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EFFECT OF PERFORATIONS ON THE LOSS OF CORRUGATED CARDBOARD BENDING STIFFNESS

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Abstract: *Bending stiffness of corrugated cardboard is a structural property that gives rigidity and strength. It depends on macroscopic structure of cardboard, different layers and thickness. The structure of corrugated cardboard used for secondary Shelf Ready Packaging (SRP) is weakened by perforations. Perforations serve as separation line used for converting SRP into the shelf-ready tray. The aim of this paper is to analyse the change of corrugated cardboard bending stiffness under the influence of perforations. The focus is on determining which of the explanatory variables affect the corrugated cardboard bending stiffness the most. The explanatory variables are: Type of perforation, Angle of perforation position and Quality of perforated corrugated cardboard. They are used to explain the variability in a measured property. The specimens with and without perforations were prepared using die cutter with machine-made knives. Three types of perforations (labelled: 1/1, 2/1 and 3/1 with the differences in the ratio of cut to uncut part) were positioned in five defined angles (0°, 20°, 45°, 70°, and 90°, where 0° represents Machine Direction, MD) and tested on three different quality of three-layer E-flute corrugated cardboard. Three-point bending tests were carried out using Instron tensile tester in order to observe the behavior of perforated specimens. Statistical analysis was performed to quantify the effect of perforation variables on the change of corrugated cardboard bending stiffness. The analysis showed that the explanatory variable Angle of perforation position was the most influential and provided the most significant information to explain the variability on the loss of corrugated cardboard bending stiffness. The trend in the measured values between all qualities of corrugated cardboard was obvious: the values decrease as the angle of perforation position increases; therefore, the highest values were for angle 0° and the lowest for angle 90°. A quantitative but not qualitative interaction between Quality and Perforation variables appeared. Hence, the "non-perforation – perforation" relationship was qualitatively always the same, although numerically it appeared somewhat different at different cardboard quality. The lowest loss of bending stiffness in the measured values was observed for the perforation type with the same ratio of cut and uncut part (labelled 1/1).*

Key words: bending stiffness, three-point bending, corrugated cardboard, perforation

1. INTRODUCTION

Shelf Ready Packaging (SRP) is secondary packaging with additional solutions for packaging functionality. Collation and protection of the product ensures successful movement through the supply chain. Additional functional requirements needed for a good SRP include ensuring easy identification, easy opening, easy shelfing, easy shopping and easy disposal (Theppituck et al., 2013). SRP should be easy to open to simplify and expedite replenishment and to facilitate in-store supply chain execution (Coles, 2013). However, easy opening should not compromise the structural integrity of the package, which is needed for safe transportation and handling (Hellström & Saghir, 2007). Perforations on corrugated boxes can be used to open the packaging in a desirable and predictable manner. Perforation lines are used to convert secondary packaging into corrugated tray or case displayed on the shelf.

Although SRP is recognized as having a significant impact on a global level by Smithers' study in 2019. with an increase of over $17 billion in 5 years (Smithers, 2019), literature reviews reveal the lack of scientific research of mechanical and structural properties for the purpose of efficient design of mentioned packaging. The classic approach to Shelf Ready Packaging design is the empirical or trial-and-error method. These methods are time-consuming and expensive.

There are studies in the form of guidelines that are created and used as part of the cooperation between international trading companies (Efficinet Consumer Respose Europe, 2007). The focus is on implementing SRP in the marketplace rather than providing tools and knowledge for the functional design of SRP opening.

Understanding the effects of perforation lines on the mechanical integrity of packaging is essential to providing a better product.

An important structural parameter of corrugated cardboard as a packaging material is flexural rigidity or bending stiffness. High bending stiffness provides rigidity and strength to paperboard packaging (Kajanto, 2008) and reduces the tendency for boxes to bulge when the contents are pressed against the wall (Fellers, 2009). Bending stiffness depends on the layered structure of corrugated cardboard that has two characteristic in-plane directions of anisotropy (Garbowski & Knitter-Piątkowska, 2022). This anisotropy results from the fiber orientation, which is commonly approximately symmetrical. Therefore, it can be assumed that the stiffness properties are orthotropic. Two in-plane directions are: Machine Direction (MD) corresponds to the manufacturing direction of the material and coincides with the x-axis; and Cross Direction (CD) corresponds to the transverse direction and coincides with the y-axis (Niskanen, 2008). Bending stiffness increases when the board is thicker and when the liners are heavier. Well-formed flutes also contribute significantly, hence the medium has a critical role both through the structural rigidity of the fluted shape and through its role in maintaining caliper (Urbanik, 2001; Frank, 2013).

It is important to understand the properties of perforated corrugated cardboard as an engineering material to understand where and how perforation decisions can impact the structural stability of the desired product. To provide tools for accomplishing better perforation decision making, three perforation variables were analyzed: Type of perforation, Angle of perforation position, and Quality of perforated corrugated cardboard. The perforation variables are sometimes referred to as explanatory variables in the text, depending on the context. With an optimal combination of perforation variables on corrugated cardboard, it could be possible to improve packaging properties by taking advantage of most of material and structural properties.

The aim of this paper is to identify the effect of perforations on the loss of bending stiffness of corrugated board in order to gain new insights into the structural properties. Furthermore, the perforation variables are analyzed and determined which one affect bending stiffness of corrugated cardboard the most. All data are mean values of ten measurements to obtain a representative result tested in direction MD, and are compared using statistical analysis.

2. METHODS AND MATERIAL

2.1 Perforated corrugated cardboard specimens

All specimens were produced using die cutter Rabolini Imperia with mPower knives, machine-made by Marbach. The perforation variables are divided into three groups and determined as three qualitative explanatory variables. The qualitative variables used to explain the variability of a measured property are:

- Type of perforation: three types of perforations were used and labelled 1/1, 2/1 and 3/1; the ratio of cut to uncut part of the perforation is 1:1, 2:1, and 3:1, respectively.
- Angle of perforation position: the specimens were perforated in five directions at five defined angles: 0°, 20°, 45°, 70° and 90°, with the 0° angle representing the Machine Direction and the 90° angle representing the Cross Direction. The selected angles cover most of the possible angles of perforation positions on SRP.
- Quality of perforated corrugated cardboard: the specimens were cut out from three different qualities of three-layer E-flute corrugated cardboard and labelled 111, 177, 177L. The basic properties of the selected cardboards, which are one of the most commonly used three-layer E-flute corrugated cardboard for perforated corrugated packaging in Croatia, are listed in Table 1.

The geometry and size of the specimens with the type of perforation and angle of perforation position are shown in Figure 1. The non-perforated specimens were also tested separately for each quality.

Table 1: Basic properties of three-layer E-flute corrugated cardboard

E-flute quality	111	177	177L
Outer liner [g/m^2]	100 testliner	125 white testliner	160 lux white liner
Fluting medium [g/m^2]	90 medium	90 medium	90 medium
Inner liner [g/m^2]	100 testliner	125 white testliner	125 white testliner
Grammage [g/m^2]	320.7	353	409.5
Thickness [mm]	1.45	1.44	1.50

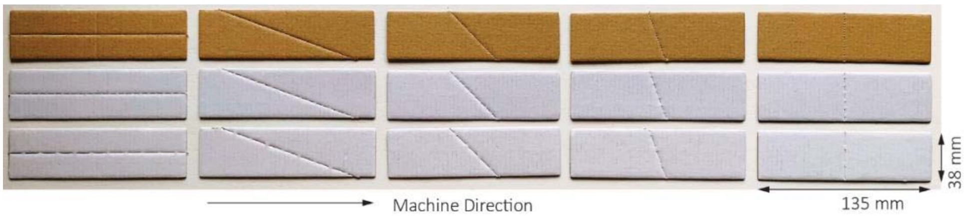


Figure 1: Real images of selected specimens

2.2 Three-point bending test

Three-point bending tests on perforated corrugated cardboard were conducted on an Instron 5567 - tensile testing machine according to ISO 5628:2019 (International Organization for Standardization, 2019). There are two supports on the bottom of the specimen and a force acting on the specimen from the opposite side (Figure 2). In Figure 2 it can also be seen that the board is bending in both directions.

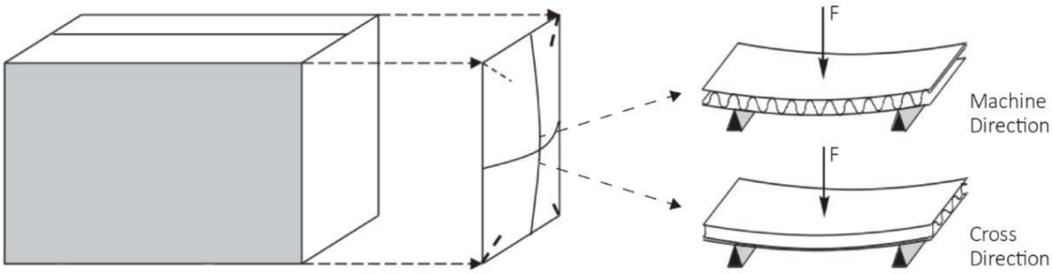


Figure 2: Schematic of corrugated box bending with principle of three-point bending test (Frank, 2013)

The bending is determined in a limited range of deviations in the elastic area with an agreed deviation of 0.2%. The limits of linearity must not be exceeded. The limit value for d_a (millimetres), the maximum allowable deflection, for the three-point loading can be calculated according to the following Equation 1:

$$d_a = \frac{0,33L^2}{t} \tag{1}$$

where L is the test length (millimetres) and t is the test piece thickness (micrometres). For three-point loading, further limitations must be considered to ensure that the errors are less than 5% (Equation 2):

$$d_a \ngtr 0,067L \tag{2}$$

Once the deflection d of the specimen has been calculated, the bending stiffness S (miliNewton metres) also can be calculated using the following Equation 3:

$$S = \frac{FL^3}{48db} \tag{3}$$

where F is a bending force (Newtons) and b is the test width (millimetres) (International Organization for Standardization, 2019).

3. RESULTS

The maximum allowable deflection d_a was calculated using Equation 1 for each quality of perforated corrugated cardboard (Table 2). The obtained results correspond to the limitation from Equation 2.

Table 2: Calculated the maximum allowable deflection d_a

E-flute quality	111	177	177L
d_a [mm]	2.27	2.29	2.20

Based on these results and the known dimensions of the specimen, the bending stiffness was calculated (Equation 3). The results were statistically analyzed to quantify the effect of the perforations on the loss of corrugated cardboard bending stiffness and to determine which explanatory variable most affects corrugated board bending stiffness.

3.1 Effect of Type of perforation on the loss of bending stiffness

In this paper three types of perforations were analyzed with the differences in the ratio between the cut and uncut part. The ratio for the type of perforation labelled 1/1 is 1:1, for the type labelled 2/1 is 2:1; and for the type labelled 3/1 it is 3:1. The data obtained from the tests can be seen as overall or main effect for each type of perforation (Figure 3) where value for perforation type labelled 1/1 are slightly higher, while the other two perforations types 2/1 and 3/1, are almost the same. Overall, the bending stiffness values were affected by the variable Type of perforation (F 12.97 P<0.0001).

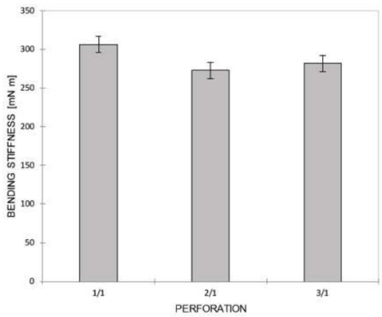


Figure 3: Main effect of variable Type of perforation on bending stiffness

3.2 Effect of Angle of perforation position on the loss of bending stiffness

The perforations on the specimens were positioned at five defined angles, with the angle of 0° corresponding to direction MD. The measured values are presented as overall or main effect for each angle. The differences between the angles are significant and are shown in Figure 4. The values decrease as the angle of perforation position increases; hence, the highest values were for angle 0° and the lowest for angle 90°. The values for angle 20° are close to the values for angle 0°, as well as the values for angle 70° are close to the values for angle 90°. Overall, the bending stiffness values were affected by the variable Angle of perforation position (F 1019.82 P< 0.0001).

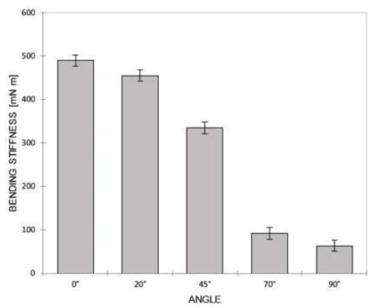


Figure 4: Main effect of variable Angle of perforation position on bending stiffness

3.3 Effect of Quality of corrugated cardboard on the loss of bending stiffness

Specimens cut from three different qualities of three-layer E-flute corrugated cardboard (labelled 111, 177, and 177L) were prepared with three types of perforation, placed on five defined angles, and tested. The data were analyzed and fitted to obtain an overall or main effect for each quality. From the data in Figure 5, it is apparent that the differences between the values for all three qualities are barely visible. Overall, bending stiffness values were affected by variable Quality of perforated corrugated cardboard (F 10,22 P<0.0001).

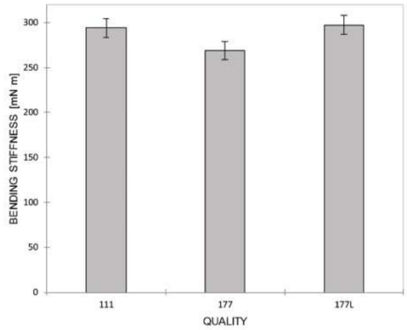
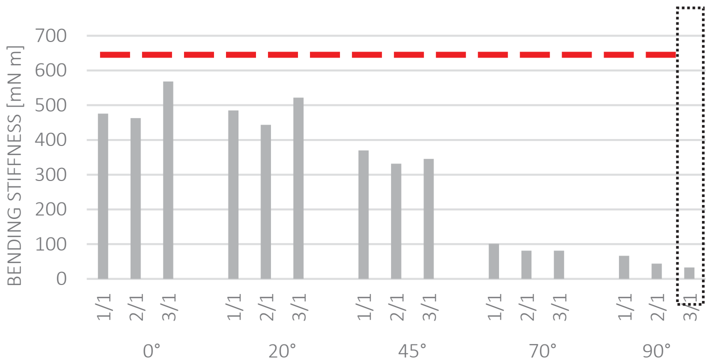


Figure 5: Main effect of variable Quality of perforated corrugated cardboard on bending stiffness

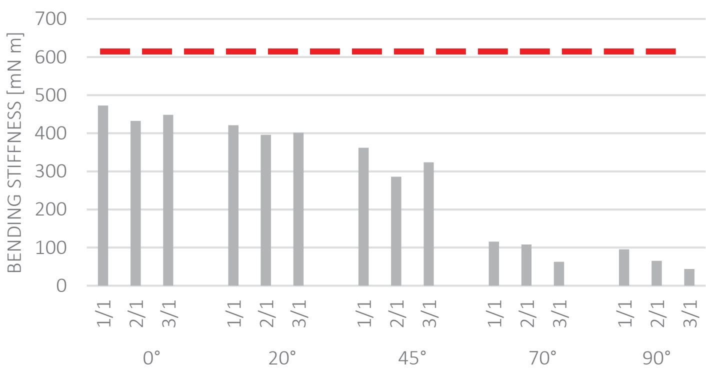
3.4. Comparing reference values and measured values

The reference values denote non-perforated specimens of all three different qualities of three-layer E-flute corrugated cardboard. Non-perforated specimens were tested and the results were compared with those of perforated specimens. Difference between reference values (dashed line) and measured values can be seen in Figure 6. The highest differences between the measured and reference values are seen at an angle of 90°, while the lowest differences occur at an angle of 0°. The highest loss of bending stiffness is observed for the combination of quality 111 with perforation type 3/1 at an angle of 90° (94.89%), while the lowest loss of bending stiffness is observed for the combination of quality 177L with perforation type 1/1 at an angle of 0° (11.49%).

a)
quality 111



b)
quality 177



c)
quality 177L

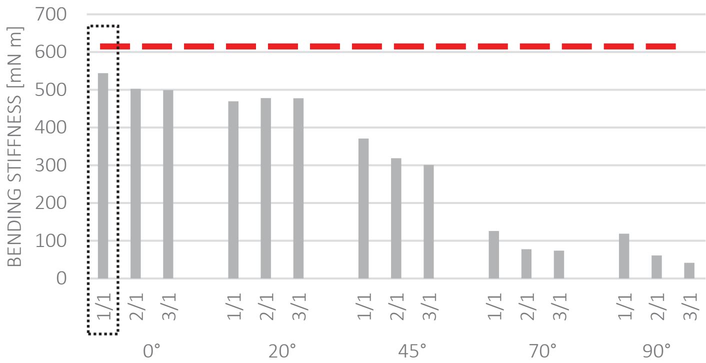


Figure 6: Loss of bending stiffness for qualities labelled: a) 111; b) 177 and c) 177L;
** red dashed line in Figures a, b, c) represent bending stiffness of reference specimen*

4. DISCUSSION

Three explanatory variables are used to explain the variability of a measured property of bending stiffness. All possible combinations were tested: three levels of the variable Type of perforation, five levels of the variable Angle of perforation position, and three levels of the variable Quality of perforated corrugated cardboard. In total, 45 test specimens were involved. Different combinations were tested to investigate the relationship between the perforation variables and the loss of bending stiffness and to identify the most influential variable. Differences in the main effect in variable Type and in variable Quality are visible, i.e. quantitative, but not qualitative. The most significant differences are seen and confirmed between the variable Angle of perforation position (Figure 4); consequently, the variable Angle is the most influential among the explanatory variables (F 1019.82 $P < 0.0001$). The trend in measured values between all qualities of corrugated cardboard was obvious: the values decrease as the angle of perforation position increases (Figure 6). All perforation types had the lowest influence on loss of bending stiffness at angles 0° and 20°. The loss of bending stiffness is less than 36% at these two angles. The greatest influence on the loss of bending stiffness was at an angle of 90°. The values at an angle of 70° were close to the values at an angle of 90°, where at both more than 80% of the loss was seen. Quality labeled 177 has the lowest measured values (Figure 5), which is related to the lowest thickness (Table 1), since the bending stiffness depends on the thickness of the material. The differences between the measured values for Types of perforation are not high, however the type with the smallest cut in the perforation line labeled 1/1 had the highest measured values, as expected.

5. CONCLUSIONS

Perforation lines are used for transforming packaging into shelf-ready trays. These lines must not compromise the structural integrity of the packaging, i.e., the packaging must remain safe and strong enough to withstand the stresses of handling and transportation. Bending stiffness, as a basic structural property of corrugated cardboard intended for packaging, was tested for selected material with different perforation combinations. The three-point bending test was performed for specimens prepared in direction MD, on different three-layer E-flute corrugated cardboards with various perforations at defined angles. The bending test is used to evaluate the protective capability of the package and by determining which variable has the greatest influence on reducing bending stiffness, it helps in the development of SRP to ensure the strength of the box during transportation. Statistical analysis has revealed that among the explanatory variables: Type of perforation, Angle of perforation position and Quality of perforated corrugated cardboard; the variable Angle of perforation position had the greatest effect on bending stiffness. Perforation at 90° has the greatest effect in decreasing bending stiffness, regardless of the quality of the corrugated cardboard or the type of perforation. When angled perforation lines are used, we recommend that an angle lower than 45° should be selected, while perforation lines in CD should be used as minimum as possible or should be used in conjunction with thicker board.

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