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Modelling of Corrugated Paper Board Boxes with FEM

The main aim of this project is the comparison between the experimental and FEM results of loaded corrugated paper boards. The corrugated paper boards have an orthotropic material behaviour, which means that the boards, depending on the direction of the corrugation, have different modules of elasticity. The research should give results about theses different material data of the plates. These results are the basis for further product designs with corrugated paper boards.

Keywords: *corrugated paper board, FEM*

1. Introduction

Cardboard can be used in many different ways. Especially cardboard is used in the packaging industry as protection for transport and stocking goods. In Europe, estimated 7 million tons of corrugated papers are produced every year [1].

In construction engineering corrugated paper boards are seen as the material of the future (Fig. 1.).

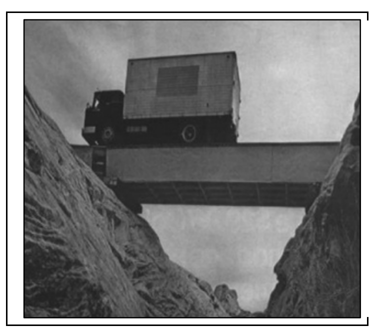

Figure 1. Corrugated paper boards bridge with a length of 10m [2]

Corrugated paper boards are plates with orthotropic material behaviour that means that the cardboard possesses different mechanical properties for each direction of the axes, contrary to materials with isotropic behaviour, whose material properties are independent from the direction.

The orthotropic results from the corrugations of the carton. Depending on the direction of the corrugation, the boards have a different module of elasticity.

But to ensure a correct and successful finite element simulation with models, which have an orthotropic behaviour, several material properties are needed.

Unfortunately, it turns out to be quite difficult and complex to measure and determine these mechanical properties. At the moment, it doesn't exist many information in the world literature about the material behaviour of corrugated paper boards. The shear modulus, for example, is independent from the modulus of elasticity and needs to be determined separately. Compared to isotropic material, the shear modulus can be calculated, if the modulus of elasticity and the Poisson's ratio is known.

For the experiments, triple wall corrugated boards (corrugation description: ACA) were used due to their high stiffness.

2. Bending tests and FEM simulations

To determine the different modules of elasticity for the different directions, several bending test were done with the corrugated paper boards. One end of the plate was fixed, the other one stayed free. (Fig.2).

The deformations were measured on two different points of the plate by dial gauges. These bending tests have been done in corrugation direction, and then crosswise to the corrugation direction. Afterwards the measures were evaluated into stress-strain charts.

On the basis of the measured deformations and the beam theory, the bending stiffness was calculated. In order to simplify the calculations for the moment of inertia, the cross sectional area of the corrugated paper boards are supposed to be rectangular with a height of 13.5mm.

Afterwards, the respective modules of elasticity were determinated.

But in reality, the corrugated paper boards have neither a rectangular cross sectional area nor behaviour as a beam element. Therefore a finite element model with shell elements was created and simulated with the same bending situation (Fig. 5.). The deformations of the simulation and of the bending test were compared and if necessary, the module of elasticity has been adjusted.

For the bending experiments, the determined data for the module of elasticity in x-direction (Fig. 6.) is E_x=221MPa and the module of elasticity in the corrugation direction (y-direction) is E_y=135MPa for the corrugated paper boards.

Figure 2. The fixation of the plate

Figure 3. Loads on the corrugated paper board

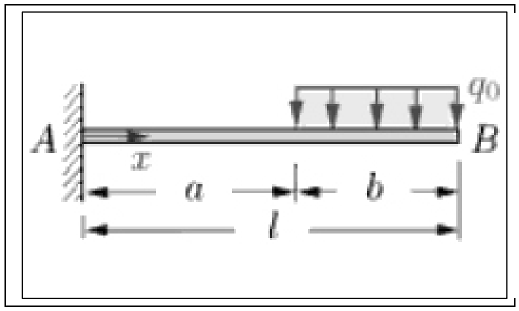

Figure 4. Kind of bend [3]

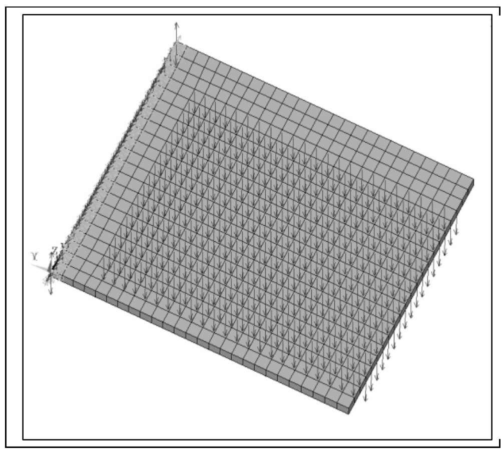

Figure 5. FEM Model

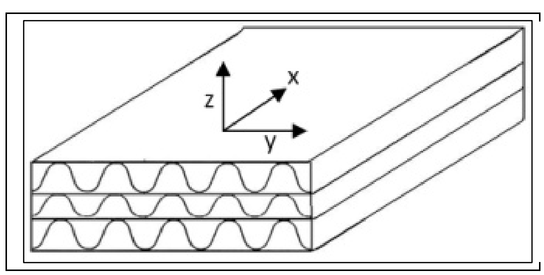

Figure 6. Coordinate system used (in the y direction is the wave propagation)

3. Calculation of the cross sectional area of the corrugated paper boards

Because of the simplification of the cross sectional area as a rectangular area for the bending test and simulations, a more detailed cross sectional was calculated. The corrugation of the cardboards was supposed to be sinus waves.

In most instances, the different dimensions of the plates, like the height of the corrugation were known from the manufacturer. Otherwise, if a dimension wasn't indicated, it was measured. The thickness of the outer and inner plates was measured as well.

By the help of the integral:

$$\int_0^a \sqrt{1+\left(\pi\,\frac{b}{a}\,\cos\left(\frac{2\pi}{a}x\right)\right)^2}\,dx \tag{1}$$

with a as the period length and b as the double amplitude of the respective waves of the corrugation), the sprawled length of the corrugation were determined and multiplicated with its thickness to obtain the cross sectional area.

The complete cross sectional area plays an important role in order to determine the strength durability, respectively the tensile strength (R_m) of the corrugated paper boards.

4. Determination of the tensile strength and module of elasticity through tensile tests

In addition, several tensile tests were done with the corrugated paper boards. From the measured data of the tests, load-displacement diagrams were created.

Because of the uneven progress of the load-displacement graph for the stress crosswise to the corrugation direction (Fig. 6., x-direction), an interpolation function for the graph was generated. By the help of this function, an initial module of elasticity for the corrugated paper boards for stress crosswise to the corrugation direction was calculated (E_x =276MPa).

The resulting load-displacement diagram of the tensile test in corrugation direction (Fig. 6. y-direction) indicates an linear slope and an module of elasticity (E_y) of 393MPa.

With the calculated cross sectional areas of the boards and the knowledge of the amount of load they could resist before they rupture, first conclusions about the fracture strength or rather the tensile strength could be made for the different orientations of the corrugation ($R_{m\,x}$ = 15MPa and $R_{m\,y}$ = 38MPa).

For the calculation of the tensile strength crosswise to the corrugation direction (Fig. 6. x-direction), the complete cross sectional area was taken. But for the tensile strength ($R_{m\,y}$) in corrugation direction, the corrugation were neglected and only the plates were taken for the calculation of the cross section, because the corrugation does not keep a constant area over the whole length of the board.

Paradoxically, in x-direction the cross sectional area is higher (four plates and three corrugation layers) than in y-direction, but the tensile strength in x-direction ($R_{m\ x}$) is 40% lower than in y-direction. This behaviour could be explained in the following way [4]:

Generally, the stiffness in fiber orientation is quite higher than crosswise to the fiber orientation and the corrugated paper boards have paper layers with fiber orientation in corrugation direction. Therefore, the cardboards are stiffed in both directions: One the one hand through the higher tensile strength from the paper layers with their fiber orientation in y-direction and on the other hand by the higher from the corrugation between the layers in x-direction.

The corrugation with their porous composition between the paper layers doesn’t have the task to carry tensile forces, but to assure the distance between the respective paper layers in order to etablish a high moment of inertia.

5. Determination of notch effect for corrugated paper board

In order to get an idea of the influence due to the notch effect for corrugated paper boards, some further simulations with FEM were done. For this purpose, a plate with semicircular notches in the middle of the longitudinal sides was modeled. The plate was meshed with solids elements and loaded with a tensile stress.

The highest stress value appeared, as assumed, in the notches. Around the notches the discretisation needed to be very fine to get an acceptable convergence for the calculation values. When a tensile load of 1 MPa was applied on the end of the plate, the received maximal stress in the notches corresponded to the notch effect. By decreasing the radius of the notch, the maximal stress increased slightly. The obtained results are listed in the table below. The difference of the values are smaller than they are for isotropic behaviour.

Table. 1.

Notch effect for tensile stress	E_x [Mpa]	E_y [Mpa]
- in x-direction	276	393
- in y-direction	393	276

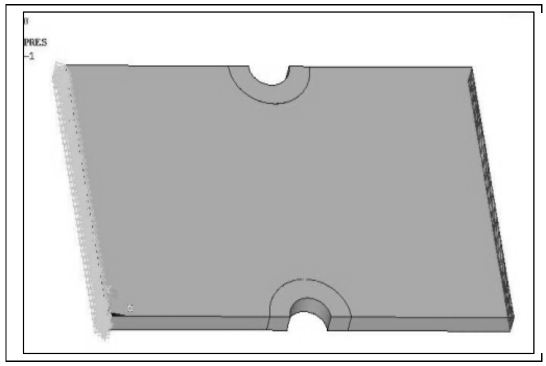

Figure 7. Model with notches

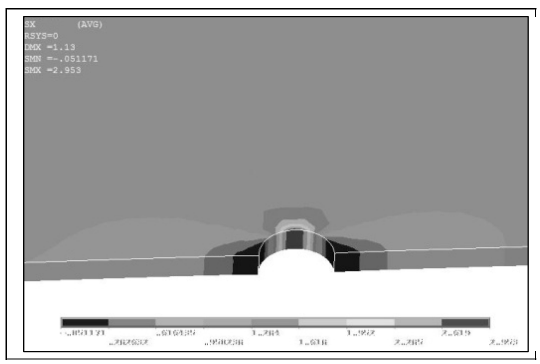

Figure 8. FEM analyzis for the model with notches

6. Conclusions

As a conclusion, it can be said, that it is possible to determine values for the module of elasticity. In the bending tests, the determined modules of elasticity are E_x = 221MPa and E_y = 135MPa.

For the tensile tests, the modules of elasticity for the corrugated paper boards are E_x = 276MPa and E_y = 393MPa. But the module of elasticity in corrugation direction (E_y) is three times higher for the tensile test compared to the results of the bending tests. Maybe the fiber orientation is stiffer against tensile stress as against bending stress.

By the help of the tensile tests, it is also possible to determine the tensile strength of the corrugated paper boards. The results were $R_{m\,x}$ = 15MPa and $R_{m\,y}$ = 38MPa.

Besides, through FEM simulations, first predications could be made for the notch effect of cardboards. But it would be advisable to do further experiments with cardboards instead of simulations to obtain better results for the notch factor. In reality, the notch factors should be smaller than the simulated ones, because the plastic deformation of the notch reduces a part of the stress.

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