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Research Paper

Compression strength of ventilated corrugated paperboard packages: Numerical modelling, experimental validation and effects of vent geometric design

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Ventilated corrugated paperboard (VCP) packaging is used for transporting fresh produce through a distribution system that requires maintaining a balance between uniform cooling of the produce and mechanical integrity of the package. A validated finite element analysis (FEA) model capable of predicting the compressive strength of two commonly used VCP packages is developed; the MK4 with higher length-to-height ratio and vent area compared to the MK6. The validated model was used to study the effects of vent geometric parameters such as vent height, shape, orientation, number and area on the strength of the packages. FEA results were in good agreement with the experimental results with a difference of 4.7% for MK4 and 8.2% for MK6. The MK6 had higher compression strength than MK4 with a difference of 11% and 17% at standard and refrigerated conditions, respectively. Results showed that the compression strength was lower by 11% and 16% respectively, for MK6 and MK4 packages when stored at low temperature (0 °C and 90% Relative humidity (RH)) compared to standard conditions (23 °C and 50% RH). With an increase in vent area from 2 to 7%, buckling load decreased by 8% for MK4 and by 12% for MK6. A linear correlation was observed between vent height and buckling load with R^2 values of 0.8215 and 0.9717 for MK4 and MK6 packages, respectively. Results showed that vent number, orientation, and shape affected the buckling of the packages. Rectangular vent holes better retained the strength of the packages. Irrespective of the vent design parameters studied, the MK6 had higher buckling load.

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Nomenclature

BCT	Box compression test
CD	Cross direction
FEA	Finite element analysis
MD	Machine direction
VCP	Ventilated corrugated paperboard
ZD	Thickness direction
W	Weight difference [%]
W_i	Initial weight of the package before conditioning, [g]
W_f	Final weight of the package after conditioning [g]
t	Corrugated sheet thickness [mm]
f	Amplitude of the flute [mm]
ψ	Wave number [non dimensional]
E_1	Elasticity modulus in the machine direction (direction of fibres) [MPa]
E_2	Elasticity modulus in the cross direction (transverse to fibres) [MPa]
ν_{12}	Major Poisson's ratio (transverse contraction due to an axial extension) [non dimensional]
ν_{21}	Minor Poisson's ratio (axial contraction due to a transverse extension) [non dimensional]
G_{12}	Shear modulus [MPa]

1. Introduction

The packaging of fresh fruit remains vital for the long and complex journey from growers to consumers. Several packages and mode of transportation may be used in handling fruits from orchard to the supermarket (Berry, Defraeye, Nicolaï, & Opara, 2016; Lu, Ishikawa, Kitazawa, & Satake, 2012; Lu, Ishikawa, Kitazawa, & Satake, 2010; Van Zeebroeck, Ramon, De Baerdemaeker, Nicolaï, & Tijskens, 2007). During handling, transportation and storage, fruits and vegetables experience various loading conditions, which may be static, dynamic or a combination of both (Lewis, Yoxall, Marshall, & Canty, 2008; Opara & Pathare, 2014; Singh, Singh, & Paek, 2009). In spite of the convenience and use of different packaging designs in fruit handling, handling conditions can lead to mechanical damage (Knee & Miller, 2002) resulting in postharvest losses of fresh fruits (Opara & Pathare, 2014; Pathare & Opara, 2014; Prusky, 2011; Van Zeebroeck et al., 2007).

Satisfying the consumer with a quality product is the main objective of the production, handling, storage and distribution of fresh horticultural produce (Opara & Pathare, 2014; Pathare & Opara, 2014). However, mechanical damage is responsible for extensive rot or decay of fresh fruits and vegetables. About 30%–40% of produce may be lost due to mechanical damage in the distribution chain between grower and the consumer (Barchi, Berardinelli, Guarnieri, Ragni, & Totaro Fila, 2002; Fadiji, Coetzee, Chan, Chukwu, & Opara, 2016; Fadiji, Coetzee, Pathare, & Opara, 2016). A clear understanding of the behaviour of the package and produce under static and dynamic loading conditions provides useful information in reducing mechanical damage and enhancing the quality of fresh produce (Abedi & Ahmadi, 2014; Ahmadi, Ghassemzadeh, Sadeghi, Moghaddam, & Neshat, 2010; Dewulf, Jancsok, Nicolaï, De Roeck, & Briassoulis, 1999; Roudot, Duprat, & Wenian, 1991). As reported by Robertson (2005), one of the major requirements for packaging of fresh horticultural produce is the ability to prevent mechanical damage, particularly that which results from compression. Understanding the performance of a package under static loads (compression) is essential in designing a better and more effective package.

Different convenient forms of packaging for handling, transporting and marketing fresh produce exist, ranging from bags, crates, hampers baskets, corrugated cartons, bulk bins, and palletised containers. Corrugated paperboard is a sandwiched structure comprising of a corrugated core called fluting and two facing liners (Fig. 1). Two main principal directions are used to characterise this material. The first is the machine direction (MD), corresponding to the manufacturing direction and the second is the cross direction (CD), corresponding to the transverse direction. A third direction, used to define the directional properties of corrugated paperboard, is the thickness direction (ZD) corresponding to the direction along the thickness out of plane (Fig. 1) (Biancolini, 2005; Talbi, Batti, Ayad, & Guo, 2009). Corrugated paperboard is used for the production of shipping containers due to its economical and efficient material characteristics (Han & Park, 2007; Talbi et al., 2009). Ventilated corrugated paperboard (VCP) package is the most widely used type of package for the packaging and distribution of a wide variety of commodities ranging from fruits and vegetables, industrial products and consumables (Hung, Nakano, Tanaka, Hamanaka, & Uchino, 2010; Pathare, Opara, Vigneault, Delele, & Al-Said, 2012). VCP package is commonly used in fresh fruit industries due to its ability to promote rapid and efficient cooling with a minimal amount of internal packaging material (De Castro, Vigneault, & Cortez, 2005; Thompson, Mejia, & Singh, 2010). Vent holes should be designed to remove the heat build-up due to respiration of the produce inside the package and provide sufficient and uniform airflow distribution (Pathare et al., 2012). Therefore, the package must be designed to have adequate ventilation to provide uniform cooling while maintaining the mechanical integrity of the package (Vigneault & De Castro, 2005; Vigneault & Goyette, 2002). A proper package design must include not only the total vent area, but also the geometrical

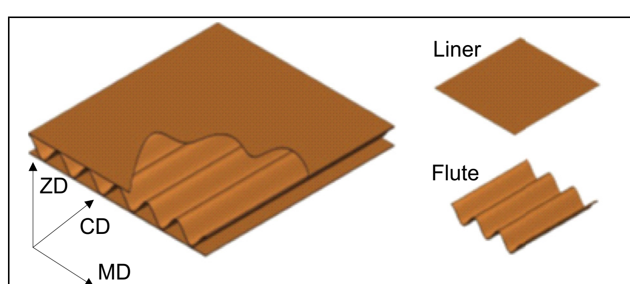

Fig. 1 – Corrugated paperboard panel geometry (MD is the machine direction, CD is the cross direction and ZD is the thickness direction).