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Research Paper

Application of finite element analysis to predict the mechanical strength of ventilated corrugated paperboard packaging for handling fresh produce

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ARTICLE INFO

Article history:
Received 5 April 2018
Received in revised form
26 July 2018
Accepted 30 July 2018

Keywords:
Ventilated paperboard packaging
Finite element analysis
Package
Produce
Box compression test

The presence of vent holes in corrugated paperboard package causes material loss of the package, which compromises its strength and stability. To improve the structural design of fresh produce packages, it is important to understand the response of packages when subjected to various types and combinations of mechanical loads. This study aimed to develop a validated finite element analysis (FEA) model to study the structural behaviour of commonly used ventilated corrugated paperboard (VCP) package when subjected to compression load by considering the geometrical nonlinearities of the packages. Two package types were used: a control package without vent holes and standard vented packages. The FEA model accurately predicted the compression strength of the corrugated paperboard, control package and standard vent package. When compared with experimental results, the model predictions for the VCP package were within 10%. Compression strength of the standard vent packages were found to be linearly affected by paperboard liner thickness. Increasing and decreasing the baseline liner thickness of the standard vent package by 80% resulted in an increase and decrease in compression strength by about 15% and 19%, respectively. From the contact FEA model, maximum Von Mises stress was produced at the corners of the package. Von Mises stress was reduced by about 25% on changing the friction coefficient from 0 to 0.1. This study provides empirical evidence for package designers on how to improve the mechanical integrity of packages while at the same time aiming to maintain an optimum ventilation.

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https://doi.org/10.1016/j.biosystemseng.2018.07.014
1537-5110/

Nomenclature

BCT	Box compression test
CD	Cross direction
ECT	Edge compression test
FCT	Flat crush test
FEA	Finite element analysis
MD	Machine direction
RH	Relative humidity
VCP	Ventilated corrugated paperboard
ZD	Thickness direction
E_{MD}	Elastic modulus in the machine direction [MPa]
E_{CD}	Elastic modulus in the cross direction [MPa]
E_{ZD}	Elastic modulus in the thickness direction [MPa]
υ_{xy}	Poisson's ratio in the MD–CD plane [non dimensional]
υ_{xz}	Poisson's ratio in the MD–ZD plane [non dimensional]
υ_{yz}	Poisson's ratio in the CD–ZD plane [non dimensional]
G_{xy}	Shear modulus in the MD–CD plane [MPa]
G_{xz}	Shear modulus in the MD–ZD plane [MPa]
G_{yz}	Shear modulus in the CD–ZD plane [MPa]
K	Stiffness of the structure [N m^{-1}]
P	Preset load [N]
P_{cr}	Critical load [N]
D	Total deformation [m]
λ	Eigenvalue
ϕ	Buckling mode

1. Introduction

The packaging of horticultural produce such as fresh fruit remains vital and crucial particularly for products with long and complex journeys from growers to consumers and over the years, the development of horticultural packages has itself become a rapidly growing industry (Berry, Fadiji, Defraeye, & Opara, 2017; Biancolini & Brutti, 2003; Fadiji, Coetzee, Chen, et al, 2016; Fadiji, Coetzee, & Opara, 2016; Fadiji, Coetzee, Pathare, et al, 2016; Giampieri, Perego, & Borsari, 2011; Opara & Fadiji, 2018). Packaging provides an economic means of minimising damage and protecting packed produce during distribution. Adapting packaging as an integral part of both internal and external part of the distribution system, makes the reduction of distribution costs possible (Fadiji, Coetzee, & Opara, 2016; Jarimopas, Singh, Sayasoonthorn, & Singh, 2007; Robertson, 2012). A good packaging system should be able to protect the products, be manufactured with minimal materials and tested to prove its optimum performance. Efficient, economical, and reliable packaging is a necessity during storage, transportation and distribution as it is an essential link between the producer and the end users (consumers) (Opara & Fadiji, 2018; Paine, 2012). Unless sound delivery of the product is achieved, the quality and the reliability of a product during production and manufacture will be wasted. Satisfaction of the consumer with quality product is thus the main objective of the handling, production, storage and distribution of fresh horticultural produce (Fadiji, Coetzee, Chen, et al, 2016; Fadiji, Coetzee, & Opara, 2016; Fadiji, Coetzee, Pathare, et al, 2016; Opara & Pathare, 2014; Pathare & Opara, 2014). Increasing consciousness of the intricacies of packaging, together with the competition in this rapidly growing industry are some of the driving forces towards achieving lighter, more economic, and reliable packaging and this requires substantial investments in the development of new technical solutions (Fadiji, Berry, Coetzee, & Opara, 2018; Giampieri et al., 2011; Robertson, 1993, 2012). Furthermore, the reliability of packaging is extremely crucial in the food industry (Kibirkštis, Lebedys, Kabelkaitė, & Havenko, 2007; Mahalik & Nambiar, 2010).

In the packaging industry, particularly horticulture, paperboard is one of the most widely used materials since it can be easily converted from a flat configuration into a solid box shape (Csavajda, Böröcz, Mojzes, & Molnár, 2017; Fadiji, Coetzee, & Opara, 2016; Giampieri et al., 2011; Gilchrist, Suhling, & Urbanik, 1998). The most important structural application of paperboard is through corrugated paperboard packages (Biancolini, Brutti, & Porziani, 2009; Csavajda et al., 2017; Fadiji, Berry, et al., 2018; Han & Park, 2007; Talbi, Batti, Ayad, & Guo, 2009; Zhang, Qiu, Song, & Sun, 2014). Corrugated paperboard packages are usually light but very stiff with the ability to sustain significant loads (Giampieri et al., 2011). Corrugated paperboard is an orthotropic sandwich structure defined by the two surface pliers known as liners, separated by a lightweight corrugated core known as fluting (Fig. 1) (Navaranjan & Johnson, 2006; Nordstrand, 1995). The liners provide bending stiffness to the board while the fluting provides shear stiffness (Dongmei, 2009). The liners are usually joined with the fluting using a starch-based adhesive to form a single wall corrugated board (Fig. 1). The linerboards are usually made from test liners (recycled paper) or Kraft paperboard (of various grades) which may be bleached white, mottled white, coloured, or pre-printed (Zhang et al., 2014). The corrugated paperboard is characterised by two main principal (in-plane) directions. The first direction is the machine direction (MD) which is the machining direction, coincides with the paperboard fibre alignment and is perpendicular to the principal axes of the corrugations. The second direction is the cross direction (CD) corresponding to the transverse direction and parallel to the corrugation axes. A third (out-of-plane) direction, is used to define the directional

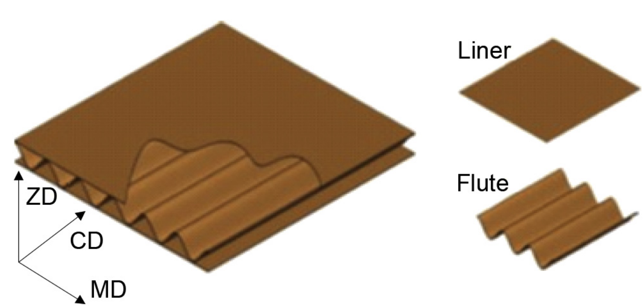

Fig. 1 – Basic geometry of a typical corrugated paperboard (MD is the machine direction, CD is the cross direction and ZD is the thickness direction).