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EFFECT OF CORRUGATED BOARD STRUCTURE ON MECHANICAL PROPERTIES

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ABSTRACT

The article shows the method for prediction of corrugated board properties based on automatic generation of a database containing material compositions of all the boards possible to be produced by a given manufacturer. With their large number it is not possible to carry out on the basis of measurements made on earlier manufactured products. As a result of the tests carried out with the use of data provided by the corrugated board manufacturer, it was found that using his paper materials and machinery it was possible to more than double increase the bending stiffness and edge crush resistance indexes of produced board. In some cases, the options for improving the indexes are slightly smaller, e.g. bending stiffness in the cross direction of three-layer board with flute C, the mentioned manufacturer can increase by approx. 40% of the maximum value obtained so far.

KEY WORDS: Corrugated board, corrugated board strength, board base, flute height.

INTRODUCTION

Corrugated boards are made of paper whose main component is wood fiber. There are many similarities when comparing corrugated board and wood considered as construction material, in particular for packaging production. Basic parts of their structures are natural fibers. Both materials are environmentally friendly, easily recycled and obtained from renewable sources.

Distribution of wood and board mechanical properties shows features characteristic of orthotropic bodies, but the advantage of corrugated board is its ability to form their mechanical properties during production process. In the plane of machine paper used for the production of corrugated board, two main directions of orthotropy of mechanical properties can be distinguished, which overlap with the production direction, also called the machine direction (MD) and perpendicular to it – cross direction (CD) (Mäkelä and Östlund 2003). In case of the corrugated board produced in corrugators, these directions coincide with the main directions in the plane of the corrugated board (Fig. 1a), while in the production of corrugated board with a single facer it is possible to rotate the layers and thus their main orthotropy directions (Fig. 1b).

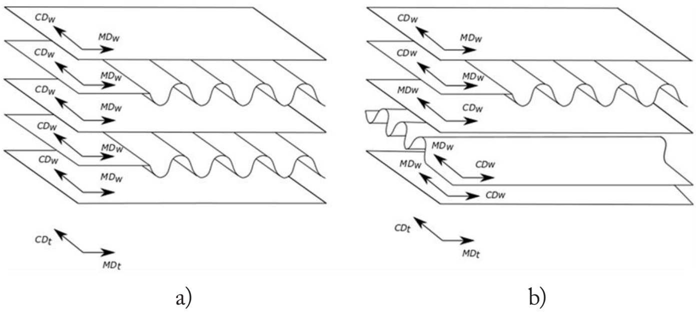

Fig. 1: Arrangement of main orthotropy directions of layers in corrugated board, index t shows direction in corrugated board, index w shows direction in layer.

Depending on the needs, various fibrous materials can be used for the production of board layers and the orientation of their main axes of orthotropy can be changed. In typical papers used for the corrugated board production, the tensile strength is in the machine direction about two to three times higher than in the cross direction, whereas the tensile stretch is the other way round (Jakucewicz 2017, Seo et al.1992, Li et al. 2016). In addition, it is possible to use fluted layers of different pitch, height and take-up ratio (Winkler and Kress 2012, Daxner et al. 2007). Combined with possibility of setting the flute peaks in the machine direction or in the cross direction of the corrugated board it allows changing the distribution of mechanical properties.

A weak point of corrugated board is its low resistance to moisture. For this reason, the wet-strength of the board should be set properly and the changes in the mechanical properties caused by moisture changes should be predicted (Olejnik and Wysocka-Robak 2005, Sundholm and Alexander 2012, Archaviboonyobul et al. 2013, Pathare et al. 2016, E and Wang 2012). Another factor affecting the strength of board products is the load duration or packaging ventilation (Fadiji et al. 2019, Beldie et al. 2001).

In practice, impact of individual factors on the strength properties of the corrugated board is analysed separately. Both the measurements and the calculations of the property value are made assuming a short time of interaction of the loads and that the product was air-conditioned in strictly defined conditions. In order to avoid analysing the impact of the time of loading and humidity of the board on its strength properties, this study assumes that all considerations concern air-conditioned cardboard in air at 23°C and 50% relative humidity, and the load duration does not exceed 20 s.

In order to obtain the corrugated board properties suitable for specific applications, it is necessary to analyse the properties which the corrugated board obtains after manufacturing. At this stage, the problem lies not only in finding appropriate mathematical models describing the basic strength parameters of the board, such as bending stiffness (BS) and edge crush test (ECT), but also on creation of a set of boards which can be produced. Various analytical and numerical methods for calculating these properties are known (Aboura et al. 2004, Biancolini 2005, Biancolini and Brutti 2003, Talbi et al. 2009). In corrugated boards and cardboards with honeycomb structure, flat crushing resistance is also determined, but it depends only on the properties of the middle layer. As a result, the number of cases possible to obtain is generally limited to several dozen and for this reason they will not be analyzed as part of the presented method (Kołakowski et al. 2015, Kołakowski et al. 2017). Before calculating BS and ECT parameters, a set of possible combinations of material compositions should be created, taking into account the allocation of materials to individual layers, and the possibility of different orientation of the main axes of orthotropy of these layers against each other. The board manufacturer usually has several dozen liners and a dozen or so flutings. Assuming that the parameters of the flutes will not be changed and that we have 30 liners and 10 flutings, we can produce about 9,000 double faced corrugated boards and about 2,700,000 double wall corrugated boards. The exact number of board grades possible to be manufactured depends on various conditions. If the manufacturing technology makes it possible to rotate the layers in the plane of the board, the number of available combinations is higher. In the case where the quality of the top facing sized in a single facer is the same as the bottom facing sized in a double facer, the number of combinations is lower.

In general, the manufacturer's offer includes several dozen to one hundred and several dozen types of the board. It means that in industrial practice, a small part of this potential is used, since it is unrealistic to produce all combinations of layers in order to examine the mechanical properties of the products obtained in this way.

MATERIALS AND METHOD

To select paper materials compositions and board structures to obtain the highest strength properties, the method was developed to generate a set of all possible combinations of layers that can be obtained from available raw materials using a specific flute type, or a combination of flutes with more than one corrugated layer. This collection will be referred to as the corrugated boards base in the further part of the article. Then, using the appropriate mathematical models, the strength parameters were calculated, which allowed to select board grades with required properties. Practical verification of the method was made using data from the corrugated board manufacturer. Amount of 33 liners and 13 flutings were considered. Double faced corrugated boards with flutes: B, C and E as well as double wall corrugated boards with flutes: BC and BE were selected for the tests.

The sets of all board grades were generated automatically using the MS Excel using the method described in patent application (Szewczyk et al. 2019). In the created sheet being the basis of parameters for all papers used by the board manufacturer, two macros were used - one of them designed to generate two sheets containing separate sets of liners and flutings, the other one to generate the corrugated boards base and calculate their strength parameters: ECT and BS.

In order to reduce the number of tested board types, the initial selection of materials for liners and flutings was made, eliminating some of the papers with worse physical properties affecting the tested board properties. For this purpose, filters defined in the MS Excel sheet were used to enable to give values of selected paper parameters. In this way, the number of tested double faced corrugated boards has been limited to around 7,000 and double wall boards to 120,000. The method described in the reference (Szewczyk and Bieńkowska 2014) and was used to calculate BS, which can generally be described by the relationship:

$$BS = \sum_{i=1}^{n} S_{b,i} \tag{1}$$

where: $S_{b,i}$ - bending stiffness of the i-th layer in relation to the neutral axis of corrugated board cross-section, (Nm),

n - number of board layers, (-).

In the case of paper products, the bending stiffness is related to the width of the sample b, therefore its value is given in Nm. When calculating the bending stiffness of corrugated layers in the cross direction, simplifications of their shape were assumed as shown in Fig. 2.

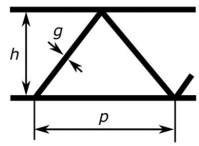

Fig. 2: Geometric parameters of simplified model of corrugated layer, p - flute pitch, h - flute height, g - thickness of corrugated layer.

Simplifying the shape of the flute allowed to treat the corrugated layer as a set of identical bending beams whose bending stiffness in the CD can be described by the relationship:

$$S_b = \frac{E_{CD} \cdot J_{CD}}{b} \quad \text{(Nm)} \qquad (2)$$

where: E_{CD} - Young's modulus of the corrugated layer in the cross direction, (Pa),
J_{CD} - moment of inertia of the layer cross-section relative to the neutral axis of the board cross-section in a plane perpendicular to the *CD*, (m^4).

Due to the negligibly low value of the bending stiffness in the machine direction, it was not included in the calculations. When calculating the bending stiffness of flat layers, they were treated like bending plates and calculated by means of the relationship:

$$S_b = \frac{E \cdot J}{b \cdot (1 - v_{MDCD} \cdot v_{CDMD})} \quad \text{(Nm)} \qquad (3)$$

where: E - Young's modulus of the flat layer in the direction of bending, (Pa),
J_{zi} - the moment of inertia of the layer cross-section in relations to the neutral axis of the board, in a plane perpendicular to the direction of bending, (m^4),
v_{CDMD}, v_{MDCD} - Poisson's ratios of the layer material, (-).

In order to avoid determining Poisson's ratios when calculating the bending stiffness of flat layers, a simplification was assumed based on the assumption that the product of Poisson's ratios in the machine and cross direction in paper is approximately 0.14 in accordance with the results presented in (Baum et al. 1981).

To calculate ECT, commonly known relationships presented in literature (Popil 2012, Markstrom 1999, Dimitrov and Heydenrych 2009, Šarčević et al. 2016) were used. In the case of double faced corrugated boards, relationship (4) was used. In the case of double wall corrugated boards the relationship (5) was used:

$$ECT = k \cdot (SCT_1 + SCT_2 \cdot \lambda + SCT_3) \quad (N \cdot m^{-1}) \qquad (4)$$

$$ECT = k \cdot (SCT_1 + SCT_2 \cdot \lambda_2 + SCT_3 + SCT_4 \cdot \lambda_4 + SCT_5) \quad (N \cdot m^{-1}) \qquad (5)$$

where: k - coefficient selected empirically, k = 0,75, (-),
SCT_1 - SCT_5 - short-span compressive test of subsequent layers of paper, ($N \cdot m^{-1}$),
λ - corrugation coefficient of corrugated layers, (-).

RESULTS AND DISCUSSION

Comparisons of measurements and calculations results are presented in diagrams where the horizontal line, described as "Measurement", shows the highest value of a given property obtained by the produced corrugated board. The results of calculations obtained for the board marked with successive numbers were set in order from the largest to the smallest values.

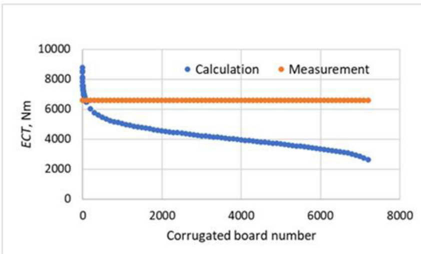

Fig. 3: ECT of double faced boards with flute C.

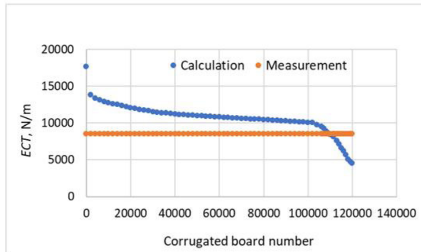

Fig. 4: ECT of double wall boards with flute BE.

In all examined cases, it turned out that there was a possibility of obtaining better mechanical properties of the corrugated boards, i.e. higher *BS* and *ECT* values obtained so far. Figs. 3 and 4 present some results of *ECT* measurements and calculations for selected double faced and double wall corrugated boards.

In the case of the double faced boards with flute C, 81 boards were found with potentially higher values of *ECT* than obtained so far and in the case of double wall boards with flute BE 110 000 such boards were found. On the basis of the tests, it was found that the *ECT* values of double faced boards with flute C and double wall boards with flutes BE are more than 2175 $N\cdot m^{-1}$ and 9130 $N\cdot m^{-1}$, respectively.

Presentation of values of tested strength property, e.g. *ECT* makes it easier to select the board with the highest strength properties. Sometimes, however, it is important to relate the strength to material consumption of the product. In such case, we can use the strength parameter relating the strength value to product grammage G. In the case of *ECT*, it is the edge crush resistance index, *ECT/G*.

Figs. 5 and 6 show measurement and calculation results of *ECT/G* whose edge crush test, is shown in Figs. 3 and 4.

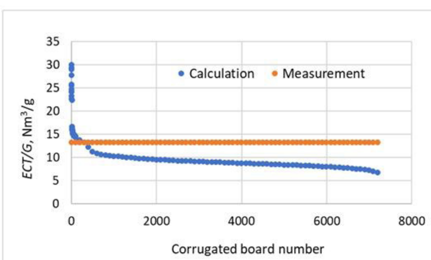

Fig. 5: Values of ECT/G for double faced board with flute C.

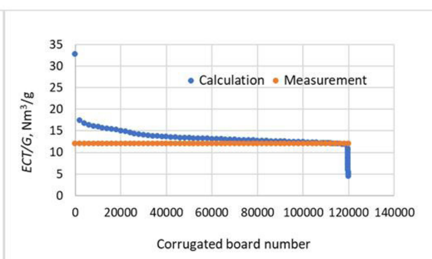

Fig. 6: ECT/G of double wall boards with flute BC.

From the liners and flutings selected for the test, about 300 double faced corrugated boards with flute C can be made with higher *ECT/G* values than obtained so far, and in the case of double wall boards with flute BE it is possible to produce about 115,000 boards with higher *ECT/G*. Possible values of *ECT/G* of the double faced corrugated boards with flute C and the double wall boards with flutes BE exceed earlier obtained by 16.7 $N \cdot m^3 \cdot g^{-1}$ and 20.7 $N \cdot m^3 \cdot g^{-1}$ respectively. The calculations show that in the case of both types of the board, it is possible to more than double the board weight reduction while maintaining the maximum *ECT* value achieved so far.

Figs. 7 to 10 present the examples of the measurements and calculations of the bending stiffness in the machine and cross direction of the double faced and the double wall corrugated boards. Having the analysed group of liners and flutings, it is possible to increase the bending stiffness of corrugated board more than twice, in comparison to the stiffness of corrugated boards produced before. The corrugated boards base created contains 5050 double faced boards with flute C and 85,500 double wall boards with flutes BE with potentially higher BS values in the machine direction than the ones obtained so far and 813 double faced boards and 52 230 double boards with potentially higher BS values in the cross direction.

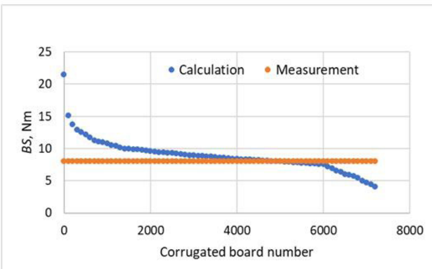

Fig. 7: BS values in MD of double faced board with flute C.

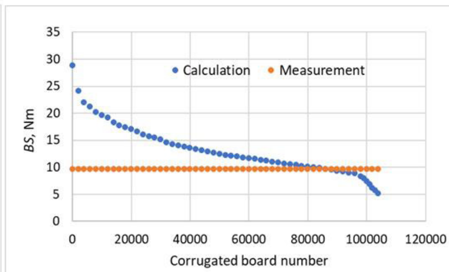

Fig. 8: BS values in MD of double wall boards with flute BE.

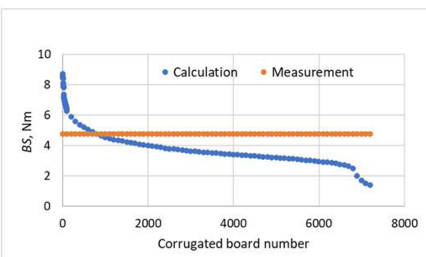

Fig. 9: BS values in CD of double faced boards with flute C.

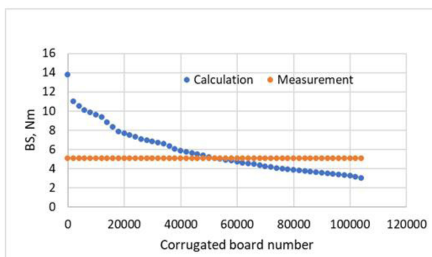

Fig. 10: BS values in CD of double wall boards with flutes BE.

Figs. 11 to 14 show the results of the measurements and calculations of *BS/G* of the boards, the bending stiffness of which is illustrated in Figs. 7 to 10.

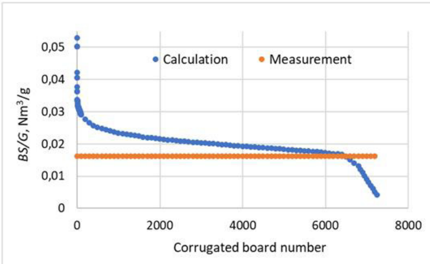

Fig. 11: Bending stiffness index of double faced boards with flute C in MD.

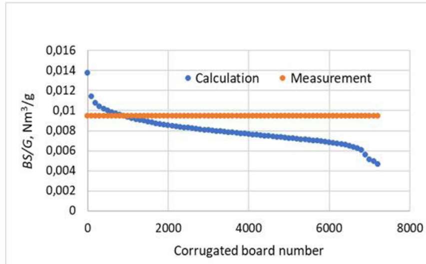

Fig. 12: Bending stiffness index of double faced boards with flute C in CD.

In the case of corrugated boards, the test results of which are illustrated in Figs. 11, 13,and 14 it is possible to increase the bending stiffness more than twice in relation to the parameters obtained by the boards produced previously. The possible increase in the *BS* of the corrugated board with flute C in the cross direction is smaller and amounts to approximately 40% of the maximum value obtained previously. In the same case, in the corrugated board base, the number of boards with higher *BS* than previously obtained is the lowest and amounts to 767, while in the other three presented cases it ranges from approximately 6,500 to 95,000.

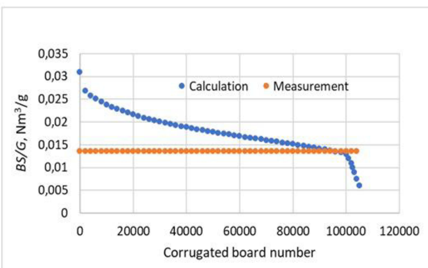

Fig. 13: Bending stiffness index of double wall boards with flute BE in MD.

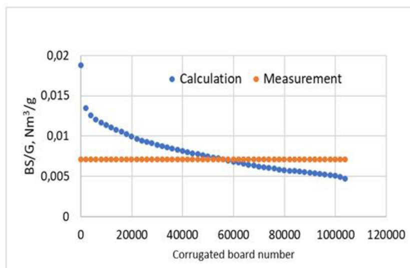

Fig. 14: Bending stiffness index of double wall with flute BE in CD.

During the tests, additional criteria that could limit the number of papers for corrugated board layers, such as printability, colour, barrier properties, etc., were not taken into the account. Such criteria can significantly reduce the number of potential material compositions generated in the corrugated board base, and thus reduce the number of boards with better properties than previously produced. When estimating the theoretical values of the strength properties, calculation errors should be expected, which usually amount to about 20% of the calculated value. Assuming an unfavourable case in which the calculation error will overestimate the calculated value by 20% of the real value, it can be estimated that the actual board properties in the same percentage will be lower than theoretically calculated, but even with this assumption, in each of the cases examined (board types, strength properties), it is possible to achieve better board properties than previously obtained. The corrugated board base can be enriched with additional data, such as the unit cost of materials for the layers, which allows it to be used to analyse the material costs of board production.

On the basis of observations of changes in the mechanical properties of the same raw materials supplied by different manufacturers, it was found that the actual values of their parameters may differ from the nominal ones by up to 25%. It makes it necessary to control continuously raw materials in order to avoid discrepancies between the measurements and calculations results. There are many publications mentioned earlier in this paper, in which methods of forecasting mechanical properties of corrugated cardboard were presented. However, in each case, the analysis concerned only a few cardboard and a small part of cardboards possible to be produced. The entire range of cardboards can be generated only by using automatic database generation described in authors' patent application (Szewczyk et al. 2019).

CONCLUSIONS

The tests proved that the proposed methodology for predicting corrugated board properties of the possible board production gives good results. Thanks to the automatic generation of the corrugated boards base, it is possible to quickly analyse thousands of raw materials and find solutions with the highest values of the bending stiffness and edge crush test as well as *BS/G* and *ECT/G*.

In all cases analysed, the corrugated boards with better properties than previously produced were found, and their number varied widely depending on the type of the board. In the case of three-layer boards with flute C, only 81 material charges were generated with higher ECT values (Fig. 3), and in the case of five-layer board with flutes BE more than 100,000 such material charges were found (Fig. 4). Similarly, in the case of bending stiffness, where more than 800 three-layer boards (Fig. 9) and 50,000 five-layer boards with potentially higher BS values were found in the cross direction (Fig. 10), and in the machine direction more than 5000 three-layer boards with flute C (Fig. 7) and 85,000 five-layer boards with flutes BE with potentially higher bending stiffness than previously achieved (Fig. 8). In the majority of cases examined, there is a potential possibility of more than doubling the strength values achieved so far. This proves that the intuitively selected by the manufacturers structures and material compositions of the corrugated boards do not guarantee obtaining the highest values of the strength properties of the product. The application of the presented methodology of analysing the corrugated properties can significantly improve their durability or reduce the material consumption.

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