ISSN 1330-3651 (Print), ISSN 1848-6339 (Online)
https://doi.org/10.17559/TV-20211126090308
Original scientific paper

Validation of Elmendorf Method for Testing Perforated Corrugated Cardboard

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Abstract: The Elmendorf method is a well-known test that provides valuable insight into the durability and lifespan characteristics of the observed material, i.e., paper or paperboard. The objective of this paper is to determine if it is possible to apply the Elmendorf test to perforated corrugated cardboard to measure tear resistance. An Instron tensile tester was used to obtain input data for a range of properties of perforated corrugated board and to validate the non-standard test technique. Correlation analysis was used to statistically verify and quantify the relationship between the results obtained by the two aforementioned methods. Specimens were cut from four different qualities of three-layer E-flute corrugated cardboards at five defined angles affected by five types of perforations. First, the graphical difference in Least Square mean values was analysed and the results were confirmed by correlation analysis. No significant difference in results between the two observed methods was determined, and the relationship was mostly interpreted as a high positive correlation. Therefore, the results obtained by the Elmendorf method can be used for a better understanding of the mechanical properties of perforated corrugated cardboard.

Keywords: corrugated cardboard; perforation; tear resistant; tensile strength

1 INTRODUCTION

Shelf Ready Packaging (SRP) is a type of secondary packaging designed to reduce in-store labour cost of stacking products on shelves [1]. However, most of the problems with SRP are involved in the area of opening and shelving. An easy opening function implies uncomplicated handling with easy separation in a predictable and desirable manner without destroying the structural integrity of the case [2]. This paper is focused on opening process that involves perforations for converting transport packaging to shelf trey. The perforation allows the cover portion to be separated from the tray portion by simply tearing off along the perforated line [3].

The recent Smithers study shows how the value of the global Retail-Ready Packaging (RRP) market (which includes Shelf Ready Packaging (SRP)) is expected to increase from about $60 billion in 2019 to over $77 billion in 2024 [4]. Although the demand for SRP is increasing, not many scientific papers on SRP design were found. The most commonly used approach for SRP design is the empirical or trial-and-error method. There are empirically different perforation patterns for each manufacturer, while there are no publicly defined standards.

There are studies in the form of guidelines that are created and used as part of the cooperation between international trading companies [1, 5]. However, there is no specific information about the selection of perforation patterns in the design of SRP.

Several studies [6, 7] have investigated the zipper tear strip (ZTS), which has two parallel rows of perforation lines on paperboards normally used for primary packaging. It was found out that the ZTS has a higher success rate when it is in the machine direction of the grain with smaller uncut pieces than in the cross direction with longer uncut pieces. In another paper, the authors made a conclusion about the optimal design of the ZTS structure. Although the work is limited due to the small sample size, they found out that the cut piece with an angle of 45° is the most functional option and should be combined with the wider 13 mm ZTS instead of the usual 10 mm [8].

Perforations on paperboard were also studied in the mirror of the human opening process in desire to develop a new test method for the opening process of perforated and folded paperboard box. By mathematically mapping human hand opening process, identifying the opening pattern, and calculating the opening speed, the data for manual opening could be compared with those for machine opening [9, 10].

In the studies which included perforations, corrugated cardboard and mechanical properties, a compression test was performed on the perforated corrugated cardboard box. The first study used a physical approach with Box Compression Test (BCT) on different corrugated boxes and for different types, dimensions and positions of perforation, although these variables were not listed or explained in the paper. They concluded that the most resistant box was the one without perforation and then the box with 2 × 2 mm perforation in position B, without knowing the other types of perforation or positions [11]. In another study, the influence of perforation was considered in an analytical-numerical approach to estimate the compressive strength of corrugated boxes. The analytical-numerical method, which used different mechanical properties of perforations in the finite element modelling, showed a positive correlation when compared with experimental results and confirmed that as the stiffness of the perforation decreases, the strength of the box also decreases [12].

In this paper, the effects of five different types of perforations on tear resistance and tensile strength were tested at five different angles and on four different qualities of three-layer E-flute corrugated cardboards. In order to meet the desired requirements of Shelf Ready Packaging, it is important to understand the mechanical properties of corrugated cardboard weakened by perforation. Since there are no standardized tests for testing the mechanical properties of corrugated cardboard with perforations, standardized tests for paper, paperboard and corrugated cardboard are used and modified. The most commonly used tear test is often referred to as the Elmendorf tear test. The Elmendorf tear test measures tear strength of paper. It is one of the most important mechanical properties of paper [13] and is still the most common method for evaluating the toughness of paper [14]. Although the Elmendorf method is only applicable to paper and paperboard, the test was applied and the results obtained were compared with the tensile strength measured on the Instron tensile tester. The objective of this work was to determine, quantify, and analyse the correlation between the two measurements. All data are mean values of ten measurements to obtain a representative result and are compared using statistical analysis.

2 MATERIALS AND METHODES

In this paper, one hundred combinations of specimens were prepared for each test, which were divided into three groups that were determined as three qualitative explanatory variables. The qualitative variables used to explain the variability of the response variables are:

a) Quality: samples were taken from four three-layer E-flute qualities of corrugated cardboard, labelled as follows: 111, 131, 177, 177L. The differences in some of the basic properties of corrugated cardboards are listed in Tab. 1. The selected qualities are the most commonly used three-layer E-flute corrugated cardboard for perforated corrugated packaging.

b) Angle: the samples were cut in five directions at five defined angles: 0°, 20°, 45°, 70° and 90°, where 0° represents Machine Direction and 90° represents Cross Direction. The angles selected for research cover the most of possible angles positions used for creating perforations on corrugated packaging.

c) Perforation: five types of perforation were used, placed in the middle of the long edge and labelled: 1/1, 2/2, 4/2, 6/2, 10/3; where the first number represents the cut part in millimetres and the second number represents the uncut part in millimetres.

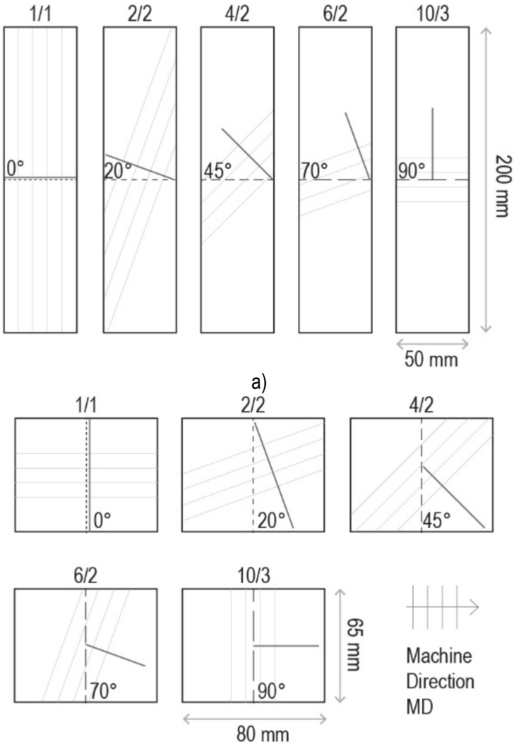
Table 1 Basic properties of E-flute corrugated cardboards

E flute quality	111	131	177	177L
Outer liner / g/m^2	100 testliner	125 kraftliner	125 white testliner	160 lux white liner
Fluting medium / g/m^2	90 medium	90 medium	90 medium	90 medium
Inner liner / g/m^2	100 testliner	100 testliner	125 white testliner	125 white testliner
Grammage / g/m^2	320,74	345,31	352,97	409,48
Thickness / mm	1,45	1,49	1,44	1,50

2.1 Specimens and Test Methods

The mechanical tensile strength test of perforated corrugated cardboard was carried out using Instron - tensile testing machine according to ISO 1924-2:2008 [15]. The specimen size for the tensile test was 50 × 200 mm and was determined by the authors. For the tearing measurements, an Elmendorf type tearing tester was used and the specimen size for the resistance measurements was 80 × 65 mm according to ISO 1974:2012 [16]. Elmendorf testing machine equipped with pendulum with interchangeable weight for different measuring range (Henry Baer & Co. Type 648 (Zurich)) was used. The pendulum capacity (strength-graduation) was up to 6400 g, and was the same for all tested specimens.

All specimens were prepared using die cutter Rabolini Imperia with mPower knives, machine-made from Marbach. The geometry and size of the specimens for tear resistant testing and tensile testing are shown in Fig. 1, including the angle at which the specimen was cut and the type of perforation. Outcome data of the tested measurements tear resistance and tensile strength, are the response variables, which are also called quantitative variables.



a)

b)

Figure 1 Geometry and size of test specimens cut in different directions with different type of perforation for: a) tensile tester and b) tear tester

2.2 Statistical Analyses of the Results

Statistical analysis of the results was performed to determine if the two methods tested on perforated corrugated cardboard yielded the correlated measurements. Least Square means tool was used to visually compare the effects of the same set of explanatory variables and interactions on different response variables. However, the strength of the relationship between two response variables was measured using correlation tests. Correlation coefficients were used to determine whether the correlations were significant or not. The measured data for each test were divided into three groups according to three qualitative variables and normal distribution was verified using Shapiro-Wilk test [17]. The results of the Shapiro-Wilk test determined the further use of the correlation coefficient.

The verification of data that are linearly related requires the use of Pearson's correlation coefficient [18, 19] according to the following expression:

$$r = \frac{\sum \left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)}{\sqrt{\sum \left(x_i - \bar{x}\right)^2 \sum \left(y_i - \bar{y}\right)^2}} \tag{1}$$

where r is Pearson correlation coefficient, x_i is values of the x variable in a sample, $\bar{x}$ is mean of the values of the x

variable, y_i is values of the y variable in a sample, $\overline{y}$ is mean of the values of the y variable.

When the data deviate significantly from the normal distribution, Spearman's Rank correlation coefficient [18, 19] is used according to the following expression:

$$r_s = 1 - 6\sum_{i=1}^{n} \frac{d_i^2}{n\left(n^2 - 1\right)} \tag{2}$$

where r_s is Spearman's Rank correlation coefficient, d is differences between rank values of two observed variables, n is number of different series.

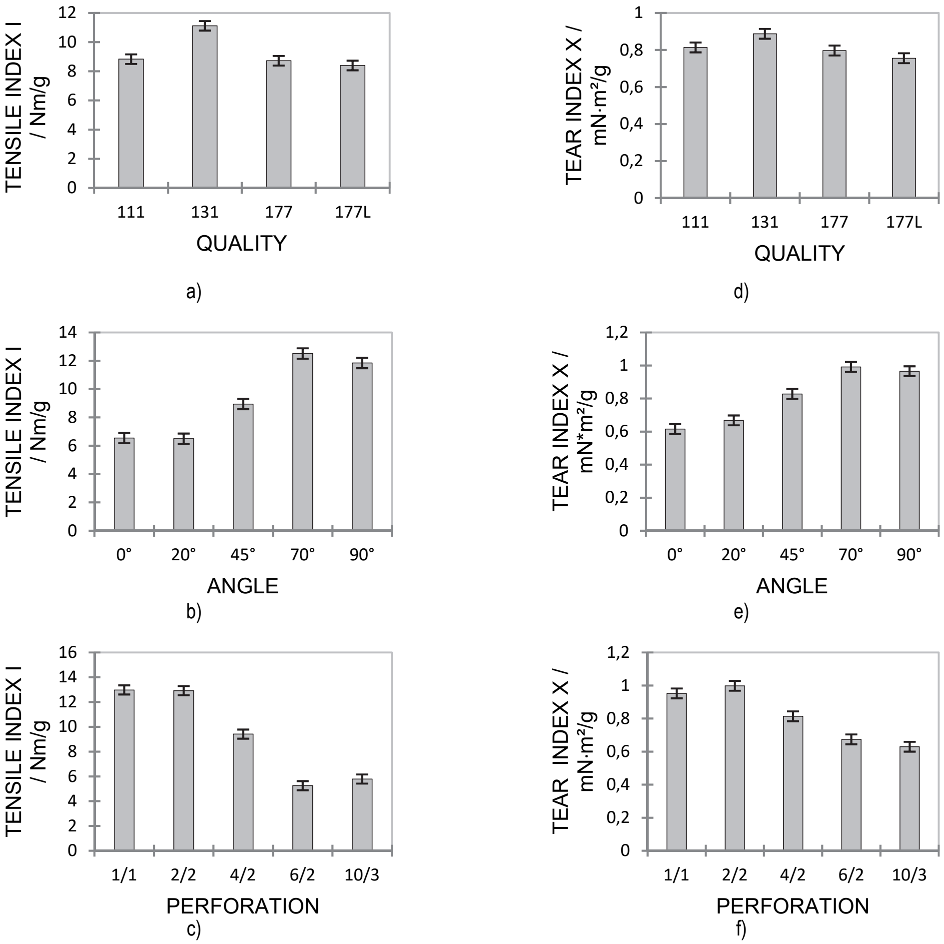
As for the strength of the relationship, the correlation coefficient for both methods can take any value from −1 (strong negative relationship) to +1 (strong positive relationship). Values at or near zero indicate a weak or no relationship [20].

3 RESULTS

To see if the two methods tested, tear resistance and tensile strength, yielded correlated measurements, mean histograms were created to visually interpret the LS Means and their differences.

The results of the measurements generated by the factor Quality (Fig. 2a, Fig. 2d) in both methods show almost the same distribution of values, with the quality of perforated corrugated cardboard labelled 131 having the highest mean value, followed by the quality labelled 111 and 177. The lowest mean was for quality labeled 177L. The values in both measurements generated by the factor Angle (Fig. 2b, Fig. 2e) are almost evenly distributed with the highest value at 70°, while the remaining values increase from 0° to 90°. In the distribution of the results obtained by the factor Perforation (Fig. 2c, Fig. 2f), three types of perforations have the same position in the distribution of values in both tests, starting with the highest mean value in the perforation labelled 2/2, then 1/1 and 4/2. The differences can be seen in the perforations labelled 6/2 and 10/3.

After visual inspection of the differences in the LS means for the tear resistance and tensile strength results, numerical methods were used. Verification of normal distribution was provided by the Shapiro-Wilk test for all three groups defined by variables. In Tab. 2 Tab. 7, the variables are labelled as E - Elmendorf tear test, and T - Tensile strength, with the designation for the defined factor type (Quality: 111, 131, 177, 177L; Angle: 0°, 20°, 45°, 70°, 90°; Perforation: 1/1, 2/2, 4/2, 6/2, 10/3).



a)

d)

b)

e)

c)

f)

Figure 2 Tensile strength under the influence of: a) quality of corrugated cardboard, b) angle of perforation position, c) type of perforation; tear resistance under the influence of d) quality of corrugated cardboard, e) angle of perforation position, f) type of perforation

3.1 Correlation by Factor Quality

It is apparent from Tab. 2 that the data defined by the factor Quality is not normally distributed, as the computed p - value is lower than the significance level α, $p < 0,05$. According to result of the Shapiro-Wilk test, further analyses were undertaken using Spearman's Rank correlation coefficient. The results in Tab. 3 show the correlation between the tear resistant and the tensile strength for the specimen according to the quality of the E-flute of the corrugated cardboard. As it can be seen, the overall results statistically determine moderate, high, or strong positive correlation. The correlation for the same type of factor Quality measured by different tests is statistically significant and characterised as positive and high for E 111 - T 111, E 131 - T 131 and E 177 - T 177; and strong positive for E 177L - T 177L.

Table 2 p - value (Shapiro - Wilk test) for distribution of data generated by factor Quality

Variable	p - value
E 111	**0,001**
E 131	**0,036**
E 177	**0,002**
E 177L	**0,035**
T 111	**0,037**
T 131	**0,023**
T 177	**0,023**
T 177L	**0,006**

*bold values are lower than the significance level α, $p < 0,05$

Table 3 Correlation matrix (Spearman) of tested properties generated by factor Quality

Variables		T 111	T 131	T 177	T 177L
E 111	Spearman Corr.	0,782	0,772	0,706	0,728
	p - value	< 0,0001	< 0,0001	0,00012	< 0,0001
E 131	Spearman Corr.	0,752	0,812	0,750	0,756
	p - value	< 0,0001	< 0,0001	< 0,0001	< 0,0001
E 177	Spearman Corr.	0,828	0,850	0,820	0,861
	p - value	< 0,0001	< 0,0001	< 0,0001	< 0,0001
E 177L	Spearman Corr.	0,811	**0,897**	0,870	**0,903**
	p - value	< 0,0001	**< 0,0001**	< 0,0001	**< 0,0001**

*Correlation interpretations: light grey - moderate correlation (from ±0,5 to ±0,69), dark grey - high correlation (from ±0,7 to ±0,89) and boldblack - strong correlation (from ±0,9 to ±1). Grey cells - same type of factor at different measurement

3.2 Correlation by Factor Angle

The Shapiro-Wilk test suggests that the data generated by the Angle (Tab. 4) are normally distributed. As the computed p-value is greater than the significance level α, $p < 0,05$, the test verified that the data follow a normal distribution (except for the variable T 90°).

To increase the reliability of the measurements, both correlation tests were performed, when the data followed a normal distribution and when they did not. The results with the lower values were used for the research, i.e. Pearson's correlation coefficient. The correlation between the tear resistance and the tensile strength according to an angle of the specimen position is presented in Tab. 5 and indicates moderate, high or strong positive correlation. The correlations for the same type of factor Angle measured by different tests are statistically significant and marked as follows: positive and moderate for E 0° - T 0°; positive and high for E 20° - T 20°, E 45° - T 45° and E 90° - T 90°, and positive and strong for E 70° - T 70°.

Table 4 p - value (Shapiro - Wilk test) for distribution of data generated by factor Angle

Variable	p - value
E 0°	0,353
E 20°	0,372
E 45°	0,300
E 70°	0,289
E 90°	0,548
T 0°	0,305
T 20°	0,171
T 45°	0,087
T 70°	0,288
T 90°	**0,025**

*bold values are lower than the significance level α, $p < 0,05$

Table 5 Correlation matrix (Pearson) of tested properties generated by factor Angle

Variables		T 0°	T 20°	T 45°	T 70°	T 90°
E 0°	Pearson Corr.	0,608	0,615	0,645	0,528	0,682
	p - value	0,004	0,004	0,002	0,017	0,001
E 20°	Pearson Corr.	0,703	0,730	0,724	0,549	0,643
	p - value	0,001	0,00025	0,0003	0,012	0,002
E 45°	Pearson Corr.	0,832	0,844	0,861	0,772	0,787
	p - value	< 0,0001	< 0,0001	< 0,0001	< 0,0001	< 0,0001
E 70°	Pearson Corr.	0,840	0,860	0,862	**0,906**	0,871
	p - value	< 0,0001	< 0,0001	< 0,0001	**< 0,0001**	< 0,0001
E 90°	Pearson Corr.	0,816	0,822	0,839	0,857	0,821
	p - value	< 0,0001	< 0,0001	< 0,0001	< 0,0001	< 0,0001

*Correlation interpretations: light grey - moderate correlation (from ±0,5 to ±0,69), dark grey - high correlation (from ±0,7 to ±0,89) and bold black - strong correlation (from ±0,9 to ±1). Grey cells - same type of factor at different measurement.

3.3 Correlation by Factor Perforation

As can be seen from Tab. 6, the data generated by the Perforation factor are normally distributed for most variables, with the exception of variables E 4/2, T 4/2, and E 10/3. After providing both correlation tests, Spearman's Rank correlation coefficient was chosen due to the lower readings. Tab. 7 shows the results of the correlation between the tear resistance and the tensile strength for the specimens according to the type of perforation. As it can be seen, the results of tear resistance measurements for the type of perforation labelled 10/3 have the lowest values, indicating a weak correlation. The other results determine moderate, high and strong positive correlation.

Table 6 *p* - value (Shapiro - Wilk test) for distribution of data generated by factor Perforation

Variable	*p* - value
E 1/1	0,165
E 2/2	0,162
E 4/2	**0,033**
E 6/2	0,175
E 10/3	**0,035**
T 1/1	0,136
T 2/2	0,475
T 4/2	**0,010**
T 6/2	0,075
T 10/3	0,082

*bold values are lower than the significance level *α*, $p < 0,05$

4 DISCUSSION

The tear resistance of perforated corrugated cardboard was tested using the Elmendorf tear tester, although the Elmendorf method is not intended for corrugated cardboard. To verify obtained data, tensile strength was also tested on the same specimens to determine if there was a correlation between the two measurements. The specimens were cut from four types of three-layer E-flute corrugated cardboard in five defined directions, with five types of perforations positioned in the middle of the long edge. Therefore, the distribution of data was divided into three groups defined by factors: factor Quality, factor Angle and factor Perforation.Visual analysis of the LS mean values of the outcome data of the tested measurements indicated similarities in the influence of the defined factor on the response variable, i.e. tear resistance and tensile strength. The only significant visible difference in the LS mean histograms is in the data set of the factor Perforation for perforation types 6/2 and 10/3. To better understand the test results and to quantify the correlation between two tested methods, a statistical measure of correlation coefficient was used. Correlation coefficients were calculated for each of the three groups defined by factors.

Table 7 Correlation matrix (Spearman) of tested properties generated by factor Perforation

Variables		T 1/1	T 2/2	T 4/2	T 6/2	T 10/3
E 1/1	Spearman Corr.	**0,863**	**0,821**	**0,566**	**0,827**	**0,857**
	p - value	**< 0,0001**	**< 0,0001**	**0,011**	**< 0,0001**	**< 0,0001**
E 2/2	Spearman Corr.	**0,756**	**0,832**	**0,648**	**0,818**	**0,857**
	p - value	**0,00017**	**< 0,0001**	**0,003**	**< 0,0001**	**< 0,0001**
E 4/2	Spearman Corr.	**0,814**	**0,802**	**0,707**	**0,812**	**0,856**
	p - value	**< 0,0001**		**0,001**	**< 0,0001**	**< 0,0001**
E 6/2	Spearman Corr.	**0,797**	**0,832**	**0,876**	**0,866**	**0,891**
	p - value	**< 0,0001**	**< 0,0001**	**< 0,0001**	**< 0,0001**	**< 0,0001**
E 10/3	Spearman Corr.	0,266	0,447	**0,680**	0,436	0,474
	p - value	0,256	0,050	**0,001**	0,056	0,036

*Correlation interpretations: light grey - moderate correlation (from ±0,5 to ±0,69), dark grey - high correlation (from ±0,7 to ±0,89) and boldblack - strong correlation (from ±0,9 to ±1). Grey cells - same type of factor at different measurement.

The correlation coefficient calculated for the tensile strength results with the Quality factor is slightly higher than the correlation coefficient for the tear resistance. However, the correlation within and between measurements is high to strong positive (moderate correlation exists only for E111 - E 177L). The results obtained with the Angle factor have slightly lower values of the correlation coefficient within the tear resistant measurement. The lowest value is for the defined angle E 0°. Nevertheless, the moderate positive correlation is still acceptable. The correlation between the measurements determines a moderate correlation (E 0° - T 0°), through a high correlation to a strong positive correlation (E 70° - T 70°). The overall calculated correlation coefficient for the results generated by the Perforation factor mostly gives a high correlation within and between measurements, although the exception is a results of tear resistant labelled as E 10/3 with a correlation coefficient of $r < 0,5$; which statistically implies an insignificant correlation.

The main issues addressed in this paper are the relationships between the same types of specimens in different measurements. The results of the same combination of the factor Perforation and the factor Angle on different three-layer E flute qualities show a significant positive correlation between the different measurements. A significant positive correlation was also calculated for the results obtained with the factor Angle and the factor Perforation (with the exception of the result for the tear resistance E 10/3 mentioned earlier). Taken together, these results approve further use of the measured values obtained with the Elmendorf tear tester.

5 CONCLUSION

The purpose of the present research was to explore the possibility of using the Elmendorf tear tester for perforated corrugated cardboard specimen in order to statistically verify the relationship between the results obtained with the Instron tensile tester and the Elmendorf tear tester.

To compare the measurements of tensile strength and tear resistance of perforated corrugated cardboard, graphical analysis of the difference in LS mean values and correlation analysis were used. The comparison of the histograms indicated and the correlation analysis confirmed that there is no significant difference between the two methods observed for specimen of perforated three-layer E-flute corrugated cardboard cut in different directions. The only exception is the results labelled as E 10/3, so this variable must be used with caution or excluded. The data from this study provide convincing evidence that measurements obtained by the Elmendorf tear method can be used to better understand the mechanical properties of perforated corrugated cardboard.

However, it is important to note that correlation only assesses the relationships between variables. Therefore, future research is needed to better understand and determine exactly how certain explanatory variables affect the response variables.

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