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Impact of Corrugated Paperboard Structure on Puncture Resistance

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Thanks to its excellent protective properties, lightness, a reasonable price, and ecology, corrugated paperboard is one of the most popular materials used in the production of packaging for various products. During transportation or storage, packaging with goods can be exposed to the mass of other commodities, dropping from heights and transportation shock loads, which can lead to their puncture damage. Depending on the purpose and size of the packaging, the thickness, grammage, constituent paper layers, numbers of layers and type of fluting of corrugated paperboard used in its production differ. A standard triangular prism, corrugated paperboard fixation plates and a universal tension-compression machine were used to investigate the impact of corrugated paperboard structure and other parameters on the puncture resistance of the material. The investigation determines the maximum puncture load and estimates energy required to penetrate the corrugated paperboard. It was found that the greatest puncture resistance is demonstrated by paperboard with a larger number of corrugating flutings and the board produced from harder paper with a smaller amount of recycled paper. It was established that the grammage of three-layered paperboard with two different fluting profiles has the greatest impact on the level of static puncture energy.

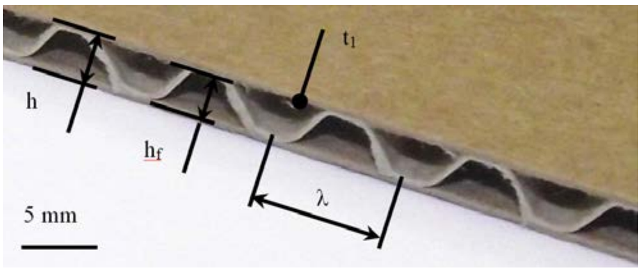
Keywords: corrugated board, puncture energy test, mechanical penetration, package.

INTRODUCTION

Corrugated paperboard (CPB) is a material with a multi-layered structure, which usually consists of 3 or 5 separate layers of glued paper. Fig. 1, a) shows 3-layered or single wall paperboard, which consists of 2 smooth liners and 1 corrugated fluting [1].

Among the given geometrical parameters of corrugated paperboard, the most important are sinusoidal shape flute height h_f and its pitch λ. The size of fluting profile affects the strength and other characteristics of the material: the greater is the height of flute, the higher is the resistance to compression and the bending stiffness of the paperboard. The same pattern is followed in manufacturing 5-layered CPB. Its structure is given in Fig. 1, b). Because of two corrugated layers of paper, this paperboard is characterized by even better strength properties.

Another equally important factor affecting the load resistance of this material is the pulp, which is the raw material in paper production. The corrugated layer of paperboard is most commonly made of: 1) semi chemical primary pulp, 2) recycled fibre pulp or 3) their mixture [2, 3]. Corrugating fluting made of semi chemical pulp is a strong and flexible material since it consists of short fibres of hard wood, which are better bound than shorter recycled fibres. Flute made of recycled fibre is not so strong and breaks easier when it is bent. The outer layers of CPB can be produced of 1) brown kraftliner, or 2) brown-grey recycled testliner, 3) mottled paper, 4) white top paper, and 5) coated white top paper [3, 4].



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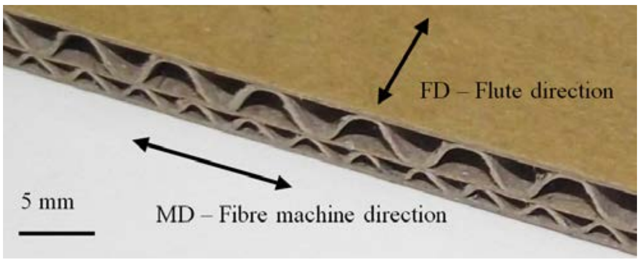

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Fig. 1. Structure of 3- and 5-layered corrugated paperboard and the key geometrical parameters: a – 3-layered paperboard; b – 5-layered paperboard; h – thickness of the paperboard sheet, t_1 – thickness of one of paper layer, h_f – height of flute, λ – pitch of flute. *MD* – pulp fibre machine direction, *FD* – flute direction perpendicular to the *MD*

The researches have showed that the shape and composition of 3-layered corrugated paperboard fluting has the least and the composition of outer liners and the distance between them has the greatest effect to the common stiffness parameters of the paperboard [5]. Evaluating the effect of corrugated paperboard structure to one of the main strength property of paperboard – bending resistance, it can be noted

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that it is strongly influenced by the general thickness of corrugated paperboard sheet and fluting step [6].

Depending on the flute profile, the number of layers, the paper pulp, the thickness of the paper layer or grammage, the properties of the produced CPB differ.

The strength of the material is defined by the following characteristics: 1) edgewise crush resistance (kN/m), 2) flat crush resistance (kPa), 3) puncture resistance (J), 4) bursting strength (kPa), 5) bending strength (Nm), and others [7, 8].

Commonly, CPB is used in manufacturing of packaging for products and transportation crates and therefore the aforesaid paperboard characteristics determine the stability of packaging dimensions under stowage loads, protection of a product in the circumstances of dynamic transportation and dropping loads. It is also important to protect products from damage if a package hits another package or a corner of a wooden pallet [8].

The CPB puncture testing is carried out pursuant to the standard ISO 3036:1975 Board – Determination of puncture resistance (rev. 2011) [9]. The puncture tests use a pendulum with an equilateral (25.4 mm high) trihedral pyramid at its end (see Fig. 2). During the test, a sheet of paperboard is fastened between the plates. One of them has a circular hole and the other has a triangular hole (see Fig. 3). The energy required to penetrate the CPB is established by changing the mass of weights in this puncture device and the angle of the puncture head [1].

The resistance of paperboard to the penetration of the puncture head is influenced by: 1) the hardness, 2) the friction between surfaces of the paperboard and the puncture head, 3) the paperboard flat crush resistance, 4) the tear strength, 5) the bending strength, and 6) the bursting strength [10].

In view of the numerous factors that affect the CPB puncture resistance and in order to objectively assess the whole puncture process, it is appropriate to use a static puncture. It is argued that the advantages of this methodology against a dynamic puncture of paperboard are the following: the dispersion of results is smaller, interim results of the testing can be obtained, the speed of puncture is steady, there are no extraneous vibrations, etc. Puncture testing results are consistent for 3- and 5-layered paperboard in both static and dynamic punctures [11].

The work [12] investigated the impact of the properties of 3-layered B flute paperboard with 2.2 mm calliper and 362.1 g/m^2 grammage and C flute paperboard with 3.2 mm thickness and 370.1 g/m^2 grammage on paperboard resistance to dynamic puncture. The presented test results show that the increasing resistance of B flute to flat crush (i.e., the increasing inner hardness of the flute [7]) results in increase in energy of dynamic puncture from 3.7 J to 4.7 J. It can also be seen that the energy required to penetrate the corrugated paperboard of B flute, when the general thickness of sheet increases from 2.2 mm to 2.3 mm, tends to decrease. The obtained results show that in B and C flute boards with the same grammage of fluting, the dynamic puncture energy for C flute is about 12 % higher than that for B flute.

Furthermore, the so-called geotextile puncture tests are conducted [13, 14]. It has been established that the speed of the puncture head of 25, 50 (standard), 75, 100 and 125 mm/min did not have any impact on the puncture energy in this material. Those tests assess the maximum puncture load and energy required for material puncture.

After recapitulating the reviewed literature sources, it can be maintained that there are not many works that have conducted tests of 3- and 5-layered corrugated paper resistance to hole puncture using static paperboard puncture testing equipment and methodology. Thus the aim of this work is to evaluate the impact of the structure and properties of corrugated paperboard commonly used for manufacturing packages on the resistance of packaging paperboard to hole puncture.

MATERIALS AND METHODOLOGY

3-layer B and C flute paperboard and 5-layer BE flute paperboards were used for puncture investigations. The marking of corrugated paperboard specimens, types of flutes, geometrical parameters of specimens and composition of their layers are given in Table 1.

The tests included 10 different types of CPB, although according to possible compositions, grammage, and numbers of their layers a greater variety of this type paperboard is possible [1, 7].

Table 1. The main technical parameters of corrugated paperboard used in the investigations

Structure	Corrugating flute	Specimen	Flute height h_f*, mm	Pitch of flute λ*, mm	Thickness (calliper) h, mm	Grammage, g/m^2	Lineboard and corrugating medium**
Single wall	B	1.1 B3	2.2	6.4	2.9	394.2	K-FR-K
		1.2 B3	2.4	6.3	2.9	381.5	WK-FR-K
		1.3 B3	2.4	6.3	2.9	410,2	TB-FR-TB
		1.4 B3	2.3	6.4	3.0	386.2	TB-FR-TB
	C	2.1 C4	3.5	8.0	4.1	451.3	K-SC-K
		2.2 C4	3.4	8.2	3.9	410.2	K-FR-FR
Double wall	BE	3.1 BE4	2.5 and 1.0	6.5 and 3.5	4.2	633.4	WK-FR-FR-FR-K
		3.2 BE4	2.2 and 1.0	6.5 and 3.5	4.1	582.0	TB-FR-FR-FR-TB
		3.3 BE4	2.1 and 1.0	6.5 and 3.5	4.1	701.7	K-FR-FR-FR-K
		3.4 BE4	2.0 and 1.0	6.4 and 3.5	4.3	880.4	K-FR-FR-FR-K

* in case of double wall or 5-paper-layer CBP, the height and pitch of both flute layers is given.

** composition: FR – recycled fluting, K – kraftliner or testliner with kraft top, SC – semi-chemical fluting, TB – brown coloured testliner, WK – white top kraftliner.

The research was based on the most common CPB types: cheaper board with less sturdy B flute and stiff and strong BE flute paperboards. The fluting of all specimens, with the exception for 2.1 C4, is made of recycled pulp, while the liner is made of 3 types of pulp (see Table 1).

Paperboard puncture test used specimens sized 210 mm × 175 mm. Two directions of flute were tested for each type of board: 1) parallel to the long side and 2) perpendicular to the long side (see Fig. 3, a) [9].

There were 6 pieces of each type of specimens; 2 days before the experiments the specimens were acclimatized in a standard 23 °C ±1 °C and 50 % ±2 % RH environment.

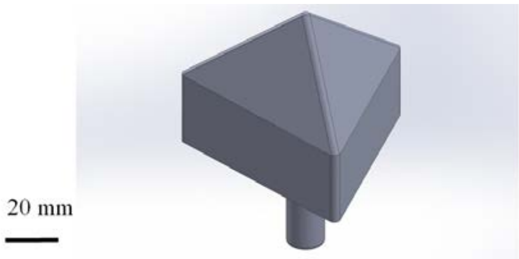
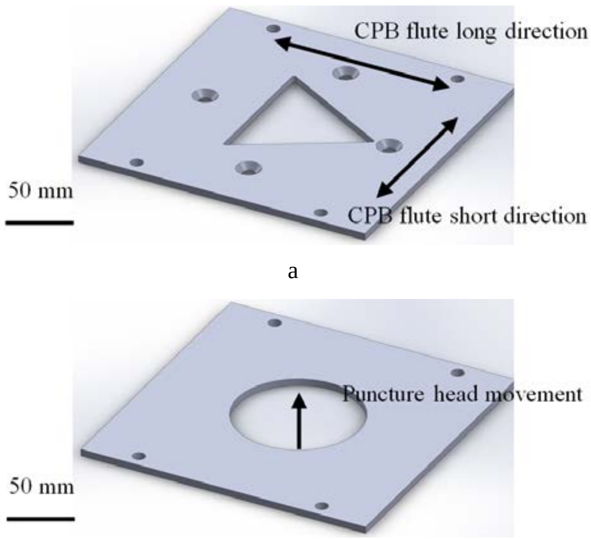


Fig. 2. Puncture head for corrugated paperboard (the shape of a trihedral equilateral pyramid)

The puncture test was performed in accordance with ISO 3036:1975 standard (rev. 2011), but using static loading instead of dynamic loading (using pendulum) intended in the standard.

It used two 210 mm × 10 mm plates, which hold paperboard, and a puncture head. The bottom plate had a Ø 90.0 mm ±1 mm hole (see Fig. 3, b)), and the other one had an equilateral-triangle-shaped opening (the length of the side is 100 mm ±1 mm) (see Fig. 3, a)).



b

Fig. 3. Fixing plates of corrugated paperboard: a – the upper clamping plate; b – the bottom clamping plate (puncture starts at the bottom)

The CPB was punctured with a puncture head that had the shape of a trihedral equilateral pyramid [8, 9] (see Fig. 2). Its height was 25.4 mm ±0.7 mm, the length of the base edge was 60.0 mm ±0.7 mm. and the tear perimeter was 107.7 mm. The rounding radius of edges was 1.5 mm.

The test was carried out using universal tension-compression machine Instron 5960. During the test the puncture head was steadily moving at the speed of 30 mm/min. The head affected the paperboard with an initial 2 N load, which is necessary for a primary contact between the tip of the head and the material.

During the experiment, the load of the puncture head and its displacement were measured. The following data can be derived from the characteristic curves of the puncture head load and displacement (see Fig. 4): 1) the maximum puncture load of the paperboard, 2) the load when the puncture head displacement equals to its height, i. e. 25.4 mm and 3) the puncture energy i. e. the area restricted by the load-displacement curve of the head (up to 25.4 mm of puncture head displacement) [14].

RESULTS AND DISCUSSION

Five stages of penetration characteristic to all test specimens can be identified in the curve of the impact of load on the displacement of the pyramidal head for B flute presented in Fig. 1.

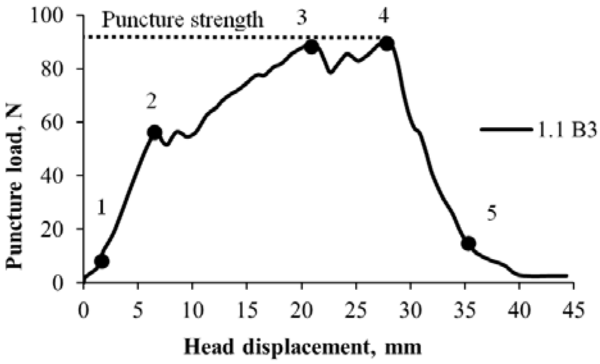


Fig. 4. Impact of load on the displacement of triangular pyramidal puncture head in penetrating corrugated paperboard

At the initial stage (up to point 1) a slight stretching of the paperboard was observed, and in point 2 the primary penetration of the layers of the board was recorded (see Fig. 5, a)). In the interval 1 – 2 the curve is most steep, i. e. the greatest resistance of the material to penetration was recorded in this particular place.

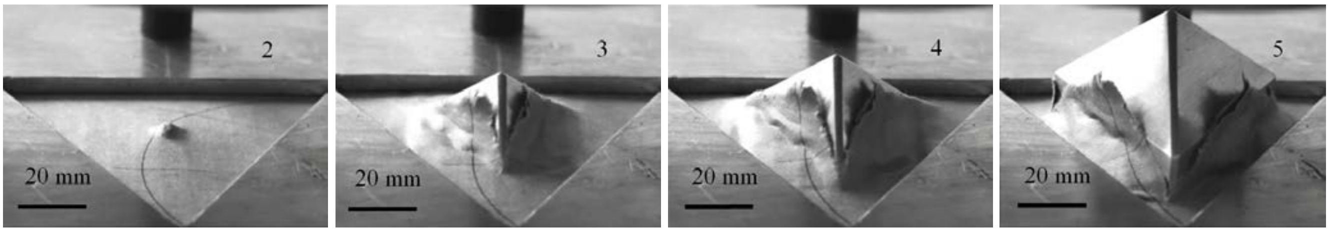
In the next 2 – 3 interval, the slope of the curve decreased considerably, i. e. the total tear length of the material decreased, and the bending strength of the paperboard was small due to the appearance of small bending jags (see Fig. 5, b)).

In the 3 – 4 interval of the curve the tear length did not change, and at this point the bending strength of the paperboard was the greatest and the contact area of the paperboard and the puncture pyramid was the largest.

At point 4 (see Fig. 5, c)) the peak puncture load was determined. In the final 4 – 5 interval a sharp fall in the slope of the load-displacement curve was observed, i. e. the puncture head had fully penetrated the tested material (see Fig. 5, d)).

Load-displacement curves show average results for all CPB specimens used in the tests (i. e. average results of penetration in longitudinal and transversal directions of the flute wave (see Fig. 3, a)).

The assessment of the difference between CPB penetrations according to the directions of the wave of the

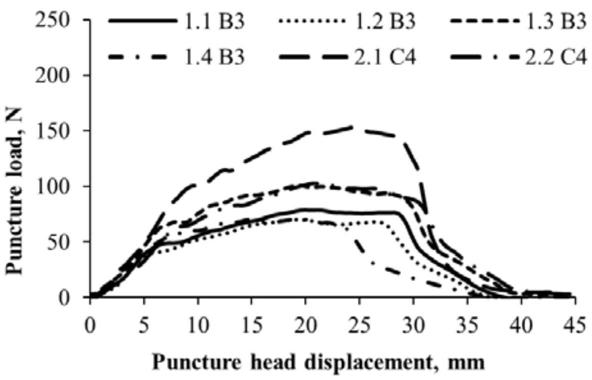


a b c d

Fig. 5. Typical stages of corrugated paperboard specimen 1.1 B3 puncture testing: a – initial penetration of the layers of the material and the highest resistance of the material to puncture; b – further tearing of the board, smaller bending jags appear; c – the greatest bending of the board and the greatest puncture load; d – the puncture head penetrates completely, only small resistance of torn parts of the paperboard remains, 2 – 5 – puncture stages

flute showed that because of the bending direction of 3 jags and the wave direction along the long side the puncture resistance of 3-layer board was 0.9 % – 10.6 % higher.

During puncture testing about half of CPB samples were punctured by the tip of the head beside of fluting top of the paperboard and the rest samples beside the fluting valley. This factor does not affect the total amount of calculated puncture energy.



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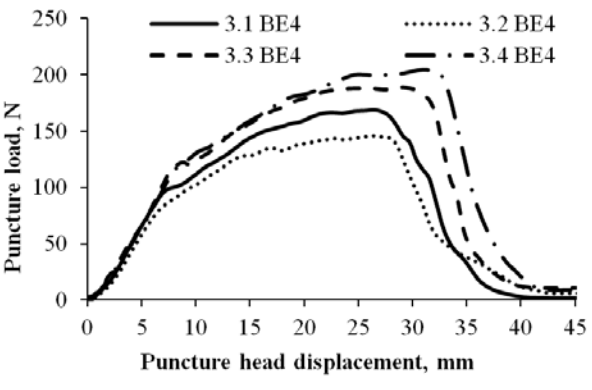

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Fig. 6. Impact of load on the displacement of puncture head in penetration of 3- and 5-layer boards of B, C and BE flutes: a – 3-layer B, C; b – 5-layer BE flute board

The load-displacement curves in Fig. 6 show that the character of the curves of 3-layer CPB is similar, with the exception for 1.4 B3 paperboard, the peak puncture load whereof is reached at approximately 22.0 mm pyramid displacement. It can be argued that this was determined by a lower bending strength of paperboard [7].

Other specimens, 1.1 B3 and 1.2 B3, and 1.3 B3 and 2.4 C4 demonstrated very similar behaviour in penetration, except that the load of the last 2 specimens during their penetration was approximately 36 % higher.

The dependences of the load impact on the head displacement for all 3-layer CPB show that the greatest puncture resistance is in 2.1 C4 paperboard with fluting made of stronger semi chemical SC pulp. The paperboard of such composition of fluting is more resistant to flat crushing and bending [7].

It was found that the character of dependences and puncture load values of 5-layer paperboard specimens 3.1 BE4 and 3.2 BE4 are rather similar to those of 3-layer 2.1 C4 paperboard. It can be seen that the structure of double-wall paperboard can compensate for less robust paperboard material.

The rest specimens of 5-layer paperboard 3.3 BE4 and 3.4 BE4 showed even better puncture resistance properties. It was also found that the dependence extremes of those CPB specimens (which is also true for 2.1 C4 and 3.2 BE4) at the point of penetration were of a “sharper” character. This can be related to the stiffness of CPB specimens and their tear strength.

In order to compare the obtained CPB puncture test results with analogous test results received by other authors, the dependences in Fig. 6 were used to calculate the required amount of energy for hole penetration of the material, which is given in Fig. 7 in the sequence of the specimens.

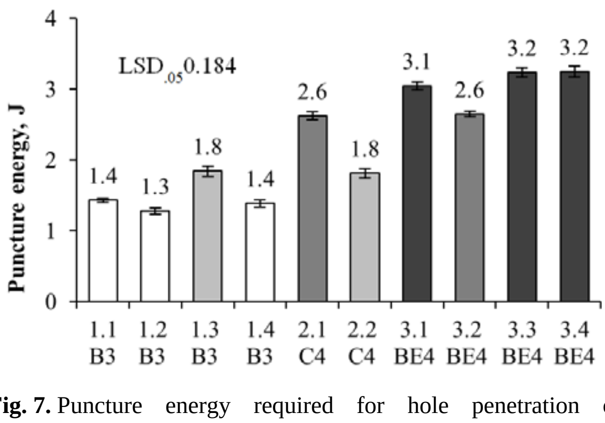

Fig. 7. Puncture energy required for hole penetration of corrugated paperboard. The bars represented confidence interval of means

The works [7, 12] identified that in case of a dynamic puncture with a pendulum the required energy for B flute paperboard of similar grammage and calliper is about 2.0 – 2.5 times larger than that of static puncture energy obtained here. In case of C flute and quite similar values of grammage and thickness, the difference was about twice as large. Such mismatch between the results could result from the tightly elastic properties and fibrous structure of the material, which demonstrates different behaviour under static and dynamic loads. This also could affect the friction between arm of pendulum puncture device and collar, catching the punctured paperboard, that additional increased the puncture energy [11].

To give a more explanation of the difference in the results, a more comprehensive research of CPB puncture should be conducted, where the same material is penetrated by static and dynamic loads.

Evaluating statistically least significant difference between the tested groups of paperboard samples, from Fig. 7 we can see that rather close properties of resistance to puncture have these groups of samples: 1.1 B3-1.2 B3-1.4 B3, 1.3 B3-2.2 C4, 2.1 C4-3.2 BE4 and 3.1 BE4-3.3 BE4-3.4 BE4.

The calculated correlation coefficients of variable parameters have showed that the amount of puncture energy has strong linear relationship ($r = 0.89$) with grammage of corrugated paperboard. An increase in grammage increases puncture resistance. The specific material weight shows it amount in the cross-section of the puncture and it is related with the thicknesses of outer and inner layers of liners [5, 6].

The obtained linear relationship ($r = 0.94$) between CPB puncture energy and biggest load of puncture (see 4, Fig. 4) allows to conclude that the resistance to puncture of paperboard can be determined according this characteristic when research of puncture of linear motion is used. Additional experimental and numerical researches are necessary.

CONCLUSIONS

1. The use of the static method in the testing of the hole puncture of corrugated paperboard due the during researches obtained low dispersion of findings of puncture energy enables to obtain a greater amount of more accurate data than in the case of dynamic puncture of the material.

2. The used testing method due possibilities of universal tension-compression machine, due simplicity of experiment (comparing with the puncture using pendulum device) due amount of obtained findings and accuracy of them can be used for the determination of properties of resistance to puncture of corrugated paperboard.

3. The obtained results of the static puncture test showed that static puncture of 3-layer B and C flute paperboard requires 2.0 – 2.5 times less energy than dynamic (pendulum) puncture of analogous grammage and calliper corrugated paperboard.

4. It was found that the static puncture resistance of 5-layer BE flute paperboard is about twice larger than that of B and C flute paperboard, even though the total calliper and grammage of such paperboards are smaller.

5. It is determined that the greatest effect to puncture energy of corrugated paperboard is caused by specific weight or grammage of material showing the amount of material in the cross-section of puncture.

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