STUDYING OF THE COMPRESSION RESISTANCE OF THE CORRUGATED PAPERBOARD PACKAGE

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Abstract: The corrugated paperboard is the most used material for producing of a large variety of packages for almost every industry. The reason lies mainly in its low price, lightness and its potential for recycling. Despite of this, different international treaties and laws require the lowering of the quantity of material used for making one package. This brings the need for implying new and advanced approaches for designing one product so its mass is reduced while its quality and strength characteristics remain unchanged. Using models of packages based on the Finite Element Method (FEM) can give the designers the opportunity to examine the distribution of stress and deformation and implement changes in the products configuration until the optimal design is reached. The document presents one such model of a corrugated paperboard package which has been created and subjected to compressive loading. Then a real package with the same geometrical configuration as the model has been tested. The results from the real experiments and the values obtained from the FEM have been compared.
Key words: corrugated, paperboard, modeling, FEM, packaging

Introduction

Corrugated paperboard is a material which has been widely used in packaging industry throughout the years since it was first presented. For the past decade however, it has become preferred material for designers not only of packaging products. Advertising accessories, pieces of art, tools used in transportation of different stock items, small toys and miniature homes for pets, furniture, temporary shelters and many more [1,3,4,6,11]. On of the reasons for this expansion of its use lies in its low cost which comes from the low energy consumption, not complicated process of production and not expensive materials. Its lightness and sustainability options also serve in its favor.

On the contrary, this expanding usage of paperboard materials in general has its drawbacks. The production of cellulose-based materials brings damage to the biological diversity and ecological balance [2,5]. Tree plants are being destroyed in order to obtain the necessary raw material. Making of paper also requires usage of chemicals [7,8,12,13] which definitely are not harmless to the environment. Greenhouse gases are also being released to the atmosphere when the heat required for the production process is being obtained [2]. While paperboard is material that can be subjected to recycling, this itself is not a solution. Recycled paper is known to be less resistance to different force loads [9,10] which occur during the use of paperboard products such as packages. Constant supply of newly obtained cellulose fibers is required.

Taking this into account, various EU and world institutions have enforced regulations asking the manufactures of paperboard-based packages to lower the quantity of material they add in their products. Naturally this must not affect the quality characteristics of these products. There are many functions of one package but one of the most important is its protective function. A package must preserved the stored products from the harmful influence of the surrounding outside environment.

In the case of the corrugated paperboard boxes, they are mostly subjected to mechanical loads. They normally occur during transportation when the packages are placed one above another, forming a multileveled stack of individual boxes. Those on the lower levels are subjected to compressive loading coming from the weight of the upper packages. It is important ability of one corrugated paperboard package to be able to withstand these compressive forces which should not bring to its collapse which would cause damage to the stored items.

The ability of the boxes to withstand compressive loading is assessed by parameter widely known as BCT – Box Crush Test. It is determined by experiment having the same name. The BCT of a box depends on many factors. Most important ones are the mechanical properties of the corrugated paperboard which the package is made of and its geometrical dimensions and configuration.

The ability of the corrugated paperboard to resist compressive loads is assed by two characteristics. The FCT (Flat Crush Test) and ECT (Edge Crush Test). As with the BCT of boxes, these two parameters of the corrugated paperboard are determined by conducting experiments bearing the same names.

There is an equation known as McKee's equation [14] which makes it possible to calculate an approximate value of the BCT of one package if its length, width and height are known as well as the ECT and FCT of the used corrugated paperboard. This equation however, produces not accurate enough results leaving the engineers to take decisions based on their personal experience. This is why most of the packages contain much more material than it is necessary in order to meet the required strength characteristics.

More accurate determination of one BCT can be achieved by using advanced methods for enginery analysis. They include creating 3-dimensional models and using the finite element method (FEM) to obtain and study the distribution of stress and deformations. This will give chance to designers to be able to spot the weak areas of the designed products, imply on-time corrections in their geometrical configuration, change dimensions and add new elements if necessary until the optimal solution is found. This can lead to general optimization and lowering the amount of used material without affecting the strength properties of the packages. Shortening of the pre-production process can be also achieved which will result in further lowering of the cost of one single product.

In order to be able to build reliable models of the corrugated paperboard based on the FEM, the mechanical characteristics of this material must be studied.

Used specimens

Corrugated paperboard is a multilayered structure consisting most often of three layers. Two external flat layers which are called "liners" and one internal fluted layer known as "flute". Important geometrical parameters of the "flute" is the pitch "P" and the height "H". Based on these two parameters, world standards have divided the corrugated paperboard into several types [8]. The most common ones are the types C, B and E (also known as micro-corrugated paperboard).

Schematically this is shown on figure 1. On it, the MD, CD and ZD markings refer to the machine direction, cross direction and ZD-direction of the corrugated paperboard [7,8,12,13].

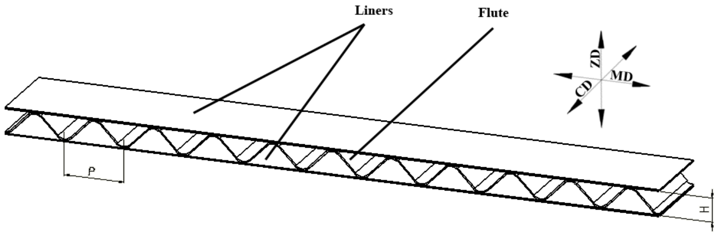

Fig 1 Schematic representation of the structure of the corrugated paperboard

In the present work, the corrugated paperboard which is used for the study is with the type of flute "C". For the purpose of ECT, rectangular specimens are cut. Their dimensions are 100 mm. length and 24 mm. height. The samples for FCT test are circular with diameter of 120 mm. All specimens are left at least 24 hours in the environment of 22,1° C and 24% relative humidity.

Fig 2 Samples of corrugated paperboard for ECT and FCT testing

Conducted experiments

ECT and FCT tests consist of placing the specimens between two plates. The bottom plate is fixed while the upper one is able to move vertically. Through it, a load is applied to the tested sample. The magnitude of this load F is measured along with the displacement S of the top plane of the specimen which is in contact with the upper plate. Those two parameters are represented in coordinate system and the dependency F(S) is therefore determined.

In the case of ECT testing the load is applied to be coincident with the cross direction of the corrugated paperboard (CD) and when FCT is performed the load is coincident with the ZD-direction (figure 1).

After processing the data from the experiments we are able to obtain the equivalent "stress – strain" curve of the tested corrugated paperboard, which is the aim of the experiments. They are shown on figure 3.

Those curves give us chance to determine important equivalent mechanical properties of this material which are afterwards used to simplify the FEM based models of packages. When creating such models, instead of having to build the complicated geometry of the multilayered structure which is the corrugated paperboard, it can be replaced by simple plate of equivalent homogenous material whose mechanical behavior would be the same as the one of the corrugated paperboard.

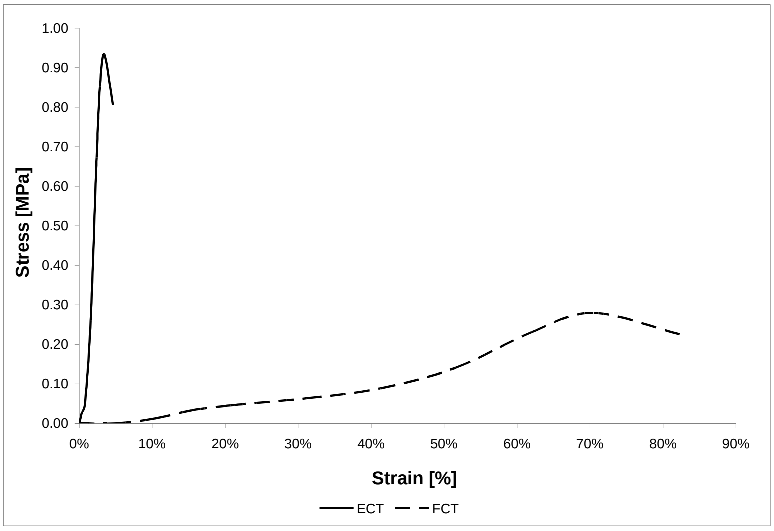

Fig 3 Obtained "stress – strain" equivalent curves from ECT testing and FCT testing of corrugated paperboard of flute type "C"

After the experiments done with corrugated paperboard samples, a box made of this material is subjected to BCT testing. The Box Crush Test is relatively similar to ECT and FCT. The tested specimen is placed between two plates. The bottom plate is fixed while the upper is able to move vertically. Through it a load F is applied on the box. Its magnitude is measured along with the displacement S of the top plane of the package which is in contact with the upper plate of the testing equipment. The loading continues until a drop in the magnitude of the force is registered while the displacement rises rapidly. This indicates that the walls of the box have buckled. The value of this maximal load is recorded in Newtons. Then it is divided by *g* to transform it into kilograms force equivalent. This newly obtained number becomes the BCT parameter of the tested box.

The recorded values for F and S are presented graphically and "load – displacement" chart of the box is obtained. It is shown on figure 4. The box which is tested is 385 mm. long, 255 mm. width and 390 mm. high. It is made of corrugated paperboard type "C" – the same paperboard which was subjected to ECT and FCT testing.

The chart which is shown on figure 4 has several distinguishable sections. At first we see a linear part of the diagram which is relatively flat, having very small slope. The reaction force of the box is rising by only 1,972 kgf per 1 mm of displacement. This is due to the fact that in these initial moments the compressive load is being absorbed by the top and bottom panels of the box. The corrugated paperboard there is subjected to compressive force whose direction is coincident with the ZD-direction of the paperboard. We can see from the chart on figure 3 the much lower slope on the "stress – strain" curve of the corrugated paperboard when it is subjected to that type of loading.

The next section we notice on the diagram on figure 4 is the curved transitional part followed by another linear area with much higher slope. The reaction force of the box there is rising rapidly by 40,11 kgf per millimeter of displacement. Here the load is absorbed mostly by the side walls of the box. They are being subjected to compressive loading whose direction is coincident with the CD of the corrugated paperboard.

This linear section is followed with curved part which is the end of the chart. This is where the package becomes unstable and then collapses. For the tested specimen the buckling occurred at 209,08 kgf – the last point of the diagram.

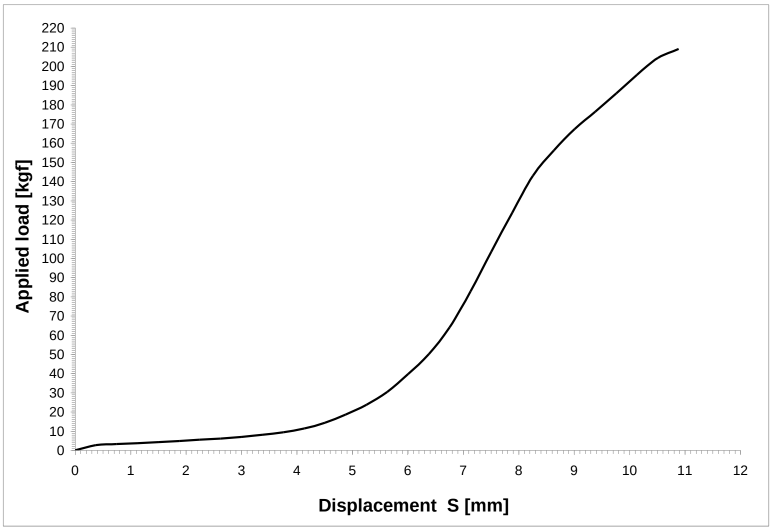

Fig 4 "Load – displacement" chart obtained from BCT testing of a box

FEM based model

After the experiments are being done, a 3-dimensional model of the tested box is built. It has the same dimensions as the used specimen. In order to mesh it, *Shell* elements are used which have 9 nodal points and six degrees of freedom are considered at each node. The mesh itself consists of 2322 elements and 6762 nodes.

The loading conditions are chosen to be the same as in the real experiment. Rigid fixtures are defined on the bottom plane and the loading force is applied on the top plane. Its magnitude rises in steps by 7,75 kgf.

After the process of calculation is over, the results are examined. The BCT value of the 3D model is estimated to be 205,30 ±3,87 kgf. The difference between this number and the one obtained experimentally is 1,81%.

Conclusions

Through experimental research important equivalent mechanical characteristics of the corrugated paperboard have been determined. This provides the opportunity to create FEM based 3-dimensional models of products that are made of this material.

The obtained equivalent "stress – strain" curves of the corrugated board when subjected to loading in different dimensions have been studied. They show significant difference in its behavior under same loading conditions.

The relation between the loading and deformation on a box subjected to compressive loading is obtained. Its examination gave more detailed information on the force absorption by the elements of the package on different stages.

Three-dimensional FEM based model on the package was developed. The data which were obtained by this model and those taken experimentally were compared. Good coincidence between the numbers was achieved. This leads to the conclusion that the FEM based models could be successfully used as a way to optimize the configuration on the existing packages. This could lead to lower quantities of used material but preserving their key quality parameters.

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