USE OF THE FINITE ELEMENT METHOD IN STUDYING THE INFLUENCE OF DIFFERENT LAYERS ON MECHANICAL CHARACTERISTICS OF CORRUGATED PAPERBOARD

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The corrugated paperboard has become a widely used material not only for producing different packages but also for making advertising materials, pieces of art, accessories used for transportation of a number of stock items and many others. With the growing demand for corrugated paperboard comes the need for more detailed knowledge about its mechanical characteristics which would serve for improving the quality and reliability of final products. A model based on the finite element method is used to study how the mechanical characteristics of the layers of the corrugated paperboard affect its complex mechanical characteristics.

Keywords: analysis, corrugated paperboard, FEM, layered materials, mechanical characteristics

1 Introduction

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Corrugated paperboard is a multi layered structure which is widely used in the packaging industry to produce various boxes. In the past few years the demand for this material has grown by hundreds of times worldwide. Apart from packages, designers around the globe are starting to make different products out of it such as pieces of art, advertising products, furniture, shelters, accessories for storing and transportation of goods and many more [1, 4, 5, 8, 9]. With this widening use of the corrugated paperboard comes the need for better knowledge of its mechanical characteristics.

Since the layers are typically made of paperboard, the complex mechanical characteristics of the corrugated paperboard will be in dependence of the characteristics of the material used for the liners and the flute. During their life cycle most of the corrugated paperboard products are subjected to the influence of different environmental conditions like variable temperatures and relative humidity. It is known that the moisture causes severe changes in the properties of the paper and paperboard [2, 6, 7] This undoubtedly brings changes in the properties of the corrugated paperboard as well. Temperature itself does not bring serious changes but relative humidity does. Paper and paperboard are hygroscopic materials. If they are transferred from conditions of lower relative humidity to an environment with higher moisture, within a certain period of time they will reach balance with these new conditions absorbing more water [2]. Schematic graphical representation of this process is shown in Fig. 2.

Conducted researches show that the effect of water is smaller in the so called machine direction. [2] This is the direction of the orientation of the cellulosic fibers. The direction perpendicular to it is called cross direction. The stronger effect of the water in this direction is explained by the fact that the mechanical properties are determined mainly by the hydrogen-based bonds between the cellulosic
fibers which the water comprises. Since the characteristics in machine direction depend on the mechanical properties of the fibers themselves, the effect of the water in this direction is smaller.

Basically, moisture causes lowering of the strength parameters of the paper such as modulus of elasticity, tensile strength, compressive strength, minimal stress which initiates plastic deformation, etc. Until about 70 % RH (relative humidity) these parameters undergo smaller change but it becomes bigger once the relative humidity rises above this level [2]. Fig. 3 schematically shows how the "stress – strain" curves of the paper differ from one another in conditions of lower and higher relative humidity.

In order to study how the changes of the mechanical characteristics of the individual layers of the corrugated paperboard affect its complex mechanical characteristics, a model based on the finite element method (FEM) is used.

2 FEM based model and conducted studies

The used 3D FEM based model is made of a piece of corrugated paperboard with "C" flute type. This is the most widely used type of flute. The pitch of the flute is 8 mm. and the total thickness is 4,1 mm. Visually these parameters are represented in Fig. 4.

The thickness of the liners is 0,26 mm while the one of the flute is 0,21 mm. These are common thicknesses for paperboard used to make these layers.

The model is subjected to tensile loading. This is due to the fact that normally the mechanical property such as modulus of elasticity, which is a crucial parameter for common FEM simulations used by designers, is determined by conducting tensile tests. On the other hand the experimental "stress – strain" curves which are available for paperboards and corrugated paperboard are also taken by running such an experiment [3].

The model is loaded using the force which rises from 0 N to 160 N by steps of 8 N each. Visually the applied load and the boundary conditions for the model are shown in Fig. 8.
This gives us the opportunity to conclude that the proposed model is reliable enough and can be used to carry out more detailed studies of the corrugated paperboard complex properties.

In order to research how the layers individually affect the complex characteristics of the paperboard we change the properties of their assigned materials by predefining their "stress – strain" curves. At first we change only the curves for the material used for the liners. Each curve is defined by 20 points (excluding the zero point). Each point has two coordinates – the coordinate for the strain and the coordinate for the stress. We multiply the coordinate of each point by 0.997 and by 0.82 we multiply their coordinates. In this way we generate 20 new points (excluding the zero point) which stand for a new curve. By following this procedure we produce 5 additional curves. They are all shown in Fig. 11. All this is done because of two main reasons. The first is that we imitate the changing of mechanical behavior of the paperboard when it absorbs water from the environment. The second is that there are no enough experimental curves available, so we can seek a reliable and accurate enough dependency.

After the calculation procedures have been carried out we examine the stress distribution in the model as well as the strain in different areas of the corrugated paperboard panel. This allows us to see which of its parts undergo elastic deformation and where plastic deformation occurs. [10]

We use the obtained results to create a theoretical complex "stress – strain" curve of the corrugated paperboard panel. We compare this curve to the experimentally determined one. [3] What we see is satisfactorily good coincidence of both curves. Visually this comparison is shown in Fig. 10.

First we study how the change of the modulus of elasticity of the material of the liners affects the equivalent modulus of elasticity of the corrugated paperboard panel.
Graphically this is shown in Fig. 13 depicted with dashed line.

We can see from the chart that this is almost a straight line, so we find the linear equation of regression which is written as follows:

\[ Y(X) = 0.12808 \cdot X + 3.11625. \]  

(1)

The coefficient of regression \( R^2 \) for this equation is 0.99949.

The change of the maximal load is also examined. The value for this load is considered to be the magnitude of the force corresponding to the stress value for the last point from the "stress − strain" curve. We determine this load for the material of the liners itself from the 6 charts which are used (Fig. 11) and for the curves obtained for the corrugated paperboard model (Fig. 12). The dependency is graphically represented in Fig. 14. The solid line on this chart depicts the linear equation of regression.

The equation of regression for this case is written as follows:

\[ Y(X) = 2.06114 \cdot X - 4.82213. \]  

(2)

The coefficient of regression for this equation \( R^2 \) is 0.99657.

The study continues with the examination of the influence of the internal corrugated layer. Just as in the case with the liners, 6 different "stress − strain" curves are given for the material of the fluted layer while the material for the liners is unchanged this time. These 6 curves, which are shown in Fig. 15, are defined using the same procedure as in the previous case − by multiplying their \( X \) coordinates by 0.997 and their \( Y \) coordinates by 0.82.
corrugated paperboard. This change is shown on the chart in Fig. 17.

We determine the linear equation of regression which is depicted with solid line. It is written as follows:

\[ Y(X) = 0.00146 \cdot X + 554.92304. \]  \hspace{1cm} (3)

After analyzing the results we notice that the change of the maximal load is so insignificant that it can be ignored. The coefficient of regression \( R^2 \) for equation (3) is determined to be 0.98485.

3 Conclusions

1. The FEM based 3D model of the corrugated paperboard has been proposed. The results obtained from this model have been compared to experimentally obtained data [3] and they show good coincidence. This gives us the chance to use the FEM for a more detailed study of the complex properties of the corrugated paperboard and how its parameters, components and geometrical parameters affect its resultant mechanical characteristics.

2. A study has been carried out to investigate how the change of the properties of the materials which are used to make individual layers affects the complex mechanical behavior of the corrugated paperboard. Such changes normally occur in conditions of changing environmental factors such as temperature and relative humidity.

3. The obtained results open the opportunity for the designers of packaging products to predict how the change of the properties of corrugated paperboard would affect the strength of the final products.

4. The investigation shows that the liners affect much stronger the complex characteristics of the corrugated paperboard than the flute, whose influence is almost insignificant. This is clearly seen by analyzing equations (1) and (3). The difference of the slope coefficients (0.12808 for equation (1) and 0.00146 for equation (3)) is approximately 88 times.

4 References


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