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Analysis of Mechanical Response during Folding of Creased and Uncreased Paperboard

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***Abstract*—** *Creasing and folding of paperboard are two essential operations to obtain a well-defined shape and strength of a package. Relative Crease Strength, RCS, is specified for process control of creasing and folding and is defined as the ratio between the maximal bending force for a crease and uncreased sample bend to the bending angle of 30 degrees at a rate of 5 degrees/sec. Thus, the present work had as objective to evaluate RCS measured in real industrial samples used for process control of creasing and evaluate the influence of paperboard properties and converting processes creasing and folding. As RCS can be measured only after creasing, the study can give directions to paperboard production process control. Creasing measurements were done on both machine direction (MD) and cross machine direction (CD) samples. The paperboard property that showed the highest correlation to RCS was Scott Bond. Based on this one pilot production with lower Scott Bond was evaluated. Lower values of RCS were obtained, as predicted. X-Ray microtomography revealed higher stratification between fiber layers in the paperboard with lower Scott Bond.*

Keywords*— *Bending moment, creasing, folding, paperboard, relative crease strength.

I. INTRODUCTION

Paperboard is a widely used material for packaging purposes, since it can be easily converted from a flat configuration into a box shaped solid [1, 10]. The final package performance depends on the folding quality which has to produce well defined edges and corners, without damaging the packaging's external surface and providing the formation of a pack of desired shape and functionality [9, 10].

Paperboard creasing is intended to facilitate folding along well-defined lines during the paperboard transformation process from a flat surface into a rigid packaging. The creasing causes a combination of bending and interlaminar shear which reduces its bending stiffness and promotes the folding around the design lines. After creasing, the paperboard presents a residual indent where the material is delaminated. The delamination extent depends on the creasing severity and on the creasing tool geometry [7, 10].

The quality of creasing of liquid packaging board is controlled by measuring Relative Crease Strength or RCS, which is defined as the ratio between the maximum bending force at or before 30 degrees registered during a standard folding test performed over the creased material, and the maximum bending force which is needed to fold the uncreased material [23]. RCS specifications in the longitudinal direction (MD - Machine Direction) and transverse (CD - Cross Direction) have been defined to ensure uniformity in the creasing process. It is desirable with a RCS-value as low as possible [2, 15, 20].

The problem is that the RCS analysis can only be performed after the creasing of the paperboard, avoiding a direct action during the paperboard production.

This paper attempts to correlate what and how the physical properties and material characteristics that are evaluated during production influence the creasing process and the RCS values, and further rank them according to their influence. In the present work, creasing of liquid packaging paperboard is considered.

To answer these questions a number of investigations were carried out, as bending moment of creased and uncreased paperboard, comparative of bending moment measurements according TAPPI T 556 and RCS method, determination of the maximum bending moment angle, RCS performance evaluation at different crease depths, investigation of physical properties of the paperboard and its influence on the RCS and finally a performance review of the variables in order to select the main feature for a focused industrial testing, with selected samples of best and worst performers for X-ray microtomography analysis.

The packaging paperboard is a layered material. The objective of the creasing process is to produce a permanent delamination damage, promoted by interlaminar shear, in addition to in-plane and

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compressive out-of-plane plastic deformation of the plies, whose extent depends on the crease depth [3, 13].

The object of study is the paperboard produced in Paper Machine A (PM-A), that is equipped with two headboxes: the main headbox and secondary box. The main headbox called 'Strataflow' concept receives the flow of bottom and middle layers, going through different chambers in the box and come into contact only to be released by the lip. Secondary inbox is responsible for the white top layer, with his jet received by the dewatering of Bel Liner [7, 8]

The introduction of the paper machine B (PM-B) belonging to the same mill, enabled comparative performance in crease with the PM-A paperboard. The PM-B is equipped with three headboxes. The bottom, middle and top layers are formed individually.

The article is organized as follows; in Section II the main parameters that impact the creasing and folding process are presented. Sections III, IV and V are focused in the method and particularities of RCS analysis. The RCS performance evaluation and the paperboard properties related to RCS behavior are discussed in sections VI and VII. Conclusions and final considerations are presented in section IX and X respectively.

II. PARAMETERS THAT IMPACTS CREASING AND FOLDING

Each ply of the paperboards considered in this study consists of a network of different fibers. The outer plies are stiffer, while the inner plies are softer, with CTMP.

The strategy of forming the plies produces an orientation of the fibers in the machine direction (MD), which thereby is the stiffest direction [5, 9, 10]. The individual plies are glued together, there are interfaces between plies. A combination of low density in the middle ply and high density in the external plies optimizes the bending stiffness. The stiffness and strength of the middle layer are provided by weak bonds mainly due to fiber entanglement. The adhesion between plies is improved using starch. [11, 19]

The paperboard is a non-linear anisotropic material and the crease behavior reflects the crease line orientation with respect to the fiber orientation, especially in shallow creases. The fiber orientation and the longitudinal properties of the fibers are important factors contributing to the in-plane behavior of paper, while the out-of-plane behavior of paper instead is largely dependent on the fiber bending properties. [10, 12, 16]

A creasing sequence is illustrated in Fig. 2.1. The paperboard is pushed by a male die with a rule into a groove of the female die. The geometry of the rule and groove (width, depth, relative clearance, geometry of the indenter) affects the final behavior of the creased material [17, 18].

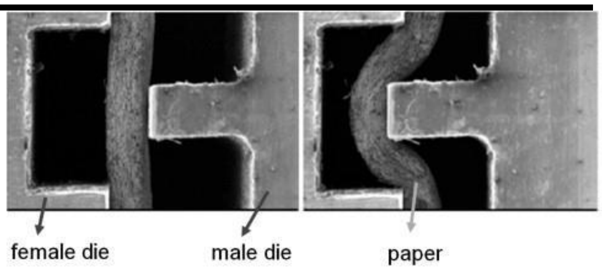

Fig. 2.1 Creasing sequence

When the die is removed, the paperboard presents a residual indent which represents an initial planarity defect for the subsequent folding process. The bending stiffness is decreased in the crease compared to the rest of the paperboard [21, 22]. During folding, the delaminated layers on the compressed side are subjected to compressive forces and undergo large deflections, under combined bending and compression. Delamination occurs not only between the midlayer and the outer layers, but also within the middle layer itself [4, 6, 10].

The bending and axial behavior of the delaminated layer is a consequence of many factors which can influence the creasing operation: the width of the groove and the penetration depth affect not only the length and thickness of the delaminated layers, but also their initial deviation from planarity due to the plastic indent. Thicker boards need a wider die and groove [6, 10, 11].

III. ANALYSIS OF INDIVIDUAL MEASUREMENTS OF THE BENDING MOMENT ON THE PAPERBOARD AND THE CREASE

For a better understanding of data, the individual measurements of the uncreased and creased paperboard were evaluated in the same chart of RCS values. This is the first time that data bending force of the crease and the paperboard are evaluated individually in order to enable the behavior of the data display that generate the final result of RCS.

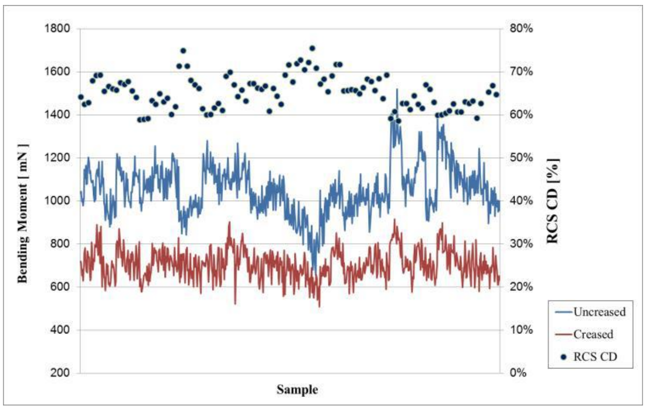

Figure 3.1 – Higher RCS values with reduced bending moment of the uncreased paperboard compared to the bending moment of the creased paperboard.

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In Figure 3.1 the individual measurements of uncreased and creased paperboard were inserted in the same chart, with the RCS values. It is observed that the two times when the RCS was higher there was a significant reduction of the bending moment on the paperboard (uncreased area). The bending moment of the crease remained at the same level.

It was expected that the larger RCS values were obtained due to the increased bending moment crease, but the observed behavior was the opposite.

The increase in RCS was due to reduced bending moment of the paperboard. The bending moment of the crease remained almost stable.

IV. COMPARATIVE OF BENDING MOMENT MEASUREMENTS ACCORDING TAPPI T 556 AND RCS METHOD

The comparison of the bending moment analysis according to TAPPI method T 556 (15 degrees and 50 mm) and the method for measuring RCS (30 degrees and 10 mm) conducted in a cross-section of a jumbo roll with 24 sectors is presented in the Figure 4.1.

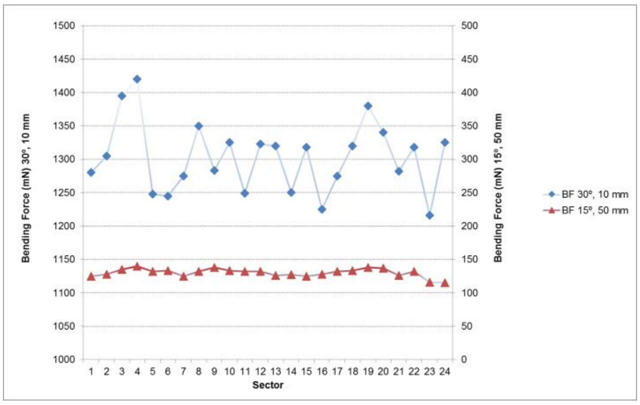


Figure 4.1 – Bending force at 30 degrees, 10 mm on the left side and 15 degrees, 50 mm on the right.

The amplitude of the bending force measurements according TAPPI method T 556 (15 degrees and 50 mm) reached 204 mN while the method for measuring RCS (30 degrees and 10 mm) presented amplitude of 25 mN. The difference was almost ten times greater. This significant difference directly affects the determination of RCS.

V. ASSESSMENT OF THE MAXIMUM BENDING MOMENT ANGLE

A conclusion section must be included and should indicate clearly the advantages, limitations, and possible applications of the paper. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

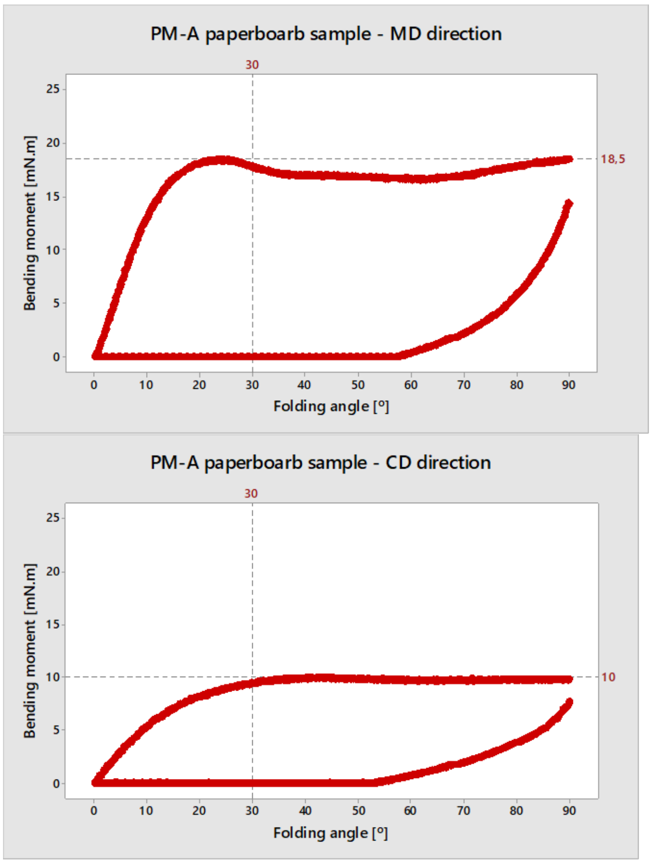
In order to assess the maximum bending moment angle of the paperboard study, the same equipment for measuring the bending moment till 30 degrees according to the method for RCS calculation was used, programming it for measurements up to 90 degrees.

The moment is recorded during folding process and the data transferred to a spreadsheet for specific software of the equipment.

Paperboard samples from PM-A and PM-B were analyzed.

In Figure 5.1 (a) the maximum bending moment in MD direction occurred at 23.5 degrees, before 30 degrees and therefore the maximum moment obtained up to 90 degrees is the same measured till 30 degrees.

Otherwise in Figure 5.1 (b) the maximum bending moment in CD direction occurred at 45 degrees. Thus the maximum bending moment time achieved is greater that obtained up to 30 degrees.



(a) (b)

Figure 5.1 – Uncreased paperboard bending moment PM-A. (a) MD direction MD. (b) CD direction.

Do not reach the maximum bending moment until 30 degrees implies impact on RCS, as a smaller denominator will lead to higher values in the calculation of RCS. This behavior may explain why the occurrence of RCS above specification have the bending moment on the lower

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paperboard because the maximum moment value has not been reached.

One possible explanation for the difference in the PM-A paperboard is the headbox with 'StrataFlow' concept. The bottom and middle layer are formed in the headbox, which gives unique characteristics to the paperboard produced, such as the inability to delaminate these layers due to the entanglement of the fibers during formation.

VI. RCS PERFORMANCE EVALUATION AT DIFFERENT CREASE DEPTHS

The RCS data were organized into webs to allow the verification of possible variations in the cross direction profile, as shown in Figures 6.1 and 6.2.

The webs 1, 4 and 7 show higher variation due to the greater number of measurements in these webs for quality control. Similar variation is observed in the crease depth analysis.

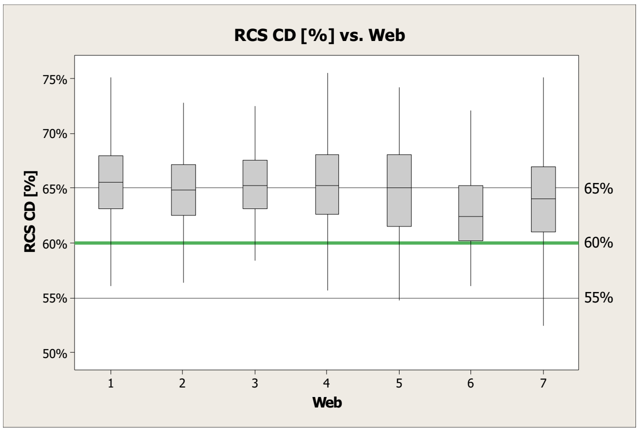

Fig.6.1: RCS CD profile of webs 1 to 7.

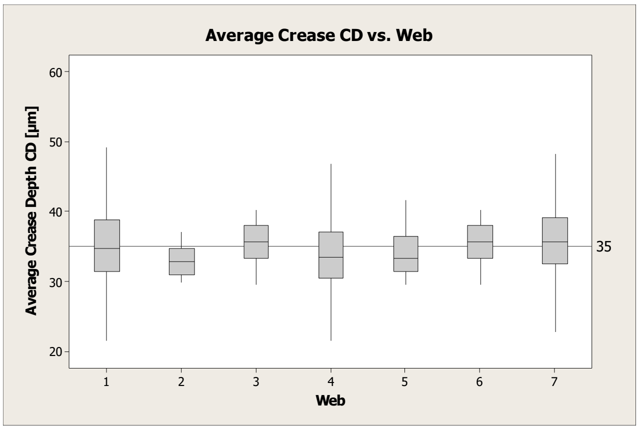

Fig.6.2: Crease depth profile of webs 1 to 7.

VII. INVESTIGATION OF PHYSICAL PROPERTIES OF THE PAPERBOARD AND ITS INFLUENCE ON THE RCS BEHAVIOR

The method of ordinary least squares regression (OLS) was applied in order to investigate the relationship between the RCS and the physical properties of the paperboard.

From the variable strongly correlated with the RCS an industrial test was proposed to validate the model.

In Figure 7.1 there is an indication that lower values of Scott Bond, lower is the RCS. For the range of RCS below 0.60 the median of Scott Bond is 202 J/m² and for RCS above 0.70, the median of Scott Bond is 217 J/m².

In Figure 5.27 the RCS MD presented showed greater reduction than the RCS CD, for lower values of Scott Bond.

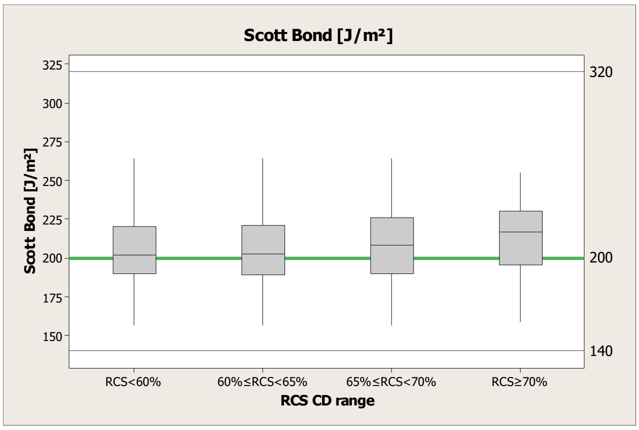

Fig7.1 – Lower Scott Bond values: lower RCS values.

The Scott bond is the most commonly used test method in the paper industry for product control for quantifying the delamination resistance of paper and board [9, 13].

This property depends on the number of fiber bonds, the average area per bond and their specific strength [14].

In the paperboard the interface properties represent the adhesion between the plies. This can be controlled in the manufacturing process by changing the dryness of the different plies before the couching point, the amount of chemicals used to increase or decrease the bonding ability of different plies and pulp properties [12, 14].

[12] observed that the interface strengths had an impact on the bending moment.

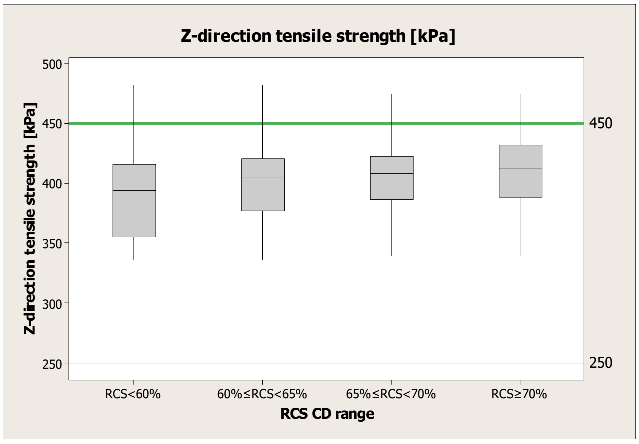

Fig7.2 - Lower values of ZDT: better RCS values range.

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Thicker paperboards generally presents lower RCS [20], but this behavior was not observed in the measurements of this study, because it is small variations in only one grade. Figure 7.3.

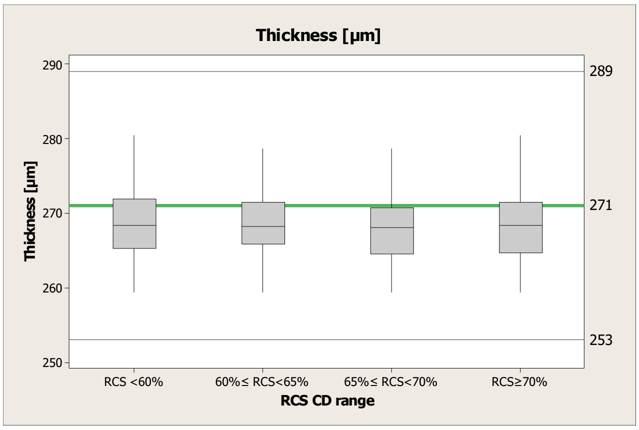

Figure 7.3 - Thickness did not presented correlation with RCS

The impact is evident when comparing products of different thicknesses. A thicker paperboard, presenting the same structure and composition, is easier creased. [24] Short compression test, tensile strength, bending force, grammage and moisture did not presented relevant correlation with RCS in this study.

An industrial test was carried out with paperboard from PM-A with high Scott Bond (271 J/m²) and from PM-B with Scott Bond close to the nominal (211 J/m²). The criterion for selection of these reels was based on the fact that Scott Bond presented the highest correlation with the RCS in the statistical analysis.

VIII. ASSESSMENT OF PM-A AND PM-B SAMPLES USING X-RAY MICROTOMOGRAPHY

Analysis of X-ray microtomography were performed in order to investigate the structure of the creased and folded area for differences that might explain the behavior in relation to the results of RCS.

The use of cutting instruments in paperboard such as scissors, knife or scalpel causes crushing of the inner layers, changing physically the fiber structure and making it impossible to view the area of interest in its original form. Computed X-ray microtomography provides the advantage of dispensing the cut sample, allowing an accurate assessment of the state of delamination of the paperboard at the wrinkle area after folding.

X-ray microtomography analyses were conducted on PM-A and PM-B samples used in the industrial test with the new creasing tool.

Figure 8.1 shows a X-ray microtomography of longitudinal and transverse creases of the paperboard produced in PM-A used in industrial test with the new creasing tool. Is it possible to observe a slight delamination between fiber layers. In the Figure 8.2 the X-ray microtomography of longitudinal and transverse creases of the paperboard produced in PM-B shows greater delamination with stratification of the various fibrous layers.

The most severe delamination facilitates the folding process, since there is a reduced strength in the crease area.

Figure 8.3 shows the X-ray microtomography of PM-A paperboard with lower Scott Bond. In this test the RCS MD showed a significant reduction in the reels with lower Scott Bond, evidenced by greater delamination between layers.

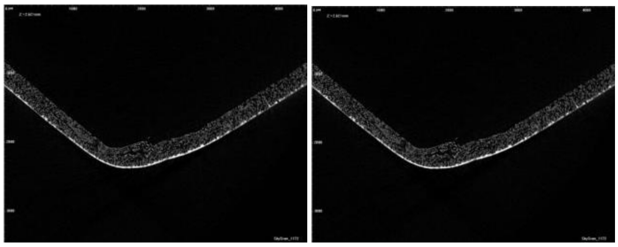

Figure 8.1 - PM-A paperboard - longitudinal crease at left and transverse crease at right.

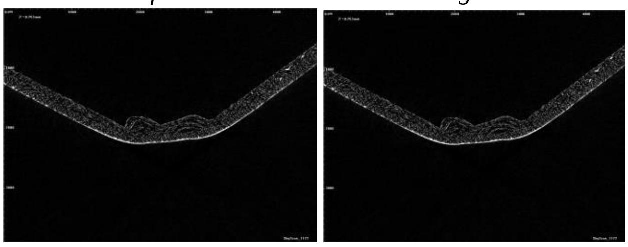

Fig.8.2 - PM-B paperboard - longitudinal crease at left and transverse crease at right

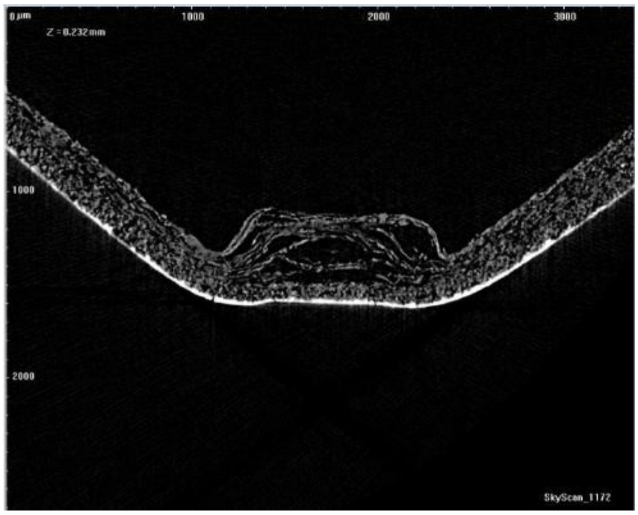

Fig8.3 - PM-A paperboard with lower Scott Bond - longitudinal crease, with significant stratification between the fibrous layers.

IX. CONCLUSION

The individual evaluation of measurements of the bending moment on the crease and uncreased paperboard revealed

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a never before observed behavior. Changes in the bending moment determine the RCS value over the crease that remains more stable.

RCS at 30 degrees analysis method cannot be applied to any paperboard for liquid packaging boards. The formation of the paperboard in the Beloit StrataFlow headbox differs from the formation of paperboard with three separated headboxes, thus it was observed that the bending moment measurements for paperboard produced with in PM-A with StrataFlow headbox showed peak after 30 degrees in cross direction creases. The bending moment measurements performed in the paperboard produced in PM-A with StrataFlow headbox showed peak after 30 and thus the analysis of RCS at 30 degrees is not suitable for this type of paperboard formation.

The bending moment of uncreased paperboard at 30 degrees presents high variability and significantly impacts the RCS results.

Regression tools and Best subsets regression of the commercial software Minitab 16 were used to define which properties have the greatest impact on RCS. The Ply Bond property was relevant in both reviews and the property was selected to carry out two industrial tests: paperboard with high and low Scott Bond.

It has been shown in industrial testing the impact of Scott Bond on crease process and RCS values. High Scott Bond values impair the internal delamination necessary for good creasing at the same time should be controlled so that there is no delamination during the conversion process. Based on the industrial test was proposed change of Scott Bond specification, reducing the nominal from 200 J/m² to 180 J/m² for this product.

The X-ray microtomography of PM-A paperboard with higher RCS values confirms the lower delamination between layers compared to PM-B paperboard, which was not observed in samples with lower values of Scott Bond, whose internal delamination is more intense.

The use of X-ray microtomography allowed an evaluation of the internal area of the crease without destroying the through thickness structure and is an interesting option to be exploited in other works such as investigation of cracks in the paperboard, for example.

X. FINAL CONSIDERATIONS

From the results it is possible to suggest for future work:

- To evaluate the effect of moisture from the paperboard during the crease, considering the impact during transport and conversion;
- RCS measuring comparative conduct held in L & W equipment and bending factor in Marbach equipment;
- Assess the applicability of X-ray microtomography analysis of the cracks observed in samples with RCS above the specification.

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REFERENCES

[1] Allaoui, S.; Aboura, Z.; Benzeggagh, M. (2009). Phenomena governing uni-axial tensile behaviour of paperboard and corrugated cardboard. *Composite Structures*, *87*(1), 80-92.

[2] Alberius, D.; Gerstner F. (2010). *Investigation of creases. How the crease is affected by displaced crease plates.* Mechanical Design Department of Design Sciences, Lund University, 2-6.

[3] Beex, L.; Peerlings, R. (2009). An experimental and computational study of laminated paperboard creasing and folding. *International Journal Solids Structures 46*(24), 1-48.

[4] Beex, L.; Peerlings, R. (2012). On the influence of delamination on laminated paperboard creasing and folding. Department of Mechanical Engineering, Eindhoven University of Technology, *Philosophical Transactions of the Royal Society, A*(370), 1912–1924.

[5] Borgqvist, E. (2014). *Continuum modeling of the mechanical properties of paperboard.* Department of Construction Sciences, Solid Mechanics, Lund University.

[6] Carlsson, L.; Fellers, C.; Ruvo, A. (1980). The mechanism of failure in bending of paperboard. *Journal of Material Science, 15*(10), 2636 – 2642.

[7] Deganutti, F. (2001). *Estudo da Seção de Secagem de Papel da Máquina MP-7 da Klabin/PR.* Chemical Engineering Department, Universidade Estadual de Maringá.

[8] Fellers, C.; Östlund, S.; Mäkelä, P. (2012). Evaluation of the Scott bond test method. *Nordic Pulp and Paper Research Journal*, *27*(2), 231-236.

[9] Giampieri, A.; Perego, U.; Borsari, R. (2011). A constitutive model for the mechanical response of the folding of creased paperboard. *International Journal of Solids and Structures, 48*(16–17), 2275–2287.

[10] Huang, H. (2011). *Numerical and Experimental Investigation of Paperboard Creasing and Folding.* Department of Solid Mechanics, Royal Institute of Technology (KTH) Stockholm, Sweden, 12-26.

[11] Huang, H.; Hagman, A.; Nygards, M. (2014). Quasi static analysis of creasing and folding for three paperboards. *Mechanics of Materials, 69*(1), 11-34.

[12] Isaksson P., Gradin P. & Östlund S. (2010). A simplified treatise of the Scott bond testing method. *Experimental Mechanics*, 50(6), 745-751.

[13] Koubaa, A.; Kouran, Z. (1995). Measure of the internal bond strength of paperboard. *TAPPI Journal, 78*(3), 103-111.

[14] Lillienberg, J.; Lörd, E. (2009). *Outside vs. inside creasing – A parameter study*. Packaging Logistics. Lund University.

[15] Makela, P.; Östlund, S. (2003). Orthotropic elastic–plastic material model for paper materials. *International Journal of Solids and Structures, 40*(21), 5599–5620.

[16] Mentrasti, L.; Canella, F.; Pupilli, M.; Dai, J. (2013). Large bending behavior of creased paperboard. *International Journal of Solids and Structures, 50*(20–21), 3089–3096.

[17] Nagasawa, S.; Fukuzawa, Y.; Yamaguchi, D.; Nagae, S.; Katayama, I.; Yoshizawa, A. (2001). *Deformation characteristics on creasing of paperboard under shallow indentation*. Department of Mechanical Engineering, Nagaoka University of Technology, Japan, ICF100202OR, 1-6.

[18] Nagasawa, S.; Endo, R.; Fukuzawa, Y.; Uchino, S.; Katayama, I. (2008). Creasing characteristic of aluminum foil coated paperboard. *Journal of Materials Processing Technology, 201*(1-3), 401-407.

[19] Nygards, M. (2013). *Rate effects during rotary die creasing. Testing of paperboards with different ZD compression properties.* Innventia report nº 416.

[20] Sebes, A. (2010). *Investigation of paperboard properties and their influence on creasing and folding*. Department of Solid Mechanics, Royal Institute of Technology (KTH) Stockholm, Sweden, 44-82.

[21] Stenberg, N. (1999). *Mechanical properties in the thickness direction of paper and paperboard.* Department of Solid Mechanics, Royal Institute of Technology (KTH), Stockholm, Sweden, 9-17.

[22] Stenberg, N. (2002). *On the out of plane mechanical behavior of paper materials.* Department of Solid Mechanics, Royal Institute of Technology (KTH) Stockholm, Sweden, 5-7.

[23] Tryding J.; Rosander J.; Just M. (2007). *Tetra Pak Packaging Solutions AB MEMO*, Base Materials, *1*(12), 95.

[24] Tryding, J. (2012). *Folding of Paperboard using the L&W Bending Tester.* Draft Version 2.0.3, Tetra Pak, 3.