002).

![Diagram of experimental apparatus and specimen size](image)

(a) Schematic of experimental apparatus of the ring crush test

(b) Specimen size of ring crush test

![Diagram showing relationship between compressive stress and nominal strain](image)

Fig. 3 Relationship between compressive stress and nominal strain of the ring crush test.

According to our preliminary investigation, the Young’s modulus value of 5.22 GPa (MD) was fairly large (high stiffness) to estimate the bending deflection behavior of a peeled thin layer. It was obvious because the real behavior was based on a sort of orthotropic elasticity, and the thickness direction must have a small value of that. The authors examined a few cases of the out-of-plane three points bending test (based on ASTM-D790-2, 2002), and they observed that the equivalent Young’s modulus of the out-of-plane three points bending test was smaller than that of the in-plane tensile test. However, the result of the three points bending method seems to be difficult to detect a value of equivalent Young’s
modulus without discussing the mechanical condition of bending tool. Among those two evaluation methods (in-plane tensile and out-of-plane three points bending), the in-plane ring crush test seems to be stable and well-known in the packaging industry for detecting the value of the equivalent Young’s modulus. Therefore, the ring crush test (JIS-P8126, 2005) was conducted for detecting the equivalent MD elastic modulus $E_{RC}$. Figure 2 (a) and (b) shows the schematic diagram and specimen size of the ring crush test. The specimen holder was a circular annular groove with a fixed outside diameter of 47.8 mm. The depth of this groove was 6.4 mm. The bottom of the groove was flat, and its walls were perpendicular to the bottom. The width and length of the specimen were 12 mm and 150 mm, respectively. The velocity of the ring crush test was chosen as 0.1 mm s$^{-1}$. The specimens were prepared 10 pieces.

Figure 3 shows the experimental result of the ring crush test. The equivalent Young’s modulus was estimated as $E_{RC} = 533$ MPa from the in-plane MD ring crush test.

### 2.3 Anaphase yield resistance model based on ZDTT

The ZDTT model is used for explaining the detaching behavior of a fibrous–wire–(fluffing)–based resistance of a white-coated paperboard to determine the z-direction (thickness direction) tensile strength of a paperboard (Koubaa, Scandinavian Pulp, Paper and Board Testing Committee–SCAN-P, Stenberg, Fellers, et al., 1995, 1998, 2001, 2012). Figure 4 shows the relationship between tensile stress and elongation in the thickness direction. Figure 4 (a) shows the schematic of the experimental apparatus of ZDTT. An acrylic-based double-sided adhesive tape NWK-15S was inserted beneath the lower worksheet and upper the worksheet for stacking on the lower crosshead. The velocity in the experiment of ZDTT was chosen as 0.1 mm s$^{-1}$. Figure 4 (b) shows the specimen size of the ZDTT test. The specimens were prepared 10 pieces as a square sheet with a length of $L_{ZDTT} = 10$ mm, a width of $B_{ZDTT} = 10$ mm, and the thickness of 0.45 mm. Figure 4 (c) shows the tensile stress response diagram of the ZDTT and shows the fitting state between the experimental data and approximation curves. Here the normalized elongation $e_z$ was subdivided into three zones: $e_z1$, $e_z2$, and $e_z3$ as shown in Fig. 4 (c). The tensile stress $\sigma$ was approximated with $e_z$ by using Eq. (1), (2), and (3), respectively. Equation (1) and (2) were approximated by the third order polynomial expressions, and Eq. (3) was approximated by the power law. Table 3 shows the coefficient values of Eq. (1), (2), and (3). The generated thickness of a weak-bonded layer was estimated as $t_{p,ZDTT} = 0.11$ (0.10–0.11) mm.

![Schematic of experimental apparatus of ZDTT](image)

**Fig. 4 Relationship between tensile stress and elongation in the thickness direction**

$$\sigma = a_1 e_z^3 + a_2 e_z^2 + a_3 e_z + a_4 \quad (0 < e_z < e_z1)$$  \hspace{1cm} (1)

$$\sigma = b_1 e_z^3 + b_2 e_z^2 + b_3 e_z + b_4 \quad (e_z1 < e_z < e_z2)$$  \hspace{1cm} (2)

$$\sigma = c_1 e_z^2 \quad (e_z2 < e_z < e_z3)$$  \hspace{1cm} (3)
The first zone of $0 < e_s < e_{s1}$ shows the elastic or elasto-plastic behavior before breaking at the weak-bonded layer. The zone of the second and third periods of $e_{s1} < e_s < e_{s3}$ is a sort of anaphase yielding behavior that is caused by the fluffing resistance of delamination.

The tensile stress $\sigma$ is described with the normalized detaching distance of $e_s$, as in Eq.(1)–(3), and this seems to be caused by fluffing or drawing phenomena of fibers. Therefore, the anaphase yielding resistance of ZDTT is applied to the resistance of the detaching layer during PCT, when the detached distance of corresponding two nodes is considered in two-dimensional freedom. This fluffing model can be described using a user defined subroutine of USPRNG (MSC software, 2010). In this user defined subroutine, the bonding line force $f = \sigma_{ZDTT}$ is defined by the stiffness $K$ and normalized distance $U^-t^{-1}$ between the first end and second end of the nonlinear spring, as shown in Eq.(4).

$$\sigma = (K \cdot L_{ZDTT}^{-1}) (U^-t^{-1})$$

In the implementation of user defined subroutine, Eq.(4) was replaced to Eq.(1)–(3) using $e_s = U^-t^{-1}$. When $U^-t^{-1} > e_{s3}$, the nonlinear spring force is defined as zero. Namely, this is the breaking criteria which is based on ZDTT model.

### 2.4 Method of Peel Cohesion Test (T-peel test)

T-peel test was applied for the mechanical investigation of the peel behavior according to ASTM-D1876-01 (2001), (Pugno and Abdalrahman, 2012). The word “T-peel” means that the one peel arm is bent by 90°. Figure 5 shows a schematic of the experimental apparatus and specimen configuration. The coated layer of the worksheet was set as the upper side. The starting position of the peeling process was shown in Fig 5. To keep the attitude of the pull-up tape in the vertical, the linear positioning stage was moved in the horizontal with the same feed velocity as the vertical pull-up velocity. Figure 6 shows the profile parameters of the peeling process. Specimens were prepared as a rectangle sheet with a length $L_{PCT} = 50$ mm and a width $B_{PCT} = 15$ mm in the MD.

An acrylic based double-sided adhesive tape NWK-15S with a length of 50 mm and a width of 15 mm were inserted beneath the worksheet for stacking on the lower crosshead, while another double-sided adhesive tape with a length of 45 mm and a width of 15 mm was set up as shown in Fig. 6. Here the adhesive tape was bent by 90° with an attached length of 15 mm. The initial distance between the clamp and the specimen was 20 mm. The adhesive tape NWK-15S had a thickness of 0.14 mm. A load cell with the maximum load 10 kN was used in Fig. 5. Each specimen placed on the double-sided tape stacked on the counter plate which was fixed on the lower crosshead. The double-sided tape was fixed on the upper crosshead, which moved upward with a velocity of $V = 0.1, 0.25, 0.5,$ and $1.0 \text{ mm/s}^{-1}$. The pull-up vertical displacement $h$ was equal to the horizontal displacement of linear positioning stage.

![Fig. 5 Schematic of experimental apparatus](image)

![Fig. 6 Profile parameters on peeling process](image)

The line force $f (=F/b)$, the height of end part of peeled layer $h$, the inclined angle $\alpha_n$, the cracked length $L$, and the coordinates of three points (a)(b)(c) were recorded with respect to the elapsed time for each feed velocity $V$, as shown in Fig.7 and Fig.8.
Figure 7 shows an early stage when $\alpha_r < < 90^\circ$ and $h/t_p < 10$, while Fig. 8 shows a peeling deformation profile under the stationary stage when $\alpha_r = 90^\circ$. The curvature radius $r_p$ was approximately calculated from the three points (a), (b), and (c), as defined in Fig. 7 and Fig. 8. As mentioned below in the experimental result of PCT, the thickness of weak-bonded peeled layer $t_p$ was about 0.11 mm when it was measured by a mechanical micrometer. This thickness was almost equal to that of ZDTT. Before the peeling test, the paperboard specimens were kept at a temperature of 296 ± 1 K and a relative humidity of 50 ± 1% in a controlled room for 24 h. The peeling test was conducted in the same room. Measurements were performed ten times for each case.

**2.5 FEM model for PCT**

The purpose of the numerical model is to explain the experimental observations described in the previous section and to predict the behavior of peeling mechanism at the early stage and/or stationary stage of a white-coated paperboard. An isotropic elastic behavior of deflection of a peeled layer and base paper were assumed. A general purpose finite element code, MSC.MARC 2012.1.0, was employed for simulating the peeling process. The updated Lagrange procedure and a large strain analysis were used. The thickness of the worksheet was $t = 0.45$ mm. Seeing the experiment of PCT, since the position (thickness) of weak-bonded layer was stably a certain constant, the peeled worksheet was modeled as a combination of a peeled layer with a thickness of $t_p = 0.11$ mm and a base paperboard with a thickness of $t_b = 0.34$ mm ($=t-t_p$).

The contact boundary of those two deformable objects (peeled layer and base paperboard) is assumed to be the same as the fluffing model, which was derived from ZDTT, for accounting the opening behavior of the peeled layer. Therefore, the user defined subroutine USPRNG that describes the detaching resistance of ZDTT with Eq.(1), (2), and (3) was adopted. A two-dimensional model was constructed in a full-length worksheet of $L_{PCT} = 50$ mm, as shown in Fig. 9. The number of divided elements of the worksheet was 8000, while that of total nodes was 10010. The four-node plane strain quadrilateral element type was adopted. The peeled layer and base paper were assumed to be elastically deformable, the lower side of base paperboard was fixed on a rigid counter plate, and the middle point of the right side of the peeled layer (a gripped node on the right side) was pulled up in the vertical direction. The Young’s modulus of the peeled layer and base paper were mainly assumed to be 533 MPa (derived from the ring crushed test) and the poison’s ratio was $v = 0.2$ (referred from Baum et al., 1981), except for the gripper jointed area which had the length $L_0 = 2.67$ mm (equal to the initial in-plane crack based on the experimental observation), as shown in Fig. 9. According to a preliminary experiment of the adhesive tape NWK-15S, the in-plane tensile test (based on JIS-P8113) had the Young’s modulus of $E = 350$ (337–362) MPa, while the out-of-plane tensile test (based on ZDTT) had the Young’s modulus of $E = 1.13$ (0.93–1.31) MPa. Although the material property of adhesive tape is really anisotropic, an equivalent Young’s modulus must be identified as an isotropic model. Thus, the behavior of the peeling mode was investigated by varying the value of the Young’s modulus in the range of 1.13–350 MPa. In this work, a value of $E = 200$ MPa was assumed for matching to the experiment.

To protect any tangential slip between the peeled layer and base paperboard during a simulation process, the left side of the peeled layer was fixed for a certain range (10% of $L_{PCT}$) in both the horizontal and vertical directions. The peeling direction was chosen as parallel to the MD of worksheet. In addition, by seeing the fibrous-wire-based resistance, the nonlinear spring model was proposed by using the user defined subroutine USPRNG. The breaking criterion was considered with an anaphase yield resistance based on ZDTT. Here Eq. (1) was used in an elastic region, Eq. (2) was used for a detaching behavior between the peeled layer and base paper, and Eq. (3) was considered for a fibrous drawing (fluffing).
Figure 10 shows the relationship between the vertical motion of the gripper point of the peeled layer (u_t) and the horizontal motion of the base paper stacked on moving table (u_x) in this FEM simulation. Here the moving velocity and time increment of gripper in simulation were virtually introduced for defining the incremental variation of forced displacement of the gripper in the MARC model. The virtual feed velocity of the gripper was empirically chosen as follows: the first stage vertical velocity of gripper v_1 was 4.62 mm s\(^{-1}\) for t_0 = 0 − t_1 (t = 0.05 ms), while the first stage horizontal velocity v_x was 0 mm s\(^{-1}\) for the same duration (t_0 = 0 − t_1). The corresponded vertical displacement of the gripper u_y was 0.231 μm, and the horizontal displacement u_x was 0 mm. The constant time step of increment was set as 0.05 ms in the first stage. In the second stage, the vertical velocity v_2 was set to 31 mm s\(^{-1}\) for t_0 = t_1 − t_2 (t_2 = 2.0 s), while the horizontal velocity of base paper v_x was 39 mm s\(^{-1}\) for the same duration (t_0 = t_1 − t_2). The constant time step of increment was set as 5 ms in the second stage. As the result, the vertical displacement of gripper u_y was 62 mm, while the horizontal displacement of base paper u_x was 78 mm at t_0 = t_2 = 2 s. Moving of base paper was empirically delayed for a bit to avoid any unstable detaching on the peeled layer. Namely, after vertically elevating the gripper up to 0.23 μm (b/l_p = 0.002, a quite small offset) without moving the table in the horizontal, the velocity ratio of vertical by horizontal was empirically fixed to 31/39 (≈ 0.795) for the sake of keeping the attitude of upper layer sheet in 90° when h/l_p ≈ 50. Since the experimental condition of feed velocity ratio was v_y/v_x = 1.0, that of simulation also seems to be 1.0. However, when considering v_y = 59 mm s\(^{-1}\) and v_x = 33 mm s\(^{-1}\) (v_y/v_x ≈ 0.53 < 1), the upper layer is remarkably deflected in the out-of-plane. Moreover, the peeling force became negative in the early duration of h/t_p < 70, while the peeling force changed to the positive and became almost same as that of the experiment for 100 < h/t_p < 300. To date, in this work, the virtual feed velocities v_y = 39 mm s\(^{-1}\) and v_x = 31 mm s\(^{-1}\) were used for discussing the simulation.

3. Results and discussion

3.1 Experimental peeling load response and deformation of peeled layer

Figure 11 shows the relationship between the normalized peeling displacement h/l_p and the tensile line force f_p kN m\(^{-1}\). Here the real feed velocity and pull-up (peel) velocity were equal with each other and chosen as 0.1, 0.25, 0.5, and 1.0 mm s\(^{-1}\). The maximum peak tensile line force f_{max} was detected in the early stage of h/l_p > 0−20. Since the stationary state of f_p occurred for h/l_p > 20 but its response was varied randomly in a small extent, the average of f_p (=f_{ave}) was calculated for 20 < h/l_p < 100 using the trapezoidal rule of numerical integration. The maximum peak f_{max} and the stationary average f_{ave} were plotted in Fig. 12. It was found that f_{max} tended to decrease with the feed velocity, whereas f_{ave} tended to increase with the feed velocity when V < 0.3 mm s\(^{-1}\). The ratio of f_{max} by f_{ave} was about 3–4.
Figure 13 and 14 show the representative side-view photographs of peeled specimens during PCT under the stationary state (for $20 < h/t_p < 400$). In those photographs, the curvature radius $r_p$ of the peeled layer, the image scanning thickness, and the thickness by mechanical micrometer were also shown. The thickness profile was measured by the mechanical micrometer and image scanned average. The thickness of the image average tended to decrease with the feed velocity, whereas the thickness measured by the mechanical micrometer was almost invariant with the feed velocity. This difference seems to be caused by a variation in the scuffing height with the feed velocity. The curvature radius was estimated as shown in Fig. 8.

Figure 15 shows the normalized thickness of the peeled layer $t_p$ with respect to the thickness of 0.45 mm of the worksheet. In this figure, the thickness measured by image processing tended to decrease with the feed velocity. This was caused by the variation of scuffing height, while the thickness measured by a mechanical micrometer was almost invariant with the velocity. Figure 16 shows the relationship between the curvature radius $r_p$ and the feed velocity. It was confirmed that the curvature radius tended to increase with the feed velocity.
3.2 Peeling load response and deformation of the worksheet on simulation

The proposed fluffing based FEM model was employed to simulate the peeling deformation of a white-coated paperboard. The maximum peak tensile line force $f_{pmax}$ was detected by the early stage of $h/t_p \approx 0$–50, while the stationary stage of $f_{pc}$ occurred for $50 < h/t_p < 300$.

In Fig. 17, “Exp.” shows the experimental relationship between the tensile line force and normalized peeling height for $h/t_p \leq 300$, while “FEM” shows the simulation result. In the experimental case, the feed velocity was 0.1 mm·s$^{-1}$. The pull-up vertical displacement $h$ was experimentally equal to the horizontal displacement $L$ of linear positioning stage, while the ratio of $h$ by $L$ was empirically set to 0.795 for $0.04 < h/t_p < 300$. Seeing the simulation of Fig. 17, the peak maximum line force $f_{pmax}$ was 0.30 MPa, while the saturated line force $f_{pc}$ was 0.05–0.08 MPa. This result was similar to the experimental result.

Figure 18 (a) shows a photograph of the experimental peeling deformation in the early stage of $h \approx 7.09t_p$, while Fig. 18(b) shows an FEM simulation at the peeling height of $h \approx 7.09t_p (=0.78 \text{ mm})$. The cracked length $L$ and inclined angle of end point $\alpha$ were respectively $L \approx 24.3 \ t_p \ (20t_p$–$27.5t_p)$ and $\alpha = 25^\circ \ (23^\circ$–$28^\circ$) in the experiment. However, the FEM simulation had $L \approx 24t_p$ and $\alpha = 29^\circ$ in the early stage. The curvature radius $r_p$ was experimentally 2.7 (2.29–3.05) mm, and that of FEM simulation was approximately 2.6 mm. Hence, it was revealed that the proposed FEM simulation was fairly matched to the experimental response. Seeing Fig. 18 (a), the detached profile of the double-sided adhesive tape was confirmed. Since the real details of detached profile were complicated deformation, the equivalent isotropic Young’s modulus of $E = 200 \text{ MPa}$ was empirically introduced for the end zone of $Lip \approx 2.67 \text{ mm}$ as mentioned in the section 2.5. When this end zone had the same Young’s modulus as that of the upper layer $E = 533 \text{ MPa}$, the peak maximum of $f_p$ was not so much changed but the reducing tendency was fairly different (small) in the range of $10 < h/t_p < 60$. This means that the early stage peeling is sensitively affected by the equivalent stiffness of the end zone of the peeled upper layer.
Inclined angle (α) ≈ 25°

Cracked length L ≈ 24.3tp
Disp. of gripper s ≈ 1.0tp

Thickness of peeled layer tp = 0.11mm
Curvature radius rp = 2.7mm

Figure 18 Representative side views of peeling deformation profile in the early stage (h < 20tp).

Figure 19 showed the peeling deformation profile in the stationary stage (α = 90°). Here, Fig. 19 (a) shows the experimental result, and Fig. 19 (b) shows the FEM simulation result. The curvature radius of the experiment was approximately 3.26 (2.73–3.92) mm, while that of the FEM simulation was about 2.63 mm. The ratio of the experimental average by FEM simulation was about 1.2. The ratios are fairly similar with each other.

So far, the fluffing-based FEM model well explains the peak occurrence of the line force at the early stage and the saturated line force as compared to the experimental result.

Thickness of peeled layer tp = 0.11mm
Curvature radius rp = 2.63mm

(a) Photograph of experiment
(b) FEM simulation

Fig. 19 Representative side views of peeling deformation profile in the stationary stage at α = 90°

Figure 20 shows the FEM inclined angle α, the FEM cracked length L/tp and the experimental cracked length L/tp with respect to the peeling height h/tp. Seeing the relationship between L/tp and h/tp, the experimental gradient of dL/dh was 0.989, while the FEM-simulation-based gradient of that was 0.998. Namely, since the derivative dL/dh is approximately 1, the increment of peeling height dh is balanced to the variation of cracked length dL. In this case, the fracture release rate of mode 1 is equal to the peeling line force itself.

The experimental inclined angle αi stably reached 90° for h/tp ≈ 55–375, while the FEM based inclined angle αi was 90° when h/tp ≈ 50–300 (L/tp ≈ 66–318).
4. Conclusions

The peeling test of a 0.45-mm-thick coated paperboard of was performed experimentally by varying the feed velocity \( V = 0.1–1.0 \text{ mm}s^{-1} \). The detaching behavior of the weak-bonded layer was discussed with respect to the early stage and stationary stage by using the proposed fluffing model, which was based on the experimental result of ZDTT.

The experimental features are as follows:
(a) The weak-bonded layer thickness (peeled layer thickness) \( t_p \) was about 0.11 mm (24.4% of the thickness of 0.45 mm) in the examined paperboard. The peak maximum of line force \( f_{p \text{max}} \) occurred at the early stage (the ratio of peeling pull-up height by the peeled layer thickness \( h/t_p \) was less than 20), while the saturated line force \( f_{\text{fc}} \) was observed for \( h/t_p > 20 \).
(b) The value of \( f_{p \text{max}} \) slightly decreased with the feed velocity \( V \) when \( V < 0.25 \text{ mm}s^{-1} \), and it remained almost unchanged for \( V > 0.25 \text{ mm}s^{-1} \). Conversely, the value of \( f_{\text{fc}} \) slightly increased when \( V < 0.25 \text{ mm}s^{-1} \), while it remained almost unchanged for \( V > 0.25 \text{ mm}s^{-1} \). The ratio of \( f_{p \text{max}} \) by \( f_{\text{fc}} \) was about 3–4.
(c) The thickness of the image average \( t_i \) tended to decrease for \( V < 0.25 \text{ mm}s^{-1} \), while the thickness measured by the mechanical micrometer \( t_p \) was almost invariant for all the measured \( V \). This difference was explained by the variation of the scuffing height with \( V \).
(d) The curvature radius \( r_p \) tended to increase with the feed velocity.
Regarding the numerical simulation, the following was revealed.
(e) The USPRNG user subroutine, fluffing model based on ZDTT response, can appropriately estimate the peeling deformation of the coated paperboard from the early stage up to the stationary stage. The existence of the early stage peak maximum of line force was characterized by the fluffing model.
(f) The crack length and inclined angle of the peeled layer also matched well to the experimental results.

Nomenclature

ZDTT: z-directional (out-of-plane) tensile test
PCT: peel cohesion test
MD: machine direction for paper making
\( t \): thickness of work sheet (paperboard) with an average of 0.45 mm in this work.
\( t_p \): thickness of weak-bonded peeled layer in PCT. Its representative was 0.11 mm in this work.
\( t_b \): thickness of base paperboard. The thickness of 0.34 mm was used in this work.
\( L_{ZDTT} \): length of the specimen for ZDTT test
\( B_{ZDTT} \): width of the specimen for ZDTT test
\( t_0 \): thickness of weak-bonded layer. This value was almost equal to the thickness \( t_p \) in PCT.
\( e_t = x/t \): normalized elongation in ZDTT
\( \sigma \): tensile stress in ZDTT
\( a_1 = a_4, b_1 = b_4, c_1 \): coefficients of Eq (1), (2), and (3)
\( f_{ZDTT} = \sigma/L_{ZDTT} \): tensile line force in ZDTT
\( U \): distance between the 1st end and 2nd end of nonlinear spring which is joined to nodes on the peeled layer
\( K \): stiffness of nonlinear spring in USPRNG subroutine
\( L_{\text{PCT}} \): length of the specimen for peeling test
\( B_{\text{PCT}} \): width of the specimen for peeling test
\( V \): experimental feed velocity of vertical motion of gripper point of peeled layer (mm s^{-1})
\( u_x \): horizontal displacement of base paper by table motion (mm)
\( u_y \): vertical displacement of gripper point of peeled layer (mm)
\( t_{eq} \): virtual elapsed time (s)
\( v_p \): virtual feed velocity of the horizontal motion of base paper (mm s^{-1})
\( v_z \): virtual feed velocity of the horizontal motion of base paper (mm s^{-1})
\( L_{eq} \): length of initial peak that was equivalent to be 2.67 mm in this work, was equivalent to be the length of initial peak of the experimental result.
\( h = h_1 - h_0 \): vertical displacement of edge of the peeled layer from the edge of base paperboard
\( h/t_p \): normalized peeling displacement per the thickness of peeled layer
\( f_p = (F_p)/h \): tensile line force of paperboard in PCT (kN m^{-1})
\( E_{\text{eq}} \): equivalent elasticity modulus derived from a ring crush test
v: Poisson’s ratio of paperboard. It was assumed to be 0.2 in this work.

\( f_{\text{pmax}} \): maximum peak tensile line force in PCT (kN-m^{-1})

\( f_{\text{bc}}\): average of saturated (stationary) resistance in PCT (kN-m^{-1})

\( r_p\): curvature radius of peeled layer sheet

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References


