Preferred citation: D. Coffin and M. Nygårds. Creasing and folding. In **Advances in Pulp and Paper Research, Oxford 2017**, *Trans. of the XVIth Fund. Res. Symp. Oxford, 2017*, (W. Batchelor and D. Söderberg, eds), pp 69–136, FRC, Manchester, 2018. DOI: 10.15376/frc.2017.1.69.

CREASING AND FOLDING

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INTRODUCTION

Pamphlets, envelopes, bags, carton, boxes and many other converted paper/paperboard products incorporate folds as an inherent component of the design. For example, consider that a blank for a simple folding carton has eight crease lines that require folding to form an edge or a flap. A person scores or creases the paper to reduce the effort required to form the fold as well as improve the quality and aesthetics of the final product. A good crease forms straight and minimally damaged edges. For a folding carton, the folded edges of the board should not exhibit cracks on the outside surface, and the crease should offer minimal resistance to bending (not store energy) so that the box panels remain straight and form a parallelogram. In the pursuit of improving the ability of paper to produce high quality folds, a science of creasing and folding paper has emerged, and is reported upon in the literature.

Our current understanding was assembled from a long history of art, craft, and industry associated with the folding of paper and board. The following provides a critical review of the current knowledge on the mechanics of creasing and folding. We focused our effort on that of folding and creasing of paperboard. As a problem in solid mechanics, creasing and folding offers a wonderful mix of issues including large deformations and rotations, significant differences in the magnitude of various relevant properties, distribution of properties and inelasticity. Yet the crease and fold themselves are quite elegant in their simplicity and so contributions on all aspects, including experimental, theoretical, and numerical hold relevance. Thus, we reviewed existing theories and models for creasing and folding and introduce some new simple models that can be used to understand creasing and folding.

From the papermaker's perspective, understanding how to produce a paper receptive to creasing and folding under a wide range of tooling geometries is valuable. A converter wants to know which set-up will yield the optimum efficiency and quality for a given paperboard. The user of the package wants a cost-effective solution that adds value and protection to their product. Although we have not answered these questions in our review, we have tried to establish a path, which can aid industry in these pursuits. Based on our study of the literature, we believe that renewed effort should be placed on establishing a design envelope that incorporates both material properties and tooling geometry. The papermaker could use this concept to develop more versatile paperboards, and the converter could use this concept to more efficiently set-up their system for a given paperboard.

Despite, the length of this article, there are still many aspects of creasing and folding that we have not covered. We hope that we have established the fundamentals of the mechanics of these operations and provided a baseline for future work.

HISTORICAL PERSPECTIVE

Since the development of paper two millennia ago, folding has likely been a common operation. Once paper as a material, achieved the ability to withstand the folding operation without cracking, scrolls where set aside for concertina-style books, butterfly-binding and finally modern bound books. Some of the oldest known books were found at the Dunhuang Mogao archeological site in China [1], which were presumably produced prior to 1000 AD [1]. Images of these documents display folded paper with cracking along the folds, similar to that shown in Figure 1.

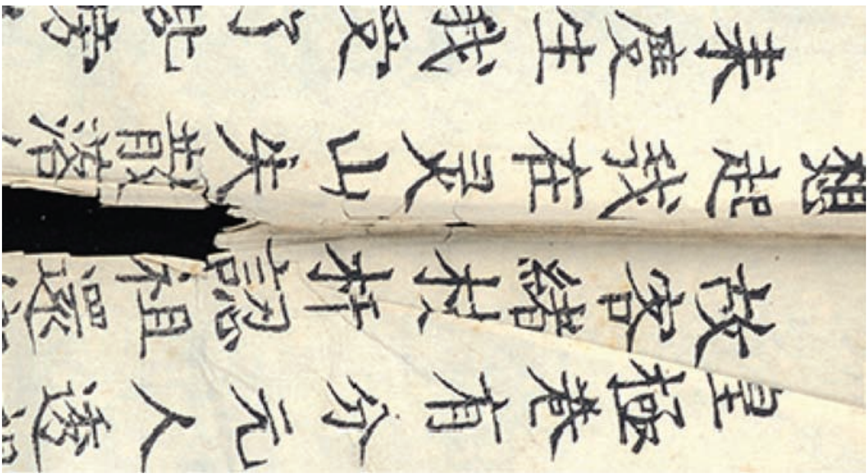


Figure 1. Example of damage in folded paper from concertina-style book (Miami University special collections, not dated).

By the time the printing press was developed, folding was a common operation. Consider Reginald Scot's 1548 book [2], *Discovery of Witchcraft*, with Chapter 26 titled "To transform any one thing to any other thing by folding paper". His description of the trick using folded paper is fairly detailed but he simply instructs the reader to fold the paper: presumably, because the ability to do this well was common knowledge at the time.

Even today in art craft, paper folding often precedes the creasing as opposed to industrial scoring and creasing proceeding the folding operation. Young children learn to carefully fold paper and then form a crease by squeezing the paper between their fingers. Similar descriptions of folding and creasing are given in Moxon's 1683 text on printing [3]. Paper folding has aided science as well. For example, Dr. Alexander Stuart prepared a folded paper model to demonstrate the function of the heart as shown in Figure 2 [4]. On a side-note, Dr. Stuart delivered the first Croonian Lecture to the Royal Society, *On the Motion of the Heart* in 1738.

As paper became a material of choice for certain products (books, envelopes, cartons), tools were developed to aid in the folding and creasing of paper. A paper folder, Figure 3, was utilized to impart a crisp crease into the folded paper. The same folder and other similar tools were used to first score thicker papers to improve the fold. In fact, today, the bone folder is still used by those that bind books by hand and create art through paper folding.

Robert Gair is credited with the development of the modern folding carton and method for rapid production in the latter half of the ninetieth century [7]. There

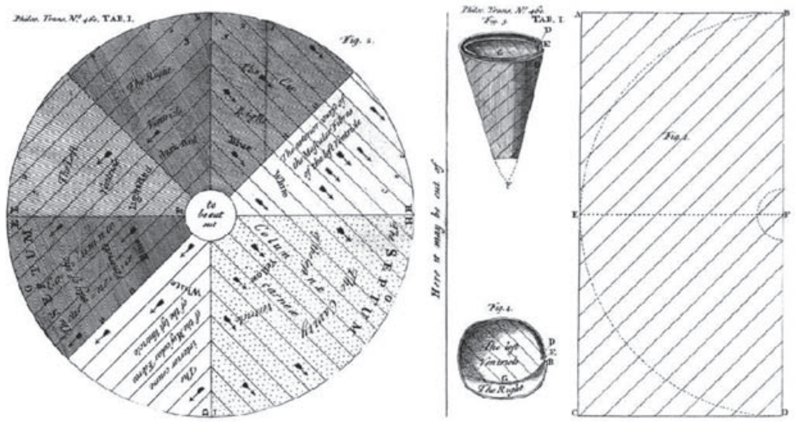


Figure 2. Folded paper model to demonstrate function of heart from 1730s [4].

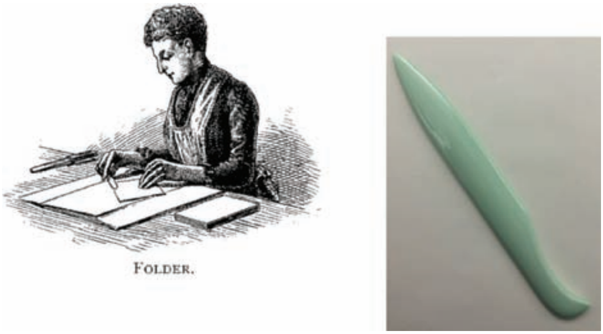


Figure 3. A nineteenth-century paper folder (both device and person) [5], and a twenty-first-century "bone folder" [6].

are many patents from this period dealing with box design and equipment for efficient production of folding cartons. One such example that specifically addresses creasing is Patent 183,423 by Edward De. F. Shelton from 1876 [8]. His patent discusses combining the printing and creasing operation to one machine. A passage form the patent follows:

> *. . . by the same act and by the same press, make the desired grooves or creases on the printed side of the paper to facilitate the after-folding, the ridges or swells thus being, as they should be, on the under or non-printed side of the paper, so as to come upon the inside of the completed box. A reason why the comparatively thick Manila paper should have its groove or crease on its outer or printed side, so that it may be bent against the ridge instead of against the groove, (aside from the advantages hereto forenamed,) is as follows: When bent against the groove-that is, so as to bring the groove at the inside of the right angle formed by two sides of the box the inclined faces of the groove, forming, as they usually do, less than a right angle with each other, come into contact and are forced against each other long before the paper becomes bent to the requisite right angle, and the consequence is a severe strain on the outer face of the paper at the ridge or angle; and if the paper be quite thick, or the bending be quickly or abruptly done, it is apt to be ruptured. When, on the other hand, the paper is bent against the ridge, and with the crease on the outside, the effect of the bending is simply to open the crease wider without any strain upon the fibers or texture of the paper, the action being very similar to the opening of the leaves of a book-cover toward its back.*

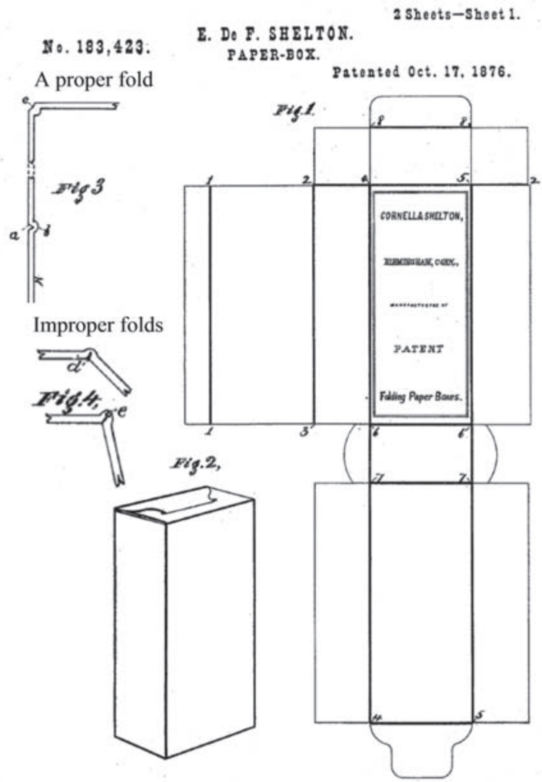


Figure 4. Early patent figures [8] showing creased board; including proper and improper folds.

The patent schematic, Figure 4, provides a clear sketch of the creased board with bending against the ridge (proper) and bending against the groove (improper) [8]. This shows that at the initial stages of the mass production of folding cartons there was an appreciation for the necessity of the crease and the importance of forming a bead on the inside of the edge, yet the direction of fold is rather counterintuitive to one who has not put much thought in to the process.

De F. Shelton [8] did not point out why forming a crease and bending against the ridge facilitates low tension on the outside of the folded-edge except that it is analogous to book binding. In a later patent from 1912 [9], Bird identifies delamination of layers at the fold, Figure 5, as a critical component for folding. It is interesting to note, that Bird's patent deals with adding reinforcing corner stays to help with the integrity of the edges and that his patent was granted three days prior to the sinking of the Titanic, which could have used a bit more reinforcing on its welds.

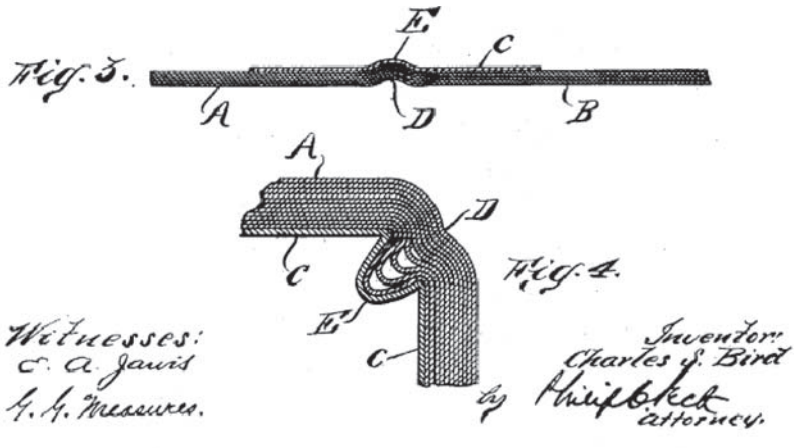


Figure 5. Figure from patent illustrating the delamination of layers in the fold of a creased board [9].

These two early patents provide us with three basic precepts for creasing and folding.

(1) The outer edge of the folded crease must be kept under minimal tensile strain to reduce the occurrence of cracks or even rupture.
(2) Bending against the ridge (compression on convex side) allows a high angle bend to be formed by pushing the ridge inwards to form a bead.
(3) The creasing must create sufficient localized damage in the paper to facilitate local delamination of the paper into layers and allows a bead to from in the inside edge during folding.

An important learning gained from this historic literature on creasing and folding is the importance of caliper to folding. A thinner paper may only need a score-line to ensure a good fold, but as the paper gets thicker, it becomes increasingly difficult to form an aesthetic fold without damage. Thus, the need for a crease. The creasing process for paperboard, prepares the paper for folding by:

- forming a permanent crease in the paper with the groove on the outside edge and the ridge on the inside edge, and
- disrupting the paper to allow for local delamination of the board into a series of plies such that the ridge forms a bead and minimizes the tension on the outside edge.

Corrugated board typically only needs a score, because the thickness can be reduced to just the thickness of the components and then a fold can be made without forming a bead, although high tensile stresses can still be created on the outer edge.

THE CREASE AND FOLD

A loss of volume is typically advantageous to creating an aesthetic fold or bend in a material. If a material is resistant to densification, a configuration other than the bend arises. There are many methods one can invoke to form a good bend. For an ideal linear elastic material, one can achieve a pure bend, but even here an instability can arise and cause additional deformation. If a material is quite ductile, such as metal piping, one can coax it in to forming a good bend [10]. For a plate material that is rather inextensible in the plane, forming a low-radius, high angle bend can be problematic. Figure 6, provides three options for forming a 90-degree bend for a material that is inextensible: (a) a laminated structure (composites) where each layer is free to slide compared to the others while forming the bend

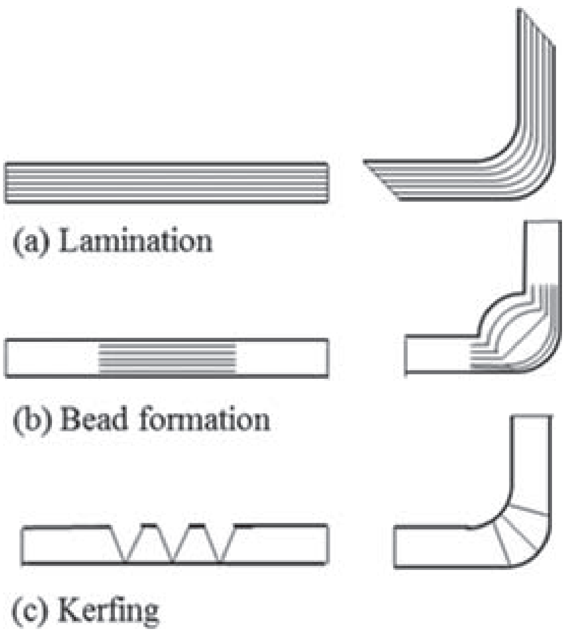


Figure 6. Methods of forming 90-degree constrained ends.

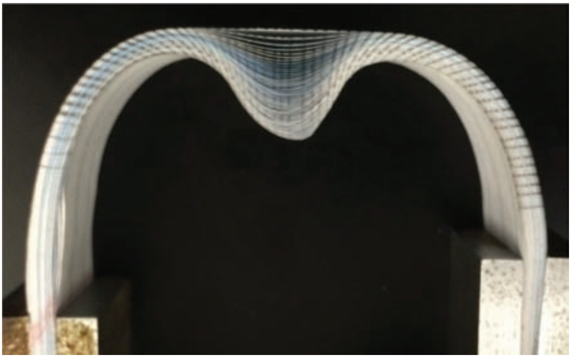


Figure 7. Folding of stack of papers with bend.

[11], (b) pushing the excess material to the inside such as forming a bead (paper materials), and (c) using kerfs to remove excess material (wood) [12]

The difference between (a) and (b) in Figure 6, is just a matter of allowing the plies to slide past each other or not. Even in composite laminates, if the processing step-does not allow for free movement of the individual plies an uncontrolled bead will form [11]. Figure 7 shows the forming of this bead in the bending of a stack of papers with the ends constrained from slippage.

A crease helps control the formation of the bead. To gain an appreciation of the importance of a crease, just look at the palm of your hand. Your crease lines formed to allow agility and take-up of excess tissue when you move. The same concept is employed in the creasing of paperboard, we place the crease in the sheet to encourage the inward movement of the excess material and produce smooth bead. In addition to paper products, products made from other materials utilize creases to help control folds such as tablet cases, clothing and leather goods.

In addition to function, a crease serves to provide form. Consider a creased pair of pants. To be considered fashionable, the crease must be straight and sharp. Many consider an uneven or irregular crease to be unappealing. The same is true with paperboard. A package with uneven, slack, or cracked edges is typically the last one left on the shelf. In addition, these attributes can hurt the quality of the package on damage the product it contains.

Creasing and folding fall in a general category of problems in mechanics with large out-of-plane deformations of layered structures. The earth's tectonic plates are probably the largest example of where folding is prevalent [13, 14]. There are examples all over the world of exposed sedimentary strata that have been permanently deformed into folds. A box fold in geology looks like a creased sample of paper and a monocline looks like half a creased sample. The mechanics of folded rock strata is not that different from creasing and folding paper. In fact, Dodwell

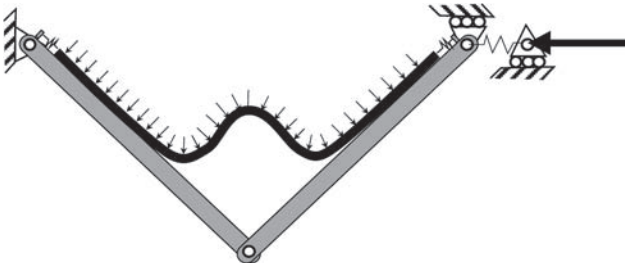


Figure 8. Model for folding of a constrained layer simplified from [20].

et al. [15] have used layers of paper (A4 copy paper) to study the folding behavior of layered media. On the other extreme of the size-scale is the folding of nanomaterials, such as graphene sheets [16–19].

Hunt, Butler, and Budd [20] recognized the generality of constrained deformation of layered structures and put forth the simple model shown in Figure 8, to predict the deformation of a single layer. Comparing Figure 7 and 8 clearly shows the relevance of this model to paper. This model accentuates the importance of buckling of layers to form the bead. The resistance to this buckling would decrease with decreased layer bending rigidity, increased free length and decreased resistance to layer movement from transverse shear and ZD tensile deformation.

An elastic-beam theory was applied to describe the 180-degree fold of a single layer graphene [19] and the results compared well to a molecular dynamics simulation. The concept of using simplified mechanistic models to understand the general creasing and folding [19, 20] is of value in understanding the relative importance of the various parameters involved in the folding and creasing behavior. This approach would add insights, reasonable interpretations, and as one moves from mechanical models to beam models to finite-element simulation of the creasing and folding of a particular board those insights can be utilized to interpret results.

The creasing and folding of paper shares many similarities with phenomena observed and studies in other fields. Future research should make more use of the results from these other fields, and additional efforts to transfer developments in the paper field to those fields.

EARLY SCIENTIFIC STUDIES ON CREASABILITY AND FOLDABILITY

At the beginning of the twentieth century, the folding carton industry was firmly established. By 1910 there were 949 factories employing 39,514 people and with sales of $54.4M [21]. In 1922, Leighten [22] stated, "the folding box has revolutionized the marketing habits of the nation; permitted country-wide distribution; built up sales; fostered economy; safeguard health". By the 1930's research was emerging, and Robert Gair had provided a fellowship to the Mellon Institute. In 1939, Halladay and Ulm [23] of the Container Corporation of America published a scientific study of creasing and folding. They quantified the creasing and folding with both a series of observations and development of kinematic equations for the deformation of paperboard during creasing. Their publication seems to have been overlooked by others in the field; yet it provides a very good foundation on which to base a critical understanding of creasing and folding. Halladay and Ulm [23] marked the edges of a paperboard with vertical ink lines and proceeded to take photographs of the edge of the board at various stages of creasing and folding. This very instructive exercise was repeated here and Figure 9 provides images during the creasing, folding (90 and 180-degree shown), and unfolding process.

The lines in image (b) of Figure 9 indicate that although there was possibly some bending (rotation of lines) the shear deformation was significant (vertical displacement with no rotation of lines). Image (c) shows that during folding, there was a large ZD-elongation in the crease zone. This ZD elongation results from a delamination of the structure. The delamination allows the ridge to bend inwards to form a bead. Image (d) shows that the deformation in the crease zone was very large and a combination of ZD-elongation, shearing, and bending of the layers. The middle of the crease had an effective ZD-elongation of about 280%. The legs of the sample have only rotated and any deformation is negligible compared to the crease-zone. Image (e) shows that most of the permanent deformation is a large ZD tensile elongation confined to the crease zone.

These images in Figure 9 also show the book-like bending of the paper as described by Shelton [8] and the importance of allowing for delamination as pointed out by Bird [9]. Based on their observations and interpretation of the deformation Halliday and Ulm [23] sketched an ideal deformed creased paper. Following along the arguments of Halliday and Ulm, one can further idealized this model assuming that all layers are inextensible to provide the same perspective as the transverse lines in Figure 7. This is shown in Figure 10, where we have also defined the basic geometric parameters for creasing.

Halladay and Ulm [23] assumed that the bottom surface forms the arc of circle and developed an equation to calculate what they term as the angle of break, shown in Figure 10(b) as θ_1. This angle of break is similar to a shear angle, g, that for very small crease deformations is the same as θ_2.

Halliday and Ulm [23] provide a several step analyses to determine the angle of break, which can be further simplified from their presentation to be

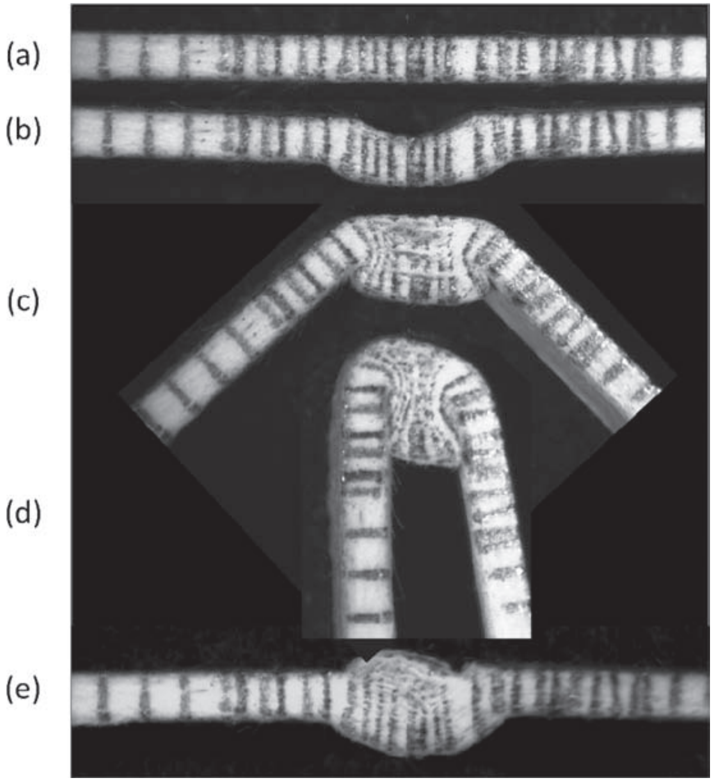


Figure 9. Figures from creasing and folding a paperboard in the spirit of the pioneering work of Halladay and Ulm [23]. (a) before creasing, (b) after creasing, (c) 90-degree fold, (d) 180-degree fold, (e) unfolded.

$$\theta_1 = \tan^{-1}\left(\frac{4z/c}{1-4\left(\frac{z}{c}\right)^2}\right), \tag{1}$$

where z is the total depth of travel and c is the channel width. We will term z, as the crease depth. This assumes that the thickness remains the same, which Halladay and Ulm [22] assumed was $h = (c - b)/2$. This corresponds to a case with no clearance between the rule and the channel. They also calculate the draw that must occur to pull and/or stretch the paper into the creased shape. They consider the

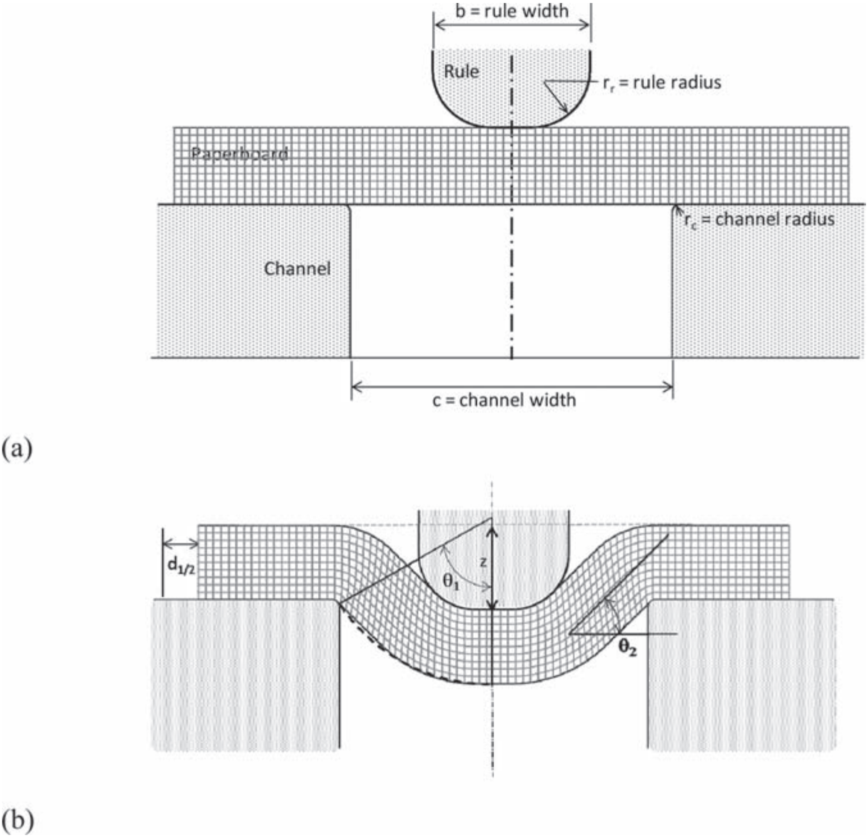


Figure 10. Creased paperboard deformation similar to [23]. (a) before creasing, (c) after creasing. Grid in paperboard shown with assumption that each layer is inextensible.

difference between the half-arc length of the bottom circle compared to half the channel width as the half-draw, $d_{1/2}$, which can be written as

$$d_{1/2} = \frac{c}{2}\left[\left(\frac{c}{4z}+\frac{z}{c}\right)\theta_1 - 1\right]. \tag{2}$$

Equations (1) and (2) suggest that deformation based criteria can be used to evaluate the severity of creasing.

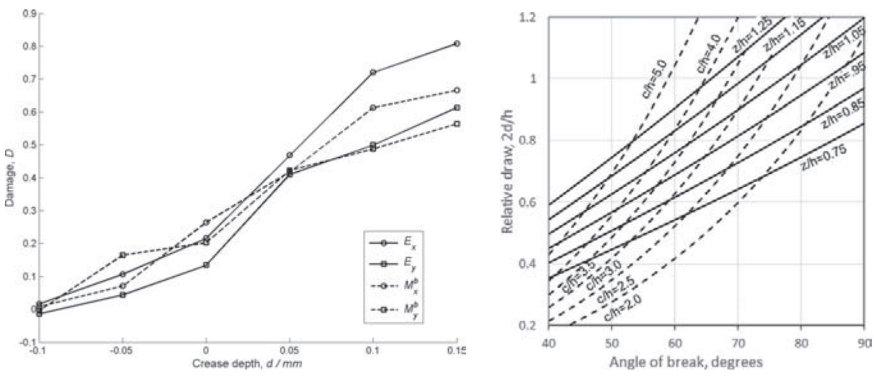
According to Halliday and Ulm [23], the crease-draw can be used with the tensile stretch of the paper to determine the minimum spacing between adjacent creases, $L_{\min}$. This was not explicitly given in their paper, but was inferred from their Figure 13 in [23] to be

$$L_{min} = \frac{2d_{1/2}}{\varepsilon_f}. \tag{3}$$

This would provide a minimum limit on the ratio *L/c*. If the adjacent spacing were less than this ratio, one might expect cracking during the creasing operation.

The results of Eqs (1) to (3) were visualized by Halliday and Ulm [23] as a dimensionless series of curves shown in Figure 11(a). For a specified angle of break and width of channel, one can determine the required depth of the crease and the draw of the board. We used the same equations and re-plotted them as shown in Figure 11(b). If the angle of break and required draw are considered as characteristics of the board, then one can determine the required channel width and rule depth for a successful crease. The shaded region Figure 11(b) suggests the idea of a window of applicability bounded by minimum angle of break, maximum draw, and minimum and maximum channel width.

Halliday and Ulm [23] suggested that one needs a minimum angle of break in the creasing operation so that the folding operation will give a proper fold. Thus, this dictates the ratio of *z*/*c* required in the creasing operation. It should be noted that Halliday and Ulm [23] designated *z* as the channel depth assuming that



(a) (b)

Figure 11. Design graph based on Eqs (1) and (2). (a) re-drawn from [23], (b) alternative plot where curves represent constant tooling geometries ($d = d_{1/2}$)

the rule pushes the paper to the bottom of the channel. In addition, they noted about a 10% decrease in caliper at maximum creasing action where the paperboard meets the edge of the female die.

The work of Halliday and Ulm [23] reinforces and solidifies the concepts gleaned from the patents of Shelton [8] and Bird [9]. Namely, that one needs to

- keep the draw below some threshold (stretch) to eliminate cracking during the creasing operation, and
- damage the sheet with sufficient angle of break to allow for delamination during the subsequent fold.
- They also suggest that a given board has a range of creasing parameters that will yield good folds that that guidelines such as suggested in Eqs (1) to (3) and shown in Figures 11(a) and (b) should be useful for designing successful creasing operations.

In 1959 and the 1960's, Hine [24–27] presented the work of creasing studies undertaken at the Printing & Allied Trade Research Association (PATRA) in England. In addition to re-stating the findings given in the previous literature (not cited in Hine's work), he introduces a Carton Board Tester and a Crease Stiffness tester. These provided tools to study and quantify creasing in the laboratory. He also provided valuable guidelines for ranges of parameters for acceptable crease forming.

By 1960, there were several instruments that could be used for studying creasing in board [28–32]. Hine [24] introduced the PATRA Carton Board Tester, which used a flat platen action to put a single crease in a paperboard. The edges could be clamped. Hine [24] reported acceptable ranges of creasing parameters for boards as determined from his tester. If the crease depth was too low, the board cracked upon folding. If the crease depth was too large, the board cracked during creasing. Hine suggested that this range be determined for a given board. Boards with larger ranges would likely be better performers in industrial creasing. For a fixed channel width (nominally two times caliper + rule width), Hine calculated a crease quality number that is $(Z_{max} - Z_{min})/h$. For characterization, Hine looked at other channel widths too. Figure 12 provides an example of the range of acceptable creasing for a specific tested paper from Hine [24]. The minimum lines represent when cracking occurred during folding and the maximum lines represent when cracking occurred during creasing. Acceptable creasing was in the range between the two lines.

Several trends can be drawn from the results given by Hine.

(1) Creases running along MD have a larger window of acceptable creasing parameters compared to creasing running along CD.

(2) Tensile constraint had very little influence on the lower curves, but limited the maximum draw that could be achieved at the upper limit.
(3) Increased moisture slightly raised both lines for both MD and CD creases.

If Eq. (1) is used to calculate the break angle for Hine's data, the minimums for CD creases are around 70 degrees and for MD creases the minimum angle of break is closer to 45 degrees. The creasing reported by Hine appears to be for deep creases $1 < z/h < 4.5$ and only the concept of creating a design window can be

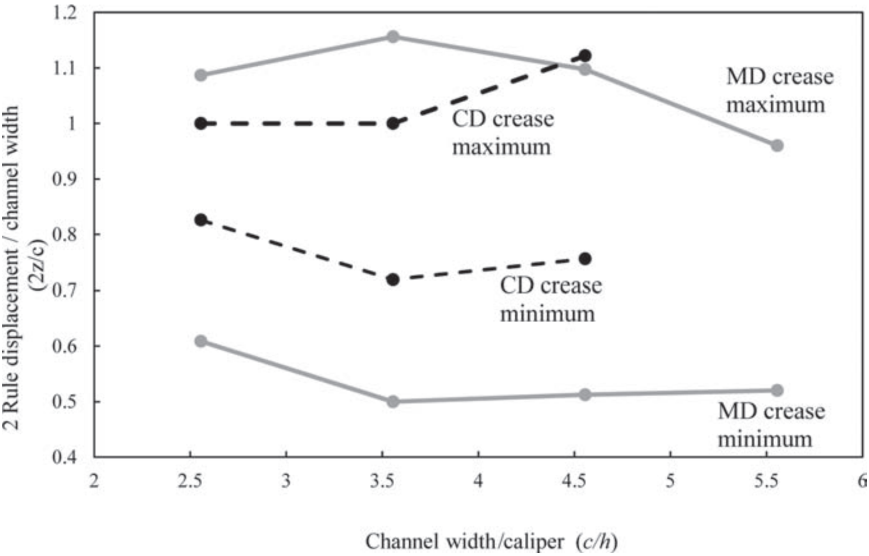


Figure 12. Example of the range of acceptable creasing parameters for a paperboard from Hines [24]. Please note that MD and CD refers to the crease directions in this figure.

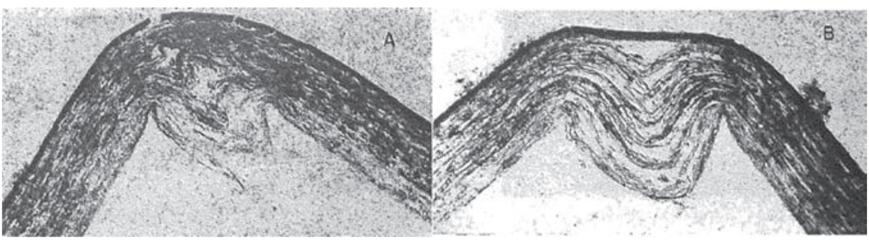


Figure 13. Outside layer cracking resulting from folding a shallow crease compared to a well-formed fold formed from a deeper crease [24].

taken from this work rather than any specific guidelines. Hine [24] presented a micrograph that compared a fold from a shallow crease with cracking to a well-formed fold from a deeper crease; shown in Figure 13.

In a subsequent paper [26] Hine introduced the measurement of the bending moment required to fold the crease and found that as the crease depth increased the moment required to obtain a fold decreased. He suggested that the fold moment can be used to characterize the crease performance and extent of bowing in panels due to stiff creases.

Donaldson [29] emphasized the idea of shear deformation as being important to creasing and used an equation similar to Eq. (1) except he ignored the squared term in the denominator. Lewis Eckhart and Luey [31] emphasized the concept of an operating window based on channel width and rule penetration.

The final early scientific work on creasing that is reviewed here is the work of Emslie and Brenneman [32]. Apparently, unaware of the previous work [23], they developed the same expressions given in Eqs (1) and (2) to describe the creasing (slightly different form). They also investigated the creasing deformation in a similar manner to that shown in Figure 10. In addition, they creased a three-ply sample with carbon paper placed between single sheets of paper to investigate where large strains exist in the crease. Their data showed large shear strain in the material drawn into the channel. Their fit of the data to Eq. (2) appears to be quite adequate. They pointed out that with creasing it is important to create enough damage in the material so it will delaminate into layers during folding. Based on Eq. (1), Emslie and Brenneman [32] creased to angle of breaks between 40 and 80 degrees. Emslie and Brenneman [32] provide some additional analyses to determine a delaminating stress. Although the analysis was perhaps overly simple, they determined that the stress was proportional to the square of the permanent set of the depth of draw, and inversely proportional to the fourth power of the arc-length of the crease

Emslie and Brenneman [32] investigated the geometry of a 180-degree fold in terms of geometry. They suggested that the length of any layer in the fold was approximately the same length as the permanent arc-length of the creased sample. They argued that the inner length of the bead formed three-square sides with approximately equal length. Figure 14(a) provides a sketch of the 180-degree fold of Emslie and Brenneman [32] and (b) an alternative kinematically admissible figure created for this review assuming the crease length is constant for each layer.

The sketches in Figure 14 are quite similar in appearance to Figure 9(d). There is not a unique configuration for the 180-degree fold and it will depend on the properties of the specific board, but these ideal creases provides insight in to creasing and folding. Emslie and Brenneman [32] suggested that the crease length needs to be about four to five times the caliper of the board so as not to fracture the outer layer. Figure 14(b), corresponds with a crease length of $(\pi+2)h = 5.14h$.

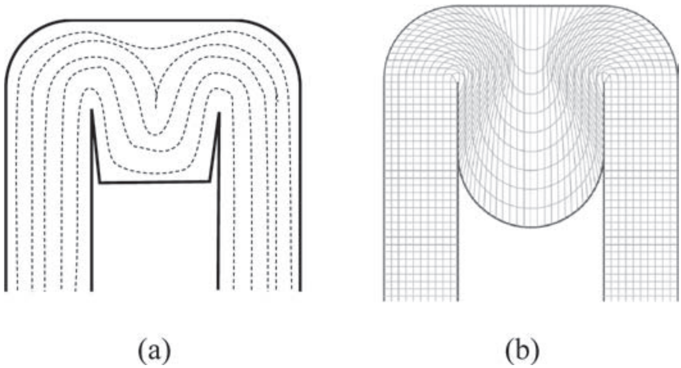


Figure 14. Geometry of 180-degree fold: (a) redrawn from [33], (b) fold assuming the in-plane is inextensible.

This is the length where the outer-layer could accommodate the fold with no elongation. The two pivot points for the fold correspond with the location where the paper met the channel. Several photos of folded board samples similar to both shapes shown in Figure 15 are provided in TAPPI Test Method T-495.

The early scientific work on creasing points to several key-factors that affect creasing performance. They are as follows:

(1) During creasing the paper experiences in-plane tensile strains, bending strains, ZD-compression, and transverse shear. The transverse shear strain developed during creasing is of prime importance and is related to the geometry of the tooling, the thickness of the paperboard, and the depth of the crease.
(2) If either the ratio of crease depth to board caliper (z/h) or crease width (c/h) is too small, the board cannot form a bead during folding, which requires excessive stretch of the top liner and possible fracture during bending.
(3) If the crease depth (z/h) is too deep, the damage in the sheet is excessive and board failure may result.
(4) If the crease width (length of crease zone) is too large (c/h), the fold will be slack.
(5) The crease must create enough damage in the board so that the ZD stiffness is reduced enough to allow large ZD strains (>200 %) during bending to 180 degrees. This is effectively done by delamination.
(6) The bending moment required to fold a crease can be used to determine the performance of a board to creasing. The maximum moment decreases with crease depth.
(7) For a given board, there should be a range of tooling geometries that yield an acceptable crease and fold.

CREASING RECOMMENDATIONS FOR PAPERMAKERS AND CONVERTERS

In the early scientific work creasing guidelines were developed as presented in Figure 11. For converters, this knowledge was transferred into industrial guidelines for crease tools. The relation between the channel or groove width and depth is then critical, and can be represented as maps that define a good creasing region, see Figure 15. When appropriate choices are made, cracking in the paperboard is avoided, and the folded corner is well-shaped. Successful creasing will weaken the paperboard along well-defined score lines, such that it will act as a hinge. As a guide for converters the Iggesund reference manual [33] and the Marbach guidelines [34] qualitatively states good creasing areas, in a similar way as done by Hine [24] and Lewis and Eckhart, and Luey [31] in Figure 15.

As shown in Figure 15, this defines a large window of acceptable creasing, and it does not consider the material behavior, which was better expressed in Figure 11. This type of figure does not even indicate that importance of paperboard thickness. Good crease performance will depend on the tool geometry and the paperboard properties see e.g. Savolainen [35] or Kirwan [36]. It should also be recognized that different paperboard grades such as folding boxboard, tobacco board and liquid paperboard would all have different requirements. This is mainly based on different requirements for the different paperboards; high converting rate for tobacco, no cracks for liquid.

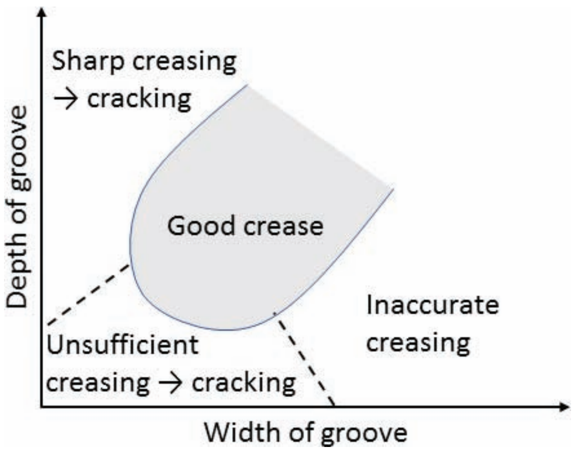


Figure 15. Illustration of creasing regions as suggested by Hine [24].

For folding boxboard, Marbach [34] suggested that the width, *b*, of the male ruler should be related to the thickness, *h,*

$$b = ah, \tag{4}$$

where *a* is a constant in the interval $1.3<a<1.7$. The recommendation for the female die width, *c*, according to DIN 55 437 is

$$c = 3h. \tag{5}$$

According to TAPPI T495, the Recycled Paperboard Technical Association (RPTA) recommends that the channel should be equal to slightly less than twice the board caliper plus the rule thickness and the ratio of the channel to thickness should be 3.5 for MD creases and between 3.5 and 4.0 for CD creases.

These recommendations on tooling serve to provide conditions that will yield a good crease when the penetration depth is zero or slightly into the channel. These guidelines may be overly simplified by ignoring how penetration depth and tooling geometry will affect the severity of damage imparted to the paper and thus, the creaseability. For example, a rounded male rule will impart different shear distributions than one with sharper corners.

The crease depth is an important parameter that affects the crease performance. In the definition used by converters the penetration depth is defined as $d = z\text{-}h$ and is equal to 0.0 mm when the male ruler and female die are aligned. This corresponds to a crease depth, *z*, equal to the paperboard thickness. From the perspective of mechanics of materials, the crease depth, *z*, is of more relevance because this is how much the paper must deform. Therefore, in the present discussions we utilize the crease depth, *z*, because it is directly proportional to the strains created during creasing, while we appreciate that from a tool set-up point of view, the crease penetration is more relevant.

It was concluded by Halladay and Ulm [23] that the creasing operation is dominated by shear deformation. It is therefore fair to introduce a shear angle, g, which accounts for the damage generated during creasing such as their angle of break, as proposed by Donaldson in Eq. (1) [31]. Nagasawa *et al*. [37] suggested utilizing a shear strain in Eq. (6), that accounts for the effect of crease depth and channel gap. The amount of shear damage can be estimated by considering the definition of shear deformation as the angle produced from the free-span, (*c*-*b*)/2, distorting by the penetration depth, *z*. Consider the creasing setup, as shown in Figure 10, where geometrical compatibility yields

$$tan(\gamma) = \frac{2z}{c-b} \tag{6}$$

In comparison, Eq. (1) can be rewritten as

$$tan(\gamma) = \frac{4\frac{z}{c}}{1-4\left(\frac{z}{c}\right)^2} \tag{7}$$

The shear angle in Eq. (6) approaches 90° when *z* goes to infinity or the channel width equals the rule depth. Equation (7) on the other hand reaches this limit when the depth is half the channel width. To account for the shape of the tool geometries and subsequent rotation of the paperboard around tool radii, Coffin and Panek [38] suggested characterizing, θ_2, in Figure 10 by assuming the material was inextensible in the plane, and that the thickness remains fixed (analogous to simple shear). Their expression was

$$tan(\theta_2) = \frac{\sqrt{(1-\kappa)^2 + \lambda(2+\lambda)} - (1-\kappa)(1+\lambda)}{\lambda(2+\lambda)} \tag{8}$$

where

$$\kappa = \frac{z}{h + r_c + r_r} \tag{9}$$

and

$$\lambda = \frac{c - b - 2h}{2(h + r_c + r_r)}. \tag{10}$$

Then, the shear angle developed in the free-span can be defined from the analytic expression of the deformation gradient as

$$sin(\gamma) = \frac{\theta_2}{\sqrt{1+\theta_2^2}} \tag{11}$$

which is equivalent to $\theta_2 = tan(\gamma)$.

Equations (8–11) imply that the severity of creasing depends on only two geometric properties: the dimensionless crease depth, κ, and the dimensionless clearance λ. The characteristic length in these quantities is the sum of the sheet thickness and the radii of curvature of the tooling. This is along the same lines as proposed in the early literature, but defines it in terms of natural parameters arising from kinematic considerations. Therefore, a large range of tooling geometries can be easily evaluated using Eqs (8–11). Because the sheet will rotate about the radius of curvature, the angle cannot exceed $\theta_2 = 90°$ and it reaches this limit at a finite-depth of penetration (κ = one and $\lambda = 0$). Therefore, the shear angle is limited by Eq. (11) such that $\gamma \leq 57.52°$. Equation (11) differs from Donaldson's [31] use of Eq. (1) because Eq. (7) was limited to the case of zero clearance. In Eq. (6), the shear angle only approaches 90° even for the case of zero clearance, although the advantage of Eq. (6) is its simplicity.

Figure 16, provides comparisons of the shear angle determined from Eqs (6), (7), and (11) for the case of (a) zero-clearance ($\lambda = 0$), and Eqs (6) and (11) for the case of positive clearance ($\lambda > 0$). If the clearance is negative, then a ZD compression needs to be accounted for, this could be accommodated in Eq. (11) by changing the thickness to the clearance.

The curves in Figure 16(a) show that Eq. (7) compares well to Eqs (6) and (11) if the channel width is three to four times the caliper. The figure shows though that as the channel width to thickness ratio increases, a larger crease depth is required to get the same shear. In addition, Eq. (11) gives larger shear for small crease depth but lower shear for larger crease depths compared to Eq. (6). The maximum shear limit for Eq. (11) is clearly shown in both graphs. Figure 16(b) shows that Eqs (6) and (11) agree well for large clearances, but for small clearances, Eq. (11) predicts more shear for small crease depths.

The creasing response can be studied in the lab by purpose made creasing tools as proposed in [39], an illustration of the setup is seen in Figure 17. This setup was

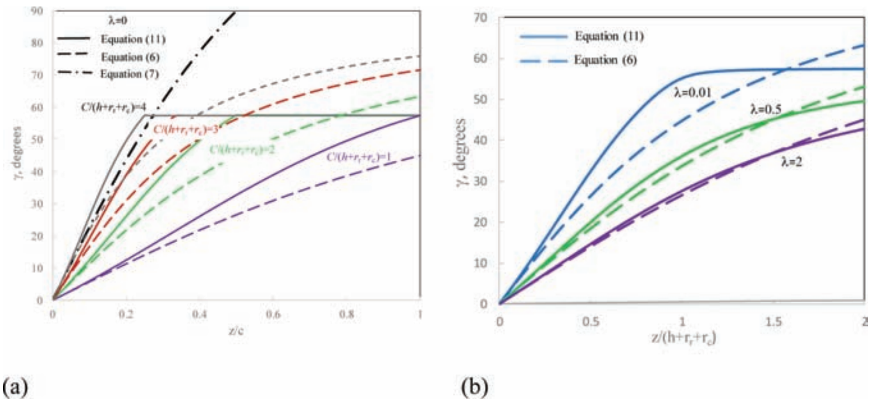


Figure 16. Comparison of shear angle predictions as a function of crease depth for various clearances (a) case of zero-clearance creasing and (b) with positive clearance

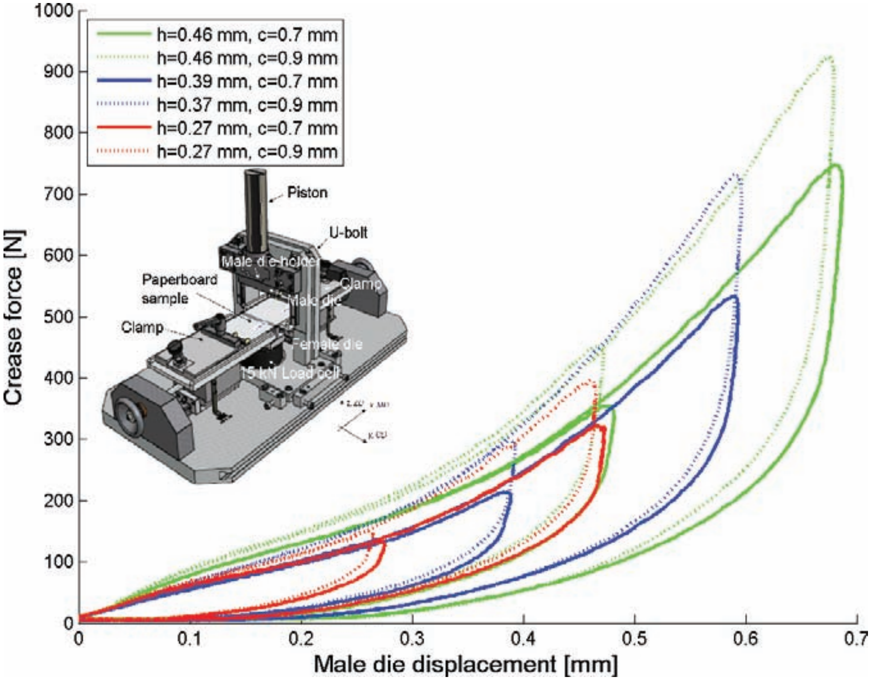


Figure 17. Creasing of paperboards using two male rulers with male ruler widths $b = 0.7$ mm and $b = 0.9$ mm [39].

used to study creasing of different paperboards in this work. The creasing tools had male ruler widths $b = 0.7$ mm and $b = 0.9$ mm and the female die width was $c = 1.6$ mm. Samples of 38 mm width were placed in the creasing tool and a 1 kN/m web tension was applied. Thereafter, the male ruler was punched into the paperboard, while its position and load was recorded. For each paperboard three samples were creased to $d = 0.0$ mm and $d = 0.2$ mm and unloaded. The paperboards were different; they had 5, 4 and 2 plies and the thicknesses were $h = 0.46$ mm, $h = 0.39$ mm and $h = 0.27$ mm respectively. To study the behavior during creasing, the creasing force-displacement curves were analyzed [39]. An alternative approach is however to utilized the definition of shear angle, using Eq. (6) as presented in Figure 17.

The creasing curves show that during the creasing operation there is a transition point between an initial linear part and a plateau formed by an exponential curve. Up to shear strain $\gamma = 0.5$ the curves for the two male ruler widths coincided for respective paperboard. The deflection point was however different for the paperboards. The thickest paperboard had the higher deflection point than the other two paperboards, which were similar. The deflection point has been identified as the onset of shear damage by Borgqvist [40]. At deeper creasing depths, the ZD compression will be different for the two male ruler geometries; using the tighter geometry $b = 0.9$ the compression will be higher. This can be seen in the raw data, but not by using the shear strain definition in Eq. (6), as seen in Figure 17, which also shows that the unloading from all levels had an exponential curve shape. The creasing operation is to large extent displacement controlled. The male ruler will punch the paperboard, and create shear deformations, which can differ within the paperboards. If the interlaminar shear strength is high the deflection point should be higher. It should also be emphasized that different creasing tools do generate different force-displacement responses, but can be well accounted for by using a nominal shear strain.

This concept of utilizing a measure of shear and draw length to characterize creasing is quite appealing. Following the same analysis of Coffin and Panek [38], the half-draw length is expressed as

$$\frac{d_{\frac{1}{2}}}{r_c + r_r + h} = \theta - (\lambda + 1) + \sqrt{(\kappa - 1 + \cos(\theta))^2 + (\lambda + 1 - \sin(\theta))^2} \tag{12a}$$

A crease length, the deformed length of the crease between the pivot points) can then be defined as

$$L = c + 2d_{\frac{1}{2}} \tag{12b}$$

When setting up a creasing operation, one needs to balance competing effects. Enough damage and lengthening of the crease is needed to form a good fold, but too much will cause excessive cracking or slack folds. As an illustrative example, assume we have a paperboard where the minimum shear angle required to make a good fold is 40° and the crease length must be at least four times the thickness. Further, assume, that if the shear angle exceeded 50° the crease is damaged, and if the crease length exceeded 5.1 times the thickness the fold would be slack. This gives an operating window, from which the tooling can be determined. Using Eqs (8–12b), several tooling set-ups were determined to give produce this limits as shown in Table 1. For this example, two channel widths and two combined radii were chosen and then the rule width and the crease depth was determined to give either the lower or upper limits. It could be considered that the channel radius is quite small, so the value of 0.5 is equivalent to a rounded rule. Table 1 represents four sets of lower and upper limit toolings that yield equivalent creasing characteristics.

Table 1. Tooling geometries that yield the same shear angle and crease length

	Channel, *c/h*	3.5	3.5	4.0	4.0
	Radii, $(r_r+r_c)/h$	0.0	0.5	0.0	0.5
lower limit $\gamma = 40°$, $L/t = 4.8$	Rule, *b/t*	1.07	1.18	1.82	1.93
	Crease depth, *z/h*	1.09	1.28	0.82	1.00
Upper limit $\gamma = 50°$, $L/t = 5.1$	Rule, *b/h*	1.31	1.40	1.92	2.01
	Crease depth, *z/h*	1.28	1.47	1.00	1.18

The example shown in Table 1 places emphasis on the concept of an operating window of creasing as previously suggested in Figures 11, 12 and 15. From a papermaker's perspective, one wants to understand how to increase the range of acceptable shear angles and/or draws while keeping an appropriate crease length.

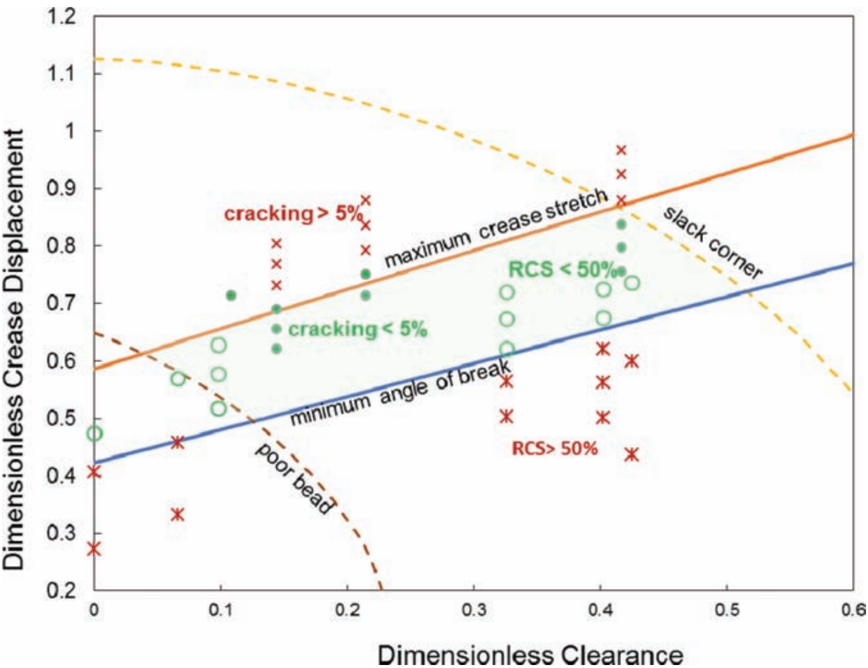


Figure 18. Example of creasing window. Green circles were judged as adequate crease and folds, red x's were judged as inadequate. [32]

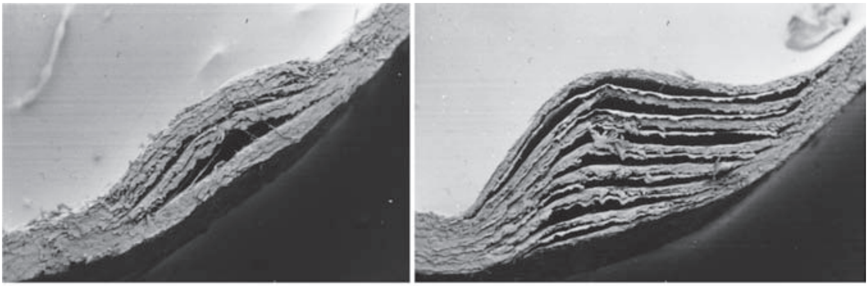
Along those lines, Figure 18 provides an example of this window for samples creased and folded in the laboratory and judged adequate by percentage of cracking or RSC strength [32]. The goal for the papermaker is to expand this window.

The creasing recommendations analyzed here provide a basis for further study. Improved analyses could be conducted to account for plasticity. For example, how should the crease depth and crease length be adjusted to account for elastic recovery. The effect of additional tension and bending could be included in the predictions. The additional damage from ZD compression when the clearance is less than zero needs to be addressed.

IMPORTANCE OF DELAMINATION TO CREASING AND FOLDING PERFORMANCE

In 1912, Bird [9] first pointed out the importance of delamination of the paperboard to form a good fold. If the sheet is delaminated, layers can slide past one another without stretching. The effective compressive stiffness is reduced because now plies can buckle and/or ZD extension offers minimal resistance. In effect, the neutral axis is being shifted towards the outer edge. This loss of stiffness, and shift of neutral axis, reduces the tension in the outer layer and avoids cracking during the fold. Halladay and Ulm [23] interpreted this required damage during creasing as a required minimum break angle to give a good crease. Emslie and Brenneman [33] incorporated the delaminated layers in their analysis of folding by adding the buckling load of inner layers and tension in the outer layers. If delamination does not occur smoothly during the folding operation, the bead will be either sharp or irregular and the top layer will experience more stretch. The creasing does not need to fully delaminate the sheet but it must provide for the smooth propagation of the delamination with little added force.

Carlsson, De Ruvo and Fellers [41] presented a parallel beam model to demonstrate how the delamination allows for bead formation, by buckling of the inner beam, and lower tension on the outer beam. They determined that the ratio of second moments of the area of the two beams and the center-to-center spacing relative to the length were the important parameters. They also presented experimental results where initial delamination zones were deliberately induced in a multi-ply sheet. The experimental results show that both the crease stiffness and bending strength decreased as the number of induced delamination layers increased. Figure 19 shows the crease after folding for the case of no induced delamination and seven layers of induced delamination. The latter had lower crease stiffness and strength of the former. The fold appears to be better formed for the case where seven plies could slip past each other rather than the more natural two to three plies of delami-



(a) (b)

Figure 19. Comparison of fold after creasing with (a) no implanted delamination and (b) seven layers induced delamination [41] (Photos from same collection as used in [41]).

nation in the unmodified sheet. Notice the similarities between Figure 19(b) compared to Figure 7. With sufficient delamination, the paper in the crease zone behaves much like the buckling of a layered system.

The literature tells us that delamination into layers makes the folding process easier and gives a well-formed bead. Delamination into more layers appears to lower the required stretch on the outer ply and provide for easy buckling of the layers in the bead. In fact, Iggesund Paperboard states in their graphic handbook [34] that

> Optimal creasing is achieved when the paperboard is de-laminated into as many thin and undamaged layers as possible along a well-defined fold line.

This statement, takes the concept of potential for delamination as a critical factor for producing good creases. In multi-ply paperboard, it is likely that the delamination will be one of inter-ply failure, and more plies would likely give better creases. If one induced intra-ply delamination, even more layers could be achieved. A single ply board also has the potential to split into many layers and could give good creasing as shown in Figure 9. However, for paperboards with fiber flocs there is a risk that fibers will entangle across the delamination cracks, and hence prevent opening of the delamination sites. There should be a smaller risk that this happens across a well-defined interface. The key attribute for creasing and folding is that the creasing operation induces enough damage spread across the thickness of the paper to induce multiple layers of delamination during folding.

We can conclude the following about delamination.

(1) The deformation induced during creasing should be sufficient to cause delamination of multiple layers across the entire crease length.

(2) The more layers, intra and inter-ply created the easier it is to induce the fold.
(3) Creasing resistance results mainly from shear deformation between layers.
(4) Folding resistance is mainly from ZD-extension, propagation of delamination, and resistance to bending of the inner plies.
(5) If delamination is insufficient, the plies will not buckle to sufficient extent and excessive extension will occur on the outer ply.

FOLDING OF UNCREASED PAPERBOARD

The folding behavior of oriented lab sheets made of chemical pulp with grammage of 440 g/m^2 and subjected to pure bending was analyzed by Carlsson *et al*. [42]. The activated failure mechanisms were analyzed by comparing the bending behavior to the uniaxial tension and compression properties. The in-plane tension and compression properties were characterized and the elastic properties in tensile a compression were the same, but the failure stresses deviated. In tension, the MD failure stress were 90 MPa, while it was 22–25 MPa in compression; in CD the corresponding values were 15–20 MPa in tension and 5–10 MPa in compression. Sample were folded by pure bending, and microscopic analysis using SEM was performed at three different folding angles; when the failure strain was reached in the outer ply, close to the maximum bending moment, and after the maximum bending moment had been reached. It was concluded that the failure occurred at the compression side during bending, as illustrated in Figure 20, where it was observed that more pronounced delamination occurred in MD samples compared to CD samples. Failure did not occur at the point where the strain in break in compression was reached but extended beyond this point. The onset of a non-linear behavior was however observed at the point where the strain at break was

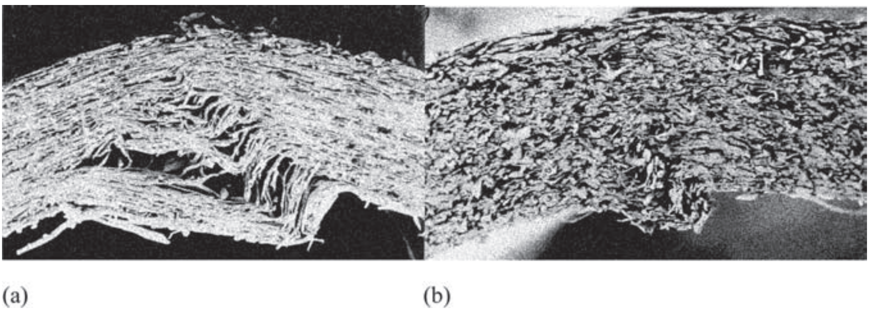


Figure 20. Uncreased (a) MD and (b) CD specimens bent to failure that were analyzed by Carlsson *et al*. [42]. (Photos from same collection as used in [42])

reached, and in the microscopic study fibers with dislocations were identified at the compressive side. It was concluded that no delamination cracks appeared prior to the point where the maximum bending moment was reached. Hence the failure mechanism was yielding due to compressive failure before the maximum bending moment was reached.

Calvin [43] attributed the peak in the moment angle curve as a compressive break in the sample corresponding to the fact that the compressive failure strain is significantly lower than the tensile failure strain. The subsequent softer zone is attributable to delamination of the sheet. There can be a second peak typically at some angle greater than 90 degrees. Calvin *et al.* [44] suggest that the peak moment is a measure of the compressive strength of the sheet, and a measure of the residual compressive strength after creasing. Compressive failure is one of delamination and transverse shear so this is not so different than saying that folding is controlled by a measure of transverse shear strength.

Paperboard folding is associated with delamination of the paperboard, which places it in the class of layered structures and different from materials that do not have such large anisotropy between the in-plane and out-of-plane directions. The same behavior in board has also been observed during folding of various papers; delamination occurs to comply with the folding compatibility and prior to cracking [45–47].

Two-point bending or a cantilevered configuration is often used to measure the bending stiffness of paper and paperboard. The standard span is 50 mm [ISO 2493 (DIN 5°), TAPPI T489]. This ensures that the shear component during folding is small. On the other hand, a span of only 10 mm is used when folding a creased paper. To analyze the stress state in the paperboard during folding a Timoshenko beam analysis [48] can be applied to uncreased paperboard samples, see further Nygårds *et al.* [49,50]. The stress state then consists of two components, an in-plane tensile/compressive stress, σ_x, and an out-of-plane shear stress, t_{xz}, which is expressed as

$$\sigma_x = \frac{PL}{I}\zeta = \frac{12PL}{wh^3}\zeta = 12\frac{M_b}{wh^3}\zeta \tag{13}$$

where the moment of inertia $I = wh^3/12$ for a square cross section and

$$\tau_{xz} = \frac{P}{2I}\left(\frac{d^2}{4} - \zeta^2\right) = \frac{3P}{2wh}\left(1 - 4\frac{\zeta^2}{h^2}\right) = \frac{3M_b}{2whL}\left(1 - 4\frac{\zeta^2}{h^2}\right) \tag{14}$$

where L is the length between the loadcell and center of rotation, h is the thickness, w the width, M_b is the measured bending moment, and ζ the

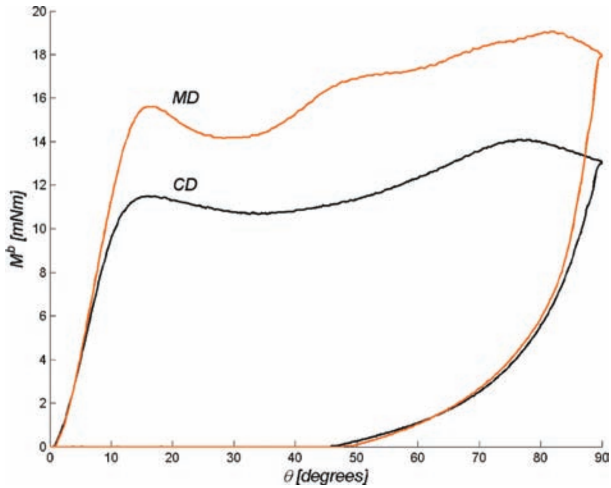


Figure 21. Typical folding curves in MD and CD for a paperboard specimen with width 38 mm [43].

distance from the centerline of the specimen. For most materials, the shear component will be small, and can be neglected. However, due to the anisotropy in paper materials, where the in-plane stiffness and strength is much greater than the out-of-plane stiffness and strength, the shear component will impact the behavior.

Folding of a paperboard will give an initial linear response associated with the bending stiffness. Thereafter, a peak bending moment will be reached, which is followed by a non-linear response as the paperboard is folded 90 degrees, see Figure 21.

The peak load can be used to calculate the stress state through the thickness of the board. In addition, if the stress is normalized with measured in-plane failure stress and out-of-plane shear stress, the normalized stress measure can be used to estimate how damage is initiated at the peak load. In Figure 22, the stress state for 3 different paperboards from Nygårds and Sundström [50] is shown. The stress state in the paperboards differ; the maximal stress value and their *z*-coordinate differ for all paperboards. It should be noted that normalized normal stress component is larger than the normalized shear component for all paperboards. The bending moments used to calculate the stress state in Figure 22 were the measured maximum bending moment for each paperboard. Note that the normalized compressive stress was close to one. Hence, it was concluded that damage due to bending was initiated when the bottom ply on the compressive side started to deform plastically, which in turn triggers shear induced delamination cracks. This

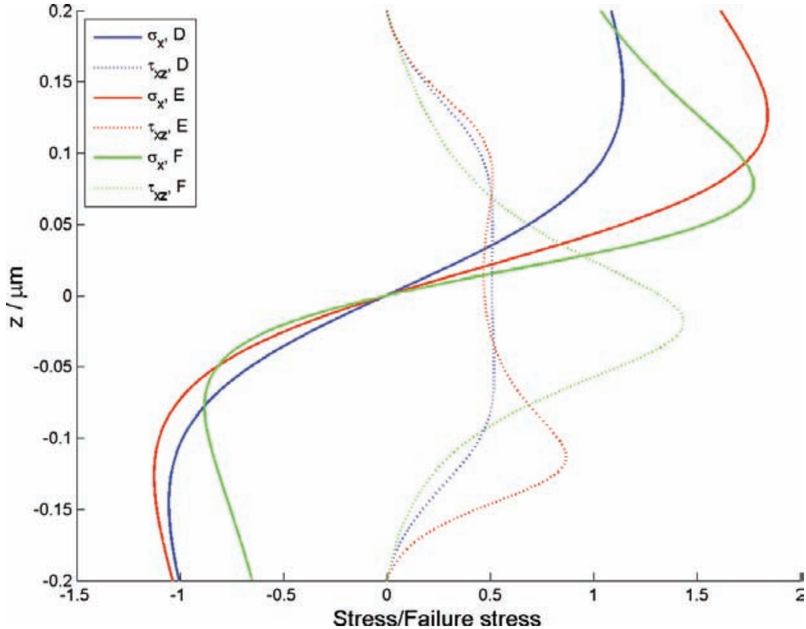


Figure 22. Normalized stress state (stress divided with yield stress and failure stress) for three paperboards in a Timoshenko beam analysis with L = 10 mm. Replotted from the data in [50].

kind of analysis can explain the failure mechanisms observed by Carlsson *et al.* [32], which were shown in Figure 20.

In product development of paperboard, one key aspect is to make a paperboard with a sandwich construction analogous to an I-beam structure. The basic idea behind this design concept is to achieve as high bending stiffness with a minimum of fibers. Therefore, the middle ply is often made bulky, which can e.g. be achieved by have less refining in the middle ply, or have CTMP or TMP pulps. On the internet [51–54] product specifications for 93 folding box boards are available. These have all been made on different machines and with different papermaking strategies. Hence, we can investigate the bending stiffness as a function of density. The bending stiffness is important because it contributes to package rigidity. The density, ρ, is of interest because it indicates the packing of the fibers and often correlates to degree of bonding. The apparent density is

$$\rho = \omega/h, \tag{15}$$

where ω is the grammage and *h is* the thickness, while the density of various plies could vary. Bending stiffness was measured in both MD and CD according to ISO 2493 (DIN 5°), where the bending force was measured at 5 degrees when the bending arm was 50 mm. To enable a comparison for different grammages the bending stiffness index, S_b^w, was used [55], hence

$$S_b^w = \frac{S_b}{\varpi^3} = \frac{\sqrt{S_b^{w,MD} S_b^{w,CD}}}{\varpi^3}, \tag{16}$$

if the geometrical mean of bending stiffness is calculated from the MD and CD bending stiffness.

Figure 23 shows the data for 93 commercial paperboard samples [51–54], which covers a broad spectrum of paperboards. It should be noted that when the density is high, the paperboards have a more uniform through thickness profile. As density increases, we expect the bending stiffness index to decrease. In fact,

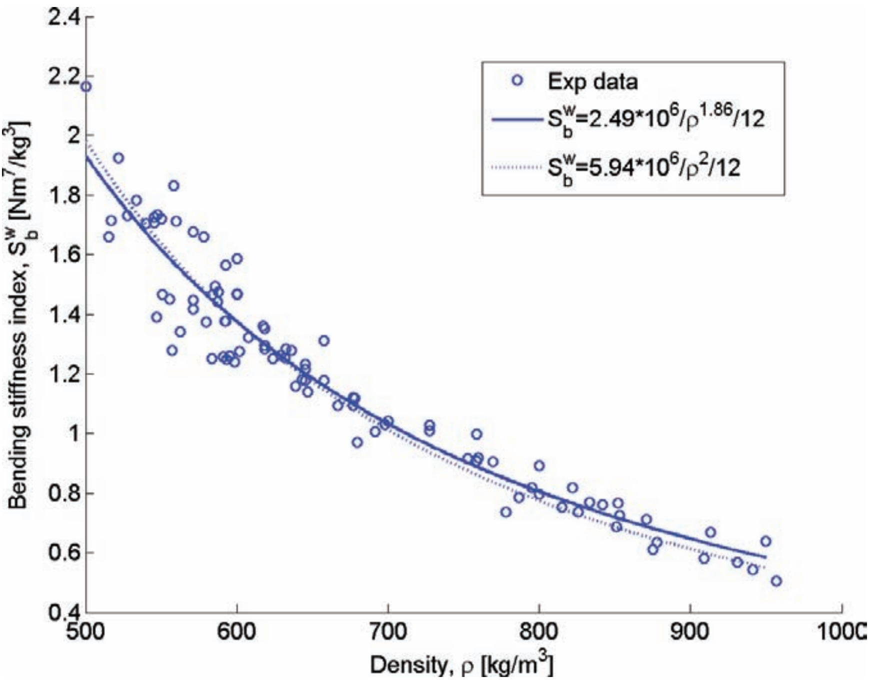


Figure 23. Evaluated bending stiffness as function density of 93 commercial paperboards in grammage range 150–350 g/m^2.

for a homogenous material, it is easy to show that the bending stiffness index is inversely proportional to density squared,

$$S_b^w = \frac{1}{12}\frac{E^{sp}}{\rho^2}, \tag{17}$$

where E^{sp} is the specific modulus (tensile stiffness index). Figure 23 shows a relationship that is approximately inversely proportional to density squared. All paperboards in the graph are multi-ply constructions, where chemical pulps were used in the outer plies. In the figure two least square fits have been made; one where only the specific modulus has been fitted to Eq. (17), and one where both the effective modulus and the ρ-exponent has been fitted. Both fits the average behavior well, although a homogenous structure was assumed in Eq. (17). The scatter at a given density might be more reflective of the sandwich structure of the boards. In the product specifications, it is not possible to find out-of-plane strengths or specific elastic modulus for all paperboards, therefore a more detailed beam analysis cannot be performed at this stage.

From the folding of paperboard, we can conclude

(1) During folding paperboard will delaminate. Normally it is the in-plane compressive stress component that will activate delamination.
(2) Paperboards with a lower specific elastic modulus as a result of thinner or weaker outer plies will have a relative lower bending stiffness.

FOLDING RESPONSE OF CREASED PAPERBOARD

As recommended in the early literature [26, 31], one could make use of various bending tests (cantilever, three-point, or four-point bending) to assess folding. In practice, cantilever bending is often utilized and can be measured by the L&W creasability tester (ABB, Lorentzen & Wettre, Sweden), the Marbach crease bend tester (Marbach, Germany) or the PTI Bending stiffness tester (Frank-PTI, Germany). The folding behavior of a creased paper depends heavily upon how much damage was induced during the creasing operation. One method utilized to characterize this resistance is measuring the bending moment as a function of bending angle [26]. In the industry, two different measures are used to indicate the quality of the crease and the foldability of the paperboard:

- the maximum bending moment, which can be used to calculate the relative crease stiffness (*RCS*) or the folding factor [33, 34] and

- the springback moment, which is the moment required to hold a ninety-degree bend after 15 seconds of relaxation.

RCS is the ratio of the maximum moment achieved during folding of a creased board to the maximum moment achieved in an uncreased board, hence

$$RCS = \frac{M_{b,creased}^{max}}{M_{b,uncreased}^{max}}, \tag{17}$$

where uncreased paperboard has $RCS = 1$, and creasing lowers the RCS value. In DIN 55 437 this is instead referred to as the bending resistance ratio.

The folding factor, F, is essentially a variant of the *RCS* value as is calculated as

$$F = \frac{M_{b,uncreased}^{max} - M_{b,creased}^{max}}{M_{b,uncreased}^{max}} * 100\% = \left(1 - RCS\right) * 100\%. \tag{18}$$

Uncreased paperboard has $F = 0$, creasing increases the folding factor, such that $F = 100\%$ would be a perfect hinge. According to Marbach [28] experience has shown that the folding factor should be $F > 50\%$ for properly creased paperboard.

An alternative definition of a folding factor, f, has also been presented in DIN 55 437

$$f = \frac{M_{b,creased}^{max}}{S_b}, \tag{19}$$

where S_b is the bending stiffness. This relation will relate to the weakening of the creased zone in relation to the uncreased paperboard, where the aim is to ensure that a paperboard folds in the crease and not in the uncreased regions.

Nagasawa *et al*. [37, 56–58] have thoroughly investigated the bending response of creased board using a cantilever configuration. Calvin [43] and Calvin *et al*. [44] summarize findings from creasing studies conducted at STFI with similar general results to Nagasawa [37, 56–58]. Here we repeated these tests for an MD sample with a crease in CD, such that an uncreased MD sample corresponds with an MD bending test. The paperboard samples were creased in the crease depth range $d = -0.2$ to $d = 0.3$ mm, and the effective shear strain, γ, was calculated using Eq. (6). In Figure 24, the folding behavior of uncreased and creased paperboard samples have been plotted. Analysis of the curves in Figure 24 shows the uncreased and creased paperboards have a similar folding behavior, and that the

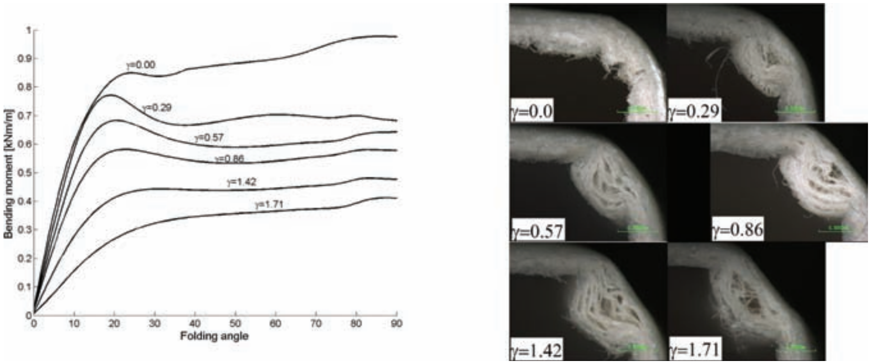


Figure 24. Folding response of uncreased and creased paperboard samples in MD, and micrographs of 90-degree bends and for samples creased to different depths as indicated by the measure of shearing, γ Eq. (6)).

damage introduced during creasing decreases both the bending stiffness and the maximum bending moment.

The photos in Figure 24 were made to validate the work in [56]. Folding in the uncreased board developed folds in the inside of the bend, but the folding wave is a higher mode than for creased paperboard. For creasing between $\gamma = 0.29$ and $\gamma = 0.86$ the bead formed quite well. For the case where $\gamma = 1.42$ or $\gamma = 1.71$, the paperboard was more severely damaged, which results in a more irregular bead. In [56] it could also be observed that the crease length was too large and the outer edge was loose. The higher strains here would not produce a tight corner. Comparing these observations to the graph in Figure 24 suggest that for deep creasing, there is no peak in the moment-angle curve and the fold is not of good quality. The presence of the peak force indicates that there is still significant force required to initiate the delamination but after that has occurred the moment required to further bend the sheet is reduced. For the results in [56] this occurred at a value close to $\gamma = 0.6$, while on Figure 25, a value close to $\gamma = 1.4$ has no significant initial peak.

Studies of folding lines of uncreased paperboards do show that the lines are uneven and kinky, which is associated with the fact that delamination is initiated at different positions along the folding line. The purpose of creasing is as stated earlier to introduce shear induced damage. The shear induced folding behavior will result in folding lines that are less kinky, see Figure 25.

Nagasawa *et al*. [56] plotted both *RCS* and the approximate springback moment, the moment at 90 degrees, M_{90}, divided by the maximum bending moment for uncreased paperboard, M_o, versus the nominal shear strain $\gamma = 2z/c$ similar to that

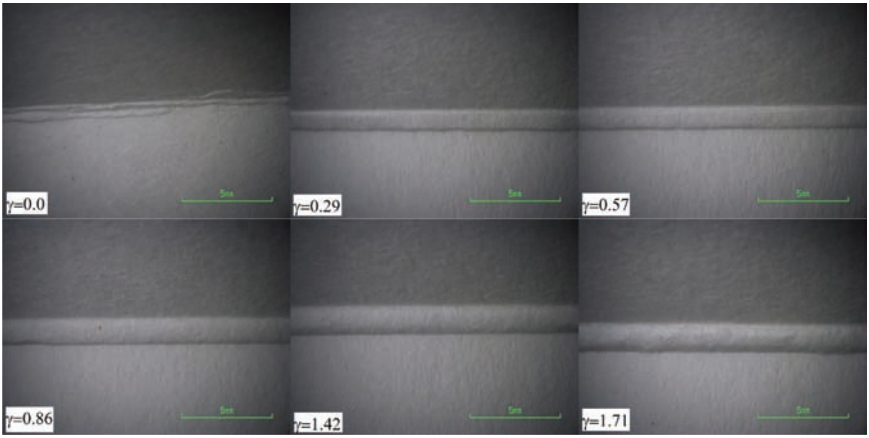


Figure 25. Photos of the inside (bead) of folded samples presented in Figure 24 at different shear strain level from $\gamma = 0.0$ to $\gamma = 1.71$.

shown in Figure 26. The results reveal interesting behavior. For shear strains less than $\gamma = 0.61$, the peak moment was significantly higher than the springback moment, and for larger strains there was no difference. It should be noted that the M_{90} for an uncreased sample was not so different than the value for a slightly creased sample ($\gamma = 0.21$). This is likely due the fact that bending the uncreased sample causes much of the same damage as the creasing does. Figure 26 indicates that *RCS* = 0.5 at approximately $\gamma = 0.45$.

Nagasawa *et al*. [56] presented the results of an interesting evaluation, where tensile tests on samples subjected to creasing and one 180-degree fold were performed, with the results shown in Figure 27. The uncreased and slightly creased samples suffered more damage during the fold than the more heavily creased samples. For the paperboards used by Nagasawa *et al*. [56] creasing to a range of $0.35 < \gamma < 1$ did not induce significant different damage to the layers in the board, but only to inter-ply connectivity.

Nagasawa *et al*. [56] also investigated the differences between MD and CD creasing on the bending moment. It is quite interesting that for the sample shown, MD-creased board carried a higher moment for $\gamma < 0.5$, but the difference was minimal for $\gamma > 0.5$ as shown in Figure 28. This result would indicate that *RCS* versus shear angle would differ for MD and CD creases mainly due to the bending moment required to bend the uncreased board.

In Nagasawa *et al.* [37] and in more recent work with Aluminium coated paperboard [57], the occurrence of surface cracks due to creasing and folding as a function of the extent of creasing was presented. The crack opening results

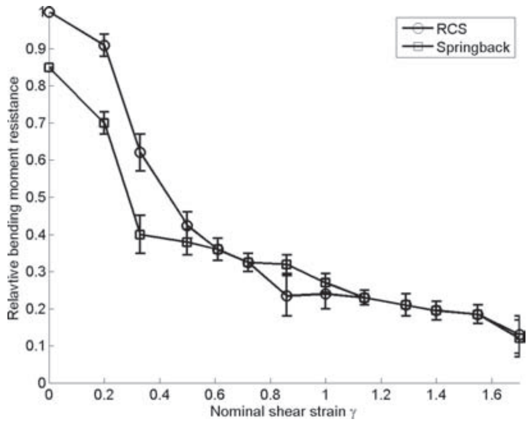


Figure 26. Effect of crease depth on bending moment resistance, replotted for 3 paperboards based on the data in [60].

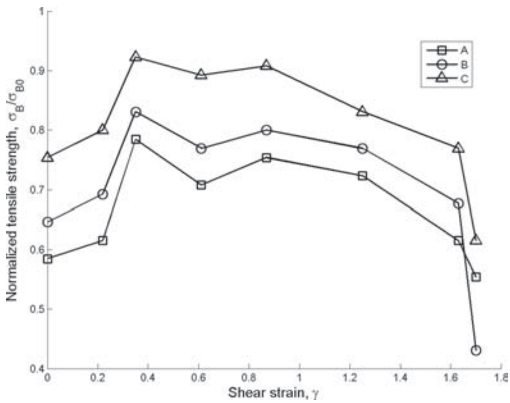


Figure 27. Normalized tensile strength after creasing and 180-fold in three paperboards, replotted from data in [50].

are given in Figure 29. For paperboards with low nominal shear strain, $\gamma<0.3$, surface cracks form regularly, and at high nominal shear straining $\gamma>0.5$ surface cracks were rarely formed. Hence, proper creasing reduced the amount of surface cracks. It was observed that there was some difference in surface cracks for MD and CD.

Mentrasti *et al*. [59] presented moment angle curves for boards up to 180-degree bends. They observe a second peak that is greater than that at the initial peak. Results for other "creases" that have been dash-cut did not have this second peak.

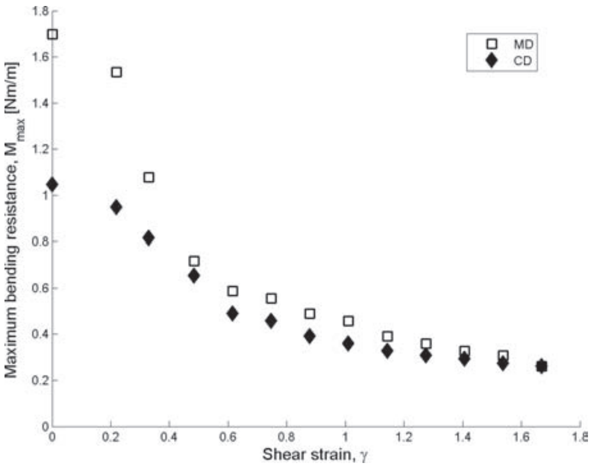


Figure 28. Maximum bending moment as a function of shear strain for both MD and CD.

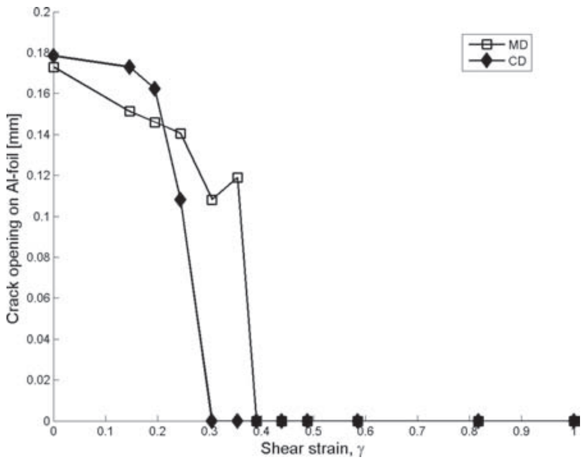


Figure 29. Net opening surface crack length after folding as a function of nominal shear strain during creasing. Replotted from data in [57].

The conclusion was that caution should be used when the folding angles get large, the methods used to measure folding moment must be investigated, and it is not clear how results in the literature should be interpreted. In addition, they showed variations of about 10% between samples cut from different locations in the same board, which suggests that variability is important.

To optimize the paperboard properties to improved creasing and folding performance, Nygårds *et al*. [60] analyzed crease formation for tobacco board, where the aim was to improve crease performance of both single creases, but also on multiple creases forming a rounded corner. For this purpose, shear strength profiles [61] were evaluated, and three-ply paperboards with desired profiles were manufactured. It was concluded that good creasing and folding performance could be achieved when the shear strength was low near the bottom interface. If in-plane cracking should be avoided on the printing side, it was advantageous to have a shear strength minimum along the top interface, since this allows the paperboard to bulge inwards. In the study the evaluation of shear strength profiles was a good tool for product development of paperboard, which were also easy to communicate to personnel running the paperboard machine.

We can conclude the following from the bending creased board literature:

(1) The reduction in the magnitude of the peak moment is indicative of the amount of damage induced during creasing.
(2) As the extent of creasing increases, the resistive moment in the paperboard appears to be relatively independent of directionality in the paperboard.
(3) To avoid crack formation during folding, the creasing must be sufficient to reduce the moment to at least 40–50%; this is a level when there is still a slight peak moment.
(4) For deep creasing, the moment is greatly reduced, visible damage occurs during creasing, and the fold is loose.
(5) Other measures such as reduction in tensile strength or percent cracking could be useful in characterizing the quality of a crease.

VARIABILITY IN FOLDING AND CREASING

There is little published on the variability of creasing and folding response for a given paperboard. Lewis *et al.* [31] discussed the development of an inclined-rule creasing tool to evaluate creaseability similar to that proposed by Calvin *et al*. [44]. For example, one could measure the depth of crease where cracking occurs. They abandoned this approach stating that the variability of material properties within the crease length rendered variability in crease quality to such an extent that the results were meaningless. Calvin *et al*. [44] stated "creasability data including various creasing depths, etc., usually show considerable scatter and it is usually very difficult to observe small effects." Mentrasti *et al.* [59] conducted tests on full folding cartons. They found the variability in bending response for samples taken from various locations along the crease in the carton. They report that the crease depth was not uniform and creases in one location on the box could be quite different from creases at another location. Variability in the set-up can affect creasing and folding. For example, Nagasawa *et al.* [56] investigated the effect of eccentricity in rule and channel alignment and the deviation that this caused in forming a symmetric fold. Therefore, it is essential that future research account for material variability for creasing and folding evaluations. Specimen sizes must be large enough to be representative and a large number of repetitions need to be conducted to better represent mean and distribution of results.

FINITE ELEMENT MODELS FOR CREASING AND FOLDING

Creasing and folding operations have been used for centuries to improve the performance of paper and paperboard in converting; yet, it has been difficult to fully understand which deformation and damage mechanisms are activated and develop correlations to measurable material properties. This difficulty is because the creasing and folding operations of paperboards do incorporate many different mechanisms of in- and out-of-plane deformation, buckling, and cracking. If one can in detail understand the behavior of paperboards when creased and folded, then the requirements of paperboards for good converting can be specified. Because of this, the creasing and folding operations have been the focus for the development of numerical models, where mainly finite element analysis (FEA) have been utilized [39, 62–83]

The extreme anisotropy between the in-plane and out-of-plane properties have made it difficult to use material models that are available in commercial finite element solvers. Hence, a major focus of the literature on creasing and folding pertains to developing numerical models to predict the behavior. At an early stage, Carlsson *et al*. [62] investigated creasing and folding with finite element analysis. This was not a fully predictive model but a utilization of FEA to demonstrate the importance of transverse shear stresses and delamination.

To successfully represent paperboards during creasing and folding simulations, the material must be represented by models that include inelastic behavior, anisotropy and failure criteria. Many existing models are quite complex and various assumptions and approaches have been taken to yield results that resemble creasing and folding. In the end of the 1990s an effort was made to develop material models that could be used to represent paperboard, and could be implemented in the commercial finite element solver Abaqus (Dassault Système). Xia [63] and Xia *et al*. [64] suggested that a combination of continuum and interface models should be used, as illustrated in Figure 30.

The continuum model should account for ply properties, and the interfaces would account for delamination. The continuum model was formulated using a large deformation formalism.

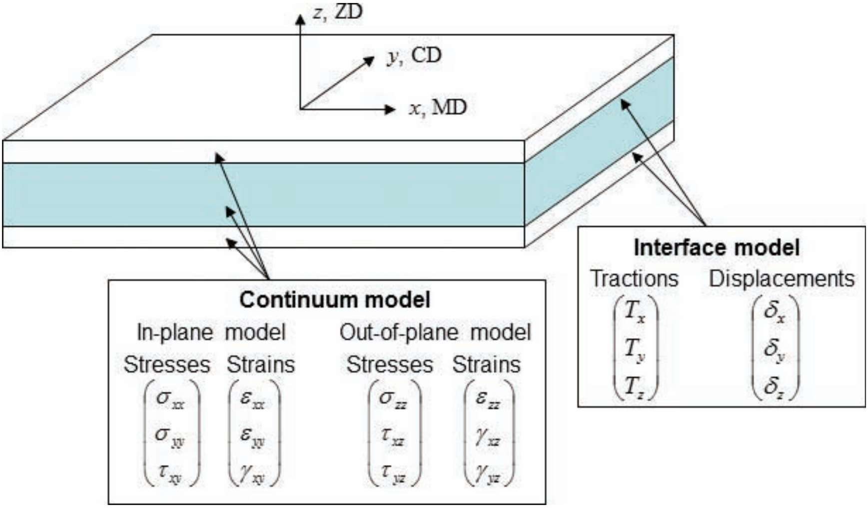


Figure 30. Schematic model setup with continuum and interface models to represent paperboards.

The Xia [63] model assumed that the continuum model should have an elastic-plastic in-plane model, while the out-of-plane continuum model was only elastic. Instead the non-linear out-of-plane behavior would be captured by the interface model. Nygårds *et al.* [65] implemented the proposed model, and showed that the assumption of an elastic out-of-plane continuum model was not sufficient to capture the mechanism during creasing. In a simulation, it could be observed that the creased region would then springback, and leave no residual indent on the paperboard, see Figure 31. Although the folding behavior could be captured with good accuracy, Figure 31, it was concluded that out-of-plane plasticity is a necessary mechanism that needs to be accounted for when creasing of paperboards is considered.

A new model was then proposed by Nygårds *et al*. [39], which included out-of-plane plasticity. With this model, comparison with experiments could be done, and the creasing behavior could be captured for the considered paperboard. The model was used to identify mechanisms that were activated during creasing. It was concluded that the creasing operation essentially was a shear test. In Figure 32, the contour plots of out-of-plane shear from the simulation of the three paperboards with different thickness, presented in Figure 17, can be found. The residual plastic deformation after the creasing operation show that the out-of-plane shear properties dominated the simulation results. But for all three paperboards there are also large amounts of ZD compression; Figure 33. In addition, simulations showed there was almost no in-plane plastic deformation and that that interfaces open-up and contribute to delamination mainly during the unloading [39].

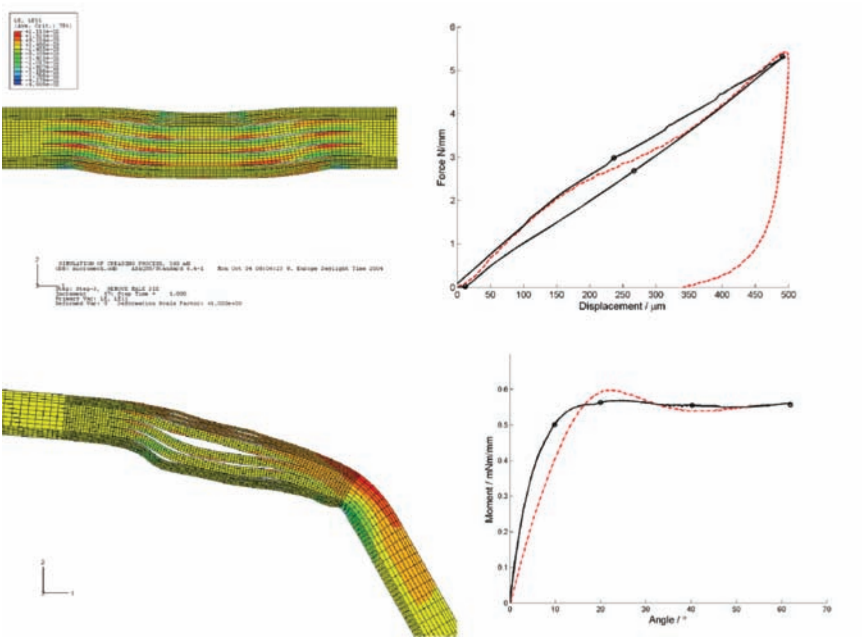


Figure 31. Creasing and folding of paperboard. The plots show strain in the MD direction. [65]

The ability of the board to delaminate into layers during folding is a main component of most studies of creasing and folding. The implementation of user defined material models can be a challenge, and especially if both continuum and interface models should be implemented. An approach to use an existing Hill plasticity model together with interface models have therefore been proposed in [67–71].

Beex and Peerlings [67, 68] developed a numerical model and focused a study on delamination of layers. In [68], numerical results for models with interaction between layers are compared to models with limited or no interaction between layers. Figure 34 shows that the folding behavior of the models are similar to folds observed in practice.

The top picture in Figure 34 gives the shape of the bead from the full model with delamination and friction between layers. The bottom picture is for a model with pre-delamination in the crease zones. Note that the middle of the sample was not delaminated giving it the flat center of the bead.

Study of the images in [68] as sketched in Figure 34 reveal the following. The full model captures the permanent set increasing and the folding behavior of the

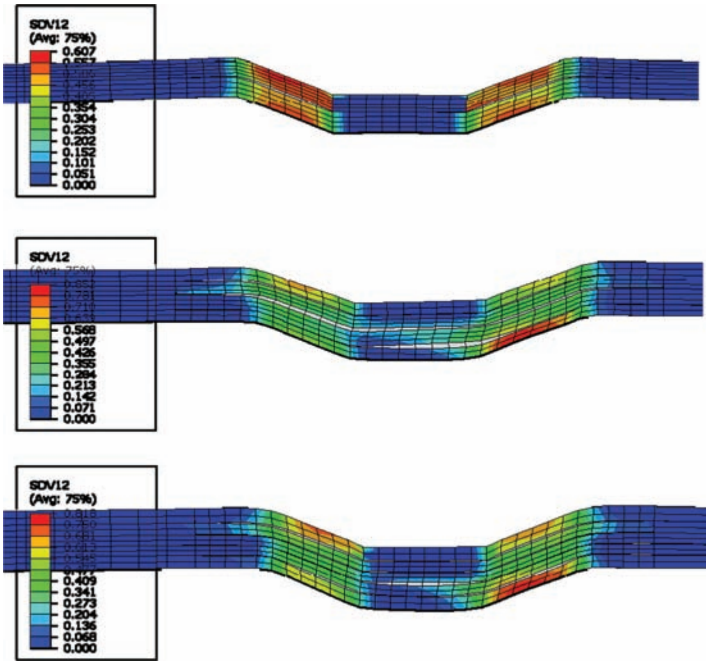


Figure 32. Plastic strains out-of-plane shear strains γ^p that have evolved in 3 paperboard models after the creasing operation, (top) $t = 0.27$ mm, 2-ply model, (middle) $t = 0.39$ mm, 4-ply model, (bottom) $t = 0.46$ mm, 5-ply model.

top plies, but not the deformation of the bottom plies during folding. The pre-delaminated model has too much permanent set from creasing, but mimics the deformation of the bottom plies during folding. The two models bracket but do not fully describes the process. The comparison shows that the delamination should follow through the full layers so that the top ply can separate during folding. It appears that the full model under-predicts the interaction of layers suggesting that the model has too much cohesive failure between layers. The paperboard was a three-ply board, but note that the middle ply separates into multiple layers during folding.

Comparison of the two creasing geometries in Figure 34 also suggests that the crease width plays a critical role in folding. Because of the extra permanent set in the crease, the middle model has a larger crease width and upon folding gives a looser corner. If the fold width is too narrow the bottom plies may not have room to fold well. If the channel width is too large, the corner fold may be too loose. One drawback with the Hill model in Abaqus, is that the out-of-plane shear and ZD

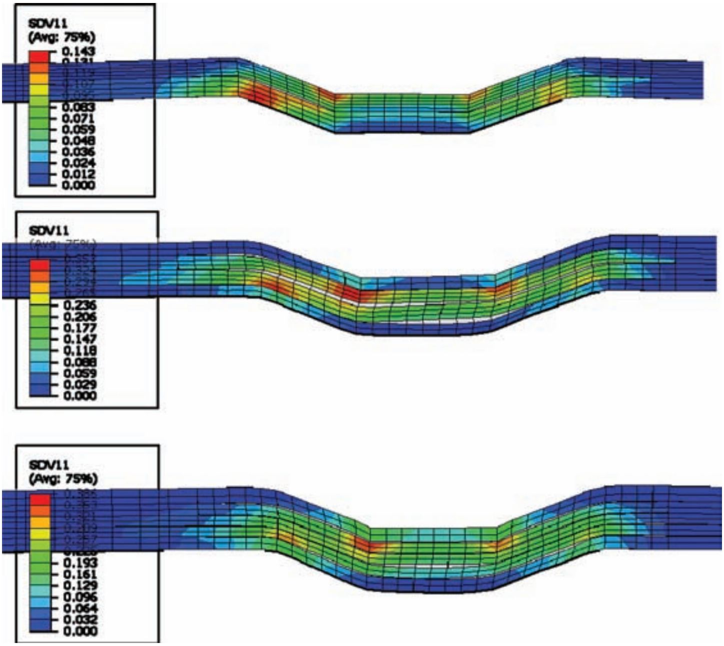


Figure 33. Plastic strains in ZD, ε^{p}_{ZD}, that have evolved in 3 paperboard models after the creasing operation, (top) t = 0.27 mm, 2-ply model, (middle) t = 0.39 mm, 4-ply model, (bottom) t = 0.46 mm, 5-ply model.

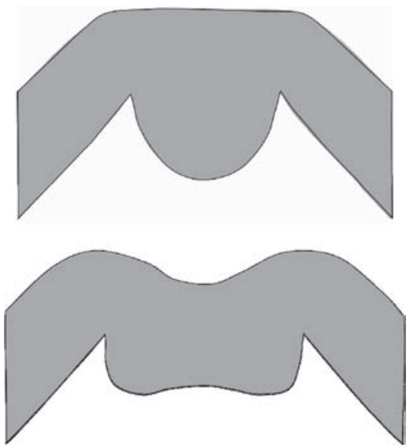


Figure 34. Outline of folded shape from numerical study focusing on role delamination (top: full model, bottom. Bottom: pre-delaminated model [68].

compression properties are uncoupled. It is then not possible to account for the increased yield shear stress in the model during creasing, which was identified as an important mechanism in [63, 64, 39]. This coupling would help the model in Figure 34 to get more square folds that better mimic the experimental observations.

The delamination has the effect of lowering the required bending moment to make the fold. Figure 35 shows numerical results for creasing and folding from Beex and Peerlings [67] for the various changes in inter-layer interactions. The graph on the left gives the creasing force versus creasing depth, and the figure on the right gives the bending moment versus bending angle in a four-point bending test. As the interaction between layers decreases the force required to crease or bend the creased board decreases. For their model, much of the force during the creasing operation results from friction between layers and the forces needed to delaminate the layers is substantially smaller. The model with no interaction requires much less force to crease. During folding, the delamination is more important, but the final moment required for a large angle is not that different for all four cases.

Huang and Nygårds [69] have presented a similar model as Beex and Peerlings [67, 68]. The model is based on a continuum model with orthotropic elasticity. The inelasticity is introduced with plasticity using a Hill yield criterion with isotropic hardening. Failure is initiated and tracked with cohesive interfaces between layers. The cohesive zone is modeled with three high stiffness, which are initially linear units with uncoupled maximum stress criteria for the normal and two tangential directions. After this maximum point is reached an exponential

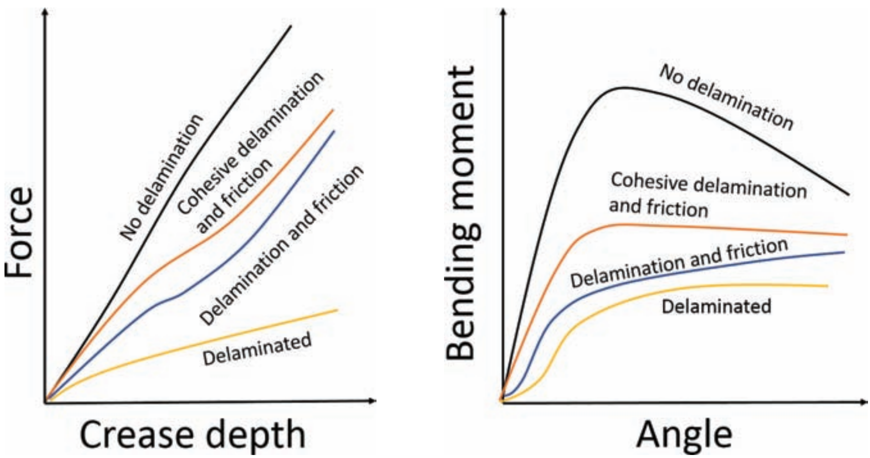


Figure 35. Creasing force and bending moment for models with various levels of inter-layer interaction. Replotted from [67].

decay in stiffness is utilized. The investigated paperboard consisted of three-plies. Interface elements were placed between the plies and at the mid-point of the middle ply. The material properties used in the simulations was determined from uniaxial and shear experiments for the free-laid three plies. Comparison between the force displacements curves from the experiments and the finite elements simulations were compared. Although the model was simplified from the previous user-defined models, the agreement between the experiments and simulations was reasonably good.

The same model was used by Huang and Nygårds [70] to simulate folding by the L&W creasability tester. However, in this analysis it was concluded that there were no distinct differences between the interfaces in the paperboard. Therefore, the material properties were assumed to follow the shear strength profiles [61]. By doing this the creasing behavior was still the same as the behavior in [69], and the folding behavior in MD and CD could be captured, see Figure 36. The initial linear region and the peak load could be captured with good accuracy, after the peak load the simulations and experiments did however deviate. The bending moment decreased more rapidly in the simulations than in the experiments. Notable was that the non-rounded shape of the folded corner could be captured.

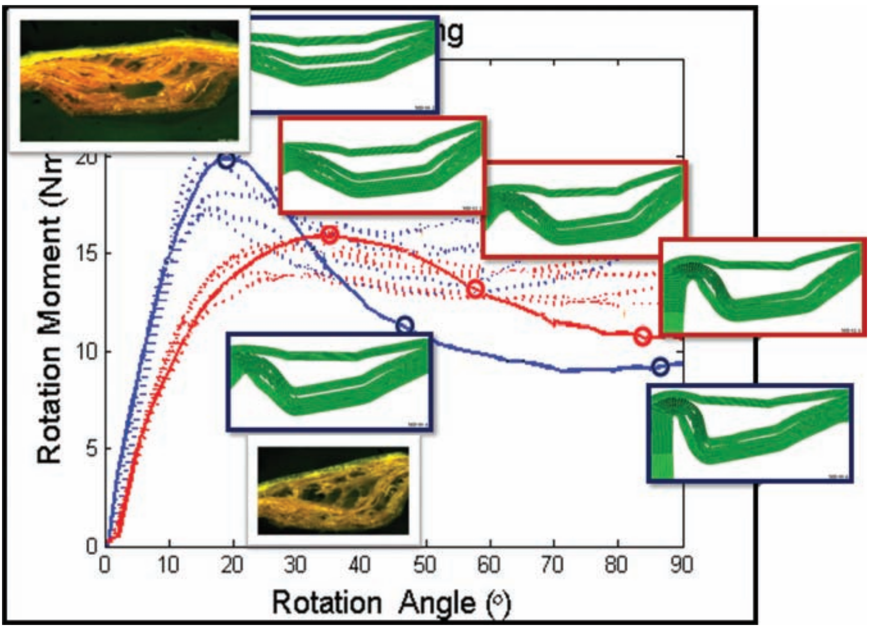


Figure 36. Comparison of experimental and numerical folding results, data from [69].

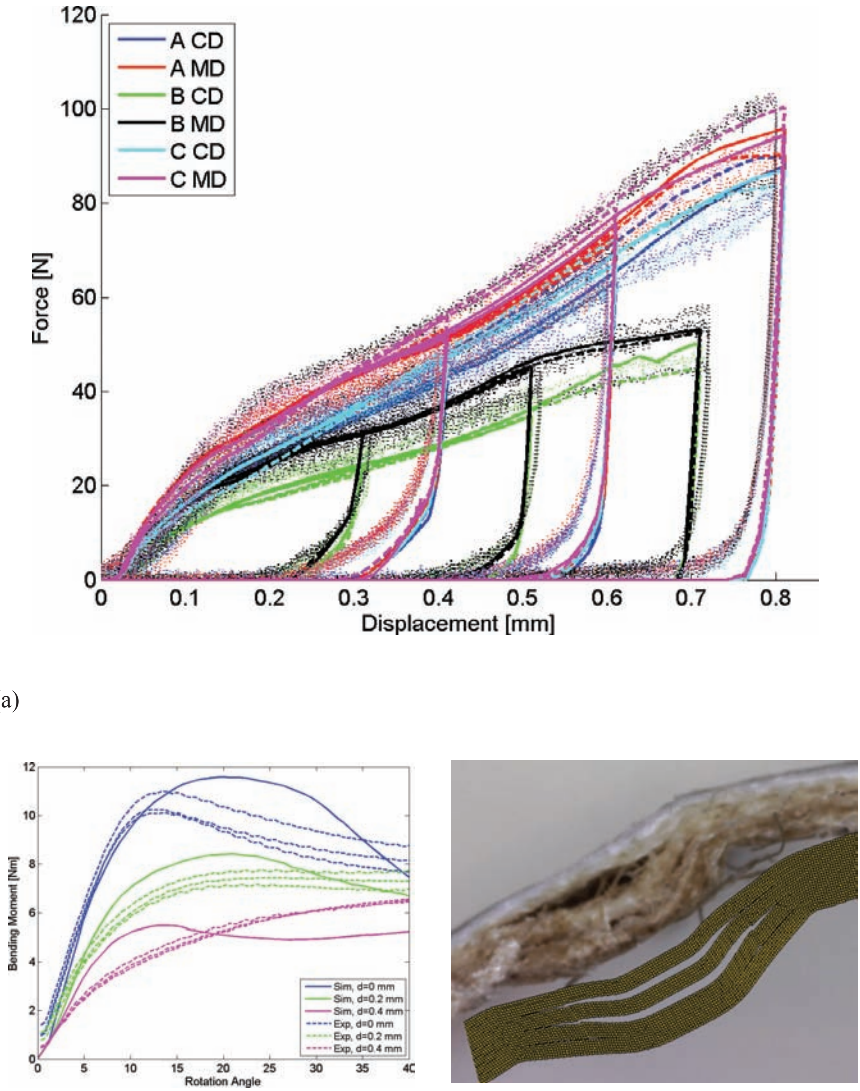
Beex and Peerlings [67] proposed a very similar model, but it was less satisfactory probably due to the assumed linear-elastic out of plane response and a different interface model. Beex and Peerlings [67] did allow for more interfaces in their middle-ply as compared to Huang and Nygårds [71]. Choi *et al.* [66] used various different elastic-plastic material models with prescribed failure criteria. The delamination appears to occur within layers due to meeting this criterion, but it is not clear how they specify the interface between plies.

Huang *et al*. [71] present a comparison of the results of an FEA analysis of creasing and folding to the experimental results of three paperboards. Also in this analysis, it was assumed that the property gradient in the through thickness direction could be predicted by the shear strength profiles [61], and were different for the three paperboards. All paperboards did however have an I-beam structure. The predicted creasing load versus crease depth profiles are compared to experimental results and given in Figure 37(a).

Inspection of Figure 37(a), does indeed show that the model gives a reasonable prediction for the crease load as a function of depth for the three paperboards in both MD and CD. But, it can be observed that paperboards creased with the same tools do not differ much from one another; paperboards A and B in Figure 37(a) are not very different from each other. Board C is more compliant than boards A and B, but it is difficult to directly assign the cause of this difference. The caliper of board C is about 15% lower than that of A and B. The fact that the responses are not so different for the three boards with distinctly different properties and distribution of properties, questions the usefulness of the FEA results for analysis for crease curves. Instead, comparisons of experimental and numerical crease curves would rather be a verification that correct material properties have been measured and used. Ideally the creasing contours should be compared with micrographs to assure that the correct behavior is captured, as suggested by Beex and Peerlings [68].

Huang *et al*. [69] also predicted the folding response up to 40 degrees. The results for Board A are given in Figure 37(b). The general trend is good, but the specifics are missing. Note, the numerical result seems to give a stiffer response with a longer peak. The deeper creases cease to have the early peak in the experiments, but the numerical results still show a peak moment. For the MD crease, it appears that the model would under predict the springback moment, but it might be better for CD creases. The comparison for boards B and C is not as good as for board A [71].

Huang *et al*. [71] provide a comparison of the folded crease at a 20-degree angle for the numerical results and the experimental results as shown in Figure 37(c). In this comparison, the delamination behavior is different in the simulation and experiments, which is partly since the interfaces have discrete positions along the interface. The interfaces do open up differently, which probably is the cause



(a)

(b) (c)

Figure 37. Experimental and numerical work from [71]. (a) Creasing result for Paperboard A–C. (b) Folding curves at different crease depths for paperboard A in MD, (c) Comparison of FEM model and experimental bending deformation at 20-degree bend for Paperboard A in MD for board creased to $d = 0.0$ mm.

of the peak differences in Figure 37(c). This shows that it is difficult to exactly capture all mechanisms with a simplified model, especially since the creasing and folding operations are complicated loading cases and histories that activates many deformation mechanism and combined loadings.

To represent paperboard with both a continuum and interface model can be tricky. First many material parameters need to be determined. Second, there is an interplay between the models that is complicated. For example, both models will deform due to out-of-plane shear loading. Huang [72] investigated how the creasing curves were affected if either both models, or only the continuum model was used. In the creasing simulations both approaches give a similar behavior, the addition of an interface model did however contribute to the first deflection point where delamination is initiated, hence the interface model better predicts the experimental curves during creasing. When multiply paperboards are modelled plies are often considered to have discrete boundaries. In real paperboards, there are however more smooth transitions, due to fines and chemistry retention. Because of this a mapping procedure was used in [70,71]. The impact this has on folding of creased paperboards was investigated by Huang [72]. The mapping lowers the bending moment about 10% for creased paperboards, such that it better predicted the experimental data. However, for deep creases, $d = 0.4$ mm there was no difference.

In the development of finite-element models that mimic creases, Perego and Giampieri [73, 74], developed a meso-scale model for folding with the delaminated layers. By this approach, the constitutive models of the crease were considered, and a crease model was created which was fitted against experimental folding data. Hence, a computationally efficient model was created. The advantage with this modeling approach is that it is more efficient for modeling a package. However, the drawback is that no damage evolution in the creased and folded region is accounted for.

A continuum model formulated in a large strain formalism has been proposed by Borgqvist *et al*. [75]. In this model, the key deformation and damage mechanisms in paperboards have been accounted for. In addition, many of the convergence problems seen in previous paper models have been dealt with in the implementation. Using the model delamination can be modelled without using separate interfaces where the location needs to be specified a priori. Simulations of creasing have been performed, and comparison to experimental data was done. The numerical simulations captured the experimental data well, for creasing to crease depths $d = 0.1$ mm, 0.2 mm and 0.3 mm, except for a deviation in the loading phase where delamination has been initiated. It was identified that the parameter controlling the shear properties under compression could be altered to better mimic the experimental curve, this did however also affect the web tension negatively.

Borgqvist *et al*. [76] also performed simulation of folding of the L&W creasability tester, and compared the experimental and simulated results. The initial response was well captured, while the folding behavior after 20 degrees was different in the model, Figure 38. In the simulations, two different out-of-plane shear strength limits were investigated. This change had a major effect of the post peak folding behavior. When the long compression test was used to determine the out-of-plane shear properties the resulting simulated bending curves were lower than the experimental ones. The results were better when the SCT was utilized, see Figure 38. In CD, the experimental and numerical curves had a similar smooth behavior. In MD, the numerical curves were kinky, and hence different from the experimental curves. This would indicate that numerical instabilities occurred in the folding simulations. Additional simulations of folding, with corresponding contour plots of effective strain and rotations in the fold were presented by Borgqvist [40].

In addition to the finite element simulation discussed above, there are some additional work by Simon *et al*. [77], Li *et al*. [78], Dai and Bennella [79], Mullineux *et al*. [80] and Domanesch *et al*. [81]. In the doctoral work by Borgqvist [40] there is additional creasing and folding work that is currently under review [82,83].

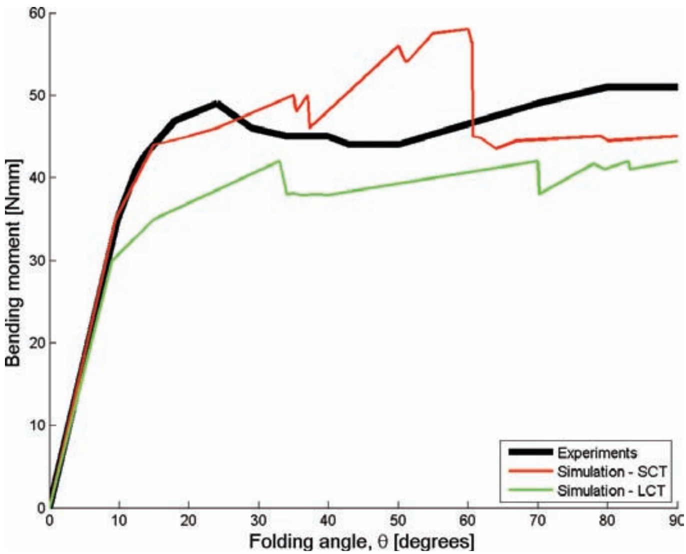


Figure 38. Simulated and experimental folding behavior in MD. In the SCT simulation shear properties have been set by fitting the behavior to capture the SCT test; in the LCT simulation shear properties have been fitted to fit the long compression test. Replotted from [76].

For creasing and folding several complicating deformation and damage mechanisms are activated simultaneously. Therefore, it becomes difficult to rely on experimental investigations only. It is in this respect that modelling and simulation can contribute positively. It is debatable whether the developed FEA analyses are sufficiently accurate to provide valuable insights from parametric evaluations. Very little has been done in this regard. It seems that some of the subtleties of the bending behavior are not adequately captured by the models, and can be misinterpreted. However, FEA has provided a good tool to better understand the creasing and folding operations. The integration of modelling and simulation in the product development of paperboard is however not straight forward. In general, it can be stated that modelling and simulation can be used to

- Learn more about deformation and damage mechanics and optimize material design
- Complement experimental investigations

Having established a model that works and is verified it becomes possible to use modelling and simulation as an integrated part of product development. The great advantage with modelling and simulation is that the effect of different parameters can easily be tested, and detailed local information is available.

A BEAM MODEL FOR FOLDING CREASED PAPERBOARD

Given that the FEA models have not been used for parametric studies and may require further development before they are available, simplified models may provide value. A beam model that captures some of the essential behavior of folding of creased and uncreased paperboards is proposed. It uses Timoshenko beam theory and suggests a damage model to account for the effect of creasing. A suggestion of how the necessary material data can be determined is also presented.

The stress state when paperboards are folded by a 2-point bending method can be assumed to be equal to the stress state in a cantilever beam. The stress state consisting of a normal stress component σ_x and a shear stress component t_{xz} were given in Eqs (13) and (14).

Failure criterion

During folding, failure can occur when either the in-plane stress, $\sigma_x = \sigma_0(z)$, or the shear stress, τ_{xz} is equal to $t_0(\zeta)$, at an arbitrary point ζ in ZD. Accordingly for uncreased paperboards

$$\frac{\sigma_x}{\sigma_0(\zeta)} = \frac{12M_b}{wh^3}\zeta = 1 \tag{20}$$

$$\frac{\tau_{xz}}{\tau_0(\zeta)} = \frac{3M_b}{t}\left(1 - 4\frac{\zeta^2}{h^2}\right) = 1 \tag{21}$$

To set up the failure criterion the property gradients need to be determined. The tensile failure gradient $\sigma_0(\zeta)$ can be determined by performing in-plane tensile tests of the top, middle and bottom plies separately, and a ZD-profile, $\sigma_0(\zeta)$, can be interpolated between these values. Most important will be the values in the outer plies.

The shear strength profile, $\sigma_0(\zeta)$, can be determined from shear strength profiles [61], where the most important values are in the middle ply. Hence, limitations in measuring shear strengths in the outer plies is of minor importance.

Folding of uncreased paperboard

To illustrate the concept of property gradients, we assume that we have two paperboards with thickness h = 0.400 mm, and two different property gradients. Paperboard 1 has a uniform tensile and shear property gradient with

$$\sigma_0^{Paperboard1}(\zeta) = 50\,MPa \tag{22}$$

$$\tau_0^{Paperboard1}(\zeta) = 1\,MPa \tag{23}$$

Paperboard 2, has a property gradient described by cosine function, such that the middle ply has lower tensile and shear strengths, according

$$\sigma_0^{Paperboard2}(\zeta) = 50cos\left(\frac{2\zeta}{h}\right) + 92.07\,MPa, \tag{24}$$

$$\tau_0^{Paperboard2}(\zeta) = -\,cos\left(\frac{2\zeta}{h}\right) + 1.84\,MPa \tag{25}$$

The failure property gradients have been plotted in Figure 39, where it should be noted that Paperboards 1 and 2 have the same average strength.

The normalized stress states in Paperboard 1 are based on Eqs (20) and (21) and are plotted in Figure 40. It shows that the tensile and compressive stress is

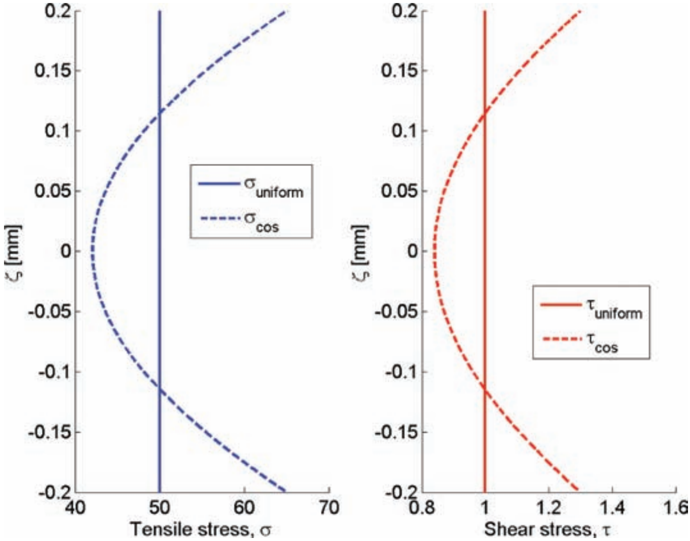


Figure 39. Assumed property gradients for the tensile and shear failure stress in Paperboards 1 and 2.

highest at the outer surfaces where $|\zeta| = 0.2$, and that the shear stress is greatest in the middle of the paperboard, where $\zeta = 0$. Hence, in this case failure should be initiated by the tensile stress when $\sigma_x = \sigma_0$, accordingly when

$$0.75\frac{12M_b}{wh^3}\frac{t}{2} = 1 \rightarrow M_b^{Paperbord1} = 3.6w \tag{26}$$

where w was the paperboard width. For Paperboard 2, we assumed that the failure stresses instead had property gradients. Then the resulting stress state in Figure 40 arise. In this case, the peak values of the two stress components are closer, but the tensile component are still larger, and failure would be initiated when

$$0.58\frac{12M_b}{wh^3}\frac{t}{2} = 1 \rightarrow M_b^{Paperbord2} = 4.6w. \tag{27}$$

Hence at a higher bending moment than Paperboard 1.

An alternative in paperboard making is to bulk up the middle ply too much, as illustrated by Paperboard 3 in Figure 41. In this way, the shear strength in the

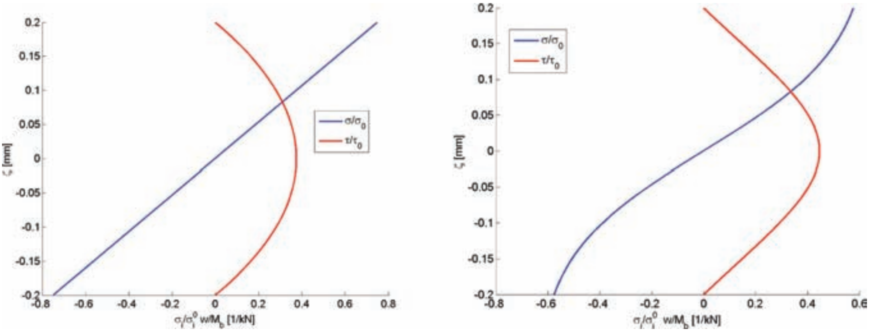


Figure 40. Normalized stress state in the assumed Paperboards 1 and 2 due to bending.

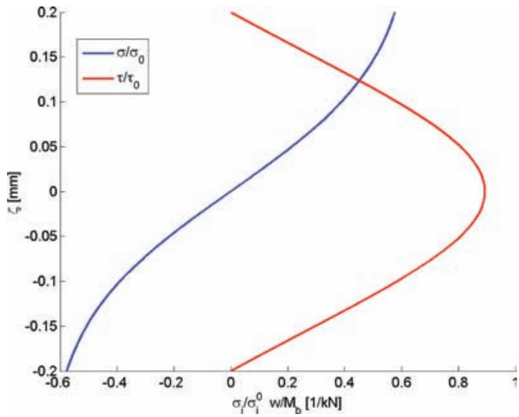


Figure 41. Normalized stress components in Paperboard 3.

middle ply can be lowered; Paperboard 3 has half the shear strength compared to Paperboard 2, hence

$$\sigma_0^{Paperboard3}(\zeta) = 50cos\left(\frac{2\zeta}{h}\right) + 92.07, \tag{28}$$

$$\tau_0^{Paperboard3}(\zeta) = -0.5\,(cos\left(\frac{2\zeta}{h}\right) + 1.84). \tag{29}$$

The normalized shear component will in this case be larger than the tensile component. Failure will then be activated due to shearing when

$$0.86^{\frac{3M_b}{2whL}} = 1 \rightarrow M_b^{Paperbord3} = 3.10w \quad (30)$$

The maximum bending moment will then become lower than for Paperboards 1 and 2, which also can affect the bending stiffness, which was illustrated for commercial paperboards in Figure 23.

Folding of creased paperboard

The tensile and shear properties in paperboard depend on the *z*-coordinate, and will also degrade due to creasing to different penetration depths, ζ. Hence, both the in-plane failure stress, σ_0, and the shear failure stress, τ_0, will depend on ζ and z, accordingly. It addition, we can assume that the in-plane stress will decrease by a damage parameter, $D^{tensile}$,

$$\sigma_0 = \sigma_0(z,\zeta) = \sigma_0(\zeta)\,(1 - D^{tensile}) \quad (31)$$

and the shear stress will be reduced by a damage parameter $D^{shear}(z)$

$$\tau_0 = \tau_0(z,\zeta) = \tau_0(\zeta)\,(1 - D^{shear}(z)) \quad (32)$$

When a properly creased paperboard specimen is tested by a tensile test it rarely fails in the crease [49]. Hence, for paperboard folding it is fair to assume that

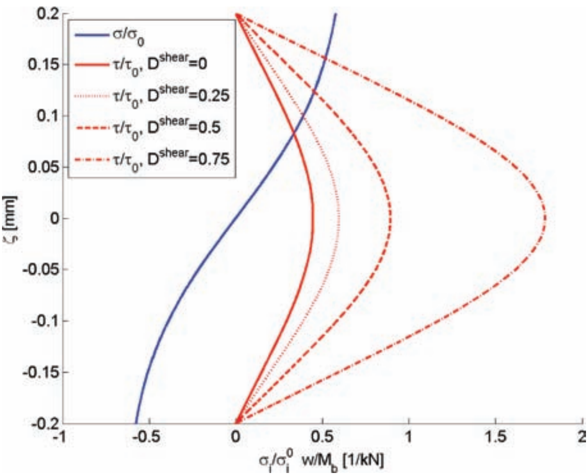


Figure 42. Stress state in Paperboard 2 when the material has been damaged due to creasing.

$$D^{tensile}(z) = 0 \tag{33}$$

Let us now assume that we have creased Paperboard 2, such that D^{shear} (z) = 0.25, 0.5 and 0.75. As damage evolves in the material, the shear component will grow, while the tensile component is constant, see Figure 42. Hence, when D^{shear} = 0, the failure will be activated by the tensile component.

When D^{shear} = 0.25, 0.5 and 0.75 the shear component will be larger than the tensile component, and hence shear will activate the failure. From the graph, we can read that shear induced failure will be activated when

$$[0.60.891.79] = \frac{3M_b}{2whL} = 1 \rightarrow M_b^{creased} = [4.43.01.5]w \tag{34}$$

Hence, the maximum bending moment decreases with increased damage.

Accounting of damage by a creasing model

It has been shown that the creasing operation is dominated by shear deformation. To account for shear damage that occurs during creasing the maximal crease damage needs to be determined. We propose that the shear damage according to Eq. (6) be calculated and a crease test performed to find the maximum penetration $z^{\max}$, which will be used to calculate the maximum crease damage $\gamma^{\max}$. It is assumed that the D^{shear} increases linearly with z, the damage parameter can be calculated as

$$D^{shear}(z) = \frac{\gamma(z)}{\gamma^{max}} = \frac{2}{\gamma^{max}} \frac{z}{c-b} \tag{35}$$

The maximum shearing $\gamma^{\max}$ which is a material property will be the failure strain during creasing. It must be remembered that this deviated from the out-of-plane failure strain, since the paperboards are also compressed during creasing. It will instead be the failure strain that can be calculated from a creasing operation to a maximum penetration $z^{\max}$, where failure occurs. Creasing to the failure strain could be obtained with arbitrary creasing geometries *c-b*. A more general shear measure could be obtained from Eq. (11). The shear damage parameter is determined from only one creasing experiment up to failure and by knowledge about the tooling geometries.

An alternative is to account for shear damage using a folding model. Damage introduced by the creasing operation will contribute to decrease the bending moment during folding, which is used to estimate the shear damage parameter

$D^{shear}(z)$. Creasing to different crease penetrations, z, will reduce the maximum bending moment and the bending stiffness.

As the paperboard has been creased, shear damage has been generated. The amount of damage affects the folding behavior, and will hence reduce both the maximum bending moment, and the bending stiffness. Nygårds [49] has previously showed that the bending stiffness and maximum bending moment decreases in a similar manner with increased crease depth. We do know that the creasing operation is shear dominated from previous discussions. Hence, a damage parameter can be defined

$$D^{shear}(z) = \frac{M_b^{creased}(z)}{M_b^{uncreased}} \tag{36}$$

where $D = 0$ means no damage, and $D = 1$ total failure, and M_b is the maximum bending moment. In this case, the shear damage parameter is determined from folding experiments to different crease depths, as seen in Figure 24.

A MECHANCIAL MODEL FOR FOLDING

Simple models can help illustrate important mechanisms and may lead to insights into the phenomenon and provide equations that could be used to guide engineering and design. In the last section, we focused on a continuum model where stress limits and damage were used to interpret creasing and folding. A simple mechanical model for folding a creased material is shown in Figure 43. This model focuses on the interaction of delaminated plies through buckling. It consists of two rigid bars that contain a bend such that they have height, t, and are connected with a spring on the top (spring stiffness k_1, and original length L-2t) and a linkage with a rotational spring (torsional stiffness, k_2) on the bottom. The rigid bars are pinned to rollers spaced a distance L apart, but are free to move horizontally. The applied load, P, creates a moment that will rotate the bar. The system could accommodate the bending with no movement of the bottom linkage, but at some load, buckling of the linkage could occur.

For this model, the tensile force in the spring and the horizontal force in the linkage form a force-couple which equals the moment caused by P. The rotation of the rigid bars, θ, and the rotation of the linkage, ϕ, describe the deformation of the system. The distance between the pins is given as

$$l = L cos(\phi) \tag{37}$$

and the length of the spring is

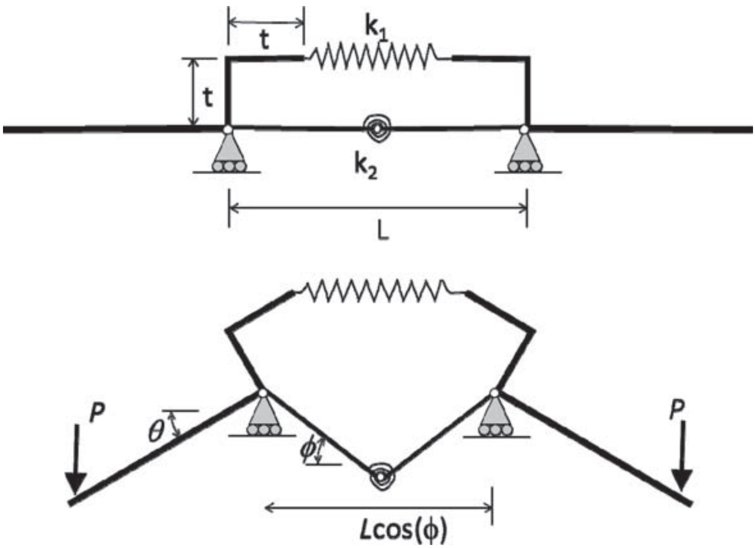


Figure 43. Simple mechanical model for folding of creased board.

$$l_s = Lcos(\phi) + 2t[\sin(\theta) - \cos(\theta)] \quad (38)$$

We allow for some initial rotation of the linkage, ϕ_0, to represent creased geometry. Therefore, the equality of forces implies

$$k_1\left[L(\cos(\phi) - \cos(\phi)_0) + 2t[\sin(\theta) + 1 - \cos(\theta)]\right] = \frac{4k_2}{L}\left[\frac{\phi - \phi_0}{\sin(\phi)}\right], \quad (39)$$

When, $\phi_0 = 0$, the critical buckling angle is given as

$$\left[\sin(\theta_{cr}) + 1 - \cos(\theta_{cr})\right] = \left(\frac{2k_2}{k_1 t^2}\right)\left(\frac{t}{L}\right). \quad (40)$$

The moment can then be written as

$$M = k_1 t\left[L(\cos(\phi) - \cos(\phi_0)) + 2t[\sin(\theta) + 1 - \cos(\theta)]\right][\sin(\theta) + \cos(\theta)] \quad (41)$$

Thus, Eq. (41) provides a relationship between the moment and the angle of rotation, where Eq. (39) can be used to determine the angle f. Figure 44 provides a series of curves based on dimensionless form of Eqs (39–41) for a set of parameters. The dimensionless moment is dependent on four parameters $(\theta, \phi_0, \frac{L}{t}, \frac{k_2}{k_1 t^2})$. In Figure 44, the dashed line represents the case where the buckling of the linkage is not allowed. Thus, the spacing between the pins remains fixed. The solid lines represent the post-buckling curves, where the parameters are varied from as one might expect from creasing (an increase in ϕ_0 and L, and a decrease in k_2.). These curves are similar to those shown in Figure 24, and illustrate the role buckling of the inner plies plays in folding. The higher the buckling stiffness, the larger the stretch that occurs in the spring. Buckling allows the pivot points to move closer together and relieves the tension in the spring. The initial crease angle, f_0, acts as an imperfection so the linkage folds for all levels of P.

In addition, nonlinear material behavior can be easily added by adjusting the constitutive relations for the springs. One might consider that k_1 to be inversely proportional to L to account for the strain rather than displacement. Likewise, k_2 could be taken as a function of L, and L could increase as a function of q to account for beam buckling and extended delamination. These changes would provide secondary changes to the shape of the curves and could create an imperfection sensitive structure. The model as presented captures the essential elements of folding for a creased board.

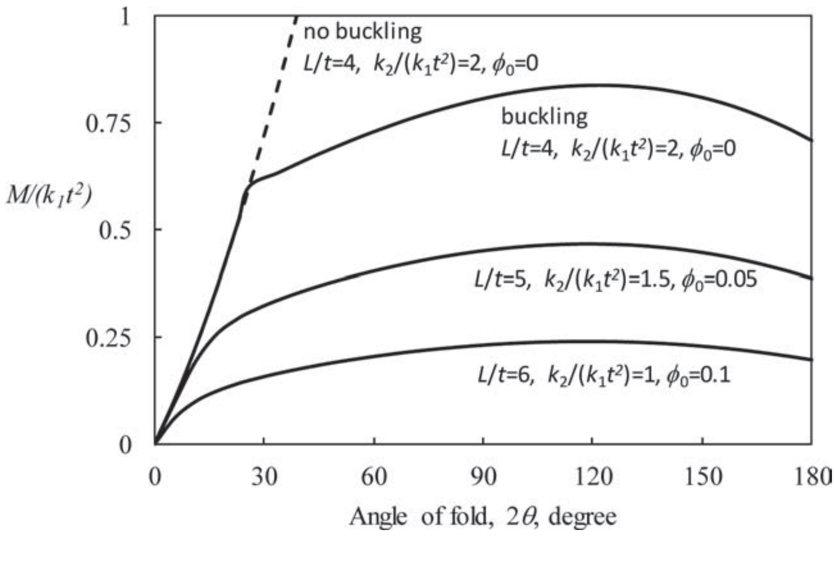


Figure 44. Folding moment versus angle of fold for model illustrated in Figure 43 illustrating effect of creasing for liner-springs and with no initial crease angle.

The simple model above can be considered as an integrated representation of the sheet during folding. It takes advantage of the observations that very little deformation occurs outside the crease zone. It incorporates the buckling of the inner plies and includes stretch of the outer ply. As it does not include plasticity it is only valid for monotonic increases in folding angle, but it could be used to represent the effects of material properties, and geometry of the crease to provide an engineering tool to understand RSC.

CREASING AND FOLDING OF CORRUGATED BOARD

In corrugated board, many of the same issues associated with the creasing and folding of paperboard exist, but there are some differences that should be pointed out. The fluted medium of corrugated board creates a large void space, that allows for large ZD compression and a fold can be produced without forming a bead. In addition, more of a scoring operation can be done where the male tool has a profile, but the female tooling is flat. The crease depth is approximately the sum of the thicknesses of liners and medium. Figure 45 shows 90- and 180-degree folds for corrugated board in both MD and CD directions. These images show how the bottom (inner) liner and the medium can easily move to accommodate the crease in both MD and CD directions.

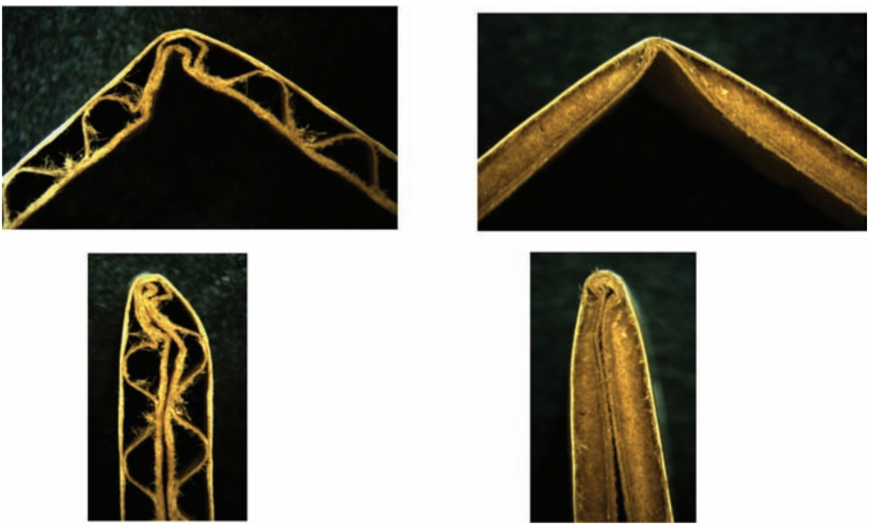


Figure 45. Folds in corrugated board.

Published literature on creasing and folding of corrugated board is sparse. In an early study, Whitsitt and McKee [84] investigated score-line cracking that occurs in the folding of corrugated board. Their study is premised on the observation that cracking of the double face liner on a fold is a common problem where the board is folded and stored in dry conditions. They further state that this is a seasonal problem, occurring in the winter when the humidity is low. This suggests that cracking is associated with damage accrued in the score-line when the board is creased and/or a lack of stretch in the sample when the board is folded. From their studies, they summarized that during folding the single-face (inside of fold) forms an anvil, which the double-face liner (outer side of fold) must bend and stretch around. They concluded that the tensile stretch of the double-face liner was an important property. Whitsitt and McKee [84] developed a foldability tester for linerboard that one could use to measure the angle-of-fold that causes cracking, but found it of limited value especially for low grammage liners. McKee, Whitsitt, and Watchuta [85] followed up this study and found that the percent of score-cracking was correlated to transverse shear modulus, stretch, tensile strength, and tensile modulus.

The influence of flap scores and folds on box compression have been studied [86–88] and in general show that the score-lines should be uniform, straight, crack-free, and offer minimal fold resistance. It was found that extra MD-crease lines in the panel reduced BCT by 30% [88]. Additional experimental creasing and folding experiments have been conducted [89–92], as well as analysis of corrugated creasing and folding [94–96].

SUMMARY

The creasing operation is dominated by shear deformation, and a measure of strain is advantageous for characterization and analysis. The shear is affected by both crease depth and tooling geometry, but recent work has focused primarily on just crease depth. Use of a nominal shear strain has the benefit of accounting for crease tool geometry in a systematic manner. Paperboards can be scored similarly by different tools widths and geometries to yield the same nominal shear strain. In this work, three approaches to calculate shear as a measure of creasing damage were presented in Eqs (6, 7, and 11). These relationships rely on different approximations and assumed complexity in the creasing operation. Although the value of such measures has been borne out in the literature, it remains to be shown, which measure of strain will suffice to adequately describe laboratory and industrial creasing, and how well this translates to industrial practice.

Although out-of-plane shearing dominates the creasing operation, crease quality is also impacted by the restraint offered by the continuity of the sample, imposed tooling constraints, and sample layout. If samples are free to move, the paper is more likely to be drawn into the female die, but if the sample is restrained the paper will undergo in-plane elongation. In the latter case, tensile stress will build up in the sample, which can contribute to in-plane failure in the crease. When crease performance is evaluated an effective crease length should be introduced, which includes the effects of shear deformation and potential draw or elongation. This would allow for improved characterization of creasing and folding. In practice, paperboards being creased are subject to a combination of free and constrained boundaries. In rotary die creasing, there is a web-tension in MD, while the paper is free in CD. Multiple crease lines will however contribute to constraining the paperboards. In flatbed creasing both ends are without web-tension, but instead the ends are held by cutting knives. The length of the crease can be inferred from the half-draw lengths given by either Eqs (2) or (12). Thus, this provides another measure in addition to the shear strain to characterize the severity of a crease. It remains to determine methods to evaluate how much of this crease length is accommodated by a draw and how much by an extension for the various tooling configurations.

In the literature, very little experimental data on creasing and folding has been presented, especially on different paperboard grades. Often studies have been conducted on one paperboard to show and verify a hypothesis, but the broad applicability of these ideas remains to be shown. As an example, many experimental series have been limited to board with a grammage of about 300 g/m^2, while paperboards in the grammage range 150–350 g/m^2 were identified in Figure 23, yet all the literature shows that thickness is of prime importance for creasing severity. Therefore, future research should expand to include a larger range of grammage. In addition, well-planned laboratory evaluations using e.g. different fiber sources and pulp mixes are completely missing in the literature. Research of this type would contribute to the understanding of creasing and folding, especially in elucidating the competing roles of shear induced damage and in-plane cracking, which can be controlled by engineering the paper. There is also a need to continue work on defining an operating window tying material properties to the creasing and folding operations. Further work in this area, would help improve correlating paperboard properties to performance, and thus is an opportunity to conduct parametric studies on the creasing and folding.

Much work has focused on developing FEA models for creasing and folding. This approach allows one to account for multiple influences of material and process conditions. On the other hand, as is the case of experiments, true understanding of the relationships is difficult to extract from the solutions. As FEA creasing and folding models continue to improve, numerical parametric studies can be conducted and the programs can be incorporated into product development. However, simple models can efficiently identify deformation and damage mechanisms important for creasing and folding from which understanding can be extracted. In addition, the transfer of knowledge to paperboard producers and converters maybe faster. We provided two examples of simplified analytic tools (beam analysis, folding-mechanism), that illustrate the value of these models.

The creasing operation is a necessity to achieve good folding. Quite much attention has been put into understanding the creasing operations, while less effort has been put into understanding the folding operation of creased paperboard. Evaluation of the folding operation is almost exclusively done using a 2-point bending method. This method is problematic, since it will bend both the paperboards and the crease. Often the uncreased paperboard can be folded initially, and the crease open up later. An improved method that can test the creased area better would be desired. This would enable us to understand the creased region better. A different folding test, may affect the moment-angle curves currently being used to evaluate crease effectiveness in manner that makes it more applicable.

Creasing generates delamination cracks in the paperboards. The location and the ease to propagate these cracks depends on the ZD gradient of the properties of the paperboard. This is where the multi-ply nature of paper becomes important. If fibers bridge these delamination cracks, they will resist opening during folding and hence the paper requires a larger moment to fold. Delamination that occurs at well-defined interfaces would offer less resistance to folding, yet not damage the individual layers. Thus, to answer the question “are many layers (think low ZD tensile stiffness) better than a few layers for creasing?” is not so simple and the answer depends on many factors.

Due to the heterogeneous fiber structure in paperboards the variability within a paperboard can be large. Yet, the literature is limited in data that analyzes many samples or studies variability. Reduced material variability is probably a key feature for improved creasing and folding performance.

From our perspective, creasing and folding offers many challenges from both fundamental and practical issues. The literature reveals that the basic understanding of the problem is simple: create a zone that can act as a hinge, yet retain enough strength, stiffness and uniformity, to ensure product quality. The complexity comes in because of the combination of large deformations, extreme material anisotropy ratios, and structural failure. Thus, the creasing and folding operations are ideal for student study as illustrated by the MSc theses devoted to this area [97–111]. Creasing and folding has given the industry an opportunity to expose challenging problems to students that otherwise would be unaware of the pulp and paper industry. If the industry continues to engage students to work in this area, significant gains will be made. We hope that our review will provide a beginning point for future research.

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Transcription of Discussion

CREASING AND FOLDING

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Jonathan Phipps FiberLean Technology

Whenever I have worked with multi-layer board producers they have often been concerned with ply bond between the layers, with the implication that the higher the bond strength the better. What you have explained is that in order to achieve good folding properties, it is necessary for the plies to debond. So is it possible to have too much ply bonding, or does the creasing process always overcome it?

Douglas Coffin

Well, Yes. If you are going to fold a paper, just to a 180-degree fold, you can always force it to fold. So the material is going to go where it wants to. It's just you want it to be controlled. You want to preserve and make it look nice. So if you have a really high ply bond strength, you are going to move the delamination from between the plies to somewhere in the plies. If that's what you want that could be good, but I would say if I was engineering a structure, I would rather get the delamination where I know it is going to occur which is going to be between the plies.

James DeWitt Sappi N.A. Basepaper Technology

When you talk about paper board and trying to look at creasing in the lab versus going out to commercial converters to see it, how important is the rate that the creases are put into the paper board in terms of their quantity?

Douglas Coffin

It certainly has an effect. You will have viscoelastic effects and if you do it really fast, you might get more cracking because you are not giving time for relaxation, but I think for the overall phenomena it is not so important to put a lot of effort in creating devices that can repeat high speed. I don't think you are going to see phenomenally different results than at slow speed. Subtle results, yes, and the strain level where you shift from no cracking to cracking could change with speed. But if you want to study the general phenomena, I don't think you need high speed. Perhaps if you are working for a company you want high speed because for your paper board you need to mimic converting operations.

Tetsu Uesaka Mid Sweden University

How important is the tensile stretch of paper in folded cracking? That is a very typical question.

Douglas Coffin

It could be totally unimportant. If you do really good creases, you can fold it and put no strain in the sample, but if you don't crease it well, then the tensile strength becomes very important because now you can't fold it without building a moment up and then it is going to crack.

Tetsu Uesaka

What I meant was that, suppose we have such a cracking problem and with all other conditions the same, people often try to look at correlations between stretch and this cracking issue, but the data often showed almost no correlation between them.

Douglas Coffin

That's true. I mean it doesn't have to correlate at all, but the contact, the physics have to be satisfied. If it's not ideal, you are going to build tension in the top layer and compress the bottom. It may have nothing to do with the effective tensile strain in a sample, but may be due to the effective strain on the top ply. So we may have to delve more into it to try to explain it, but I don't think it implies there is a totally different mechanism at play.

Torbjörn Wahlström Stora Enso

Considering the very long development and study of this subject, especially during the past 20 years, while a lot efforts has been put into numerical simulations, I am not sure why we, as a community, have not done more parametric studies of paper board trying to find mechanics relating to the paper properties.

What is your guess? I think this is what we should do next, so we can start to control this on the board machines.

Douglas Coffin

So here is my guess. A lot of that work is done by students and they spend all the time developing the model, getting into work, doing experiments, and they get a match and they are happy and they graduate. With them goes the code, with them goes that model and nobody else works on it. So, I am sure that there are companies out there that have developed models and they are using them, but they are not publishing. So it's about longevity, you need someone who works a long enough time to have the time to do a lot of parametric studies. I think that's probably the bigger issue.

In addition the models are not perfect yet. We are not sure if they are describing everything exactly and it is easy to lump what you observe globally with some attribute that you model differently and it may not be the right thing. You can match results. In order to make it generally applicable, we need to get the right mechanisms for the whole model and I am not sure whether they are yet there.

Torbjörn Wahlström

Perfection is the enemy of the good.