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# Finite element analysis of paperboard package under compressional load

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#### Abstract

Paper and paperboard based packages are widely use in domestic storage and commercial transportation applications. However, the structural integrity of the packages can be damaged with the applied compressional load. The stacking of boxes one above the other or the external load deform the thin wall of paperboard package. Moreover, the packages are also locally creased to enhance the folding. The folded edge also provide support against the deformation of the package. In this article, the effect of compressional force on paperboard packages was analyzed with the aid of finite element analysis. Two packages with and without crease were modelled and their elastic limits, stress distribution was compared. The creases were applied using hinge connectors restricting 5 degrees of freedom. Only the rotational motion is allowed that assist the folding of paperboard. The paperboard is modelled as an orthotropic elastoplastic material. The plastic behavior was defined with Hill's yield criteria and isotropic hardening. The Eigen value analysis was performed to determine the critical forces and the buckling. The results obtained from finite element analysis show that the package with creases resist the total strains and stresses compared to the package without creases and theoretical calculations were close to the calculated values.

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Keywords: Paperboard; finite element method; creases; critical load; plasticity

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#### 1. Introduction

Paperboard packages are consider as a mean of protection from physical hazards, information provision and advertisement of the product. However, the most of the products transportation were done in paperboard based packages. The compressional loading issue is of in sight when the packages are placed above the other. The external loading on the base package with low compressional strength can collapse the structure and lead to the product damage. The increase demand of paperboard packages induce to fulfil the compatibility of today's requirement. Therefore, the material and structural properties need to be optimized. The load distribution under the compressional forces are presented in Fig. 1. Another reason to select the paperboard material over plastic or metal packages is the recyclability, biodegradability, inexpensive, high strength to weight and stiffness to weight ratio.



Fig. 1. The load distribution subjected to the compressional loading [1].

The box compression resistance is a traditional method to measure the mechanical strength of the package. It gives the estimation of the load a box can carry. Other factors such as vibrational loading, creep and climate are also influence the integrity of the box. For example, when the boxes are loaded for a longer period of time in a warehouse. The maximum load that a box can carry before damage is less due to creep. The factor of climate and vibrational loading have a strong influence on the strength properties during the transportation [2].

Numerous studies have been done to address the issue the damage of paperboard package. Erikkson D et al [2] investigated the carton board package damage under concentrated loads. He specifically studies the damage process and package collapse loads in laboratory scale. The results show the damage development at the crease and the associated peak at force displacement curve. The converting of paperboard with creases was studied by Awais M et al [3], who investigated the press forming model and novel crease approach to analyze the crease behavior. The elastoplastic model of paperboard was used and the results show that the creases reduce the bending stiffness of the paperboard in an in plane compression and enhance the convertibility. Nordstrand T [4] studied the critical buckling of orthotropic linear elastic sandwich plate including the transverse shear. The inclusion in the governing equilibrium equations of the moment gives the buckling coefficient which approaches to infinity when the aspect ratio goes to zero. The results were also complemented by the simulation and experimental studies.

The recent study of paperboard boxes damage under compressional load includes the novel crease model as hinge connector and the results were compared with the uncreased paperboard box. The elastoplastic material model represents the material behavior and default setting were used for the hinge connector. The finite element model is simulated using the commercial software Abaqus. Moreover, the effect of buckling is also included. The critical loads and stresses were calculated and compared with the uncreased package. The proposed model will give the detailed overview of the compressional loading of paperboard in our daily life applications.

#### 2. Finite element model

### 2.1. General overview

The finite element analysis was done using the commercial software Abaqus. The model comprises of the deformable plates joined with hinge connectors, see Fig. 2 (b). To reduce the computational time, the plate of 30\*30 mm was modelled. The S4R shell elements were used with the thickness of 0.414 mm. Moreover, a discrete rigid plate was fixed below to support the loading. The material directions were allocated machine direction as x-axis, cross direction as y-axis and out the plane as z-axis to the reference plate. The directions was changed as the box rotated. The influence of mesh refinement was also included.



Fig. 2. Geometric model of paperboard box with creases at the edges

# 2.2. Creases

The basic idea behind the crease approach was to interpret the folding mechanism of creased paperboard. In reality, the creases locally deform the material (shear deformation) and assist the folding of paperboard. Therefore, a hinge connector allowing the rotation along one axis and restricting the rest of the 5 degree of freedoms defines the basic mechanism, see Fig. 3. Paperboard was finely meshed and two nodes small offset were connected with hinges. The default stiffness values were established for the creases. In other words, node A and B are connected in such a way that together they can be translated in x, y and z directions but locked with reference to each other. The similar idea was presented by Amigo [5].



Fig. 3. Hinge connector and interpretation with crease folding [5].

#### 2.3. Material model

The total strain rate is the combination of elastic and plastic part in classical elastoplastic material model. The elastic strain is directly proportional to the stress is given by

$$\varepsilon^e = \boldsymbol{D}\boldsymbol{\sigma} \tag{1}$$

where **D** is the symmetric compliance matrix. The plastic strain can be defined as

$$\varepsilon^p = \lambda \frac{\partial f}{\partial \sigma} \tag{2}$$

Where the  $\lambda$  is the plastic multiplier and f is the yield function. The plane stress state compliance matrix for orthotropic material is given by

$$\boldsymbol{D} = \begin{bmatrix} 1/E_x & -\nu_{yx}/E_y & 0\\ -\nu_{xy}/E_x & 1/E_y & 0\\ 0 & 0 & 1/G_{yy} \end{bmatrix}$$
(3)

where  $E_i$  are the elastic moduli in the principal material direction,  $G_{ij}$  is the shear modulus and  $v_{ij}$  are the Poisson's ratio. The Hill's yield function can be defined as [6]

$$f(\sigma) = \sqrt{(G+H)\sigma_{xx}^2 + (F+H)\sigma_{yy}^2 - 2H\sigma_{xx}\sigma_{yy} + 2N\sigma_{xy}^2}$$
(4)

where F, G, H and N are material constants. The yield condition for linear isotropic hardening is given by

$$f(\sigma) = \sigma_o + K\alpha \tag{5}$$

where  $\sigma_o$  is the reference yield stress, K is the isotropic hardening modulus and  $\alpha$  is the hardening variable.

The simulations were performed the classical elastoplastic constitutive model including Hill's yield criteria and isotropic hardening. The properties of ply was determined from literature. Huang [7] determines experimentally the material parameters of individual plies. The material parameters are presented in Table 1.

Material parameters	Middle ply properties	
$E_x$	3203	
$E_y$	1233	
$G_{xy}$	638	
$v_{xy}$	0.47	
F	4.24	
G	0.50	
Н	0.50	
Ν	1.39	
$\sigma_o(MPa)$	22	
K(MPa)	3203	

Table 1. Material constant of paperboard with grammage 356 g/m<sup>2</sup>

# 3. Simulation results

#### 3.1. Total In-plane principal strains

In Fig. 4, the total strains of the boxes with and without creases are compared. The paperboard packages were displaced from the top to1.5mm corresponds to the 5% of the total height. The package with creases have low total strain compared to the box without creases. It is clear from the results that creases enhance the compressional properties of the package by reducing bending stiffness in folding direction and increasing stiffness in perpendicular direction.



Fig. 4. LE total strains of paperboard package (1) creased (b) uncreased.

#### 3.2. Von Mises stresses

Similarly, in Fig. 5 the Von Mises stresses of the packages with and without creases are compared. The stresses in uncreased paperboard package are more localized at the edges and indicate the capability to damage as the load increases.



Fig. 5. Von Mises stresses of paperboard package (a) creased (b) uncreased

#### 3.3. Reactional force

In Fig. 6, the reactional force against the displacement was calculated to estimate the maximum force on package before the plastic deformation. The force increases initially until it reaches the maximum value. Then, there is a sudden decrease in force indicate the limit of elastic point. In plastic region, the force is nearly constant.



Fig. 6. Reactional force (N) against the displacement.

# 3.4. Effect of mesh size

The effect of stresses and the refinement of global mesh was also simulated and compared. The global mesh size of 2, 5, 10 and 20 was modelled and its effect was mapped against the element size, see Fig.8.The total displacement in this case was 10mm. The results show that finer mesh size demonstrate more localized stresses, see Fig. 7.



Fig. 7. Mesh refinement (a) Global size 2 (b) Global size 5 (c) Global size 10 and (d) global size 20.



Fig. 8. Maximum reactional force against element numbers

#### 3.5. Eigen Values calculation

The Eigen values analysis was done to evaluate the buckling and critical load bearing capacity of paperboard package. Packages with different dimensions were modelled and their respective critical load were measured, see table 2. Later, the values were compared with the theoretical values and the nature of the curve was similar, see Fig. 9.

Table 2	Critical load values of different dimension packages				
	Length (mm)	Width (mm)	Height (mm)	Critical load (N)	
	100	100	100	51.4	
	100	100	200	41.7	
	100	100	300	39	
	150	100	100	44	
	200	100	100	43.5	
	300	100	100	51	



Fig. 9. Critical load calculation of different geometries.

#### 4. Conclusion

A finite element model of paperboard packages was developed to study the effect of effect of stresses and strains distribution. Moreover, different geometries were adopted to evaluate the critical load and buckling. The paperboard was modelled as orthotropic plastic material. The effect of creases was also compared with the uncreased package. It was found that the creases enhance the load bearing capacity of the packages. The uncreased box shows more localized stresses that lead to permanent damage. The global mesh size effect was also simulation reveal the optimized critical load. It is concluded that the developed finite element model can estimate the load carrying capacity with sufficient accuracy. The simplest approach was used to reduce the computational time and complexity.

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