Experimental Characterisation and Finite Element Modelling of Paperboard for the Design of Paperboard Packaging

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Abstract. In this work, tensile tests were first conducted on the paperboard. Then, the in-plane orthotropic elastoplastic model (IPE-Isotropic Plasticity Equivalent model) was implemented in Abaqus software. The advantage of this model lies in its capability to describe the in-plane anisotropic behavior of paperboard by a limited number of material constants. The calibration procedure was handled by inverse identification method on tensile tests. The model was shown to predict satisfactorily in-plane stress-strain behavior for different orientations. Box compression tests (BCT) were conducted to investigate the performance of the implemented model. The predicted deformed boxes and force-displacement curves were compared to the experimental ones, displaying a good agreement.

1. Introduction

Paperboard is one of the most frequently used material for packaging due to its beneficial characteristics, such as low price, sustainability, and recycling. It is used to design containers to protect the product from hazards of the distribution, transportation and storage environment so that the product can be shipped to consumers without damage. The package performance relates the load during transportation or order to accurately protect the goods. It can also relate to the behavior during consumer contact. Mechanical tests, which offers prompt verification of structural strength in the product design stage for deciding whether proper buffering is required in the packing design, is one of crucial items for validating the design. Therefore, the package should be designed such that it performs well. In recent years, many authors have studied the mechanical properties of paperboards by using in-plane tensile tests, short compression tests, creasing tests, folding tests and bending tests [1-12,19]. These studies have shown that mechanical properties of the paperboards depends on many factors such as thickness of paperboard, the direction of bending (MD, CD). Thereby, it highlights the most important mechanical properties is bending stiffness, which is directly related to the mechanism of failure in paperboard. The results of these studies also indicated that crack length, crack propagation and delamination are the typical forms failure of paperboard. It is the main cause of the reduction of the mechanical properties of the paperboard when bending, folding and creasing.

Using finite element simulations allows avoiding numerous experimental tests and predicting possible failures during the early design stage [18]. However, to get results close to the experimental ones, we need to know precisely the mechanical behaviour of the material. Paperboard is an anisotropic material. In the process of converting paperboard into a functional container, the paperboard undergoes large deformations. Mäkelä and Östlund [13] proposed an orthotropic elastoplastic model for in plane stresses (IPE-Isotropic Plasticity Equivalent model) to accurately describe the behavior of paperboard. The parameters in the model are determined from simple tests. This model was implemented in Abaqus software using the user subroutine VUMAT [14]. Material parameters were
determined by inverse method: finite element simulations of the tensile tests in MD, CD and 45° are used, and the parameters are varied systematically until agreement between simulations and experiments is achieved. To validate the identified model, we have developed a finite element model for the box compression test (BCT). The simulation results were then compared to the experimental ones.

2. Anisotropic Elastoplastic Behavior Model of Paperboard

Paperboard consists mainly of wood fibers with three components: cellulose, hemicellulose and lignin. The board used in the construction of a carton is an orthotropic material. The production of its layers, the paper fibres adopt a preferred orientation, giving three characteristic directions: the machine direction (MD), the cross direction (CD), and out-of-plane direction (ZD). In this study, we used paperboard with a grammage of 320 g/m² and thickness is 0.51 mm

The in-plane properties of paperboard are relatively easy to determine by tensile tests. Due to its low thickness, out-of-plane properties are more difficult to obtain. Stenberg [15] showed that the Young’s modulus along normal direction (ZD) is about 200 times lower than that of MD. Stenberg et al. [16] observed that the deformation in the plane is negligible during the compression according to the thickness. The Poisson coefficients $v_{xx}$ and $v_{yy}$ consequently are close to zero.

In this study, we used the IPE model [13] to describe the behavior of paperboard. The orthotropic elasticity behavior in plane stresses is defined by:

$$\{\sigma\} = \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix} = \begin{bmatrix} H \end{bmatrix} \{\varepsilon\} = \begin{bmatrix} 1 \\ (1 - v_{xy}) \end{bmatrix} \begin{bmatrix} E_x & v_{xy}E_x & 0 \\ v_{xy}E_y & E_y & 0 \\ 0 & 0 & G_{xy}(1 - v_{xy}) \end{bmatrix} \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_{xy} \end{bmatrix}$$

The deviatoric stresses vector and the IPE plasticity criterion are given by:

$$\{s\} = [L] \{\sigma\} = \begin{bmatrix} 2A \\ C-A-B \\ 3B-C-A \end{bmatrix} \begin{bmatrix} \sigma_x \\ \sigma_y \\ \sigma_{xy} \end{bmatrix}$$

$$f = \sigma_{eq} - Y = \left(3 \frac{\langle \varepsilon \rangle}{4} \langle \varepsilon \rangle \right)^{1/2} - E_0 \left(\varepsilon_{eq} + \varepsilon_{eq}^p \right)^n = 0$$

where $Y$ is the yield stress, $A$, $B$, $C$, $D$, $E_0$, $\varepsilon_0$, $\varepsilon_{eq}^p$, $n$ are the parameters of the IPE model that can be determined using experimental tests.

This IPE model was implemented in the ABAQUS software using the VUMAT user subroutine.

3. Inverse identification of the anisotropic elastoplastic behavior of paperboard

Standard specimens were made using a cutting table (ZÜND M-1600). To ensure a better grip in the jaws when clamping the specimen, we glued pieces of rigid cardboard at both ends of the test specimens. Experimental tensile tests were carried out for three directions (MD, CD and 45°) at a crosshead speed of 10 mm/min under standard conditions (23°C and 50% relative humidity). The experimental tensile results are shown in figure 1.

To identify the parameters $(A, B, C, D, E_0, \varepsilon_0, \varepsilon_{eq}^p, n)$, an inverse method was used: finite element simulations of the tensile tests in MD, CD and 45° are run, and the parameters are varied systematically until agreement between simulations and experiments is achieved. The objective function minimized is the quadratic difference between the numerical and the experimental tensile forces:

$$F_{obj} = \frac{1}{N} \sum_{i=1}^{N} \left(F_{num}(t_i) - F_{exp}(t_i)\right)^2$$

(4)
where \( N \) is the number of data set, \( t_i \) denotes the time of the corresponding experimental point \( i \) and \( F_{num} \) and \( F_{exp} \) are the forces numerically computed and experimentally measured, respectively.

\[
\begin{align*}
\text{Figure 1. Force-displacement curves from tensile tests of paperboard.}
\end{align*}
\]

In this study, we used the genetic optimization algorithm MOGA-II to minimize the objective function in equation (4). Figure 2 shows the experimental and numerical curves obtained by identification of the IPE model, and table 1 summarizes the parameters identified for paperboard.

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\begin{align*}
\text{Figure 2. Experimental traction curves and identified for paperboard.}
\end{align*}
\]

\[
\begin{align*}
\text{Table 1. Parameters of IPE model identified for paperboard.}
\end{align*}
\]

| \( E_x \) (MPa) | \( E_y \) (MPa) | \( \nu_{xy} \) | \( G_{xy} \) (MPa) | \( E_0 \) | \( n \) | \( A \) | \( B \) | \( C \) | \( D \) | \( \varepsilon_0 \) |
|----------------|----------------|--------------|----------------|---------|------|-----|-----|-----|-----|-------|
| 3710           | 1559           | 0.36         | 1200           | 301     | 2.31 | 1.0 | 2.04 | 2.48 | 1.08 | 0.0046 |
4. Finite element model of box compression test (BCT)

A finite element model of the box, whose drawing is shown in figure 3, was created using ABAQUS software. This model used to simulate compression behaviour of the box was meshed with reduced-integration four node shell elements (S4R) with 1 mm element size. The actual process of converting paperboard into a functional container includes a number of operations such as creasing to reduce resistance to bending and folding. It leads to the possibility of material damage such as loss of hardness, crack propagation and delamination of layers in paperboard [1-4, 6, 9]. The interlaminar bond strength is typically reduced by up to 80 per cent [17]. The creases then act as hinges, which encourage the board to fold into three-dimensional structures.

To compare the simulation results with experimental ones, boxes were made using a cutting table (ZÜND M-1600). The boxes were cut to have compression axes along MD and CD directions. The boxes were subjected to compression tests at a crosshead speed of 10 mm/min under standard conditions (23°C and 50% relative humidity).

Figure 4 shows the comparison of BCT experimental and numerical results for MD and CD oriented boxes. The numerical curves are in good agreement with the experimental ones. As expected, the maximum load bearing capacity of the box ($F_B$) is higher for MD-oriented box. Figures 5 and 6 show the experimental and numerical deformed boxes at maximum load bearing capacity of the boxes ($F_B$). For both boxes, the load is concentrated in narrow zones along the corners. However, the stresses on the MD-oriented box ($\sigma_{\text{max}} = 79.5$ MPa) are higher than those on the CD-oriented box ($\sigma_{\text{max}} = 59.0$ MPa).

![Figure 3. Drawing of the studied box.](image-url)
Figure 4. Comparison of BCT experimental and numerical results: MD (Left) - CD (Right).

Figure 5. Comparison of experimental and numerical deformed MD-oriented box at $F_B$.

Figure 6. Comparison of experimental and numerical deformed CD-oriented box at $F_B$. 
5. Conclusion

In this paper, we have implemented an orthotropic elastoplastic model for in plane stresses (IPE - Isotropic Plasticity Equivalent model) in Abaqus software using the user subroutine VUMAT. We have developed an inverse identification procedure by coupling the Abaqus finite element software and an optimization procedure to identify the material parameters of the paperboard. Box compression tests (BCT) were carried out to validate the identified model. The finite element model compares well with the experimental results in terms of maximum load bearing capacity and deformed shapes of the boxes.

6. References

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