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ORIGINAL RESEARCH ARTICLE

THE ROLE OF HORTICULTURAL PACKAGE VENT HOLE DESIGN ON STRUCTURAL PERFORMANCE

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ABSTRACT

Globally, ventilated paperboard packaging has been widely utilised particularly in the horticultural industry to protect packed produce against damage to satisfy consumer needs. During postharvest activities, the packages are exposed to cold environment and mechanical hazards. The mechanical hazards may result from different loadings such as drop, impact, vibration, compression or a combination of all. Designing ventilated packages should be such that they can provide uniform air distribution to cool the packed produce and protect the produce against mechanical damage. However, the presence of vent holes causes material loss of the package, thereby reducing the stacking strength of the packages and consequently resulting in produce damage. The strength of the package is crucial for preserving the produce and therefore optimising the package is essential to save time, money and resources. This research was aimed at evaluating the structural behaviour of ventilated packages. Finite element analysis was used to create models to study the buckling of three ventilated package designs when subjected to compression load. Packages with different vent area and paperboard grades were studied. Experiments were used to quantify box compression strength. Results of mechanical strength evaluation showed a negative linear relationship between carton strength and vent area. Board thickness increased the compression strength of the packages. At 2% and 4% vent areas, packages with C flute board reduced in strength by as high as 46% when compared with the strength of the packages with B flute board. Numerical results and experimental results were in good agreement, within 12%. This study suggests the need for alternative package designs, considering the mechanical strength while still providing proper and adequate ventilation to the packed produce.

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1.0 Introduction

Packaging is a crucial step in the long and complicated journey of fresh horticultural produce from the grower to the consumer (Fadiji *et al.,* 2018a). The advent of ventilated paperboard packaging has been adopted globally to allow for rapid cooling, promote efficient cooling of the produce, and for proper air circulation within the package (Thompson *et al.,* 2010; De Castro *et al.*, 2005). However, ventilation openings adversely affect the mechanical strength of the packages, consequently resulting in the damage of the packed produce (Opara and Pathare, 2014). The structural performance of ventilated paperboard packaging is dependent on numerous factors such as quality of the cellulose fibres, strength of the paperboard components (liners and flutes), and the mechanical properties of the combined paperboard (Fadiji *et al.,* 2018a). Furthermore, a proper package design must take into consideration different geometrical configurations of the vent such as the vent area, shape, size and location to enhance cooling while still providing sufficient mechanical strength (Pathare *et al.,* 2017, 2016, 2012; Han and Park, 2007; Émond and Vigneault, 1998). According to Pathare *et al.* (2017), the strength and cooling capabilities of ventilated packages is dependent on the geometrical locations, sizes and shapes of the vent holes. To save money and resources, optimising the strength and adequate cooling capabilities is therefore crucial.

During handling of ventilated packages, they are often stacked in a pallet, resulting in increased weight on the bottom packages, which could lead to produce damage (Opara and Pathare, 2014). Box compression test (BCT) is often used as a measure to evaluate the performance potential of the packages (Pankaj *et al.,* 2016; Fadiji *et al.,* 2016; Markström, 1988). A decrease in carton mechanical strength was reported to be a function of increasing vent sizes (Singh *et al.,* 2008). The compression strength of ventilated packages was influenced by package designs (Fadiji *et al.,* 2016). Several researchers have reported the confidence of simulation techniques such as finite element analysis (FEA) and computational fluid dynamics (CFD) in replacing experimental analysis (Fadiji *et al.,* 2018b; 2016; Pathare and Opara, 2014). Experimental and numerical analysis evaluation of the mechanical behaviour of paperboard packages was done by Biancolini and Brutti (2003). Fadiji *et al.* (2018b) developed a FEA model to predict the buckling of corrugated paperboard and packages. Results were validated with experimental tests and good agreement was reported. Among many factors that affect the strength of corrugated paperboard packaging, ventilation opening configurations and board grades play a crucial role. The aim of this research was to investigate the role of vent design on the structural performance of the package.

2.0 Materials and Methods

2.1 Packaging design

Three telescopic package designs were used in this study. The Standard vent, Edge vent and the Multi vent designs. The Standard vent package is commonly used for commercial pome fruit export in South Africa (Berry *et al.,* 2017, 2015). The Edge vent was used based on its successful application in the South African citrus industry (Defraeye *et al.,* 2014; Delele *et al.*, 2013a, b). The Multi vent was proposed as an alternative design to the Standard vent design. Two corrugated paperboard grades were used in this study: B-flute and C-flute. The thickness of the B and C flute paperboard grades was 2.8 mm and 3.9 mm, respectively. For each package design and board grades, two vent areas were used: 2% and 4%. Figure 1 shows the geomtry for the different package designs.

2.2 Finite element analysis

Mentat/Marc (MSC Software Corporation, California USA) was used for the FEA. The paper grammage (g m^{-1}) combination for B and C flutes was 140T2/175SC/165SC and 175T1/175SC/125FL, respectively. The thickness of the paper samples were 0.1992 mm, 0.2174 mm, 0.2646 mm, 0.2604 mm and 0.2225 mm for 125FL, 165SC, 175SC, 175T1 and 140T2, respectively. Elastic-plastic material properties reported by Fadiji et al. (2018b) were used. Due to computational time and cost, the homogenisation procedure proposed by Biancolini (2005) was used in the simulation for the package. Boundary conditions were set to represent the physical model accurately. Buckling analysis was performed on the packages to obtain the compression strength. Further details of the FEA setup can be found in Fadiji et al. (2018b).

2.3 Box compression strength (BCT)

BCT is a pure top-to-bottom compression load test between flat parallel steel plates that is carried out on an empty or filled sealed corrugated board package using a constant deformation speed. All compression tests were conducted using a box compression tester (M500-25CT, Testomatic, Rochdale, UK). Prior to the BCT, packages were preconditioned and conditioned according to ASTM D4332 standard. The BCT was done in accordance with the ASTM D642 Standard. A preload of 222 N was applied prior to the compression test remove initial transient effect. The fixed-platen mode of the compression tester was used to conduct all testing at a speed of 12.7 ± 2.5 mm min^{-1} until failure was observed. The compressive load and displacement are recorded continuously until collapse occurs. Statistical evaluations were performed using Statistica (v. 13.0, Statsoft, USA).

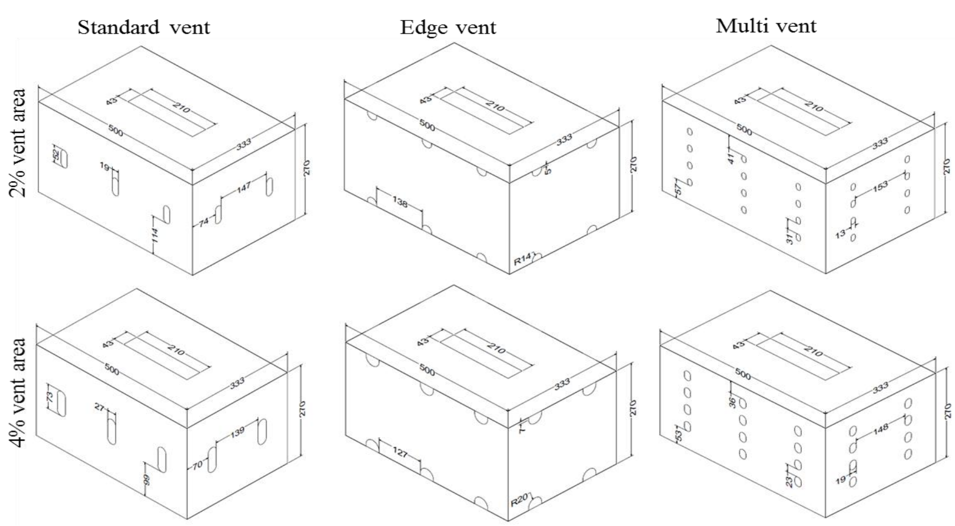

Figure 1. Geometry of the package designs (mm).

3.0 Results and Discussion

3.1 Compression strength of the package designs

Figure 2 shows the compression strength and its correspnding displacements for all the package designs for both B and C flute board grades at 2% and 4% vent areas.

From Figure 2, the compression strength of the packages with C flute board was observed to be higher than the packages with B flute board. In addition, there was a significant difference ($P \leq 0.05$) between the compression strength of the packages with B flute board and the packages with C flute board. At 2% vent area, the compression strength for the Standard, Edge and Multi vent designs with C flute board reduced by about 46%, 43% and 45%, respectively when compared with the compression strength of the same packages with B flute board. At 4% vent area, the compression strength of the Standard vent design with C flute board reduced by about 43% when compared with the compression strength of the Standard vent design with B flute board. The compression strength of both the Edge and the Multi vent designs with C flute board reduced by about 41% when compared with similar packages with B flute board. These results show the vital role of the board grades as failure of the combined board initiates package failure (Dimitrov and Heydenrych, 2009). The combination of corrugated paperboard was reported by Biancolini *et al.* (2005) to be an important factor that can significantly influence the strength of paper packages. In most cases, the compression strength of the packages reduced with an increase in vent area (Figure 2A).

The compression strength at 2% vent area of the package designs was higher than the compression strength at 4% vent area for both board grades. Although, the compression strength at 4% vent area for the Standard vent and Multi vent designs with B flute board was slightly higher than the compression strength at 2% vent area. However, there was no significant difference statistically. Singh *et al.* (2008) reported a linear relationship between the loss in compression strength of a package and vent area, although with >40% of material removed from the package, the relationship does not stay linear. The ventilation opening on a package is a crucial factor affecting the mechanical resistance of the package, the physical support to protect packed produce against bruise damage and the cooling efficiency of the package (Defraeye *et al.,* 2015; Pathare *et al.,* 2012; De Castro *et al.,* 2005; Baird *et al.,* 1988). Therefore, there should be a compromise between the adequate cooling and the mechanical integrity of the package in designing an optimal package vent.

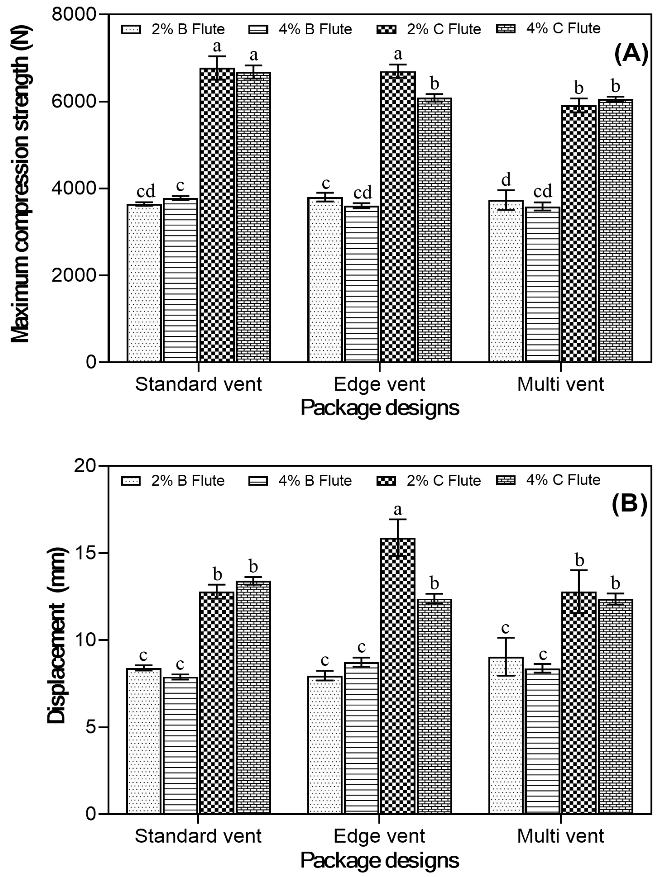

Figure 2. Bar chart showing (A) compression strength and (B) Displacements at maximum compression strength for all the package designs for both B and C flute board at 2% and 4% vent area. The letters on the error bars are used to show the statistical difference. Means with the same letters are not statistically different at P≤0.05.

The corresponding displacement at the maximum compression strength for all the package designs is shown in Figure 2B. The displacement for the packages with C flute board was observed to be the highest compared to the displacement of the packages with B flute board. This indicated that the more resistance a package has to compression load, the higher the displacement. The range of the displacement for the packages with B flute board and C flute board was 7.8 – 9.1 mm and 12.4 – 15.9 mm, respectively. More deflection means that the impact of the load is spread over a longer duration, thereby reducing the intensity of the load impact (Campbell, 2010). Hence, the packages with C flute board offer better cushioning and protective ability to the packed produce, thereby minimising the mechanical damage incurred by packed produce. No significant difference (P≤0.05) in the displacement of the packages with 2% and 4% vent areas.

3.2 Simulation result

Typical fringe plots of the buckling behaviour of the packages with B flute board under compression load is shown in Figure 3. It can be seen that the buckling of the package originated from the middle of the package, which is more predominant on the length side of the package. According to Panyarjun and Burgess (2001), package failure is due to the cumulative effect of the localised crushing that occur on the face of the package.

Buckling was affected by the package designs. The length side of the Standard vent with 2% vent area buckled inward while the length side of the Standard vent with 4% vent area buckled outward.For the Multi vent with 2% and 4% vent area, the buckling on the length side of the package was outward and inward, respectively. The length side of both Edge vent with 2% and 4% vent area buckled inward. The compression strength obtained from the simulation an experimental results showed a significant dependence of the package resistance to compresion load on vent area and board grade. Both simulation and experimental compression strength agree well, within 12%.

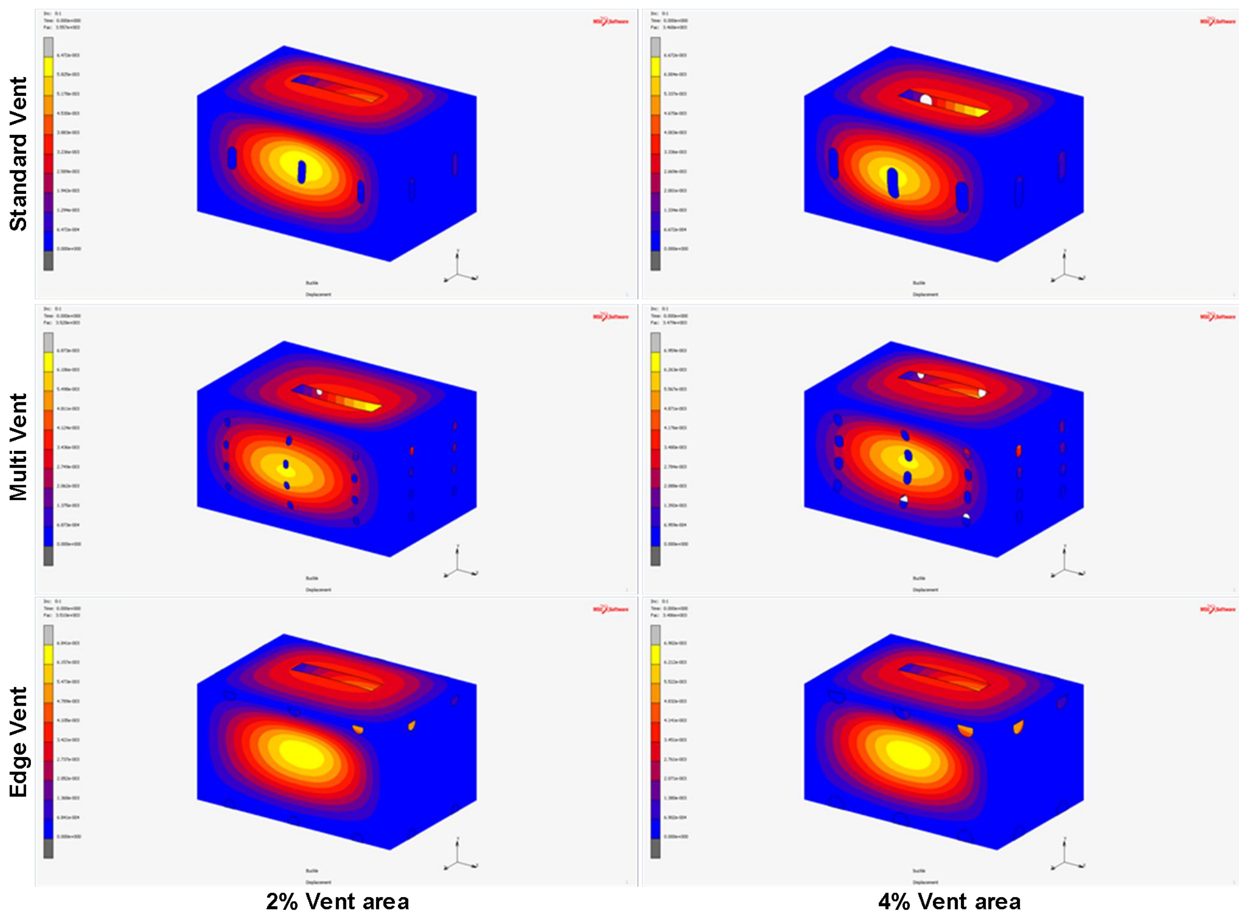

Figure 3. Typical Fringe plots of the buckling of the package designs with B flute board grade.

4.0 Conclusions

This study evaluated the effect of package geometrical configurations on mechanical strength experimentally and numerically. Three different package designs, with two vent area (2% and 4%) and two paperboard grades (B and C flute) were used. The compression strength of the package reduced with an increase in vent area. The percentage difference in compression strength for all the packages with 2% and 4% vent area was in the range 1 – 10%. The thickness of the paperboard affected the strength of the packages. Packages with C flute board had higher compression strength than packages with B flute board. Numerical simulations were able to predict the compression strength of the packages, with good correlation, within 12% when compared with the experimental results. Results showed the importance of paperboard combination and vent hole designs to improve the structural integrity of the packages.

5.0 Acknowledgements

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