Mechanical Design and Performance Evaluation of Ventilated Packages

by
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Declaration

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Summary

Mechanical Design and Performance Evaluation of Ventilated Packages

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Ventilated corrugated paperboard (VCP) packages are used extensively in the fruit industry to minimize damage and facilitate airflow around the produce to maintain the cold chain. In the postharvest journey of fruit, these packages are subjected to a multitude of dynamic and static forces such as impacts, compression and vibration which results in damage and reduces the quality of the packaged fruit. This thesis aims to develop a validated finite element analysis (FEA) model to assist in the mechanical design of VCP packages. Another aim is to evaluate the performance of apple fruit packaging by investigating the resistance of the packages to the forces they are subjected to during postharvest handling, and characterising the bruise susceptibility of the fruit inside the packages. A validated FEA model was used to study the effect of vent height, shape, orientation, number of vents and area on the strength of the packages.

Results showed that incidence and susceptibility to bruise damage of the apple fruit was affected by package design when subjected to impact, compression and vibration loads. Bruise damage increased with an increase in drop height with a significant increase of about 50% when the package drop height increased from 30 cm to 50 cm. The bottom layer of the package was more susceptible to bruise damage when subjected to impact load. Under vibration load, the highest bruise damage was observed at a frequency of 12 Hz, where the greatest packaging transmissibility of 243% occurred. The top layers of the package were prone to bruise damage under vibration load. Compression strength of the packages reduced by about 16% when environmental condition was changed from standard condition (23℃ and 50% RH) to refrigerated condition (0℃ and 90% RH). Under compression load, irrespective of package design, the highest and lowest bruise incidence of bruise damage occurred at the top and bottom layers of the package, respectively.

The incipient buckling load of the package obtained from the FEA model could accurately predict the experimental value obtained during the compression test. The difference between the numerical and experimental values was within 9%. Increasing the vent area from 2 to 7% reduced the buckling load with about 12%. Vent number, orientation, and shape affected the buckling load of the packages. Rectangular vent holes better retained the strength of the packages compared to circular vent holes. Vent height significantly reduced the buckling load of the packages. The results obtained from this research provided practical guidelines for improving future design of packages for the South African fruit industry.

Opsomming

Meganiese Ontwerp en Evaluering van Werksverrigting van Geventileerde Sakke

(“Mechanical Design and Performance Evaluation of Ventilated Packages”)

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Geventileerde geriffelde kartonverpakkingsakke (ventilated corrugated paperboard (VCP)) word algemeen in die vrugtebedryf gebruik om skade aan die vrugte te beperk en lugvloei tussen die vrugte te fasiliteer asook die koue ketting te handhaaf. In die vrugte se reis vandat dit geoes is, word hierdie sakke onderwerp aan verskeie dinamiese en statiese kragte, soos impak, samedrukking en vibrasie, wat lei tot skade en sodoende word die kwaliteit van die verpakte vrugte verlaag. Hierdie tesis het ten doel om ’n beproefde/geldige eindige element analise (EEA) model te ontwikkel om te help in die meganiese ontwerp van die sakke. Nog ’n doel van die tesis is om die doeltreffendheid van appel-vrug verpakking te bepaal deur die weerstand van die sakke gedurende die tyd na die oes te ondersoek, en ook die moontlikheid van kneusing binne die verpakking te bepaal. ’n Geldige EEA model is gebruik om die effek van luggat-hoogte, vorm, oriëntasie, getal luggate en area op die sterkte van die sakke.

Resultate het gewys dat raakpunte en vatbaarheid vir kneusing van die vrug geaffekteer is deur die ontwerp van die sakke wanneer dit onderwerp word aan impak, samedrukking en vibrasie-kragte. Daar was meer kneusing met ’n toename in val-hoogte, en die kneusing het noemenswaardig toegeneem (rondom 50%) toe die val-hoogte verhoog is van 30 cm na 50 cm. Die onderste laag van die verpakking is meer vatbaar vir kneusing as dit onderwerp word aan impak. Die meeste kneusing, met vibrasie-kragte, is waargeneem by ’n frekwensie van 12 Hz, met die hoogste verpakkings-oordraagbaarheid van 243% wat waargeneem is. Die boonste lae van die verpakking was meer vatbaar vir kneusing met vibrasie-kragte. Samedrukking-sterkte van die verpakking is met ongeveer 16% verlaag toe die omgewingsfaktore verander is van standaardtoestand (23℃ and 50% RH) na verkoelde toestand (0℃ and 90% RH). Onder samedrukkingskrag het die hoogste en laagste voorkoms van kneusing onderskeidelik voorgekom op die boonste en onderste lae van die verpakking, ongeag die ontwerp van die verpakking.

Die aanvanklike buigingslading van die verpakking soos waargeneem in die EEA model kon die eksperimentele waarde akkuraat voorspel soos gesien in die samedrukkingstoets. Die verskil tussen die numeriese en eksperimentele waardes was nie meer as 9% nie. Deur die luggat groter te maak met tussen 2 en 7% is die buigingslading verlaag met sowat 12%. Die hoeveelheid luggate, oriëntasie en vorm affekteer die buigingslading van die verpakking. Reghoekige luggate het beter vorm behou as sirkelvormige luggate. Die hoogte van die luggate het die buigingslading noemenswaardig verminder. Die resultate verkry uit hierdie navorsing bied praktiese riglyne vir die verbetering van toekomstige ontwerpe van verpakkings vir die Suid-Afrikaanse vrugte-industrie.

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Dedication

To my family, for your love, encouragement, giving me the opportunity and nurturing me in the way of truth; you are truly wonderful

To the Lord Almighty God, the author and the finisher of my faith in Christ Jesus for your blessing.

Contents

Parts of this study have been presented at the following conferences:

*Impact damage to apples inside ventilated cartons - PHI Postharvest Conference, Stellenbosch, November 2013.

**Resistance of apples to mechanical damage inside ventilated corrugated paperboard package – 7thInternational CIGR Technical Symposium, Stellenbosch, November 2012.

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Abbreviations

BA	Bruise area
BCT	Box compression test
BS	Bruise susceptibility
BV	Bruise volume
CAD	Computer aided design
CD	Cross direction
CFD	Computational fluid dynamics
ECT	Edge compression test
FEA	Finite element analysis
IE	Impact energy
LDPE	Low density polyethylene
MAP	Modified atmosphere packaging
MD	Machine direction
NIR	Near infrared
PSD	Power spectral density
VCP	Ventilated corrugated paperboard
ZD	Thickness direction

NOTE

This thesis presents a compilation of manuscripts where each chapter is an individual entity and some repetition between chapters, therefore, has been unavoidable.

Chapter 1 General introduction

A major role of packaging in fresh produce handling is to protect the product from extrinsic factors such as gas composition, spoilage micro-organisms, contaminants, and mechanical damage, thereby providing consumers with highly nutritious, fresh and safe products (Mangaraj et al., 2009; Faber, 1991). Packaging provides other important functions, which include identifying and advertising the contents, protection during transport and ease of transport, and facilitating stacking and storage of the products (Jonson, 2000).

The types of packaging used for fresh horticultural produce include wood crates, corrugated shipping cartons, polymeric film pouches, bags, baskets, crates, trays, paper sheets, pouches, etc. (Pascall, 2010). Paper and paperboard-based packaging is widely used because it meets several criteria for successful packaging, such as method of containing the product, protecting goods from mechanical damage and preserving products against deterioration and spoilage. Corrugated boxes have been the most widely used type of package for handling goods ranging from fruits and vegetables, consumer products to industrial items. The popularity of corrugated packaging also stems from the fact that it is practical, useful, economical, renewable and recyclable (Thompson et al., 2010; De Castro et al., 2005).

Ventilated corrugated packages are used for packaging perishable products especially pome fruit (apples and pears) in the South African packaging industry. Fruits are usually packed in a multi-scale packaging system using several layers inside the carton (Berry, 2013). The internal packaging such as thrift bags, trays, polyethylene liner bags and punnet may be used to improve handling, storage and ultimately enhance marketability of the produce depending on the destination (Ngcobo, 2012; Robertson, 2005). This class of packaging has sufficient ventilation and helps to keep the fruit fresh for long.

Global marketing of fresh produce widely adopts the use of ventilated packaging. Ventilated packaging is one of the most important technological innovations with a minimal amount of internal packaging material to promote rapid, uniform and an efficient cooling process of horticultural produce (Pathare et al., 2012; Ngcobo et al., 2012; Thompson et al., 2010; De Castro et al., 2005). Ventilation holes added on the package enhance and maintain adequate airflow channels between the inside of the package and the surrounding, thereby reducing resistance to airflow (Pathare et al., 2012; Han & Park, 2007). This design has been proven to reinforce the preservation function of the containers (Han & Park, 2007).

In addition, vents allow the heat built-up by respiration to escape. Ventilated packages should therefore, be designed in such a way that they can provide uniform airflow distribution and consequently produce uniform cooling (Pathare et al., 2012). However, the presence of vent holes in corrugated paperboard packages reduces the mechanical strength (Singh et al., 2008; Han & Park, 2007). The package must have enough openings to provide uniform airflow through the entire mass of produce, while providing suitable mechanical resistance of the package (Vigneault & de Castro, 2005; De Castro et al., 2004a; Vigneault & Goyette, 2002).

During postharvest life of fresh fruit, the package and fruit are subjected to a multitude of dynamic and static forces such as impacts, vibration and compression. These factors may reduce the value of the fruit as a result of the presence of mechanical damage such as bruise defects (Jarimopas et al., 2007; Bollen et al., 2001; Armstrong et al., 1991). Therefore, the strength of corrugated board containers is crucial for preserving the content, and optimisation of corrugated board containers' strength and ventilation is essential to save financial and material resources (Biancolini & Brutti, 2003).

Over the last decades, mathematical modelling techniques have served as alternatives to time-consuming and expensive experiments. The use of modelling tools is more efficient and less expensive with readily available software, which serves as an important tool to studying the effects of different operating parameters once the model is validated (Delele et al., 2010; Zou et al., 2006a, b).

However, the results of numerical models need to be validated experimentally. Therefore, as the use of corrugated packages increases in fruit packaging, the need to develop validated finite element models to guide in the mechanical design and performance evaluation of fruit packaging systems is crucial. In this regard, it is necessary to acknowledge the multipurpose role of the finite element modelling in understanding the numerical intricacies of structural designs as a whole.

Package designs are commonly based on years of industry experience and rule of thumb (Han & Park, 2007; Talbot, 1988), with minimum use of objective packaging design and performance evaluation methods. This results in limited innovation which may reduce competitiveness. In order for packaging industries to stay competitive, there is a need to advance their products and services to retain market advantage. Therefore, developing and validating mathematical models to predict the mechanical performance of packaging materials, as well as optimizing package design and stacking parameters, is of utmost importance for developing practical guidelines for industry. This will help improve future package designs to the benefit of the fruit industry. A wide range of ventilated package designs are used to handle apples and other horticultural fresh produce in South Africa (Berry, 2013). In recent times, experimental and computational fluid dynamics (CFD) modelling studies conducted at SARChI Postharvest Technology Laboratory at Stellenbosch University have investigated the airflow pattern, heat and mass transfer inside multi-scale ventilated packages used to handle fresh fruit in South, including table grape (Delele et al., 2013; Ngcobo et al., 2013; Ngcobo et al., 2012) and citrus (Delele et al., 2013a, b; Defraeye et al., 2013). While these studies provide better insights on the cold chain performance of these packages, little is known about the susceptibility of both the package and fruit to damage under impact, compression and vibration loads which occur during postharvest handling and storage. The objectives of this study were, therefore, to:

- Investigate the resistance of ventilated packaging to compression, impact and vibration loads;
- Characterise the bruising susceptibility of fruit inside ventilated packages; and
- Develop an experimentally validated finite element model that predicts the mechanical strength of the package system;

This thesis is organised as follows. Chapter 2 reviews the developments in horticultural produce packaging with focus on corrugated paperboard packaging. Chapter 3 reports the results on impact bruise damage susceptibility of apple fruit packed inside ventilated corrugated paperboard packages, including the effects of package design and drop height. The simulated transport damage of ventilated corrugated paperboard packages was studied in Chapter 4 to determine the packaging transmissibility and fruit susceptibility to bruising due to vibration load. Chapter 5 investigated the mechanical properties of packaging materials experimentally and numerically. Chapter 6 investigated the compression strength of two ventilated corrugated paperboard packages commonly used in the South African apple industry using finite element analysis (FEA). The model was validated with experimental results. In addition, the susceptibility of apple fruit packed inside the ventilated corrugated paperboard (VCP) packages to compression damage was reported. In Chapter 7, the effect of geometrical design parameters on the strength of ventilated corrugated paperboard packages was investigated numerically using the validated model in Chapter 6. Finally, the conclusions are reported in Chapter 8.

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Chapter 2 Literature review

Developments in horticultural produce packaging

2.1 Introduction

Globally, packaging is an essential part of fresh product handling and logistics. Packaging protects products from physical damage, chemical and microbiological contamination (Opara & Pathare, 2014; Cutter, 2006**;** Quintavalla & Vicini, 2002; Petersen et al., 1999) and facilitates processing and manufacturing through storage and handling to the end user. In addition, a package advertises the content to the final customer (Dhurup et al., 2014) and influences customer decision to buy (De Chernatony & Segal-Horn, 2003). Packaging is essential and prevalent in today's society. Packaging enhances and protects the goods we buy through its distribution, from processing, manufacturing, handling and storage to the final and ultimate user of the goods. Packaging in postharvest management of fresh produce is to protect the product from extrinsic factors such as gas composition, spoilage micro-organisms, contaminations, mechanical damage, and to provide consumers with nutritional and ingredient information (Mangaraj et al., 2009; Farber,1991). Packaging therefore provides a means of ensuring safe delivery of a product to the ultimate user in a sound condition, at a minimum overall cost (Robertson, 1993).

Packaging has many other important functions, such as keeping the products together so it does not spill (containment), identifying and advertising the products, protection during transport and ease of transport, facilitating stacking and storing of the products (Jonson, 2000). Packaging provides an economical way of protecting products during distribution. If the packaging is also adapted to the distribution system and is considered an integral part of both internal and external distribution, it is possible to minimize distribution cost (Robertson, 1993). As a result, all packaging has to be designed to protect products, reduce materials and then be tested to prove its optimum performance. Efficient packaging is a necessity for almost all types of products as it is an essential link between the producer and the end users (consumers). The quality and the reliability of a product during production and manufacture will be wasted, unless sound delivery of the product is ensured. Hence, properly designed packaging is the main way to ensure the products reach the end users in good condition.

2.1.1 Functions of packaging

Although the definition of packaging covers the basic role of ensuring that products are delivered safely to the final end user in a sound and good condition has been outlined, it is necessary to discuss the functions of packaging in detail. Thus, the basic functions of packaging are stated more specifically.

Containment

Depending on the product's physical form and nature, a package has to contain the product before they can be moved from one place to another. For example, a hygroscopic free flowing powder or viscous and acidic pastes (tomato) concentrate and also some liquid products need packages that can hold them together and are sealed to avoid spillage and loss. The containment function of a package contributes to the protection of products from the outside environment and hazards that may occur during distribution from the manufacturer to the ultimate user (Schoorl & Holt, 1982; Holt & Schoorl, 1981). Containment function also emphasizes the need to increase the number of fruit per volume of space. To better utilise the available space in shipping containers, palletised stacks of pome fruit (apple, pears, etc.) are used (Ladaniya, 2008; Thompson, 2003). This maximises the available space of a cargo ship.

Protection

This is mostly regarded as the primary function of the package, protecting the products from outside environmental effects, such as water, gases, high temperature, moisture vapour, dust, micro-organisms or prevention of mechanical damage such as shock, impact, vibration, and compression forces (Babarinsa & Ige, 2012; Thompson, 2003; Martzinger & Tong, 1993) that may occur due to distribution hazards. Protection of the products tend to increase the life cycle. Packaging provides protection from three major classes of external influences namely; chemical, biological and physical (Marsh & Bugusu, 2007). Chemical protection minimises the compositional change caused by environmental influences such as exposure to gases (typically oxygen), moisture gain or loss, or light. Depending on the package material, a chemical barrier can be provided for the products (Marsh & Bugusu, 2007). Glass and metals provide a nearly absolute barrier to chemicals and most environmental agents. Plastic packaging has a large range of properties but is more permeable than glass and metal (Mangaraj et al., 2009). Biological protection prevents diseases and spoilage of the product by providing a barrier to micro-organisms, insects, rodents, and other animals. This barrier functions through multiplicity of mechanisms, including maintaining the internal environment of the package and preventing odour transmission (Marsh & Bugusu 2007). Physical protection shields the product from mechanical damage encountered during distribution. This damage may be caused from shock and vibration or impacts, abrasions and crushing (Marsh & Bugusu 2007).

Convenience

The design of a package should make it easy to hold, move, transport, lift, drop, open and pour as appropriate. A regularly shaped package can be stacked easily without wasting too much space between each package, enabling more packages to be transported in the distribution process. In contrast to this, unusually shaped packages can lead to space being wasted, which consequently increases the cost of transportation if thousands of the packages are to be transported. Therefore, the shape and strength of packages should be such that they can be stored side by side leaving no void and also can be stacked safely one above the other. Easy handling and space-saving storage and stowage should be a criteria for a good package design. For example, corrugated paperboard packages may have hand holes to facilitate manual handling of large or awkwardly designed packages and improve ergonomics (Singh et al., 2008). Packaging thus has a crucial impact on the efficiency, handling and storage of products.

Communication

Packaging is the main way products can be identified and advertised. A package is the face of a product and most often the only product exposure to the consumer prior to purchase. According to an old saying that “a package must protect what it sells and sell what it protects”, a package functions as a “silent salesman” (Judd et al., 1989). The package is intended to attract the ultimate user’s attention and to have a positive impact on the purchasing decision. The package should also be able to instruct users on how to use the product correctly. At first glance, a consumer should be able to instantly recognise the products through the branding and the labelling. Although, legal requirements are very often involved for wholesale distributors to communicate certain information on the outside of the package (Thompson, 2003), right implementation of communication improves the presentation of the product. Vital information to the ultimate users usually printed on the outside of the package include; ingredients, production date, expiry date, price, special offer, manufacturer’s address, contact information and the barcode, which tend to enhance the development of the product (Gonzalez & Twede, 2007). Figures 2.1 and 2.2 show the summary of the primary and the secondary functions of packaging.

2.1.2 Package environment

Packaging has to perform its functions in various environments. Knowing how a package performs in the various environments enhances the design of the package in an optimum way thereby reducing damage to products and cost of production.

Ambient environment

The ambient environment of a package is the surrounding of a package. Gases, moisture, the effect of heat and cold, light, microbial activity as well as environmental contaminants such as dirt and dust have their way into a product if the package has low barrier properties (Robertson, 2012).

Physical environment

The physical environment is the environment where physical damage can occur to the product (Robertson, 2012). These may arise from drop and impact of the package, compression of the packages due to excessive stacking, crushing, and damage from vibration during the transportation and distribution (Robertson, 2012; Cole et al., 2003).

Human environment

This environment tends to interact with people to know the strength capabilities as well as visions and limitations of humans. The regulatory and legislative requirements are also paramount in the design of the packages (Thompson, 2003). The package should clearly pass information such as manufacture date, expiry date and other information that can give the end user adequate knowledge about the product (Robertson, 2012). Ease in opening, holding and usage by the end users maximises the convenience function of the package.

2.1.3 Limitation on suitable packaging

The following may result in inadequate packaging:

- Depending on the country, the choice of packaging material may be limited. Transportation may be a problem as the place of purchase of the packaging material could be far. If supplies are located in urban areas, this may cause problems for package producers in the rural areas (Hewett & City, 2012).
- Each product varies in its characteristics and packaging requirement (Brody et al., 2008), therefore, lack of knowledge of the materials, requirement or a combination of both may result in inadequate packaging.
- Packaging can represent a large part of the total cost of processed food (Marsh & Bugusu, 2007). This may be in part the result of the higher unit cost when small quantities are ordered for small-scale production.

2.1.4 Paper and paperboard

The design and construction of packages influences and plays a significant role in determining the shelf life of a product (Hotchkiss, 1997). Selecting the right material or technology for packaging maintains the quality and freshness of the product, and also keeps the product intact during distribution. Among the numerous types of packaging materials such as glass, metals, plastics etc., paper and paperboard are predominantly used in packaging of horticultural products.

In packaging today, a wide range of paper and paperboard is used, from light weight infusible tissues to heavy duty boards used in the distribution of products. Paper and paperboard account for about one-third of the total packaging market and approximately 10% of all paper and paperboard consumption is used for packaging with over 50% of the paper and paperboard used by the food industry (Kirwan, 2003). The use of paper and paperboards in the food industry dates back to the 17th century and accelerated during the latter part of 19th century in order to meet the needs of the packaging industry (Kirwan, 2003). Paper and paperboard are sheet materials obtained from an interlaced network of cellulose fibres obtained from wood by using sulphate and sulphite (Marsh & Bugusu, 2007). With no rigid or sharp distinction between paper and paperboard, paperboard is generally thicker, usually over 0.25 mm. According to the International Organisation for Standardisation (ISO); paperboard is a paper with a basic weight above 200 $\mathrm{g/m^2}$, but there are exceptions (Robertson, 2005). The numerous uses of paper and paperboard includes bags, sacks, wrapping paper, tissue paper, rigid boxes, fibre drums, moulded pulp containers, cushioning materials, corrugated boxes and folding cartons.

Paper - Paper is a sheet of material made up of many small discrete fibres bonded together. Due to its poor barrier properties and its inability to be sealed by heat, paper is not used for long term protection of foods. Paper is coated, treated or impregnated with materials such as wax or resins to improve its protective and functional properties when used in contact with foods (Robertson, 2005). The main types of packaging paper used in food packaging are shown in Table 2.1.

Paperboard – Paperboard is generally thicker and heavier than paper, having a higher weight per unit area. They are usually made in multiple layers from a variety of materials called furnishes on papermaking machines (Marsh & Bugusu, 2007; Soroko, 1999). Paperboard is commonly used to make boxes and containers for shipping. The different types of paperboard are shown in Table 2.2 (Soroko, 1999).

Corrugated boxes, folding cartons, milk cartons, wrapping papers, bags and sacks are some of the common uses of paper and paperboard. Due to the strength and economic advantage of paper and paperboard, bulk packaging of sugar, powder, dried fruit and vegetables have been possible (Raheem, 2012).

2.1.5 Recent trend in food packaging

Modified atmosphere packaging (MAP) has been used to increase the shelf life of whole and minimally processed food products, especially fruit and vegetables (Caleb et al., 2013; McMillin, 2008). This packaging technique may involve relying on the respiration properties of the produce in combination with packaging film of permeability (passive MAP), or based on removal of air from a pack and replacement with a single gas or combination of gases (active MAP) (Raheem, 2012; Blakistone, 1999). Intelligent packaging provides for sensing of the food properties and the environmental conditions so as to give relevant information on the quality of the food or status of the environment during transportation and storage (Raheem, 2012; McMillin, 2008; Kerry et al., 2006; Ahvenainen, 2003).

The increasing demand for products free of preservative has led to a surge in demand for antimicrobial packaging. Cha & Chinnan (2004) reported that a low level of preservative coming in contact with the food can be achieved by using appropriate coatings. An et al. (1998) suggested a polymer based coating as the best method to achieve desirable stability and adhesiveness. Furthermore, the author reported that microbial activity can be reduced by coating low density polyethylene (LDPE) films with polyamide resin mixed with bacteriocin solution. Nanotechnology in food packaging is also an emerging technology. This improves the barrier and mechanical properties of packages, detects pathogens, enhance intelligent and active packaging for food safety and to increase the quality of food (Brody et al., 2008).

2.2 Corrugated paperboard

Corrugated packaging is a versatile light, economic, robust, recyclable and practical form of packaging. Corrugated paperboard is an efficient material for fabricating shipping containers (Han & Pack, 2007) and have been used extensively for the distribution, transportation and storage of products, particularly fruits such as apples and pears (Singh et al., 1992). The use of the corrugated paperboard dates back to over a century ago. Since its inception, it has become a strong and leading choice for protective packaging in all sorts of applications in all spheres of daily life and this will probably remain so in the near future.

2.2.1 History of corrugated paperboard

Corrugated paperboard was first used in Victorian England. The tall hats worn by men at that time were stiffened by rolled sheets of flat paperboard which was later replaced by corrugated paperboard because the hats made with the flat paperboard were fragile and susceptible to damage. The corrugated paperboard was made by a hand-driven corrugator and was stiffer and provided more cushioning to prevent damage than the flat paperboard. In 1856, the first patent on corrugated paper was received by two Englishmen, Healy and Allen. This is known as ‘’unfaced corrugated’’. Jones (1871) patented the process in which heat was used to manufacture corrugated paper. This is a later application of the unfaced corrugated paperboard in which a plain sheet is attached to the corrugated paper. This was used to cushion glass bottles, glass lamps and other similar products. To improve the strength of the corrugated paperboard, Oliver Long invented corrugated board with facings also known as liners on both sides (Long, 1874) and was patented in 1874. The boxes were lighter and cheaper than the wooden boxes.

In the same year, the first machine for producing large quantities of corrugated board was produced by G Smith. In 1895, shipping tests were conducted on the corrugated boxes and were accepted as shipping containers. Corrugated boxes were initially used for packaging of glass and pottery. Its later use was in packaging of fruits without bruising which thereby improved return to producers and the export market increased. Wax and plastics were used to coat corrugated boxes making it adaptable in wet conditions. This improvement made corrugated boxes suitable for vegetables, meat and similar products. In the 1920's, the advent of improved machines made it possible for the production of higher quality of corrugated boards for the corrugated boxes, which started to replace wooden boxes. The market has been expanded further by new technology, such as packaging wine in plastic bags inside a corrugated box.

2.2.2 Manufacturing of corrugated paperboard

Corrugated board is manufactured on a large high precision machine known as the corrugator. The corrugator is a combination of several machines, that is, the manufacture of the corrugated board is a machinery line process. Corrugated board consists of several layers of corrugated paper glued on or in between plane sheets of paper. Paper is the main raw material used in corrugated board. Corrugated board has a sandwich material structure comprising a central paper called the corrugating medium (which has been formed, using heat, moisture and pressure, in a corrugated, i.e. fluted shape on a corrugator) and two outside sheets called the linerboards. The most common type of corrugated board is the single wall corrugated board. Others are the double or the triple wall corrugated board produced for more demanding packaging solutions (Figure 2.3). The properties of the different corrugated paperboard are shown in Table 2.3.

Two parts are involved in the manufacturing process of corrugated boards: the wet part and the dry part. The fluting is corrugated between two rolls and then glued to the liners in the wet part while heat is applied to dry the corrugated board in the dry part. The manufacturing process is illustrated in Figure 2.4. Warp and Washboarding are problems that occur during manufacturing of corrugated board. These occur due to imbalance of moisture content in the different layers of the corrugated board. Warp occurs when the corrugated board can deform in a buckling shape and Washboarding occurs when there is a dip in the facing between the corrugations. Corrugated board is manufactured in several standard profiles. Table 2.4 illustrates the most common flute designations. The letter designation relates to the order that the flutes were invented and not the relative sizes. The structural features of the corrugated boards make them an ideal packaging solution (Sek et al., 2005; Lu et al., 2001). They are regarded as packaging material for the future. They have advantages and disadvantages; however the advantages outweigh the disadvantages. Some of the advantages are (Thompson et al., 2010):

- low weight and hence very convenient to handle,
- it is inexpensive,
- strong and stiff compared to its weight,
- better printing and graphics capabilities, i.e., easy to print on,
- can easily be customised to any specific requirement,
- easily available,
- fully recyclable in nature making them eco-friendly.

One major disadvantage of corrugated board is its high sensitivity to humidity and hence under extreme pressure or on stacking, deformation may occur (Dimitrov & Heydenrych, 2009). Proper handling and stacking of corrugated board package is crucial as they are easily damaged by careless handling. Some fruit industries treat the cartons with wax layers when exposed to high moisture (Thompson et al., 2008).

2.2.3 Structural performance of corrugated paperboard

The structure of corrugated board gives it a high stiffness to weight ratio, a high strength to weight ratio and a considerable rigidity and resistance. The structural performance of corrugated board is a function of various factors such as; the quality of the cellulose fibres, the mechanical properties of the liners and the medium (flutes), as well as the structural properties of the combined board (FEFCO, 2010). These properties give the board resistance to compression forces, impacts, vibration or a combination of the three (Frank, 2014). The air movement in the medium also serves as insulator, which provides protection against fluctuating atmospheric conditions. The structure of corrugated board makes it resistant to buckling and gives it a high stacking strength. This makes it an ideal choice for packaging in many industries, including the fresh fruit industry. As discussed earlier, there are different types of corrugated boards and depending on the purpose, the compressive strength of the board can be increased by adding layers. The single wall corrugated board comprise one fluted medium and two layers of the linerboard, double wall corrugated board comprise two layers of the fluted medium and three layers of the linerboard, while the triple wall corrugated board comprise three layers of the fluted medium and four layers of the linerboard.

2.2.4 Application fields of corrugated paperboard

The main application of corrugated board is in packaging and it can be customised for a specific purpose due to its versatility. The major use of corrugated board is in the manufacture of shipping containers (corrugated paperboard packages). Some of the other uses include:

- corrugated paperboard packages for fruits, vegetables, perishables, etc,
- trays,
- billboards,
- fast food packages,
- packages for electronic gadgets, cosmetics, etc.,
- separator sheets between layers of cans, bottles, and other products mainly on pallets.

2.2.5 Corrugated paperboard in the fresh produce industry

The most common renewable packaging materials are cellulose-based, including corrugated board, paperboard and paper (Gällstedt & Hedenqvist , 2006). The ease with which the corrugated paperboard can be recycled, its printability and high strength to weight ratio makes it a good choice in the fresh food industry. Over 90 % of the packaging in the USA used in the fruit industry is corrugated paperboard or paperboard (Little & Holmes, 2000). Fresh produce has a rapid spoilage rate, therefore, proper storage condition (temperature and relative humidity) are needed to lengthen the storage life and maintain quality (Uchino et al., 2004). During distribution, the corrugated packages are exposed to several environmental conditions before arriving at its final location. Fresh produce need a low temperature and high relative humidity to reduce the respiration and slow down the metabolic process. Due to its sensitivity to environment, corrugated packages must be able to withstand changes in temperature and relative humidity throughout the lifecycle of the products as this has a severe effect on the strength of the package (Frank, 2014; Singh et al., 2008).

A suitable packaging for fresh produce keeps the content well ventilated to prevent the accumulation of heat and carbon-dioxide. The ease to create vent holes on corrugated paperboard packages makes it suitable for transport and storage of fresh produce. Ventilation holes improve airflow, however, proper care must be taken as mechanical integrity of the packaging can be influenced negatively (Pathare et al., 2012; Émond & Vigneault, 1998). Corrugated packages experience creep, fatigue or buckling when stacked on a pallet for a long time. When the packages fail, it severely affects the products leading to damage. The corrugated package must be able to resist high compression forces for the duration with which they are stacked (Frank, 2014; Skidmore, 1962). Jinkarn et al. (2006) observed a correlation between the size of the ventilation opening and the mechanical strength of the package. The author suggested that, to reduce the loss in mechanical strength, stronger materials should be used for the walls of the package. Similar observations were reported by Singh et al. (2008) and the authors concluded that due to ventilation openings, the loss in mechanical strength of a single walled corrugated paperboard package is between 20 to 50%.

Although ventilation holes are important for cooling of fresh horticultural produce, there must be a balance between ventilation holes large enough to effectively cool the produce, and still maintaining the mechanical stability of the package (Biancolini & Brutti, 2003). In this regard, Thompson et al. (2002) recommended a trade-off for cooling performance and strength of about 5 – 6% total ventilated area (TVA).

2.3 Mechanical damage to packages

During transportation of horticultural products, damage free packages must be properly ensured with minimal handling. The proper packaging of products requires a good understanding of the products, distribution environment, packaging materials and the type of damage of the package and the packaged products. Mechanical damage is considered as a type of stress that occurs during the harvest and postharvest handling of horticultural products. The stress is accompanied by physiological and morphological changes that affect the fruits, causing reduction in quality (Aliasgarian et al., 2013; Shewfelt, 1998). Horticultural products experience a variety of loading conditions that may lead to mechanical damage (Lewis et al., 2008). Bollen et al. (1995) described two different types of mechanical damage: impact during fruit harvest, selection, manipulation, and transport; and compression loads during storage or packing lines. More sources of mechanical damage have been considered by other researchers: abrasion between fruits and accompanied materials such as stones and insects (Ericsson & Tahir, 1996a), punctures, and prolonged vibration during transportation (Timm et al., 1996). Table 2.5 shows some types of mechanical damage and their effect on packaging containers. However, from previous studies, compression, impact and vibration forces cause the majority of mechanical damage (Opara & Pathare, 2014; Sidebang, 2012; Jarimopas et al., 2007; Blahovec & Paprštein, 2005; Knee & Miller, 2002; Bollen et al., 2001; Armstrong et al., 1991). Good packaging design enhances the attractiveness of the produce, enables it to be handled and marketed in convenient units, and helps to prevent mechanical damage (FAO, 2005).

2.3.1 Compression damage

Compression of the corrugated paperboard packages occurs when external forces are applied to the sides, faces, or corners of the package (Frank, 2014). Inadequate packaging performance may result from: over packing the packages, too high stacking of the packages, collapse of stacked packages during transportation, material handling equipment, shocks and vibration during transportation all generate compression forces that subsequently cause damage and bruising or crushing of the product (Kitthawee et al., 2011). Appropriate and good packaging offers vital protection against compression forces. The use of strong packages able to withstand multiple stacking can reduce this damage. The packaging should also be shallow enough so as to prevent the bottom layer of the produce from being damaged due to the weight of the top layers.

2.3.2 Impact damage

This occurs during handling, storage and transportation as a result of impacts from forklifts, racks, throwing or dropping of the packages, sudden stopping and accelerating of the vehicle, and shock during transport. Impact damage can result in bursting of the package and bruising or crushing of the products. Impact damage occurs usually at each stage of handling and is difficult to eliminate (Opara & Pathare, 2014; Gołacki et al., 2009). Depending on the products, some level of shock protection to prevent damage is required during transportation and handling. Rigid packages with proper cushioning can reduce the damage caused by impact forces.

2.3.3 Vibration damage

This damage generally occurs during transportation in transport vehicles such as trucks (especially with bad shock absorbers), planes or ships and also on nearly everything that moves such as conveyors and forklifts. Weak packages with inadequate cushioning, bad or rough roads and transmission vibration also result in vibration damage. During transportation, fruits incur vibration damage when the fruit rub against each other or with the package (Thompson et al., 2008; Acican et al., 2007; Berardinelli et al., 2005; Kader, 2002). Collapse of packages and damage to the products are the effects of vibration forces. Filling the products in the package tightly can reduce vibration of the produce within the package and thus reduce the damage. But it also ensures that fruit does not rub against each other or are forced together. The use of cellular trays, cushioning pads and individual fruit wraps can prevent fruit from rubbing against one another. Proper cushioning can absorb and reduce the adverse effects of vibration on the products.

2.3.4 Minimising mechanical damage

Mechanical damage can be reduced by using packages that can withstand:

- Compression from the heavy weight of other packages;
- Rough handling during stacking and unloading;
- Impact and vibration during transportation;
- High humidity during pre-cooling, transit and storage.

Furthermore, the geometric design of packaging has shown to significantly influence the degree of protection to the packed product. Holt & Schoorl (1984) investigated the protection ability of three apple package types; telescopic cartons, plastic crates and wooden boxes, using varying pack-densities and dropped from 0.5 m. The authors reported that the telescopic carton with trays protected the apple fruit more due to its ability to absorb more kinetic energy with less energy remaining to cause damage to the apples. Internal packaging also has a great influence on protecting the product from mechanical damage. A good interior packaging was described by Peleg (1985) as that which considers a fruit as a separate component, avoids contact between fruit, and absorbs the impact energy. Jarimopas et al. (2004) reported that at an impact level of 1.1 J, apple fruit was protected from damage when a net made of dry banana strings was used as wrapping. In another study by Jarimopas et al. (2008), the authors observed a minimal produce loss and maximum loss of 33.9% and 57.3% respectively when sweet tamarind was packed in corrugated packaging. In order to minimise losses, the authors proposed the use of a packaging sleeve and a specific ratio of foam balls to the product. The authors observed that there was a mechanical damage reduction of about 16 – 20% with the new proposed packaging. A more recent study by Eissa & Hafiz (2012) compared the cushioning capability of three materials (foam-net, paper-wrap and without (control)) by assessing the dynamic behaviour of the package and damage to apple due to transient vibration during transportation. The authors concluded that the foam net package was more suitable, reducing the damage by 50 – 63%. Preservation of the packed produce is therefore very important and can be achieved through good handling and proper packaging.

2.4 Mechanical analysis on horticultural packaging

Several studies have been performed on the mechanical performance and modelling of paperboard, corrugated paperboard and packages. Some of these studies include; box compression tests on packages, impact testing on packages, vibration testing and other aspects of the dynamics of paperboard and packages (Navaranjan et al., 2013; Babarinsa & Ige, 2012; Haj-Ali et al., 2009; Jarimopas et al., 2007; Biancolini, 2005; Nordstrand & Allansson, 2003; Beldie et al., 2001; Ragni & Berandinelli, 2001; Bajema & Hyde, 1998; Nordstrand, 1995; Pang et al., 1992b; Chen & Yazdani, 1991). Reviewing these studies on the experimental, numerical and mathematical modelling of paperboard and paperboard packages will help to understand the fundamental aspects of the design, the performance of ventilated corrugated package and the ability of the packages to adequately protect the packed product against mechanical damage.

2.4.1 Experimental analysis of package susceptibility to damage

Studies on packages have been carried out by several researchers from different viewpoints and these include; package type, products, damage mechanisms, package-product interaction, vibration transmissibility, etc. Some of these are studied for better understanding of the phenomenon involved. One of the essential functions of a package is to protect the packed product against mechanical damage. Therefore, it is very important for a designer to obtain reliable information about the mechanical properties of a package in an early stage of its development. Corrugated paperboard packages represent today a large and constantly growing part of the packaging industry owing to its lightness, recyclability and low cost (Talbi et al., 2009). The corrugated paperboard is an orthotropic sandwich with the surface plies (facing) providing bending stiffness, separated by a lightweight bending core (fluting) that provides shear stiffness. Two main directions characterise this material. The first, noted MD (machine direction), corresponds to the direction of manufacturing of the material. It coincides with the “x” axis as depicted in Figure 2.5. The second, noted CD (cross direction), corresponds to the transverse direction and coincides with the “y” axis. To refer to the out-of-plane direction (through-thickness), a third direction, ZD, is introduced. It is generally composed of three paperboard constituents: upper layer, lower layer known as the liners and fluting as shown in Figure 2.6**.** The same direction is observed for the paperboard, where the machine direction corresponds to the feel orientation of the cellulose fibres. This preferred orientation is due to the continuous nature of the material manufacturing process (Allaoui et al., 2011).

There are basically two types of holes in a corrugated package; the vent holes and the hand holes. The vent holes on the package exist to keep the air circulating and maintain a stable temperature, while the hand holes help to easily carry the packages. Global marketing of fresh produce widely adopts the ventilated packaging; one of the most important technological innovations with a minimal amount of internal packaging material to promote rapid, uniform and efficient cooling process of horticultural produce (Thompson et al., 2010; De Castro et al., 2005). A properly designed package for fresh produce must have enough vent holes to provide uniform air through the mass of the produce while still providing suitable mechanical stability to protect the produce (Vigneault & Castro, 2005; De Castro et al., 2004a; Vigneault & Goyette, 2002).

Various studies have been done on the compressive strength of the corrugated packages and corrugated board panels (Biancolini & Brutti, 2003; Lu et al., 2001; Nyman & Gustafsson, 2000; Maltenfort, 1996; Kellicutt, 1959). The compressive strength of the package is predicted from these studies through different approaches. The compression strength of a corrugated board package is a measure of the stacking strength of the package and also indicates the performance potential of the corrugated board. A standard test to measure the compression strength of a corrugated paperboard package is the box compression test. The box compression test (BCT) measures the top to bottom load of the package. The package is compressed between two parallel platens that could be fixed or swivelled in a compression testing machine, at a constant compression rate.

McKee et al. (1963) introduced a formula shown in Equation 2.1 that predicts the compression strength of a single wall corrugated package. The formula gives the compression strength as a function of the edgewise compression test value (ECT), the package/box perimeter and the flexural stiffness of the board. The ECT measures the ability of a small vertically placed sample of combined board to withstand top to bottom load and it is the single most important factor/property in predicting box compression and in the validation of the raw materials.

$$BCT = cECT^{b}\left(\sqrt{D_{MD}D_{CD}}\right)^{(1-b)}Z^{(2b-1)} \tag{2.1}$$

D_{MD}, D_{CD} are the geometric mean of the bending stiffness in the machine and cross directions respectively, Z is the perimeter of the package, the empirical constants c and b are a function of the panel rigidity and size.

For a corrugated board, the formula can be adopted as;

$$BCT = cECT^{0.746}\left(\sqrt{D_{MD}D_{CD}}\right)^{0.254}Z^{0.492} \tag{2.2}$$

The constant c is chosen so as to obtain the BCT value in Newton (N). The McKee’s formula has been further simplified relating ECT value, board calliper (h) and the perimeter of the box (Z) as;

$$BCT = 5.87(ECT)\sqrt{h \times Z} \tag{2.3}$$

The BCT has been widely used to evaluate the performance of a package. It is however, important to test the quality of the corrugated board and its components and evaluate the influence of environmental factors such as humidity, temperature and load durations (Pathare & Opara, 2014; Nordstrand, 2003) as regards to package performance. Post-buckling deflection of the side panels is the most common failure mode of a corrugated package loaded in top-to-bottom compression. The instabilities of the liners and the flutings also contribute to the failure development (Westerlind & Carlsson, 1992). The cushioning properties of corrugated paperboard were predicted by Sek & Kirkpatrick (1997) from static and quasi-dynamic compression data. The quasi-dynamic compression test was used to measure the rate of dependency of the deflection of the corrugated paperboard and the static/drop test was used to measure the cushioning behaviour of the corrugated paperboard.

The mechanical behaviour of paperboard package subjected to static compression was analysed by Beldie et al. (2001). This was done in three parts. Firstly, the edge compression loading of the paperboard panels. Secondly, the different segments that made up the paperboard package were subjected to compression after which the whole package was subjected to compression loading. The study showed that the middle segment was stiffer than the upper and the lower parts as well as to the whole package. The authors concluded that low stiffness of the upper and lower corners led to the low initial stiffness of the whole package. Panyarjun & Burgess (2001) developed an equation to predict the compression strength of different package properties by testing packages with different lengths, cross-sectional shapes, direction of flutes and the board strength. The authors observed that the package failure was attributed to the localised crushing at the point where the load was applied rather than collapse of the whole package.

It is important to consider factors such as vent size, shape and location for enhancing package performance (Pathare & Opara, 2014). Singh et al. (2008) initiated a study to understand the loss of compression strength in corrugated packages as a function of size, shape and location of ventilation and hand holes. The authors concluded that the presence of ventilation and hand holes can cause a reduction in strength of between 20 to 50% in a single wall corrugated shipping package, with the shape of the hole being critical to the loss of strength. Furthermore, the authors found that vertical holes that are rectangular or parallelogram in shape are better in retaining corrugated package strength as compared to circular holes. In the study, they showed a linear relationship between the loss of strength and the total area of the holes made for venting and handling, but it becomes nonlinear when over 40% of the face material is removed. In another study conducted by Jinkarn et al. (2006), the effect of carrying slots on the compression strength of corrugated board panels was performed. The authors focused on the shape, position and size of the carrying slots. Among all the shapes, circular slots showed the highest compression strength in contrast to the study by Singh et al. (2008). The perforated style showed higher compression strength compared to other true cuts of different shape.

The impact damage on packages has been studied by several researchers (Lu et al., 2012; Lu et al., 2010; Van Zeebroeck, 2005; Ragni & Berandinelli, 2001; Bajema & Hyde, 1998; Pang et al., 1992a; Chen & Yazdani, 1991; Jarimopas et al., 1990; Peleg 1985; Peleg, 1981; Schoorl & Holt, 1974). During transportation and storage, package can fall onto the floor resulting in damage (Pathare & Opara, 2014). It is however important to determine the potential height that a packaged product experience and the product’s fragility (Pathare & Opara, 2014) and the ability of package to protect the product under a shock due to free fall

(Djilali Hammou et al., 2012). Damage caused by impact has been correlated to several other mechanical parameters such as the energy absorbed (Jarimopas et al., 2007; Bollen et al., 2001) and force (Brusewitz et al., 1991). Drop testing is performed for several reasons: (a) to design impact-tolerant and portable products, (b) to replicate the abuse that may occur during manufacturing, shipping and installation, (c) for accelerated life testing (Pathare & Opara, 2014; Goyal & Buratynski, 2000).

Holt & Schoorl (1984) compared the resistance of three different apple packages against impact loads. The authors used telescopic fibreboard tray packs, plastic returnable crates and wooden boxes dropped from a height of 0.5 m onto a solid concrete floor. Tray packs gave the best protection to the apples with only 15% of the impact energy absorbed by the fruit, followed by returnable crates and then wooden boxes. Lu et al. (2010) studied the damage caused by impact in a single-wall and double-wall corrugated paperboard box by the pressure sensitive film technique. The boxes were subjected to impact at different heights; 20, 30, 40, and 50 cm. The authors observed that for both the single-wall and double-wall corrugated paperboard boxes, damage increased with drop height. Average pressure in the double-wall corrugated paperboard box was found to be lower than that in the single-wall corrugated paperboard box. In the study of the effects of continual shock loads performed by Xiang & Eschke (2004) on test specimen in the laboratory, the findings were used to deduce the relationship between acceleration amplitude and the number of continual shock to failure. A corresponding mathematical model was developed to carry-out the experiment. On the basis of the individual models for the tested products, two further models were proposed for all products, thus making it possible to arrive at a better assessment of the fragility of different types of products when exposed to continual shock loads. These models are capable of reducing the cost of package designs substantially as they allow the cushioning to be tailored more precisely to the fragility of products.

Package damage is also associated with the vibration forces that originate from the transportation mode during distribution. It is of utmost importance to know the level and type of forces by designing packaging (Jarimopas et al., 2005). Although vibration damage is often overlooked when considering mechanical hazards affecting fresh produce, it can be as damaging as impact and compression (Pathare & Opara, 2014). Several types of packaging such as paper pulp tray, polystyrene soft trays, wood bin, bulk bin, and corrugated paperboard are used to transport fresh produce. The effects of the transportation on fresh produce is dependent on the type of packaging as package types such as bulk bin can amplify vibrations during transportation (Vursavufi & Özgüven, 2004).

Vursavufi & Özgüven (2004) evaluated the effect of vibration frequency, vibration acceleration, different packaging methods and vibration duration on the mechanical damage of apples during transportation. The authors conducted the research in three stages. Firstly, vibration acceleration and vibration frequency were measured on the truck-bed for determining the vibration acceleration and frequency distribution; secondly, they measured the packaging transmissibility and vibration frequency sensitivity for all the packaging methods and thirdly, the road transportation was simulated using a laboratory vibrator and this was used to obtain factors that could influence damage of apple fruit during transportation. The volume packaging method had the highest packaging transmissibility. At a high vibration frequency interval of 8 – 9 Hz the packaging transmissibility was similar for all packaging methods. In their study, pattern packaging method had the lowest apple bruising and was the most suitable for transit. Chonhenchob & Singh (2005) performed an actual shipment and vibration tests on papaya fruit packages. These packages were evaluated in terms of physical protection, heat transfer characteristic for rapid cooling, maintenance optimum temperature, relative humidity during postharvest, quality maintenance and marketing issues. They concluded that paper-based cushions showed similar protection to plastic foam net materials. However, paper-based cushions increase the ripening response for papaya fruit. Park et al. (2011) provided relevant data for protective packaging in transportation. The authors evaluated the vibration transmissibility of corrugated paperboard with corrugation shape and equilibrium atmospheric conditions by a sinusoidal sweep vibration.

Distance, road roughness, travelling speed, load, suspension, and number of axles of the vehicle affect the vibration during transportation (Berardinelli et al., 2003). The consequence of these factors on agricultural products depends on the type of packaging. The vertical vibration component of the vehicle has the largest effect during transportation. O’Brien et al. (1969) reported that the primary cause of in-transit fruit damage was the vertical acceleration applied to the packages. The acceleration of fruit in a package is increased due to resonance if the resonance frequency of the fruit column is the same as the excitation frequency of the vehicle or road (Sitkei, 1986). The intensity and duration of vibration will determine the severity of damage and the intensity of vibration was evaluated with the magnitude of acceleration used as a criterion (Mohsenin, 1978). The incidence of damage was highest at the top layer in the package and the magnitude of damage was influenced by the depth of fruit in the package, tightness of the fill, type of suspension system used in the vehicle, magnitude of forced vibration from the road bed and vibration characteristics of the fruit cultivar. Damage in fruit has been minimised by proper packaging (Singh et al., 1992) and cushioning of the top layer (Vursavufi & Özgüven, 2004).

Rouillard & Sek (2000) investigated the frequency of response of packages when it undergoes progressive damage during a sine dwell vertical vibration test. The authors claimed tracking the resonance by feedback control of the excitation frequency during resonance dwell is essential, thus the system remains in the resonance condition and the effect of resonance on the system will be controlled. Results showed that a substantial shift in the resonance frequency of a package can occur during a sine dwell test and damage is maximised when tracking of the resonance frequency of the packaged unit is used during a sine dwell test. The trend in the resonance frequency can be used as an indication of damage growth.

2.4.2 Finite element analysis (FEA)

Finite element analysis is the application of the Finite Element Method in which the object or system is represented by a geometrically similar model consisting of multiple-linked, simplified representations of discrete regions. This numerical analysis uses a complex system of points called nodes which form a grid called a mesh. This mesh is programmed to contain the material properties which defines how the material will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated diffusion levels of a particular area (Roduit et al., 2005). In practice, finite element analysis usually consists of three principal steps, namely: pre-processing, analysis, and post-processing.

Pre-processing – This is the modelling of the structure to be used for the analysis. Using the computer aided design (CAD) program that either comes with the software or provided by another software supplier, the structure is modelled. The structure is divided into a number of discrete sub-regions known as “elements”, connected at discrete points known as “nodes”. The structure represented by nodes and element is called the “mesh”. The elements not only represent subdivisions of the structure, but also the mechanical properties and behaviour of the structure. Complex regions of the structure such as curves, requires a higher number of elements so as to accurately represent the shape of the geometry, whereas regions with simple geometry can be represented by fewer elements. Choosing an appropriate element for a structure requires some factors such as; prior knowledge of FEA, knowledge of the behaviour and properties of the structure, the elements available in the FEA software and the characteristics of the elements. In the pre-processing stage, the constraints, loads, boundary condition and the material properties of the structure are defined. Also, the entire structure is entirely defined by the geometric model at this stage.

Analysis – The dataset such as the geometry, constraints, load, and mechanical properties of the structure are used as input to the finite element code to generate matrix equations for each element. They are then assembled together to generate a global matrix equation of the structure. That is, these datasets are used as input to the FEA code which constructs and solves a system of linear and nonlinear algebraic equations. The form of the equations is (Cook et al., 2002);

$$\{F\} = [K]\{u\} \tag{2.4}$$

where $\{F\}$ is the external force vector, $[K]$ is the global stiffness matrix and $\{u\}$ is the displacement vector. The stiffness matrix is reliant on the type of FEA problem being solved. The equations are solved for deflections and using these values, stress, strain, and reactions are calculated. The data generated are stored and can be used for graphical plots in the post-processing step.

Post-processing – This is the last step involved in FEA. Raw data stored in the analysis step makes it difficult to interpret. In the post-processing stage, these data is used to generate the deflected shape of the structure, stress plots, and other animations, which are useful in better understanding of the behaviour of the problem being analysed.

Advantages and disadvantages of FEA

Some of the advantages of FEA are (Srirekha & Bashetty, 2010);

- Can handle very complex geometry.
- Can handle complex restraints. They can solve indeterminate structures.
- Complex loadings such as nodal loads, element load (inertia force, thermal, pressure) and time or frequency dependent loading can be handled.
- It is a reliable tool because it can perform different analysis of the same model under different situation by changing the loads, material properties, or boundary conditions as the problem demands.
- Used in a wide variety of engineering problems such as solid mechanics, heat transfer, dynamics, fluid, and electrostatic problems among others.

Some of the disadvantages of FEA are;

- FEA is still an approximate technique, that is, it obtains inexact solutions.
- Need for computer programs and facilities which are expensive to acquire.
- There are inherent errors in FEA.
- Blunder or mistakes made by users can be catastrophic.
- Gives solution only at the nodal points.

Constitutive properties of paperboard

Due to the manufacturing process of paper, it is made of oriented wood fibre of which the strength and stiffness properties are anisotropic. The stiffness properties of paper can be assumed to be orthotropic, i.e. three planes of symmetry for the elastic properties can be found. Paperboard is a multilayer and in characterising the whole paperboard, constitutive properties must be determined for each layer. Thus the constitutive relation, i.e. the relation between the stresses and strains of paperboard is assumed to be (Ugural & Fenster, 2003):

$$\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{12} \\ 2\varepsilon_{13} \\ 2\varepsilon_{23} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_1} & -\frac{\nu_{21}}{E_2} & -\frac{\nu_{31}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{12}}{E_1} & \frac{1}{E_2} & -\frac{\nu_{32}}{E_3} & 0 & 0 & 0 \\ -\frac{\nu_{13}}{E_1} & -\frac{\nu_{23}}{E_2} & \frac{1}{E_3} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{12}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{23}} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix} \tag{2.5}$$

where σ_{11}, σ_{22}, σ_{33}, σ_{12}, σ_{13} and σ_{23} are the stress tensor components expressed in $\mathrm{N/m^2}$. E_1, E_2 and E_3 are the Young's moduli in the principal directions of the material; the machine direction (MD), cross direction (CD) and thickness direction (ZD) (Figure 2.7), while G_{12}, G_{13} and G_{23} are the shear moduli in the principal directions. Also, ν_{12}, ν_{21}, ν_{13}, ν_{31}, ν_{23} and ν_{32} are the Poisson's ratios. Due to the symmetry of the compliance matrix given in Equation 2.5, it leads to;

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}, \qquad \frac{\nu_{13}}{E_1} = \frac{\nu_{31}}{E_3}, \qquad \frac{\nu_{23}}{E_2} = \frac{\nu_{32}}{E_3} \tag{2.6}$$

Therefore only nine parameters remain as a result of the symmetry and these are; E_1, E_2, E_3, G_{12}, G_{13}, G_{23}, ν_{12}, ν_{13} and ν_{23}. These parameters are generally measured experimentally. However, it is not straightforward to measure some of the parameters. This is due to the small dimension in the thickness direction compared to other directions. Using the stress–strain curves from the measurement of the applied force and the displacement, the in-plane properties; E_1 and E_2 can be obtained.

A good approximation of the Young's modulus in the thickness direction can be estimated according to Beldie (2001) is given by:

$$E_3 = \frac{E_1}{200} \tag{2.7}$$

According to (Mann et al., 1979; Baum et al., 1981; Beldie, 2001), the shear moduli can be estimated by:

$$G_{12} = 0.387\sqrt{E_1 E_2} \tag{2.8}$$

$$G_{13} = \frac{E_1}{55}$$

$$G_{23} = \frac{E_2}{35}$$

Biancolini & Brutti (2003) evaluated the shear modulus using a third series of tensile tests for the paperboard specimens oriented at $45°$ to the transverse direction. To evaluate G_{12} from $E_{45°}$ (Equation 2.9), the $45°$ rotated stiffness matrix was used.

$$G_{12} = \left[\frac{2\nu_{12}}{E_1} - \frac{1}{E_1} - \frac{1}{E_2} + \frac{4}{E_{45°}}\right]^{-1} \tag{2.9}$$

The authors also determined the Poisson's ratio with image processing, acquiring a magnified image of the specimen before and after an impressed displacement of $0.7\ \mathrm{mm}$ in the machine direction. The experiment was repeated five times evaluating both the longitudinal and the transverse strain of a square target printed in the central region of the specimen. The Poison's ratio was computed using:

$$\nu = \frac{\varepsilon_T}{\varepsilon_L} \tag{2.10}$$

The Poisson's ratio was evaluated by researchers (Baum et al., 1981; Han & Park, 2007) with:

$$\sqrt{\nu_{12}\nu_{21}} \approx 0.29 \tag{2.11}$$

$$\frac{\nu_{12}}{E_1} = \frac{\nu_{21}}{E_2}$$

where ν_{12} is the Poisson's ratio of the machine direction and ν_{21} is the Poisson's ratio of the cross direction.

Applications in packaging studies

According to Delele et al. (2010), mathematical modelling techniques has increasingly become an alternative to the difficult, time-consuming and expensive experiments. Investigation of appropriate package design and behaviour analysis of packages using finite element analysis has been made (Han & Park, 2007; Biancolini & Brutti, 2003; Park & Lee, 1999; Patel et al., 1997). The finite element method has been considered by corrugated board industry as a tool for replacing the traditional application of semi-empirical expressions (McKee et al., 1963), looking for both improved accuracy in the prediction of package strength (Biancolini, 2005; Urbanik & Saliklis, 2003; Gilchrist et al., 1999; Rahman, 1997), and extending the analysis to package types as different as possible.

Biancolini & Brutti (2003) studied the buckling behaviour of corrugated paper packages by means of experimental and theoretical analysis. The mechanical behaviour of paperboard was first evaluated after which a finite element model able to reproduce buckling loads obtained from the standard edge compression test experiment was developed. A corrugated board finite element was introduced by means of a dedicated homogenization procedure in order to investigate the buckling of the complete package. The finite element model of the package assembled with this element can accurately predict the experimental results of incipient buckling observed during the standard box compression test. In the study of Han & Park (2007), the principal design parameters of ventilation holes and hand holes in the facing of corrugated paperboard packages was investigated using finite element analysis. The authors studied with respect to stress distribution and stress level, the various designs of ventilation holes. The finite element analysis was used to determine the appropriate pattern, location and size of the vent/hand holes. A good agreement was found between the simulation results and the actual experimental results. It was found that the most appropriate pattern and location of the ventilation holes was vertical oblong-shaped and symmetrically positioned within a certain distance to the right and left from the centre of the front and rare facing of the package. To improve package strength, hand holes should be located higher than the centre of the side face, with the appropriate horizontal oblong shape. To achieve a minimum decrease in compression strength, it was recommended that the length of the holes should be less than a quarter of the depth of the package, while ratio of width to length of the holes should be $^1/_{3.5} - ^1/_{2.5}$ and even-numbered holes should be located symmetrically.

Weigel (2001) developed a computer model of a palletized bulk bin with fruits by using the finite element analysis method. Unit loads consisting of palletized bulk bins of apples and peaches were tested and the model was found to accurately predict the resonance frequencies of these loads. The effects of product mass, package design, and pallet design on the natural frequencies were analysed using the model. Various pallet designs were analysed using finite element analysis by Masood & Rizvi (2006) relating information on weight, loading and safety conditions.

For corrugated paperboard, the compressive strength, crush strength, bending deflection and flexural stiffness, creep property and recoverability were studied (Lee & Park, 2004; Urbanik, 2001). Using finite element models and commercial finite element code such as ABAQUS or ANSYS, the mechanical behaviour of corrugated paperboard such as buckling, transverse shear, stability, collapse and ultimate failure were studied (Talbi et al., 2009; Haj-Ali et al., 2009; Aboura et al., 2004; Nordstrand, 2003; Gilchrist, 1999). However, the reliability of models used in various studies has been checked by comparing the numerical results with the experimental ones (Han & Park, 2007; Biancolini & Brutti, 2003; Beldie et al., 2001; Patel et al., 1997). There was a unanimous agreement between the measured ECT and BCT results for the corrugated paperboard packages with those predicted by the finite element models in the study by Biancolini & Brutti (2003). In addition, the study by Han & Park (2007) in the determination of the pattern and location of ventilation and hand holes using finite element analysis simulation reported an agreement with experimental results. In contrast, Beldie et al. (2001) discovered that numerical results showed the models are stiffer than those of experimental results of the paperboard package in their numerical studies of paperboard package under compression loading using ABAQUS finite element code. The stiffer models were concluded to be due to the behaviour of the creases of the paperboard package that was not considered.

2.4.3 Analysis of produce damage (bruising)

Mechanical damage experienced by horticultural produce especially fruit, manifests as bruising (Bollen et al., 1999). Consumers primarily judge fruit quality based on their appearance (Opara & Pathare, 2014) and even a moderate amount of bruise can alter a consumer's decision to purchase the produce. Harker (2009) reported bruising to be a more important barrier to purchasing than price.

Bruising appears as brown spots on fruit due to fruit-to-fruit contact or contact with the package (Blahovec & Paprštein, 2005). The extent of bruising is usually described in terms of bruise volume and the effect of bruising is the deterioration of the product quality. Several researchers have correlated bruise levels with some mechanical parameters such as impact energy or absorbed energy (Jarimopas et al., 2007; Bollen et al., 2001), drop heights (Lu et al., 2010; Bollen, 1993), impact velocity (Pang et al., 1994) and force (Brusewitz et al., 1991). A linear correlation between bruise volume and absorbed energy was observed by Kitthawee et al. (2011) and the extent of bruising increased with drop heights (Lu et al., 2010).

In the review of Opara & Pathare (2014), the authors classified the techniques for quantifying bruising into three different categories; (a) manual measurement of bruise dimension to estimate bruise area and volume (Lu et al., 2010; Opara et al., 2007; Bollen, 2001), (b) image analysis of bruise tissues to determine the size of the bruise (Menesatti & Paglia, 2001), (c) non-destructive techniques (Dang et al., 2012; Zhao et al., 2010; Lu, 2003). The extremity of bruise may be reported as bruise diameter, area or volume. Bruise area (BA) has been generally calculated (Equation 2.12) by measuring the major (w_1) and minor (w_2) diameter of the bruise, assuming an elliptical shape (Lu et al., 2010; Lewis et al., 2008; Bollen et al., 2001).

$$BA = \frac{\pi}{4} w_1 w_2 \tag{2.12}$$

Bruise volume has been evaluated by sectioning and estimation from depth and diameter measurements. Different methods for evaluating bruise volume were compared by Bollen et al. (1999) as shown Table 2.6. The author concluded that no single method is available for bruise volume estimation and each method may be suitably unique depending on the bruise characteristics. The bruise thickness method considers an additional measurement such as the fruit radius making it a simpler method compared to the other methods reported and it is suitable for small impacts of less than 50 mm. Enclosed volume and full depth methods assume bruising to extend to the surface. Bruise damage caused by less than 100 mm drop is best evaluated using the enclosed volume method while the ellipsoidal method estimates bruise volume with the actual bruise depth. The author reported that the accuracy of bruise volume estimation can be improved by treating the bruise as an elliptical shape.

Opara & Pathare (2014) reviewed other methods used for estimating bruise volume and reported the method by Diener et al. (1979) that considered bruise volume (BV) to be part of a sphere (Equation 2.13).

$$BV = \frac{\pi}{6} h(0.75D^2 + h^2) \tag{2.13}$$

where h is the bruise depth (mm) and D is the diameter (mm).

By considering the shape of the bruise to be a semi-oblate spheroid that cuts through the bruise region, Jarimopas et al. (2007) and Chen & Sun (1981) estimated the bruise volume by measuring the bruise depth, h and the bruise diameter, D using:

$$BV = \frac{\pi}{6} hD^2 \tag{2.14}$$

The selection of appropriate shape and formula for estimating bruise volume is very important in quantifying mechanical damage (Opara & Pathare, 2014), given that bruise shape varies considerably depending on tissue type, impactor type, energy of impact and fruit maturity status (Mowatt, 1997).

In order to determine the susceptibility of fruit to bruising, the bruise size is required. Therefore, the bruising susceptibility, BS $(\mathrm{mm^3 J^{-1}})$ can be determined, as the ratio of the bruise volume, BV $(\mathrm{mm^3})$ to the impact energy, IE (J) (or absorbed energy) (Opara, 2007).

$$BS = \frac{BV}{IE} \tag{2.15}$$

$$IE = m_i g h_d \tag{2.16}$$

where m_i is the mass of the falling object (kg), g is the acceleration due to gravity $(\mathrm{m.s^{-2}})$, and h_d is the drop height (m).

Recently, non-destructive bruise detection techniques have been used in fresh produce industries in bruise analysis. The use of a conventional charged coupled device have successfully been used to classify fruit in relation to size, appearance, colour as well as bruising indices (Opara & Pathare, 2014; Van Zeebroeck et al., 2007). Hyperspectral imaging, also known as chemical imaging has been used to detect and evaluate fruit bruising (Zhao et al., 2010; Xing et al., 2005; Qin & Lu, 2005). This technique combines the conventional imaging and spectroscopy to obtain spectral and spatial data from an object (Gowen et al., 2007). A typical hyperspectral imaging system consists of a light source (illumination), a wavelength dispersion device (spectrograph), an area detector (camera), a translation stage and a computer (Liu et al., 2013). Due to its quick detection ability, visible and near infrared (Vis–NIR) spectroscopy technology has become widely used in fruit injury detection (Zhang et al., 2013; Magwaza et al., 2013a, b). To determine bruise surface using the near infrared technology, the produce is exposed to NIR radiation and the transmitted radiation is measured. Other non-destructive emerging techniques are thermal imaging and nuclear magnetic resonance imaging.

2.5 Conclusion

Packaging plays a major role in fresh produce transportation and storage by protecting produce from physical or mechanical damage, modifying the environment and improving produce transport density per volume. The structural design of corrugated packaging is important to adequately withstand a number of different loading conditions during postharvest handling of fresh produce. The different loading conditions such as vibration force, stacking, filling, impact, and storage operations experienced by the package can be associated to produce damage. The strength of a corrugated box is commonly reported by the box compression test (BCT). During stacking on pallets, the highest compression load is experienced by the boxes at the bottom of the stack. Ventilated packaging is most commonly used for handling fresh produce. The geometrical design (shape, size, position and number) of the ventilation holes significantly affects the airflow rates and distribution, which in turn influences the cooling rates and homogeneity of cooling. In addition, the presence of ventilation holes also negatively influences the mechanical strength of the packaging. Optimising the corrugated box should therefore maintain structural integrity and allow for improved cooling of the packaged produce. Although numerous studies have focused on optimising the mechanical strength of packages which has enhanced the understanding of package resistance to loadings. However, no universal recommendation has been possible as each package and fruit type is unique. Furthermore the susceptibility of fruit to mechanical damage is important in the design of packages.

The strength of packages has been widely studied through experimental studies and mechanical strength of corrugated package have been predicted using various empirical formulae. However, the drawback is that most of the formulae do not incorporate the effect of the geometrical design of the vent holes. Finite element analysis has therefore been considered to improve the strength studies of the ventilated corrugated packages with consideration of the geometrical design on the package.

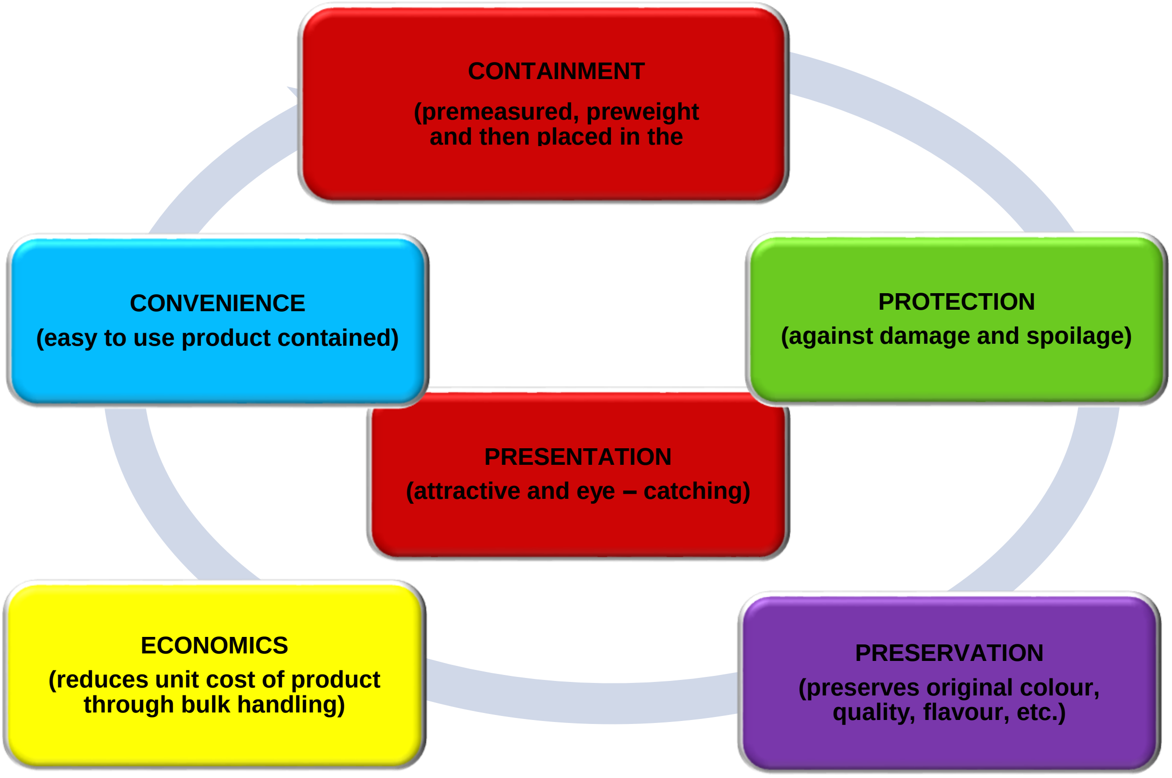


Figure 2.1: Summary of the primary function of packaging.

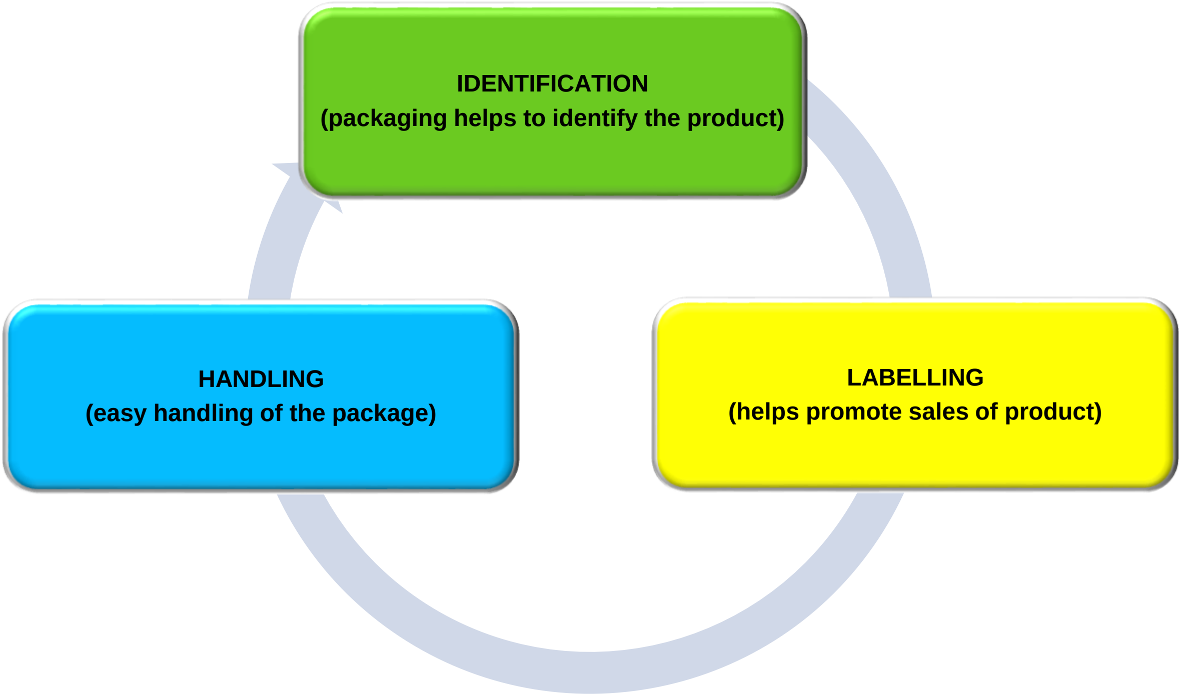


Figure 2.2: Summary of the secondary function of packaging.

Table 2.1: Main types of packaging papers.

Basic Material	Source	Weight range kg/1000 m^2	Tensile Strength	Properties and Uses
Kraft papers	Sulphate pulp from softwoods	70 – 300	250 – 1150	Heavy-duty paper, bleached, natural or coloured; may be wet-strengthened or made water-repellent, strongest of all papers. Used for bags, multi-wall sacks and liners for corrugated. Bleached varieties are used for food packaging where strength is required.
Sulphite papers	Usually bleached generally made from mixture of softwood and hardwood	35 – 300	Very variables	Lighter and weaker than Kraft paper, clean, bright paper of excellent printing nature and used for smaller bags, pouches, envelopes, waxed paper, labels and for foil laminating etc.
Greaseproof papers	From heavily beaten pulp	70 – 150	180 – 450	Grease-resistant for baked goods and fatty foods.
Glassine papers	Similar to greaseproof, but super-calendered	40 – 150	140 – 535	Oil and grease resistant, used as an odour barrier for lining bags, boxes, etc. and for greasy foods.
Parchment paper	Treatment of unsized paper with concentrated sulphuric acid	12 – 75	215 – 1450	Non-toxic, high wet strength, grease and oil resistant for wet and greasy food.
Tissue paper	Lightweight paper from most pulp	20 – 50	Low	Lightweight, soft wrapping paper.

Table 2.2: Main types of paperboard.

Paperboard types	**Sources**	**Properties and uses**	
White paper	From several thin layers of bleached chemical pulp	Coated with polyethylene, polyvinyl chloride or wax for heat sealability. Used for the inner layer of a carton and suitable for direct contact with food.	
Solid paper	Multiple layers of bleached sulphate board	Durable and possesses high strength. Laminated with polyethylene and used for liquid cartons otherwise called milk cartons. Fruit juice packages are made from solid paper.	
Chipboard	usually from recycled paper	Contains impurities and blemish from the original paper. Lined with whiteboard to improve appearance and strength. Used for making the outer layers of cartons for food such as cereal and not suitable for direct food contact.	
Fibreboard	Made out of wood fibres	Solid fibreboard	Inner white board layer and outer Kraft layer. Laminated with aluminium or plastic to improve barrier properties. Resistant to impact and compression loading. Used to in the packaging of dry products such as milk powder
		Corrugated fibreboard	Assembled from three or sometimes more sheets of Kraft paper consisting of liners and a central core (fluting). Widely used in shipping due to its resistance to crush damage and impact abrasion. Major use is for the manufacture of corrugated boxes used as shipping containers.

Table 2.3: Different forms of corrugated board.

Forms of corrugated board	**Properties**
Single face board	Combination of one fluted corrugating medium glued to one flat facing of linerboard.
Single wall	Also known as the double face corrugated. It is the combination of one corrugated medium and two facings of linerboard, with one linerboard glued to each side of the corrugated medium. Mainly used for the manufacture of shipping containers
Double wall	Combines two corrugated medium layers and three flat facings of linerboard. The order of assembly is in the form: linerboard, medium, linerboard, medium, linerboard. Mostly used where strength and cushioning are significantly required.
Triple wall	Combines three corrugated medium layers and four flat facings of linerboard. The order of assembly is in the form: linerboard, medium, linerboard, medium, linerboard, medium, linerboard.

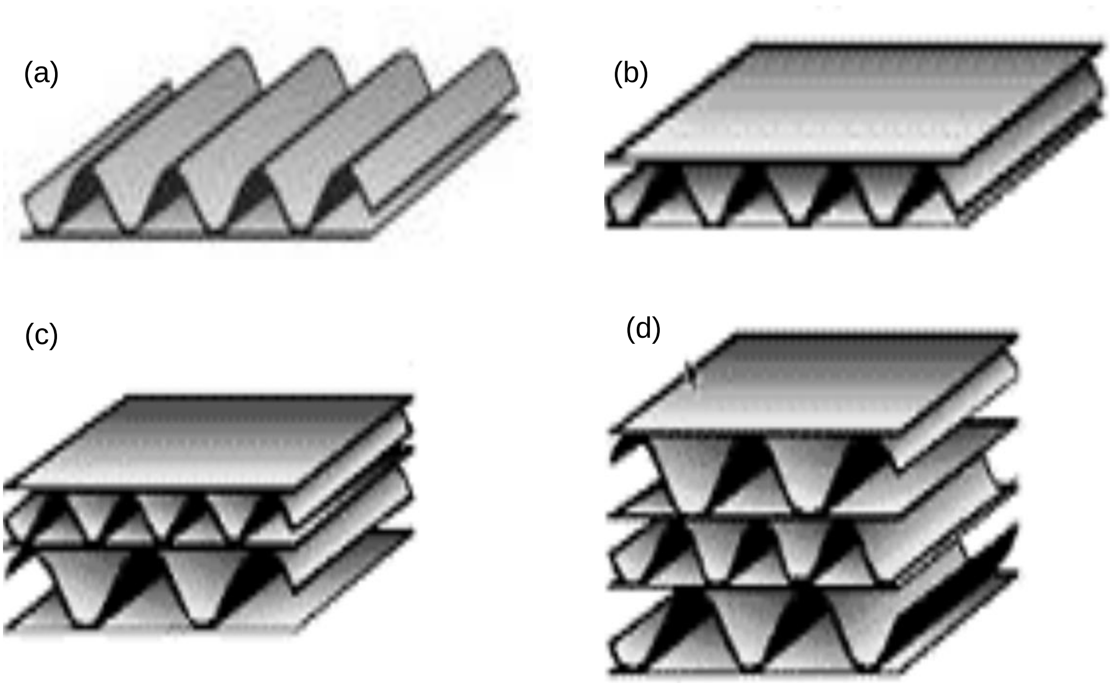


Figure 2.3: Diagram of a (a) single face, (b) single wall, (c) double wall and (d) triple wall corrugated paperboard (Twede & Selke, 2005).

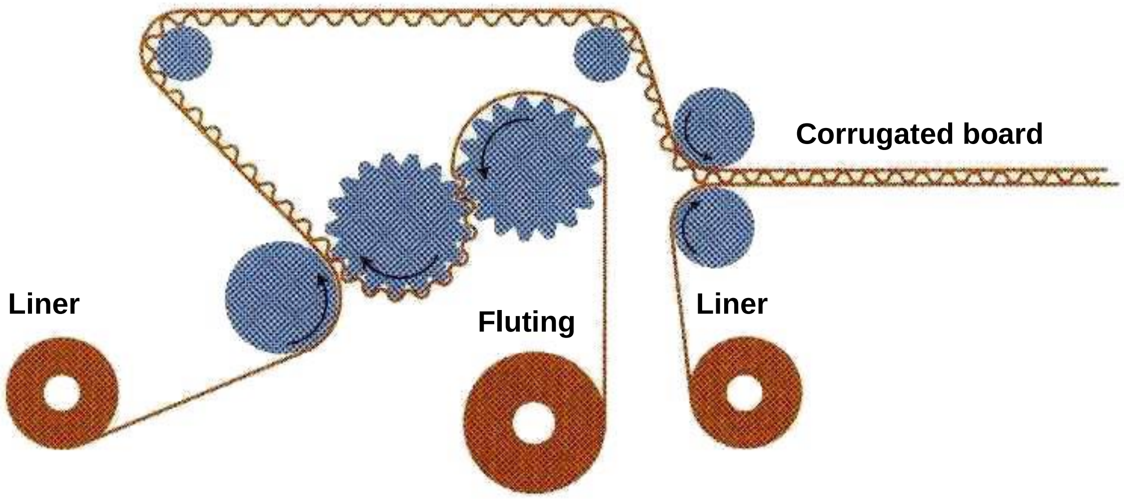


Figure.2.4: Manufacturing of a corrugated board (Allansson & Svard, 2001).

Table 2.4: Different types of fluting medium profiles

Flute profile types	**Properties**	**Approximate flute height (mm)**	**Approximate take-up factor**	**Number of corrugations per metre**
A flute	First standard board style. The largest flute, seldom used at present.	3.99 - 4.90	1.54	110
B flute	Most widely specified profile, difficult to crush, good compactness and high compression strength.	2.21 – 3.00	1.32	150
C flute	Larger than B flute, higher compression strength but can be easily crushed.	3.48 – 3.68	1.32 – 1.43	130
E flute	Usually fine with an excellent flat crush resistance.	0.99 – 1.80	1.29	290
F flute	Also known as the microflute, usually very fine, with excellent flat crush resistance and rigidity.	0.74	1.25	350

Table 2.5: Typical mechanical damage and their effect on packaging containers (Walker, 1992).

Types of damage	**Container**	**Result**	**Important factors**
Impact damage	Sacks - woven and paper	Splitting of seams and material causing leaking and spillage loss.	Seam strength
	Fibreboard boxes	Splitting of seams, opening of flaps causing loss of containment function. Distortion of shape reducing stacking ability.	Bursting strength Closure method
	Wooden cases	Fracture of joints, loss of containment function.	Fastenings Wood toughness
	Cans and drums	Denting, rim damage. Splitting of seams and closures causing loss of containment and spoilage of contents.	
	Plastic bottles	Splitting or shattering causes loss of contents.	Material grade Wall thickness
Compression damage	Fibreboard boxes	Distortion of shape, seam splitting causing loss of containment and splitting of inner cartons, bags, and foil wrappings.	Box compression strength
	Plastic bottles	Distortion, collapse and sometimes splitting, causing loss of contents.	Design, material, wall thickness
vibration	Woven sacks	Sifting out of contents.	Closeness of weave
	Corrugated fibreboard cases	Become compressed and lose their cushioning qualities. Contents more prone to impact damage.	Box compression strength
Snagging, tearing, hook damage	Sacks - woven and paper	Loss of containment function - spillage (more severe with paper sacks).	Tear strength
	Tins	Punctured, loss of contents.	Metal thickness

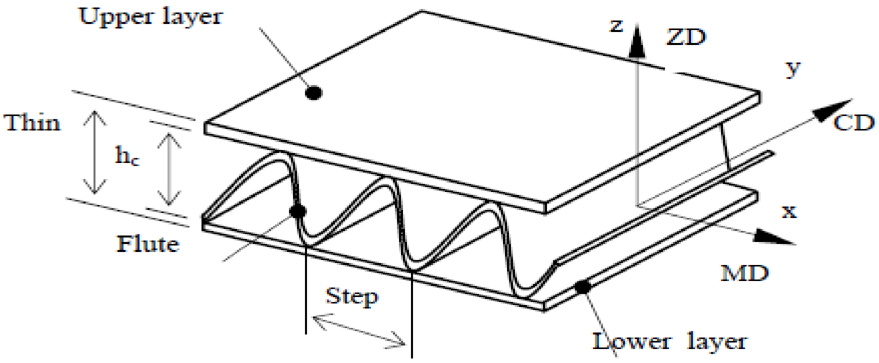


Figure 2.5: Corrugated board panel geometry (Allaoui et al., 2011).

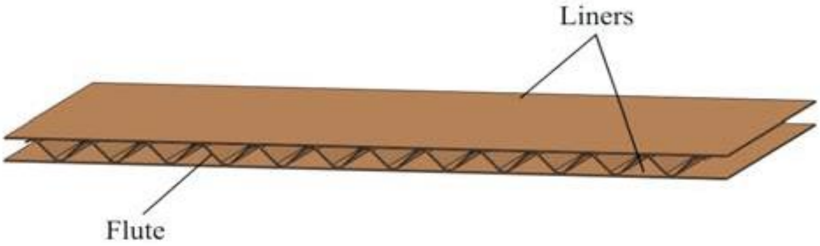


Figure 2.6: Structure of the corrugated paperboard showing liners and the flute (Gospodinov et al., 2011).

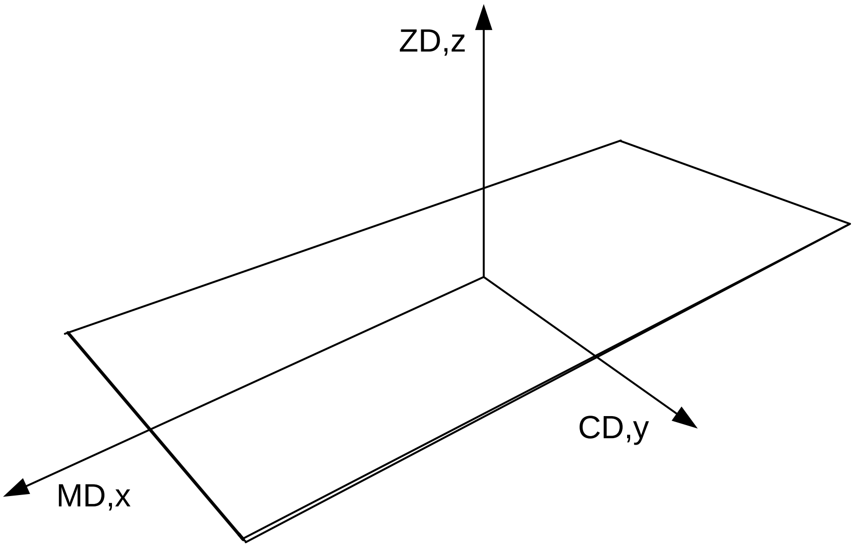
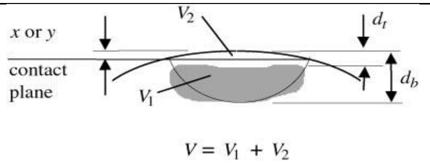
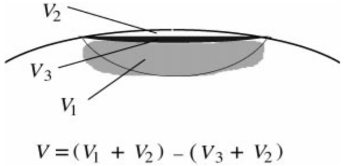
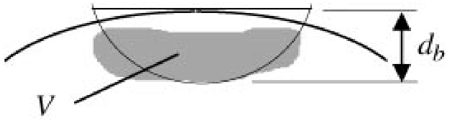
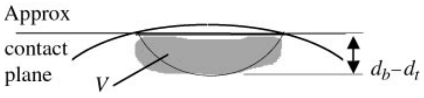
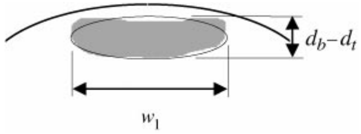


Figure 2.7: Directions in paper or paperboard where MD is the machine direction, CD is the cross direction and ZD is the thickness direction.

Table 2.6: Methods for calculating bruise volume.

Method	Figures of bruise	Estimate	
		Circle	Ellipse
Enclosed volume (Holt & Schoorl, 1977)		$V = \frac{\pi}{24}(3w_1^2 d_b + 4(d_b - x)^3 + 4x^3)$	$V = \frac{\pi}{24}(3w_1 w_2 d_b + 4(d_b - y)^3 + 4y^3)$
Unbruised volume removed (Holt & Schoorl, 1977)		$V = \frac{\pi}{24}(3w_1^2(d_b - d_t) + 4(d_b - x)^3 + 4(d_t - x)^3)$	$V = \frac{\pi}{24}(3w_1 w_2(d_b - d_t) + 4(d_b - y)^3 + 4(d_t - y)^3)$
Full depth (Saltveit, 1984)		$V = \frac{\pi d_b}{24}(3w_1^2 + 4d_b^2)$	$V = \frac{\pi d_b}{24}(3w_1 w_2 + 4d_b^2)$
Bruise thickness (Mohsenin, 1986)		$V = \frac{\pi(d_b - d_t)}{24}(3w_1^2 + 4(d_b - d_t)^2)$	$V = \frac{\pi(d_b - d_t)}{24}(3w_1 w_2 + 4(d_b - d_t)^2)$
Ellipsoid (Hung & Prussia, 1989)		$V = \frac{4}{3}\pi\left(\frac{(d_b - d_t)w_1^2}{8}\right)$	$V = \frac{4}{3}\pi\left(\frac{(d_b - d_t)w_1 w_2}{8}\right)$

V, is the estimated bruise volume measured in mm^2; d_b and d_t are the full depth of bruise and the depth from fruit surface of bruise respectively, measured in mm; w_1 and w_2, the bruise width across the major and the minor axes in mm; x is the height of fruit section above the contact plane in a circular bruise and y, is the height of fruit section above the contact plane in an elliptical bruise, R, is the radius at bruise. $x = R - \sqrt{R^2 - \frac{w_1^2}{4}}$, $y = R - \sqrt{R^2 - \frac{w_1 w_2}{4}}$.

Chapter 3 Susceptibility to impact damage of apples inside ventilated corrugated paperboard packages: the effects of package design

***Keywords*: ventilated packaging, impact damage, bruise susceptibility, accelerometer, apples**

Abstract

The incidence of fruit postharvest losses and waste due to mechanical damage during handling is a major problem in the fresh produce industry. Ventilated corrugated paperboard (VCP) packages used extensively in the fruit industry are designed to minimize handling damage and to facilitate airflow around the produce to maintain the cold chain. During handling and transportation, both the package and contents experience a range of force loading conditions, including impact, compression and vibration which may result in bruise damage. The objectives of this study were to investigate the impact bruise damage susceptibility of apples packed inside two ventilated carton designs (one with fruit on tray layers and the other with fruit in retail plastic bags). The spatial variation of bruise damage inside the packages and the incidence of physical damage of the packages were also investigated. Results showed that both the incidence and susceptibility to bruise damage of the apples were affected by package design and drop heights; with more than 50% higher incidence and 66% higher bruise susceptibility occurring on fruit packed in the bulk package design than on those packed in the layered package design. Irrespective of package design, both bruising incidence and susceptibility were highest at the bottom of the package, which increased significantly by about 50% when the package drop height increased from 30 cm to 50 cm.

3.1 Introduction

Packaging fresh fruit and vegetables is an important step in the long and complicated journey from the grower to consumer. Bags, crates, hampers, baskets, cartons, bulk bins, and palletized containers are common forms of packaging used when handling, transporting, and marketing fresh produce. However, despite the availability and use of different packaging formats and designs in fruit handling, the occurrence of bruise damage is still a frequent quality problem (Opara & Pathare, 2014; Lu et al., 2010).

Consumer perception of fresh produce quality is influenced by the appearance, shape and textural characteristics, and these in turn influence purchasing decisions. Consumers desire high quality produce that is free from bruise, cuts, punctures, physiological disorders and pathogens (Timm et al., 1996; Martzinger & Tong, 1993). The presence of bruising and other types of physical damage reduce the aesthetic appeal of fresh produce. Previous studies have shown that bruising due to excessive compression, impact and vibration forces is the most common type of postharvest mechanical injury (Opara & Pathare, 2014; Lewis et al., 2008; Opara, 2007; Jarimopas et al., 2007; Knee & Miller, 2002; Brown et al., 1993). In addition to the loss of appearance quality, bruised fruit is also susceptible to high risk of fungal and bacterial contamination and excessive moisture loss, as high as 400 times more than that of intact fruit (Wilson et al., 1999). Several researchers have studied fruit bruising due to impact (Ragni & Berandinelli, 2001; Bajema & Hyde, 1998; Pang et al., 1992; Chen & Yazdani, 1991; Peleg, 1985; Jarimopas et al., 1984; Peleg, 1981; Schoorl & Holt, 1980; Holt & Schoorl, 1977).

Peleg (1985) describes good interior packaging as that which treats individual fruits as separate units, avoids fruit-to-fruit contact, and absorbs the impact energy. Holt & Schoorl (1984) compared three different types of packaging for their protection afforded to apples against damage due to impact. The authors found that wooden boxes afforded the least protection, followed by returnable crates and tray packs. In another study of apples in bulk bins during semi-trailer transport, Timm et al. (1996) found that fruit in plastic bins had less abrasion damage in comparison to those packed in hardwood and plywood bins. In contrast, Acıcan et al. (2007) studied the mechanical forces exerted on apples in wooden crates during transport from harvest to market under free fall, horizontal impact and vibration forces and found that the mechanical forces acting on the apples at the bottom of the crate was greater than those at the upper layer and that there was a significant difference between the damage at the lowest and the uppermost layers.

Ventilated paperboard carton is the most common type of packaging used for handling fresh fruit (Pathare et al., 2012). In the two main types of ventilated packaging designs used in the fruit industry, produce may be packed on tray layers or placed inside plastic bags each containing up to ten pieces of fruit. Both types of package design and multi-scale packing are used extensively in long distance (export) and local fresh fruit supply chains. However, little is known about the susceptibility of fruit to bruising inside such packaging designs. The objective of this research was to investigate the susceptibility of apples to impact bruise damage inside ventilated corrugated paperboard packages, including the spatial variability and severity of bruise incidence inside the package.

3.2 Materials and methods

3.2.1 Fruit supply

Golden Delicious apples were purchased during commercial harvest from a packhouse in Grabouw, Western Cape, South Africa $(34°48'14''\text{S}, 19°02'50''\text{E})$. Fruit of uniform size and maturity based on the background colour, firmness and free from physical defects were used for the experiments. The mean diameter and mass of the apples were 65 ± 2.0 mm and 148.7 ± 7.0 g, respectively.

3.2.2 Packaging materials

Two types of ventilated paperboard package designs (Bushel MK4 and Econo packages) used for handling apples were studied (Figure 3.1). The MK4 package design consists of inner and outer boxes separated by pulp trays, while the Econo pack has an open top. The MK4 package dimensions (length by width by height) were 495 mm × 326 mm × 266 mm externally and 488 mm × 319 mm × 266 mm internally. The Econo package dimensions were 460 mm × 292 mm × 238 mm. Fruit were placed in the ventilated paperboard package in layers (with trays) for MK4 package and in bulk (without trays) for the Econo package. The final mass was 18 kg and 12 kg for the MK4 and the Econo package designs respectively. For the packaging arrangement with trays, apples were placed into the package in four layers of 30 fruits per tray and the trays were labelled A to D, starting with the bottom tray. The apples were placed carefully with the flower stalk axis horizontal and in the same direction in the moulded pockets of the trays. Apples in the Econo type of package were arranged in bulk, in polyethylene plastic bags. These were arranged in two layers with each layer containing four packs and each pack contained eight apples in total. The lower packs were numbered 1 to 4 while the upper packs were numbered 5 to 8. The apples were numbered so as to aid in the bruise position analysis.

3.2.3 Drop test

The Lansmont Model PDT-56 Drop tester (Lansmont Corporation, Monterey CA, USA) was used. Impact bruises were produced by dropping the ventilated corrugated paperboard packages five times from a specific dropping height onto a steel surface. The PCB 353B15 accelerometer (PCB Piezotronics, Inc., Depew, New York, USA) was used to measure the shock response. The packages with fruit arranged in layers and in bulk were dropped from the specific height. In this study, the packages were dropped from two drop heights, 30 cm and 50 cm. The test was done in duplicate for the two packaging methods at the different heights. Figure 3.2 shows the Drop tester used.

3.2.4 Bruise damage measurement and analysis

For full development of bruises and for the bruises to become more apparent, the apples were left at room temperature for 24 h after being dropped. Bruise dimensions (major and minor width, and depth) were measured using digital callipers $(\pm 0.01\ \mathrm{mm})$. Bruise depth was measured by cutting perpendicularly along the major axis of the fruit. Bruise area (BA) and bruise volume (BV) were quantified by assuming an elliptical bruise shape (Opara & Pathare, 2014; Lu et al., 2010; Bollen et al., 1999):

$$BA = \frac{\pi}{4} w_1 w_2 \tag{3.1}$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm).

$$BV = \pi \frac{d_b}{24}\left(3w_1 w_2 + 4d_b^2\right) \tag{3.2}$$

where d_b is the depth of the bruise (mm). Figure 3.3 shows a typical cut section through bruised tissue while Figure 3.4 shows the bruise dimensions. The bruise susceptibility $BS\ (\mathrm{mm^3 J^{-1}})$ was calculated as the ratio of bruise volume $BV\ (\mathrm{mm^3})$ to the impact energy $IE\ (\mathrm{J})$ (Opara & Pathare, 2014; Opara, 2007).

$$BS = \frac{BV}{IE} \tag{3.3}$$

$$IE = m_i g h_d \tag{3.4}$$

where m_i is the mass of the falling object (kg), g is the acceleration due to gravity $(\mathrm{m/s^2})$ and h_d is the drop height (m).

3.2.5 Package damage assessment

After each drop test, a subjective pass/fail determination was made on the package. A box passed if it had no major gaps or tears, retained all products and could still be manually handled. Conversely, a box was deemed to have failed if it had major holes or gaps, the contents spilled out or was exposed, or if the box could no longer be manually handled.

3.2.6 Statistical analysis

The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p < 0.05$ considered statistically significant. The statistical tests were performed using Statistica (v. 11.0, Statsoft, USA). Graphical representations were made using GraphicPad Prism 6 software (GraphicPad Software, Inc. San Diego, USA). Error bars on the figures indicated standard error of the mean. The letters on the error bars were used to show the statistical difference. Means with the same letters are not statistically different.

3.3 Results and discussion

3.3.1 Effects of package design and drop height

Bruise size

The results in Figure 3.5 show the total apple bruise area and volume for each package design after impact. Bruise size in both package designs increased as the drop height increased. These results agree with the findings in a previous study by Lu et al. (2012) who reported that the bruise area and volume increased relative to drop heights and number of drops. The fundamental damage of bruise to apples in packages is energy transformation as some of the kinetic energy of drops is absorbed by bruising (Saeed et al., 2010; Jarimopas et al., 2007; Holt & Schoorl, 1984; Schoorl & Holt, 1982). Irrespective of drop height, fruit in the Econo package experienced more bruising than those packed in the MK4. This suggests that the energy being transferred to fruit in the MK4 is less than the energy absorbed by fruit in the Econo package. Furthermore, the result suggests that aside from the energy absorbed by the fruit due to the impact load, the pattern in which the apples were packed in the two package designs influenced the bruising incurred by the fruit. The higher bruise damage obtained from the Econo package indicates that there was fruit-to-fruit contact due to the bulk arrangement of the apples in the package as compared to the MK4 package design where individual apple fruits were located in pockets moulded in the trays, preventing apple-to-apple contact.

There was a significant difference in total bruise volume between the different drop heights for the two package designs, while, with regard to the bruise area, there was no significant difference between MK4 dropped at height 50 cm and Econo package dropped at height 30 cm. There was an increase of about 50% in the bruising from height 30 cm to height 50 cm for both package designs as more energy was transferred to the fruit at height 50 cm. The overall damage to the fruit which is higher in the Econo package than the MK4 package indicates that the MK4 package could absorb more energy than the Econo package, and releases less of the remaining energy to the fruit, thus resulting in fewer bruises on the fruit. The energy absorbed by the apple fruit determines the quality of the fruit during handling and storage to a large extent because, the bruising which results from the impact increases the subsequent deterioration of the fruit. Hence, minimizing impact that results in the damage ensures the quality of the fruit (Opara & Pathare, 2014; Ahmadi, 2012; Ahmadi et al., 2010; Jarimopas et al., 2007).

Figures 3.6 and 3.7 show the percentage of bruising for the MK4 and Econo package, respectively. The percentage of bruising in trays B and C in the MK4 package were higher than in the other trays, A and D. At both heights, the highest percentage of bruising occurred at tray B, which was between the ranges of 30 – 40% of the total bruising, while on the other hand, tray D had the lowest bruise percentage in the range 11 – 17% of the total bruise.

For the Econo package, packs 1 – 4 and packs 5 – 8 were considered as the lower and upper layers, respectively. The lower layer at both heights had the highest bruise percentage, in the range of 59 – 71%. The damage at height 50 cm was almost 75% of the total bruise area and volume, which shows how apples are damaged severely with respect to the height and the position in the package. The upper layer at both heights exhibited a bruise percentage in the range 29 – 41%. The bruise percentage at the different positions occurred as a result of less impact energy being transferred.

Bruise susceptibility

Table 3.1 shows the impact energy on the package designs (both MK4 and Econo). The impact energy increased with an increase in drop height. There was an increase of more than 50% in the impact energy as the height was also increased from 30 cm to 50 cm. From the results obtained, the impact energy on the MK4 package was at both heights higher than the impact energy for the Econo package. From this, the bruise susceptibility which indicates the extent of bruising on fruit under impact conditions, in terms of the ratio of the bruise volume to the impact energy (Pang et al., 1996) was found to also increase with increase in drop height. Apple fruit in the Econo package had higher bruise susceptibility than fruit in the MK4 package. Bruise susceptibility in the Econo package was higher than in the MK4 (Figure 3.8), indicating that the fruit in the Econo package was more susceptible and prone to bruising than in the MK4 package. However, as shown in Table 3.1, the impact energy on the Econo package was lower than the impact energy on the MK4 and the bruise susceptibility when compared with the bruise susceptibility of the MK4 package, was higher, suggesting that more of the impact energy was absorbed by the MK4 package than the energy it transferred to the fruit in the package.

The trays in the MK4 package were very effective in minimising the bruising in the apple fruit. The combination of the tray and the package absorbs energy in four ways (Van Zeebroeck et al., 2007; Holt & Schoorl, 1984). On dropping the package, there is a lengthwise stretch of the trays resulting in a tear failure, a crosswise stretch of the tray, and compression between the apple contact surfaces. The package walls also buckle sideways absorbing some of the energy. This observation is attributed to better cushioning material to protect the apple fruit in the MK4 package.

Figure 3.9 shows the typical acceleration–duration curve of the package at both heights. The maximum acceleration increased by 35% from height 30 cm to 50 cm for the Econo package, while for the MK4 package, the maximum acceleration increased by 30% from height 30 cm to 50 cm (Figure 3.10a), with a significant difference for both package designs. The impact duration at both heights was longer in the Econo package than in the MK4 package (Figure 3.10b) with a significant difference for both package designs. This suggests why the bruising incurred by the fruit in the Econo package was more than the bruising incurred by the fruit packed inside MK4 package as longer contact duration will result in more damage (Van linden et al., 2006).

Package damage

Ideally, a good package should absorb most of the kinetic energy, thereby protecting the fruit and reducing the amount of bruising incurred. The package being an integral and important part of the distribution system, requires an acceptable damage at a minimum cost. After the impact test, a subjective evaluation of both package designs was done. There was no visible damage to either type of packaging at both heights; however, at height 50 cm, in the case of the MK4 package there was a crack in the trays inside the package, and in the case of the Econo package, there was a tear in the polyethylene plastic bag used for the packaging (Figure 3.11). The trays in the MK4 package also absorbed energy due to impact. Hence, the apple fruit in the package incurred less damage than the fruit in the Econo package.

3.3.2 Effects of fruit position inside the package

Results on the effect of drop height on bruise damage in the MK4 package showed that the amount of fruit damage increased with drop height. Both the bruise area and the bruise volume increased with drop height as shown in Figure 3.12. At height 30 cm, there was no significant difference between trays A, B and C for the bruise area and bruise volume, but there was a significant difference between tray D and the other trays A, B and C in the package. The least damage to the apple fruit occurred at tray D on the top of the stack, while the largest damage to the apple fruit occurred at tray B. Bruise area at tray B and tray D were 336.68 mm^2 and 166.33 mm^2 respectively at height 30 cm, indicating a percentage difference of 68% while the bruise volumes were 961.81 mm^3 and 266.69 mm^3, indicating a percentage difference of 113%. At height of 50 cm, similar to the occurrence at height 30 cm, apple fruit on trays D and B had the least and the largest damage respectively. Bruise area at tray B and tray D were 592.01 mm^2 and 264.64 mm^2 respectively at height 50 cm, indicating a percentage difference of 76% while the bruise volumes were 1953.07 mm^3 and 588.55 mm^3, indicating a percentage difference of 107%. The damage to the fruit on tray D was significantly lower than the damage on trays A, B and C with respect to both the bruise area and the bruise volume. Also, the damage at tray B which was notably the largest compared to the other trays is most likely due to more of the energy that was absorbed by the package was released to the fruit on tray B. At both heights, there was a significant increase in damage to the fruit of about 50%. This result agrees with the findings in a previous study by Lu et al. (2010). The authors studied the incidence of damage and damaged area for apples in corrugated fibreboard boxes and found that the damage to apples in the boxes increased with an increase in drop height.

When comparing the bruise area and the bruise volume of the corresponding tray positions for the two heights (30 cm and 50 cm), it can be seen that there was a significant difference between the trays of the same position at the two heights except for tray D at 50 cm. Also, the damage to the apples on tray B at 30 cm was statistically not different from the damage to apples on tray C at 50 cm. This indicated the effect of height on the susceptibility of the fruit to mechanical damage caused by impact as more energy was released to the fruit as the height increased.

There was a similar trend of spatial variation of bruising inside the Econo package (Figure 3.13). The damage incurred on the apple fruit in the Econo package increased with drop height. The highest level of bruising occurred in the packs arranged at the bottom of the package (packs 1 - 4), while the lowest level of bruising occurred in the packs arranged at the top of the package (packs 5 - 8). There was no significant difference in the bruise volume of apple fruit in the package at height 30 cm; however, the bruise areas at height 30 cm are almost evenly distributed as there was no significant difference between packs 5 - 8 at the bottom of the package. A similar trend occurred at height 50 cm. With regard to the bruise area, there was no significant difference between packs 5, 6 and 7, but pack 4 did differ. The bruise area in pack 3 also differed from those in packs 5 and 7.

When comparing the bruise area and the bruise volume of the corresponding pack positions for the two heights (30 cm and 50 cm) in the Econo package design, it can be seen that the drop height had significant impact on both the bruise area and the bruise volume. Also, the pack location in the Econo package had a slight influence on the bruise area and the bruise volume.

3.4 Conclusion

In this research, the susceptibility of apple fruit to mechanical damage inside two designs of ventilated corrugated paperboard packages (MK4 and Econo) was investigated. The induced force on the packages led to bruise damage, thereby reducing the quality of fruit. The mechanical force acting on the apple fruit at the bottom of the package was significant and had more influence on the apples than the force at the top of the package. Hence, it will be economical if force absorbing material such as polypropylene foams or bubble wraps is placed at the bottom of the package to reduce the damage incurred by the fruit. Based on the data obtained from this present study, package design and packaging pattern had a significant influence on the bruising incurred by the apple fruit. The Econo package released more energy to the fruit while the MK4 package absorbed more of the impact energy and transferred less to the fruit packed inside, thereby protecting the fruit from bruise damage. Furthermore, the drop heights had significant effect on the level of damage to the fruit as the damage increased with an increase in drop height. This research can be of great help to packaging designers, and handlers of various types of processing equipment at different distribution stages in order to minimise the mechanical damage due to impact, thereby ensuring a quality product to the ultimate users.

Figure 3.1: Packaging designs used: (A) MK4 box; (B) Tray arrangement in MK4 box; (C) Econo box; (D) Fruit packed in plastic bags inside Econo box.

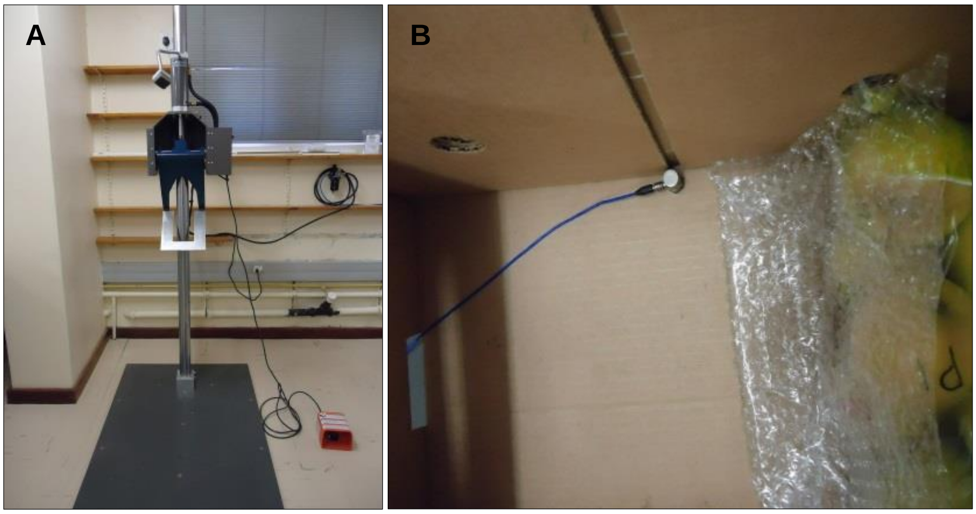


Figure 3.2: Drop testing equipment used (A) Lansmont model PDT- 56 drop tester (B) PCB model 353B15 accelerometer.

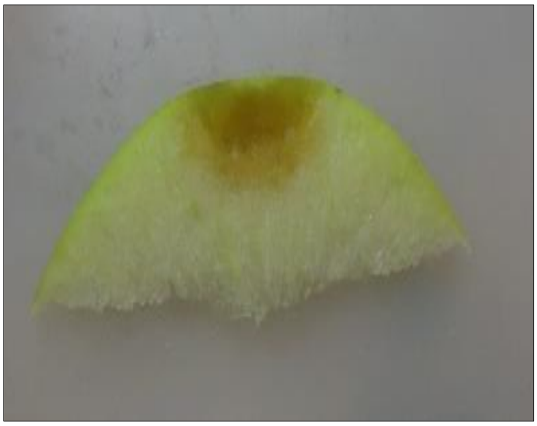


Figure 3.3: Section of the apple prepared for the bruise depth measurement.

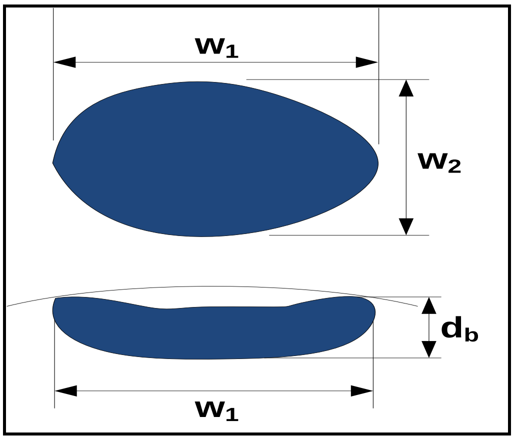
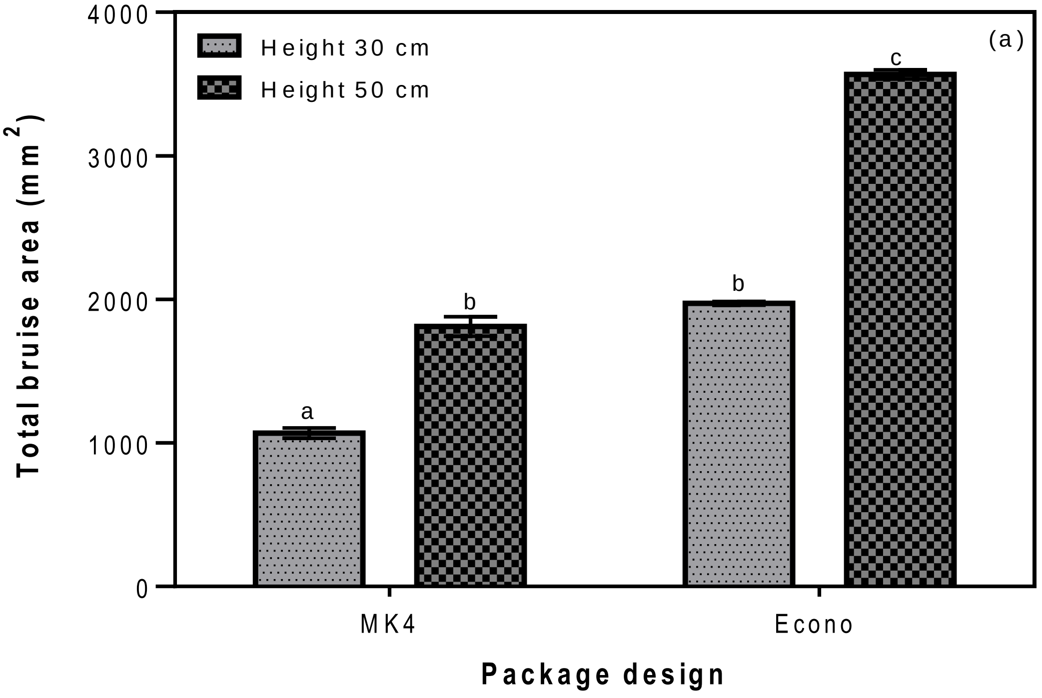


Figure 3.4: Elliptical bruise thickness method for bruise determination.



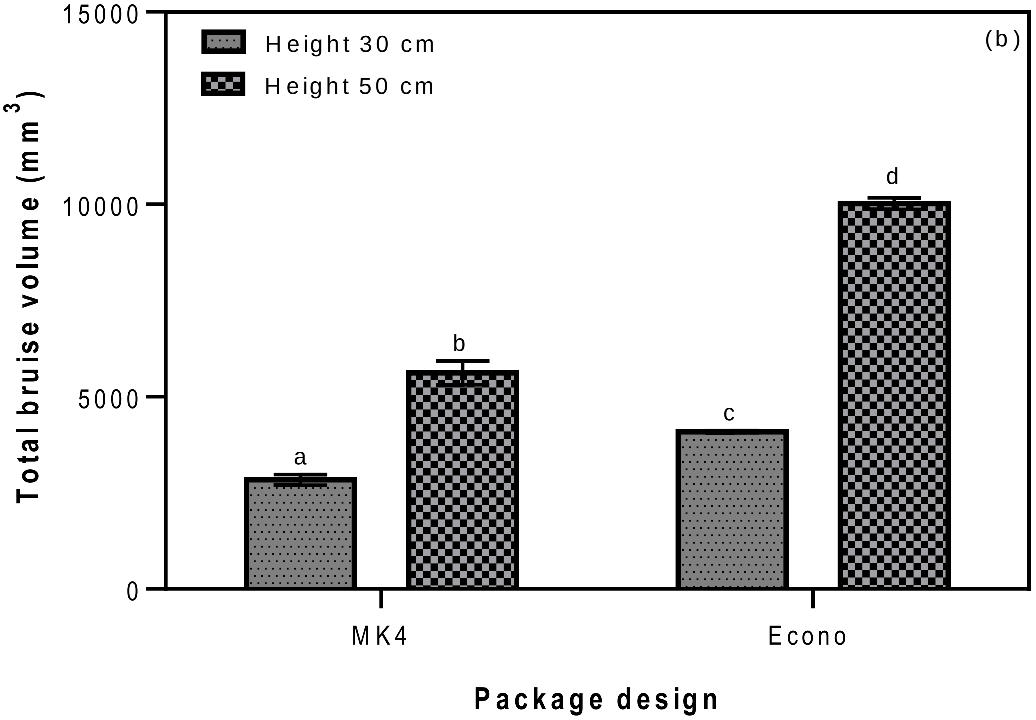
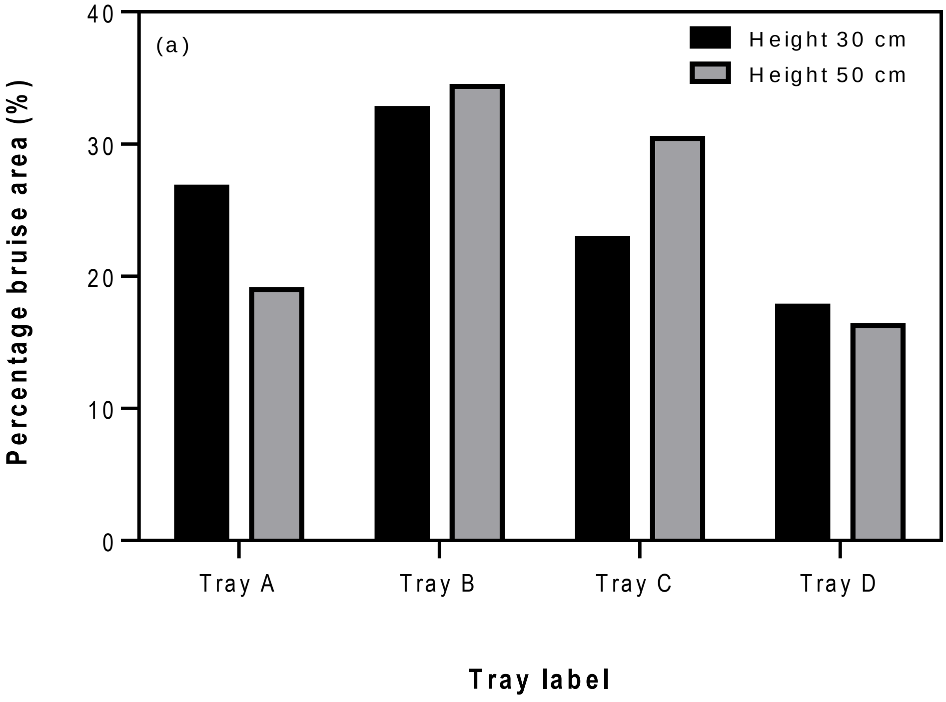


Figure 3.5: Total apple bruising on the MK4 and Econo package designs.



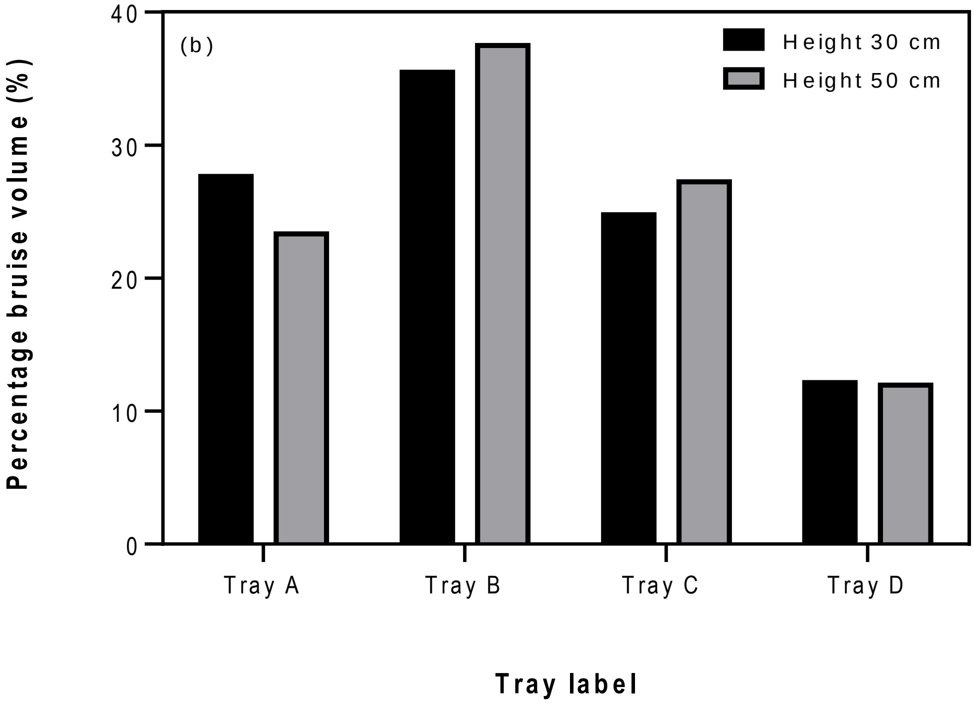


Figure 3.6: Distribution of fruit bruising inside the MK4 package design.

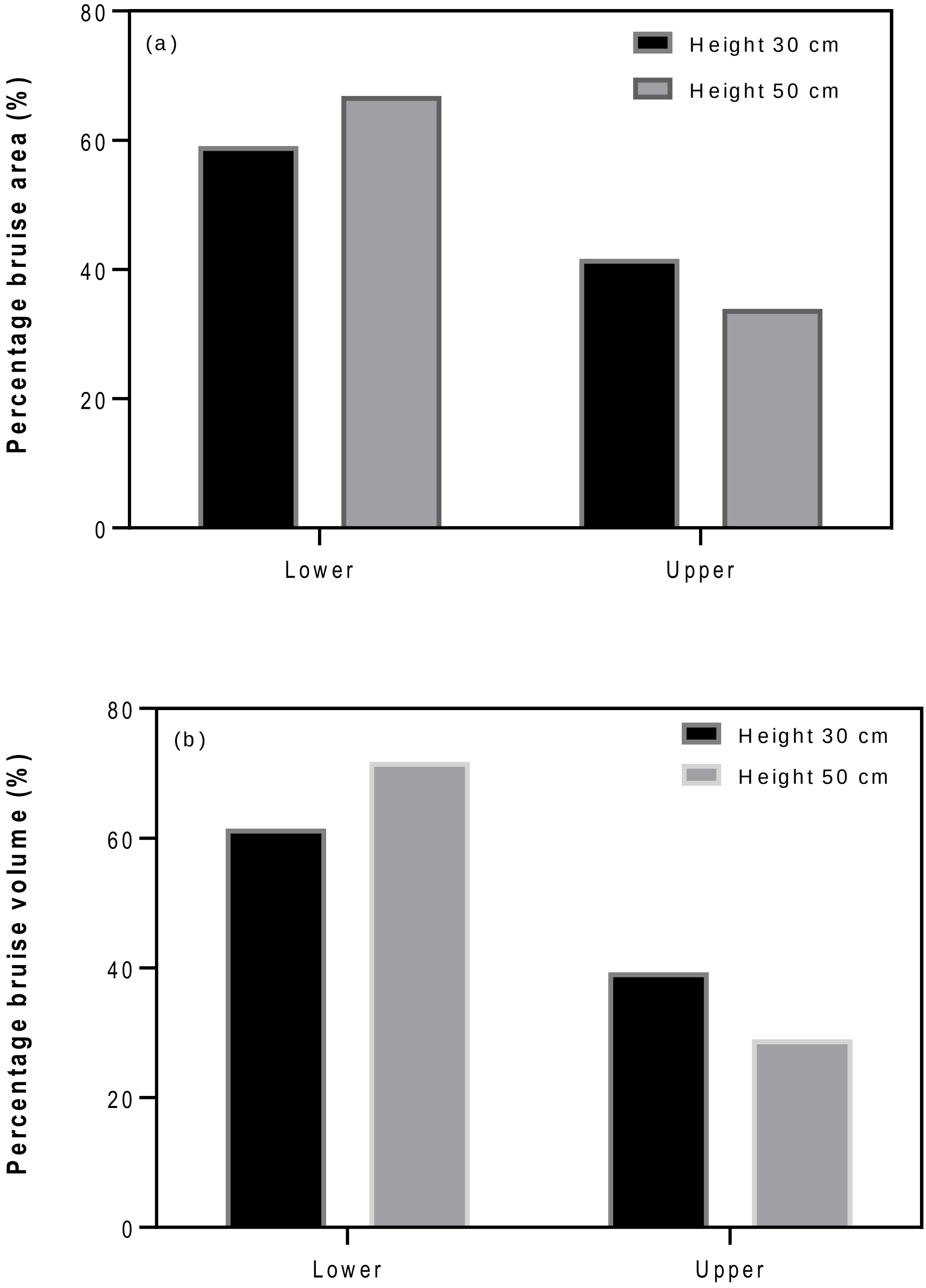


Figure 3.7: Proportion of apple bruising inside the Econo Package design.

Table 3.1: Equivalent impact energy (J) on the packages.

Package design	Height 30 cm	Height 50 cm
MK4	52.97	88.29
Econo	35.32	58.86

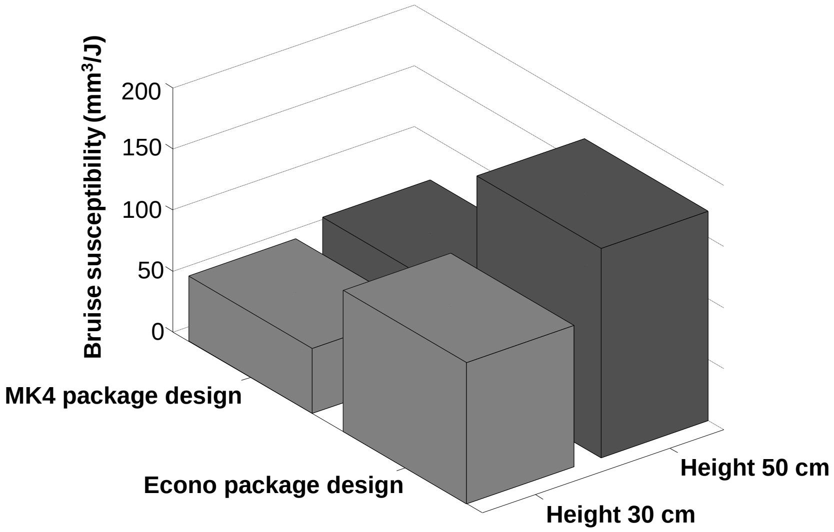


Figure 3.8: Bruise susceptibility of the packages at different heights.

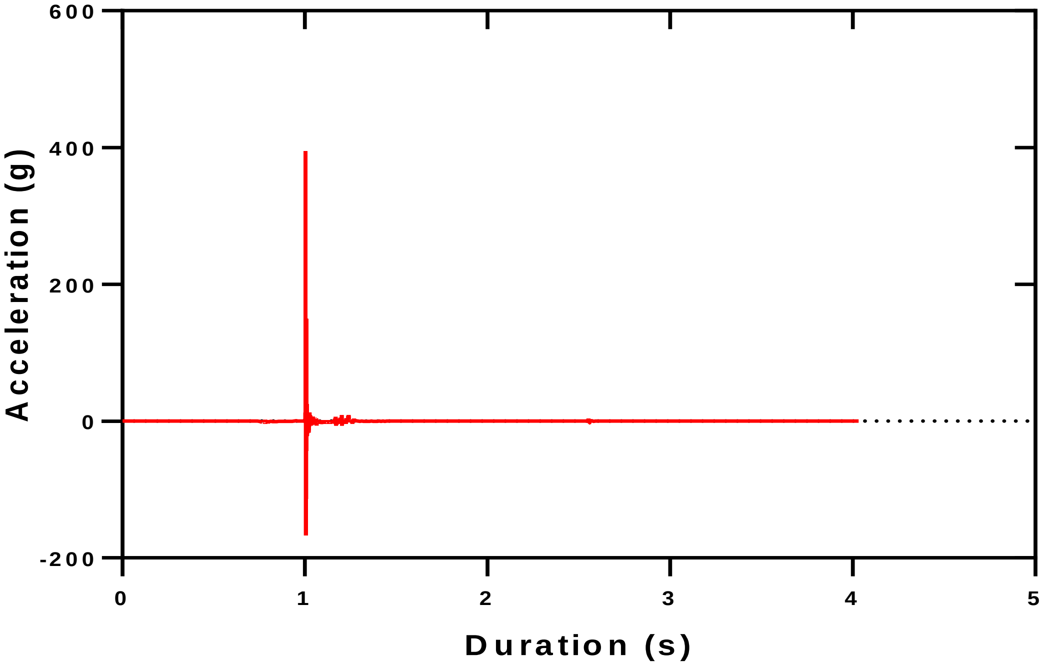
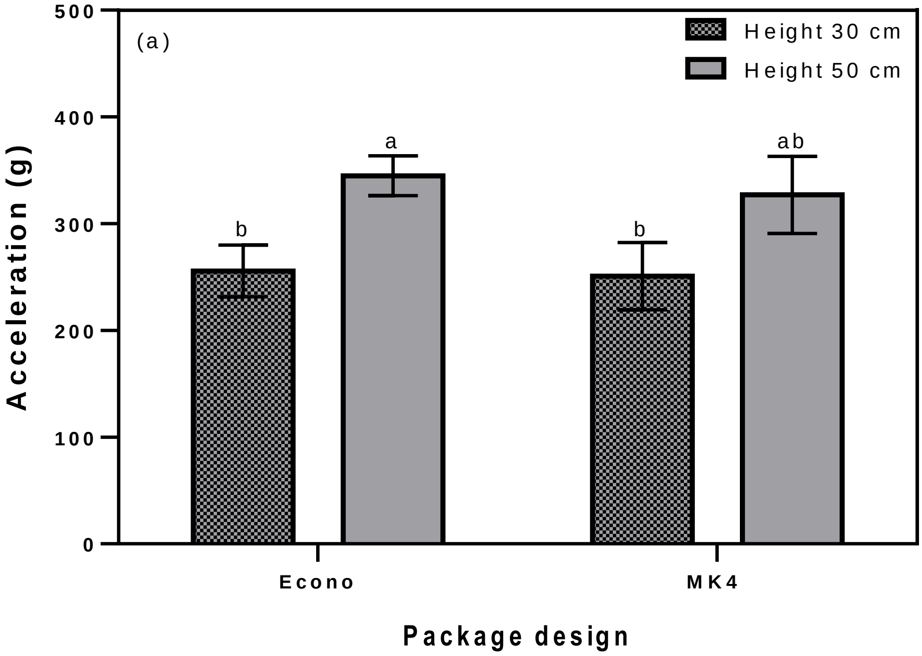


Figure 3.9: Typical acceleration – duration curve for Shock response.



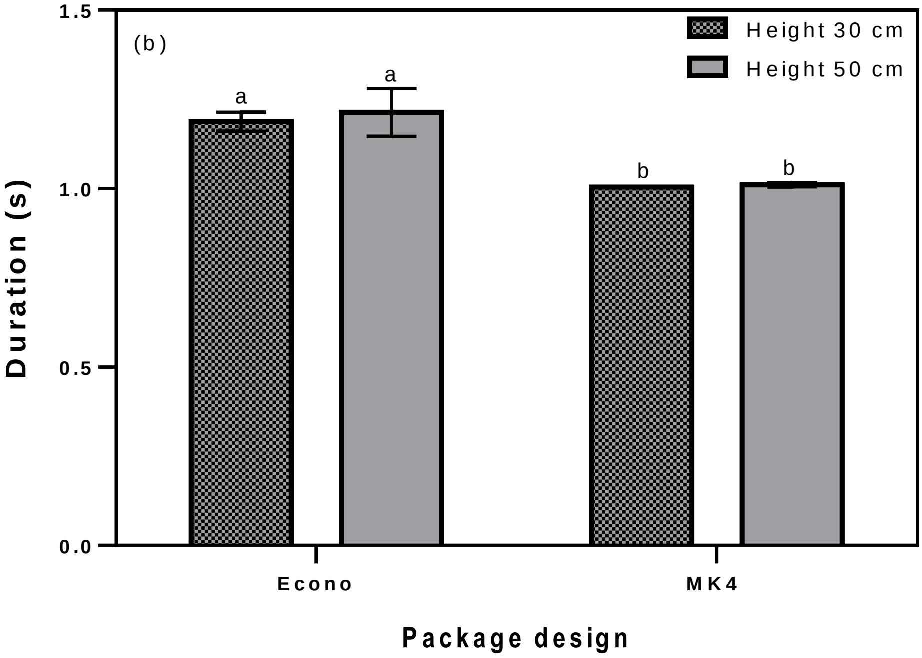
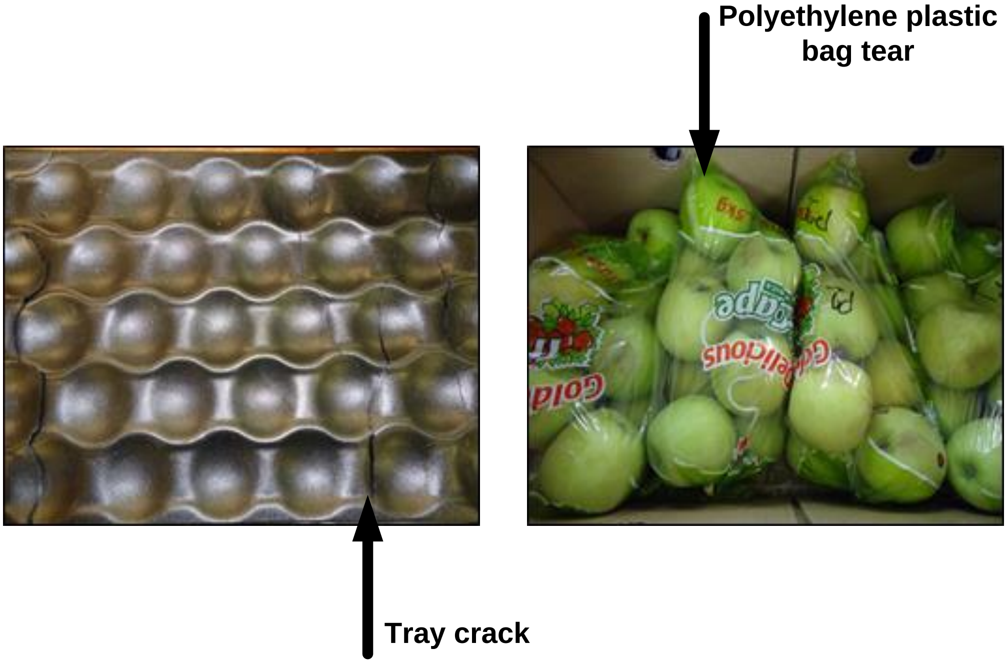


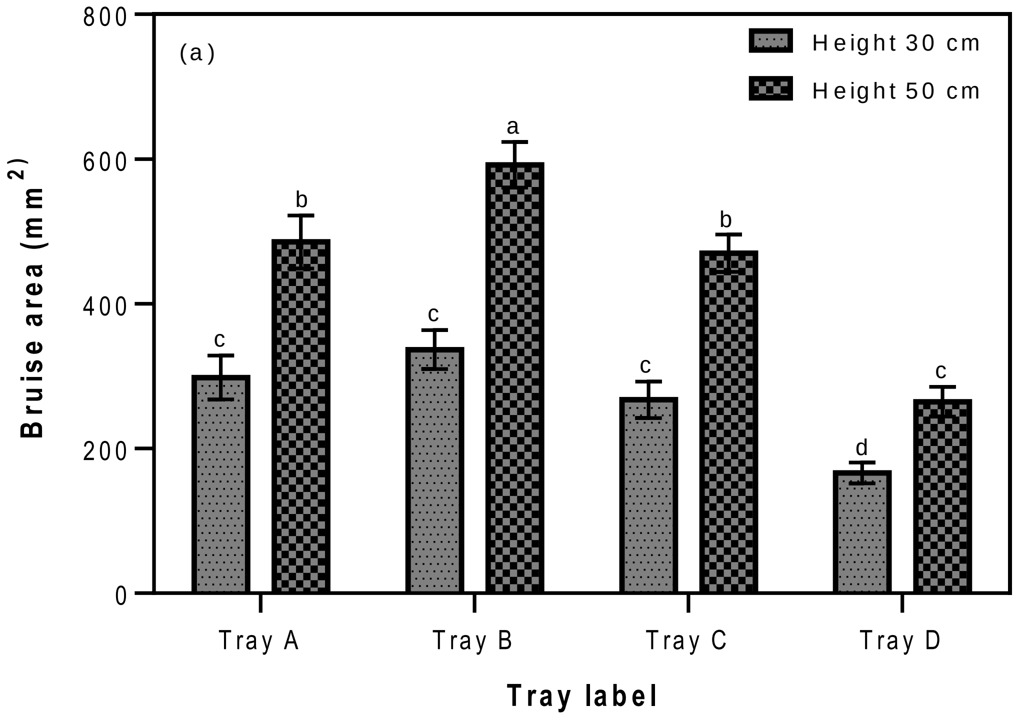
Figure 3.10: Maximum acceleration and duration of the shock response.



Polyethylene plastic bag tear

Tray crack

Figure 3.11: Cracked tray and torn polyethylene plastic bag after impact test.



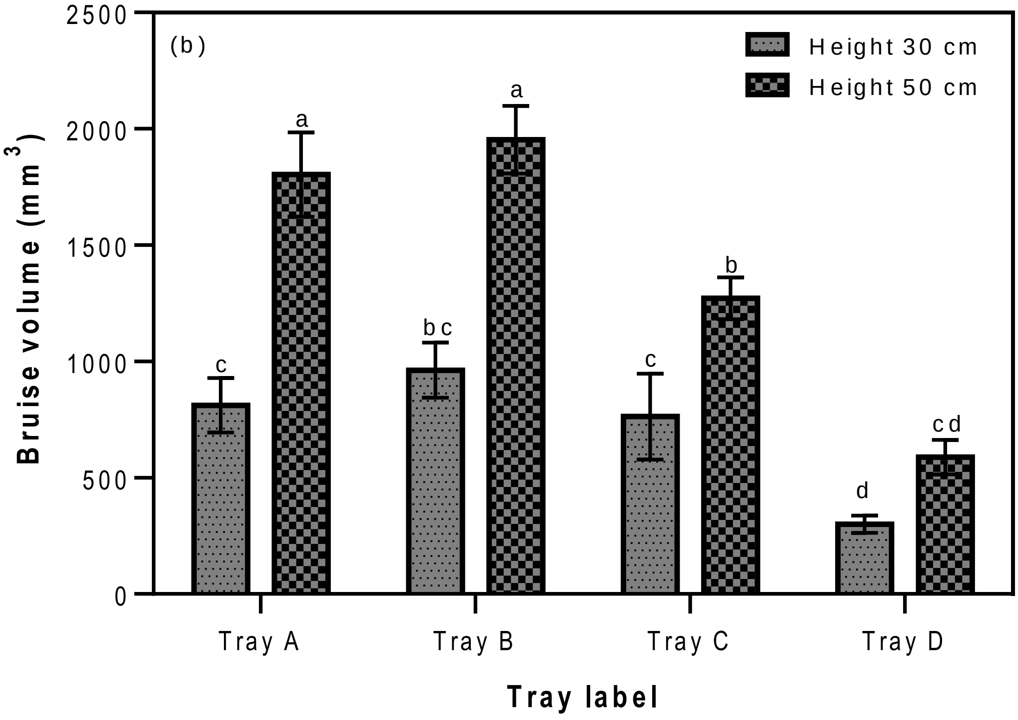


Figure 3.12: Spatial variation of bruise area and volume for MK4 package design.

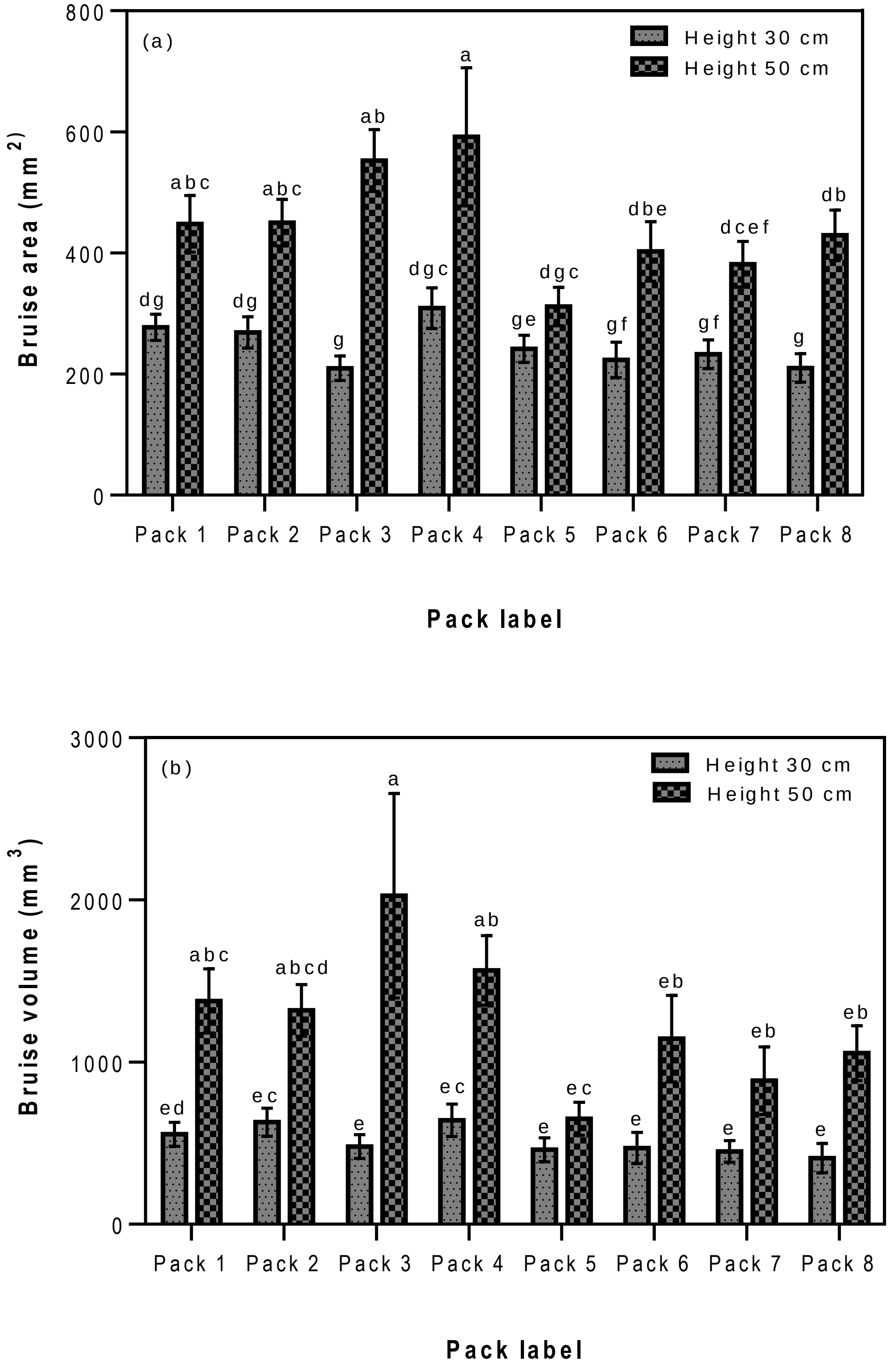


Figure 3.13: Spatial variation of bruise area and volume for Econo package design.

Chapter 4 Simulated transport (vibration) damage on ventilated corrugated paperboard packages and apple susceptibility to bruising

Keywords**:** ventilated packaging, vibration, packaging transmissibility, accelerometer, apples

Abstract

Vibration is one of the key factors causing the bruising of fruit during transportation and distribution. The type of package used during handling of fruit could significantly affect the physical quality of the fruit. A simulated transport study under laboratory conditions was used to assess the performances of two ventilated corrugated paperboard (VCP) packages; Bushel MK4 and Bushel MK6 used for apple packaging. An electro-dynamic shaker was used to excite vibrations at frequencies of 9, 12 and 15 Hz and an amplitude of 0.9 g. Packaging transmissibility and bruises were measured at different frequencies. Results showed that apple bruising in the packages was affected by package design and frequencies after four hours of excitation. Packaging transmissibility for both package designs at the three frequencies was between the ranges of 100 – 250% with the greatest packaging transmissibility observed on the MK6 package at 12 Hz. The fruit in the MK6 package had the highest bruise area while for the bruise volume, no significant difference was observed between MK4 and MK6 packages. For both MK4 and MK6 packages, the non-bruised apple fruit was in the range of 9 – 17%. Irrespective of package design, the top layers of the package were prone to bruise damage and bruising at the middle layers was the smallest. The results obtained will enhance better understanding of the acceleration level and frequencies that occur during transportation of fresh produce. This will help package designers to develop better and efficient packages that will dampen the vibration energy and reduce the losses due to mechanical damage.

4.1 Introduction

Horticultural products, especially apples are highly susceptible to damage during transportation and postharvest handling (Eissa et al., 2012; Sittipod et al., 2009). The need to provide high quality products without blemish, cuts, bruises, physiological disorders and pathogens is important, which is emphasised and insisted on by consumers (Eissa et al., 2012; Remón et al., 2003; Timm et al., 1996). Various studies have been conducted which indicates that impact, compression and vibration forces result in majority of the mechanical damage of horticultural products (Ahmadi, 2012; Babarinsa & Ige, 2012; Eissa et al., 2012; Lu et al., 2012; Lu et al., 2010; Idah et al., 2007; Jarimopas et al., 2007; Opara et al., 2007; Zeebroeck et al., 2007). Transportation is important in the distribution process of horticultural products. However, vibration during transportation causes critical damage to packages and produce (Sittipod et al., 2009). Mechanical damage is responsible for the deterioration in the quality of fresh produce. Disposed produce due to mechanical damage is estimated to be about 40% (Vursavufi & Özgüven, 2004; Barchi et al., 2002). Cautious handling and proper packaging have shown to minimise the losses of fruits due to mechanical damage (Chonhenchob & Singh, 2003; Singh et al., 1992). Evidence of severe problems of mechanical damage is on the increase and is affecting the trade in fruits and vegetables (Okhuoya, 1995), giving a clear indication of the need to improve the handling methods, particularly optimising the packages to provide better protection.

Several studies have been carried out on investigating the effect of vibration during transport on different horticultural products such as peaches (Oeguet et al., 1999; Vergano et al., 1991; O'Brien et al., 1969), loquats (Barchi et al., 2002), pears (Zhou et al., 2007; Berardinelli et al., 2005; Jancsók et al., 2001, Slaughter et al., 1993), tomatoes (Bello et al., 2013; Babarinsa & Ige, 2012; Idah et al., 2012; Singh & Singh, 1992; Olorunda & Tung, 1985), kiwifruits (Tabatabaekoloor et al., 2013) and apples (Eissa et al., 2012; Acıcan et al., 2007; Van Zeebroeck et al., 2006; Vursavufi & Özgüven, 2004; Timm et al., 1996). Hinsch et al. (1993) studied the vibration of cherries, nectarines and pears on semi-trailers with steel spring suspension systems. The authors reported that the highest Power Spectral Density (PSD) levels occurred at the rear of the trailer at a frequency of 3.5 Hz. Also, frequencies of 3.5, 9, 18.5, and 25 Hz were the most frequent during transportation. Vertical acceleration was much higher than the horizontal acceleration with similar observations reported by Singh & Marcondes (1992). Similar to these findings, Slaughter et al. (1993) found the most severe damage at frequencies of 3.5 and 18.5 Hz in transit damage of Bartlett pears. Chonhenchob & Singh (2005) performed an actual shipment and vibration test in order to compare the packaging performance and the effect on quality of two cushioning systems; foam nets and paper-based wrap materials for exporting papaya fruit. The authors reported that although the paper-based cushions provided a similar protection as to the plastic foam nets materials, the paper-based cushions offered a better ripening response for papayas. In another study by Park et al. (2011), the authors evaluated the vibration transmissibility of corrugated paperboard with corrugation shape and equilibrium atmospheric conditions by a sinusoidal sweep vibration test. Vursavufi & Özgüven (2004) studied the effects of vibration parameters and packaging methods on mechanical damage in apples. The volume packaging method had the highest packaging transmissibility. The authors concluded that the equivalent severe bruise index was affected significantly by vibration frequency, vibration acceleration, packaging methods and vibration time. In a recent study by Eissa et al. (2012), the authors compared the package cushioning materials for apples to vibration damage using an exciter vibration table and a force transducer to evaluate the damage on the apple.

Vibration due to transportation is influenced by the road roughness, distance, traveling speed, truck suspension, load and number of axles (Pathare & Opara, 2014; Idah et al., 2012; Vursavufi & Özgüven, 2004; Berardinelli et al., 2003). A clear understanding of the behaviour of package and produce under static and dynamic loads provides information in minimising the mechanical damage to packaged produce and enhancing the quality of fresh horticultural produce (Eissa et al., 2012; Idah et al., 2012; Jarimopas et al., 2005). Careful handling and proper packaging have been reported to reduce mechanical damage (Singh et al., 1992). Minimised mechanical damage would ensure that the produce gets to the ultimate users in a desirable condition. The objective of this study was to simulate the transport damage on ventilated corrugated packages under laboratory conditions. Also, to evaluate the susceptibility of apples packaged inside Bushel MK4 and Bushel MK6 ventilated corrugated paper packages with the aim to ascertain the effect of these package types on the extent of bruise damage on the apples.

4.2 Materials and methods

4.2.1 Fruit supply

Golden Delicious apples were purchased during commercial harvest from a packhouse in Grabouw, Western Cape, South Africa (34°48'14"S, 19°02'50"E). This variety was selected because of its susceptibility to bruising and bruises are easy to visually observe. Fruit of uniform size and maturity based on background colour, firmness and free from physical defects were used for the experiments. The mean diameter and mass of the apples were 65 ± 2.0 mm and 148.7 ± 7.0 g, respectively.

4.2.2 Packaging materials and preparation

The experiment was conducted using two ventilated paperboard package designs used for handling apples in international trade; Bushel MK4 and Bushel MK6. Both package designs consist of separate inner and outer boxes (Figure 4.1). Fruit were placed on tray layers inside each package, resulting in a gross package mass of 18 kg and 13.3 kg respectively, for the MK4 and the MK6 package design. MK4 package is designed to hold 120 apples per package, 30 apples per layer while MK6 is designed to hold 84 apples per package, 21 apples per layer. The trays were labelled A to D, starting with the bottom tray. The apples were placed carefully with the flower stalk axis horizontal and in the same direction in the moulded pockets of the trays (Figure 4.2).

4.2.3 Vibration test

An electro-dynamic shaker (Brüel & Kjær, Model L148) driven by a power amplifier was used (Figure 4.3a). Three ICP 333B32 accelerometers (PCB Piezotronics, Inc., Depew, New York, USA) were used. Two of the accelerometers were fixed at two opposite corners at the bottom of the package while the third accelerometer was fixed on the shaker (Figure 4.3b). The LMS SCADAS system (Model SCM01) was used for data acquisition. Firstly, a vibration sweep test was done to determine the frequencies with the greatest responses on both MK4 and MK6 package designs, by sweeping over the frequency ranges normally encountered during transportation. The ASTM D4169-09 Standard was adopted for the test. Based on the sweep test and the greatest frequency response obtained, the package and fruit was subjected to vibration at three frequencies; 9, 12 and 15 Hz at an amplitude of 0.9 g. The specified duration to simulate an average distance of 2100 km was 4 h. Two replicates for both package designs were completed for the vibration test at each frequency.

Packaging transmissibility at each frequency for the two package designs was calculated using the following equation (Vursavufi & Özgüven, 2004):

$$P_T = \frac{a_b}{a_t} \times 100 \tag{4.1}$$

where $P_T =$ packaging transmissibility $(\%)$, $a_b =$ vibration acceleration on the package (g), $a_t =$ vibration acceleration on the shaker (g).

4.2.4 Bruise measurement and analysis

For full development of bruises and for the bruises to become more apparent, the apples were left at room temperature for 24 h after completion of the vibration test. Bruise dimensions (major and minor width, and depth) were measured using digital callipers $(\pm 0.01\ \mathrm{mm})$. Bruise depth was measured by cutting perpendicularly along the major axis of the fruit. Bruise area (BA) and bruise volume (BV) were quantified by assuming an elliptical bruise shape (Opara & Pathare, 2014; Lu et al., 2010; Bollen et al., 1999):

$$BA = \frac{\pi}{4} w_1 w_2 \tag{4.2}$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm).

$$BV = \pi \frac{d_b}{24}\left(3w_1 w_2 + 4d_b^2\right) \tag{4.3}$$

where d_b is the depth of the bruise (mm). Figure 4.4 shows a typical cut section through bruised tissue while Figure 4.5 shows the bruise dimensions.

4.2.5 Statistical analysis

The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p < 0.05$ considered statistically significant. The statistical tests were performed using Statistica (v. 11.0, Statsoft, USA). Graphical representations were made using GraphicPad Prism 6 software (GraphicPad Software, Inc. San Diego, USA). Error bars on the figures indicated standard error of the mean. The letters on the error bars were used to show the statistical difference. Means with the same letters are not statistically different.

4.3 Results and discussion

4.3.1 Effect of frequency and package design on packaging transmissibility

Figure 4.6 shows a typical transmissibility curve for frequencies with the greatest responses for both MK4 and MK6 package designs. As shown in Figure 4.7, the highest and lowest packaging transmissibility was observed at a frequency of 9 Hz and 15 Hz respectively for the MK4 package with a difference of 25%. For MK6 package the highest packaging transmissibility was 243% at a frequency of 12 Hz while the lowest was 123% at a frequency of 9 Hz. When comparing the packaging transmissibility for both package designs at the three frequencies, there was no significant difference observed. The highest packaging transmissibility occurred on the MK6 package at a frequency of 12 Hz with a difference of about 98% when compared to the lowest packaging transmissibility that occurred at a frequency of 9 Hz on the MK6 package.

The packaging transmissibility obtained for both package designs (MK4 and MK6) at the three frequencies was observed to be above the horizontal line at 100% (Figure 4.7). This indicated that both package designs vibrates at higher acceleration levels than the shaker. Consequently, these frequencies are most critical for both package designs. Similar results were reported by Vursavufi & Özgüven (2004) who measured the packaging transmisssibilty of three apple packaging methods; paper pulp tray, pattern and volume packaging methods. The authors reported that the most critical frequencies occurred between 3 and 15 Hz, with the highest packaging transmissibilty observed at a vibration interval of 8 – 9 Hz.

4.3.2 Effect of frequency and package design on bruising of apples

Figure 4.8 shows the total apple bruise area and volume of apple fruit inside MK4 and MK6 package at frequencies of 9, 12 and 15 Hz. For the MK4 package, when comparing the bruise area of the three frequencies, the highest bruise area of 588.32 mm^2 occurred at a frequency of 9 Hz while the lowest bruise area of 571.92 mm^2 occurred at a frequency of 15 Hz. The highest and lowest bruise area observed at these frequencies can be attributed to the packaging transmissibility observed in the MK4 package at the same frequencies (9 and 15 Hz) which were observed to be the highest and lowest respectively. Due to the high packaging transmissibility, vibration forces transmitted from the shaker to the apple package are absorbed by the fruit in the package, thereby causing bruise damage (Vursavufi & Özgüven, 2004). For the MK6 package, the bruise area at 9 Hz was significantly different to the bruise area at 12 Hz. However, there was no significant difference between the bruise area at 15 Hz to the bruise area at frequencies of 9 and 12 Hz. The highest bruise area for MK6 package was 661.10 mm^2 and it occurred at a frequency of 12 Hz which corresponded to the frequency with the highest packaging transmissibility while the lowest was 622.07 mm^2 at 15 Hz. The bruise area at 9 Hz for the MK6 package was significantly different from the bruise area at 12 Hz for MK6 package, and at frequencies of 9 and 15 Hz for the MK4 package. The highest bruise area observed at 9 Hz for the MK4 package and at 12 Hz for the MK6 package was similar to a study by Vursavufi & Özgüven (2004), who reported the highest equivalent bruise index at a frequency of 8.2 Hz. In another study, Tabatabaekoloor et al. (2013) investigated the vibration damage to kiwifruit during road transportation and reported that the highest damage to the fruit occurred at a frequency of 13 Hz.

When comparing the bruise volume of both MK4 and MK6 packages, there was no significant difference at the three frequencies. For the MK4 package, the highest bruise volume was 957.10mm^3 and it was observed at a frequency of 15 Hz while the lowest bruise volume was 806.46 mm^3 at 9 Hz. The highest bruise volume for the MK6 package was 974.75 mm^3 at 9 Hz with about 14.6% and 15.3% decrease at 15 Hz and 12 Hz respectively. The number of non-bruised apples was highest in the MK6 package at a frequency of 9 Hz while the lowest was observed at 12 Hz in the MK4 package. Furthermore, for each of the package designs, the lowest number of non-bruised apples was observed at 12 Hz with about 9.2% and 9.5% in the MK4 and MK6 package respectively (Figure 4.9). The results obtained can be used by package designers and handlers of apple fruits to reduce mechanical damage due to vibration. Furthermore, since the distribution systems such as the vehicles and the roads are already in place, simulated transport studies provide a better understanding of how packages used for transportation of fresh produce can be improved to ensure delivering good quality fruit to the consumers (Babarinsa & Ige, 2012; Idah et al., 2012). Susceptibility of apples to vibration load during transportation was confirmed by previous studies underlining the influence of the type of package (Timm et al., 1996; Shulte Pason et al., 1990). Vursavufi & Özgüven (2004) suggested the use of properly sized trays inside the package to provide the minimum clearance and that the use of similar sized fruit will help in reducing bruise damage.

4.3.3 Spatial variation of apple bruising in relation to frequency and package design

Figure 4.10 shows the bruising at different positions inside the MK4 and MK6 package. For the MK4 package at 9 Hz, tray A at the bottom of the package had the highest bruise area of 159.47 mm^2 with a reduction of about 15% on tray D, placed at the top of the package with the lowest bruise area. At 12 Hz, the highest and lowest bruise area occurred on tray C and tray A respectively. The scenario was different at 15 Hz, with the topmost tray D having the highest bruise area while the lowest bruise area was observed on tray B. There was no significant difference between the bruise areas on tray A at 9 Hz, tray A at 12 Hz and tray C at 15 Hz. For the MK6 package at 9 Hz, the highest bruise area was 176.85 mm^2 while the lowest was 160.61 mm^2 observed on the topmost tray D and bottom tray A. At 12 Hz, tray B had the highest bruise area compared to other trays inside the MK6 package, with the lowest bruise area observed on tray D. Similarly, at 15 Hz, the highest bruise area was 176.89 mm^2 on tray B and the lowest was 134.83 mm^2 on tray A. Bruise area on trays A at 9 and 12 Hz for the MK6 package was not significantly different from the bruise area on trays B and C at 9 Hz. Mohsenin (1986) stated that the damage due to vibration increases gradually from the bottom layer to the topmost layer in a package. Although peach was used in the study, the author based the conclusion on all fruits. Similarly, the study by Vursavufi & Özgüven (2004) reported that apples placed in trays at the top layer subjected to vibration are more susceptible to bruising. Another study by Jarimopas et al. (2005) measured the bruising in tangerines after subjecting it to vibration and found that the fruit damage was greatest in the topmost container. Greatest damage to pears in the topmost container was also reported by Zhou et al. (2007) with lowest damage in the bottom. This can be attributed to the higher acceleration in the topmost container (Slaughter et al., 1993). This trend was observed in the bruise area for the MK6 package at 9 Hz. In contrast, several authors reported that apple damage subjected to vibration gradually decreases from the bottom layer to the top layer (Armstrong et al., 1991; Jones et al., 1991; Holt et al., 1981).

When comparing the bruise volume for the MK4 and MK6 packages, the highest bruise volume was 312.26 mm^3 and it was observed on tray C at 12 Hz inside the MK4 package, while the lowest bruise area was 143.45 mm^3 observed on tray D at 12 Hz inside the MK6 package. For the MK4 package at 9 Hz, the highest bruise volume was 249.90 mm^3 and it was measured on bottom tray A with a reduction of about 60% on the topmost tray D where the lowest bruise volume occurred. This trend was in agreement with the study by Armstrong et al. (1991). At the same frequency, 9 Hz for the MK6 package, the opposite trend was observed. Tray D had the highest bruise volume while tray A had lowest bruise volume. The reduction from the highest to the lowest bruise area and volume on all the trays was in the range of 10 – 75% at all the three frequencies for both MK4 and MK6 packages.

4.4 Conclusion

The effects of two package designs (MK4 and MK6 packages) on mechanical bruising to packaged apple fruits were evaluated by means of simulated transport vibration at three frequencies; 9, 12 and 15 Hz. The highest total bruise area occurred in the MK6 at 12 Hz which had the greatest packaging transmissibility. Results showed that the MK6 package had more bruise damage than the MK4 at all the three frequencies. The top tray was observed to be more prone to bruise damage. Therefore, the use of cushioning materials for both package designs can help in minimising bruising.

The results obtained from this study can be of great importance to packaging designers and handlers of apple fruit at different transportation and distribution stages. This will reduce losses due to mechanical damage especially due to vibration and will ensure that good quality fruit are delivered to the final consumers or processors.

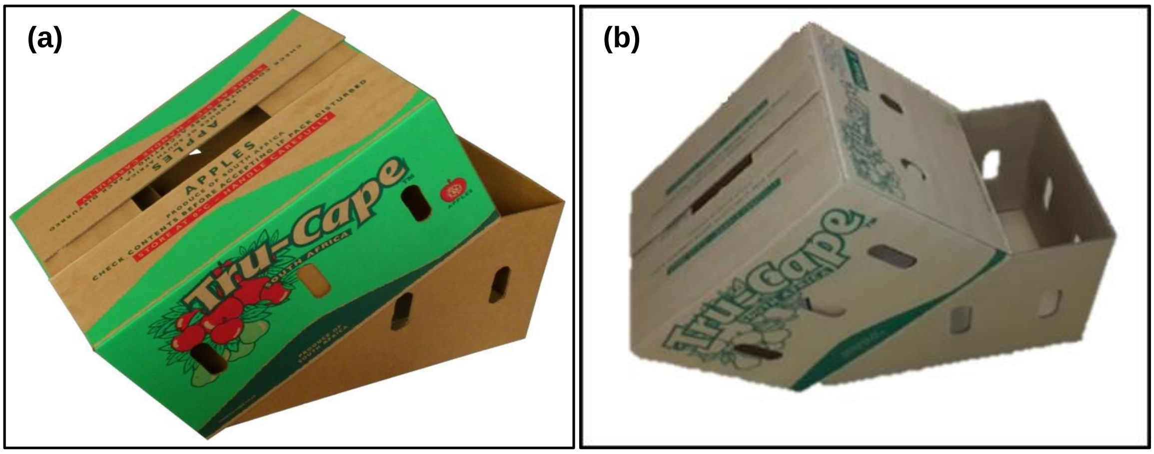


Figure 4.1: (a) MK4 package and (b) MK6 package.

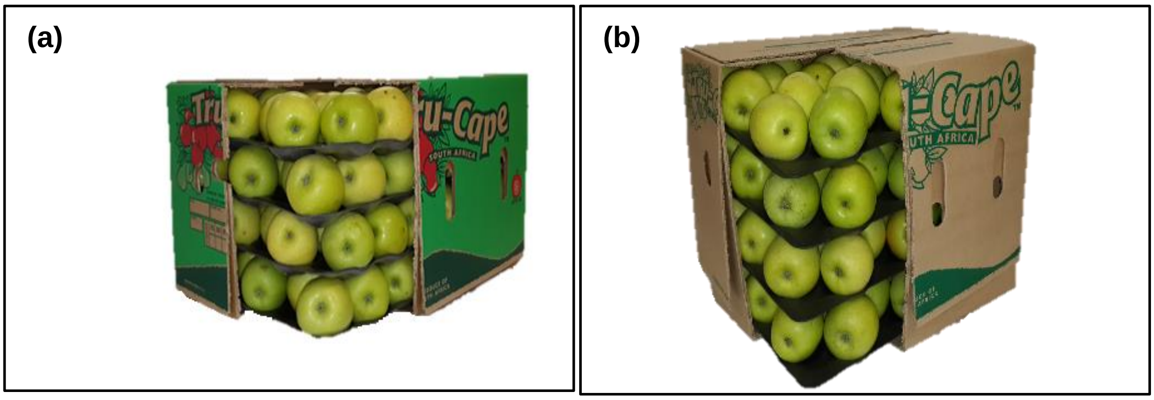


Figure 4.2: (a) Tray arrangement inside MK4 package and (b) Tray arrangement inside MK6 package.

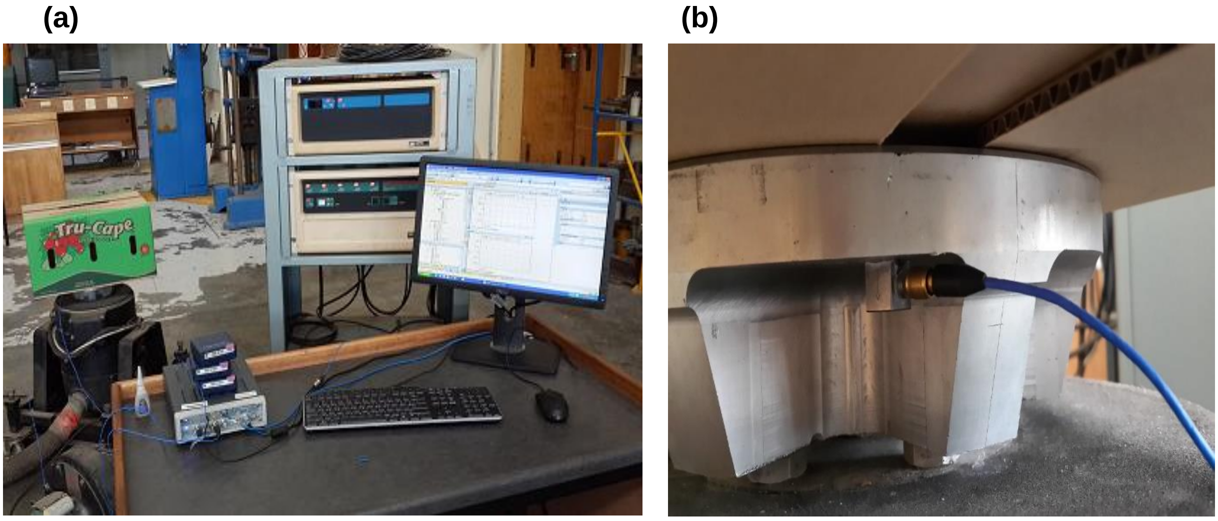


Figure 4.3: (a) Vibration test set-up; (b) Accelerator placement on the shaker.

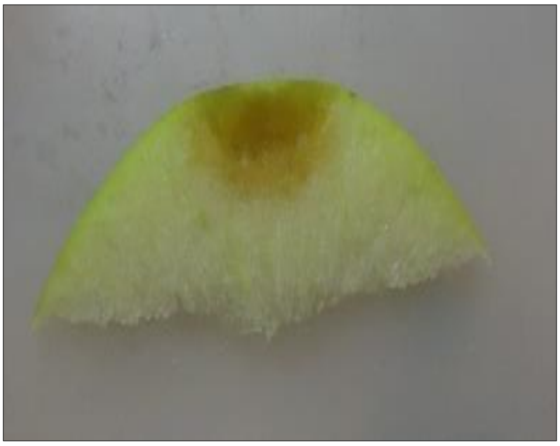


Figure 4.4: Section of the apple prepared for the bruise depth measurement.

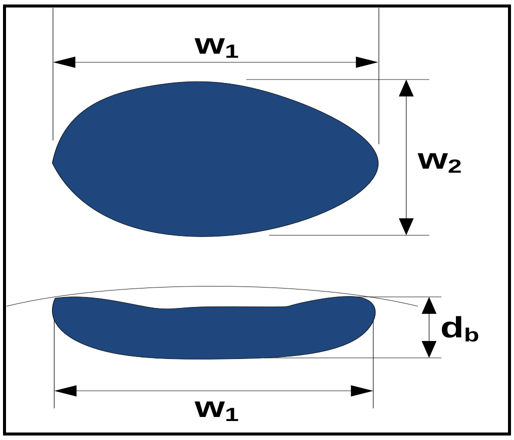
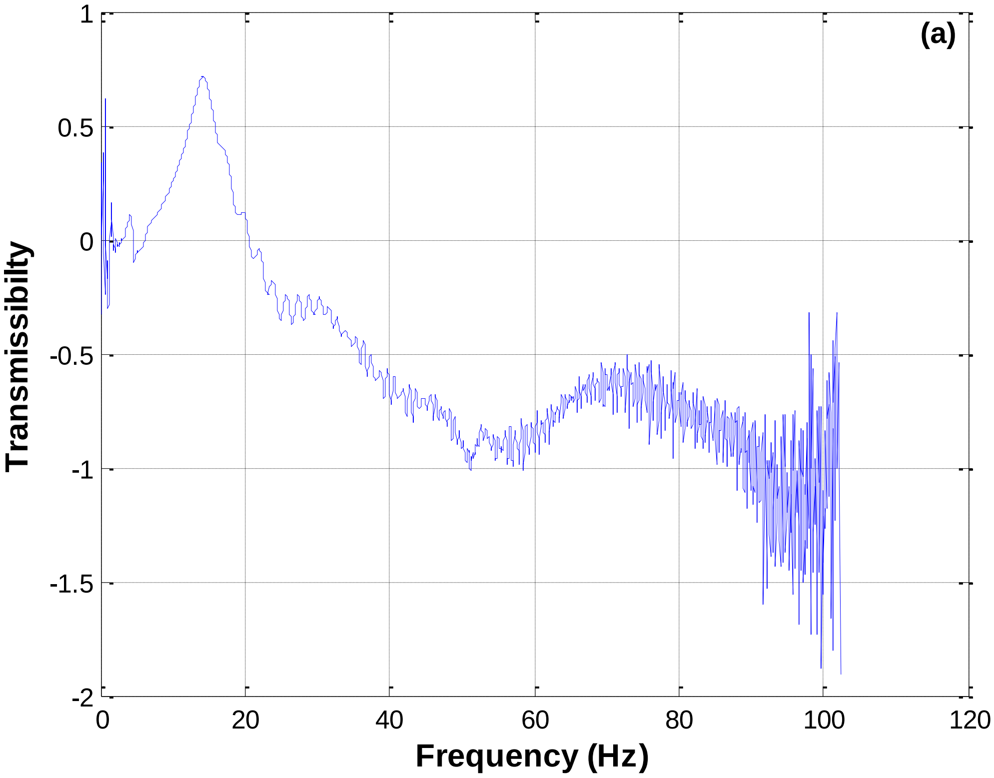


Figure 4.5: Elliptical bruise thickness method for bruise determination.



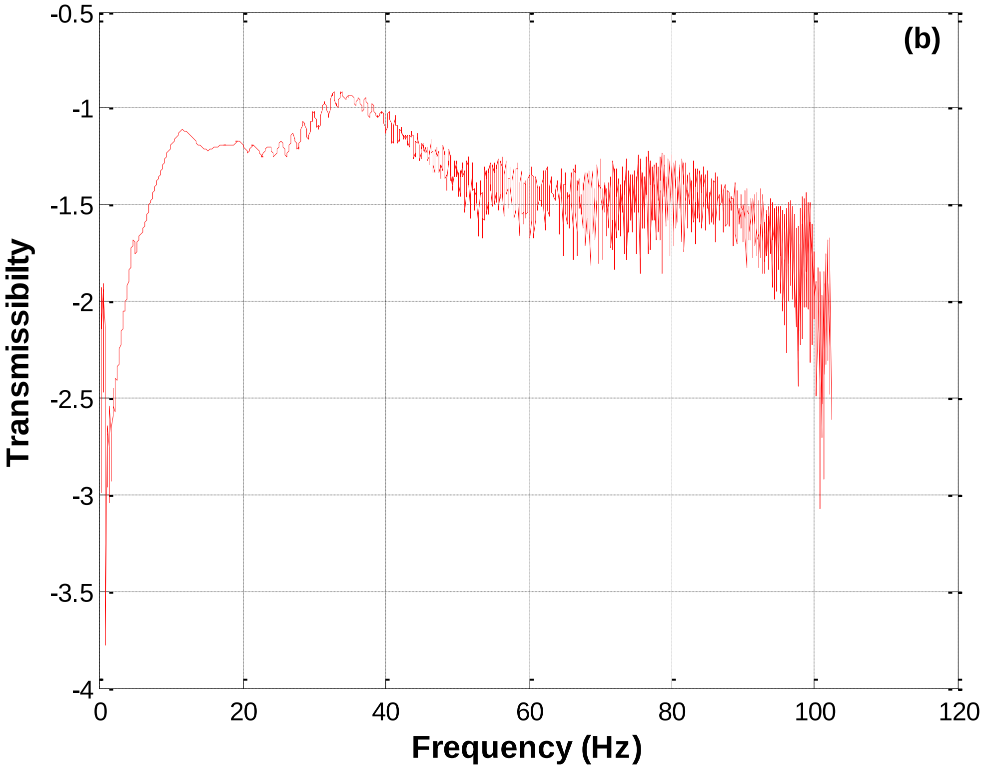


Figure 4.6: Typical transmissibility curve (a) MK4 package and (b) MK6 package.

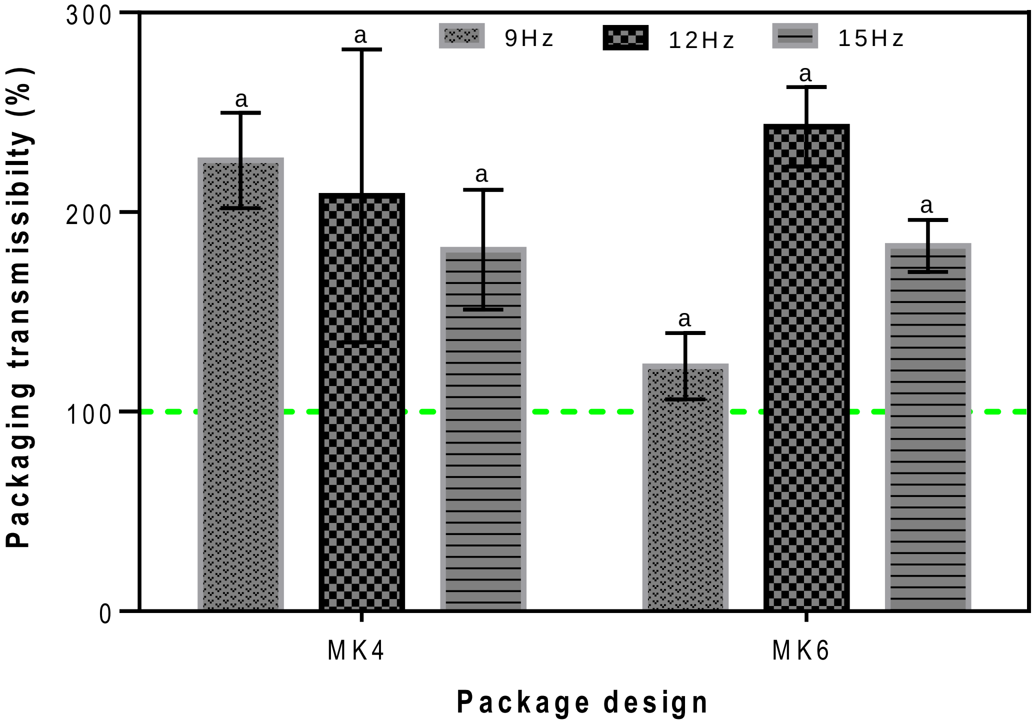


Figure 4.7: Packaging transmissibility for both MK4 and MK6 package designs.

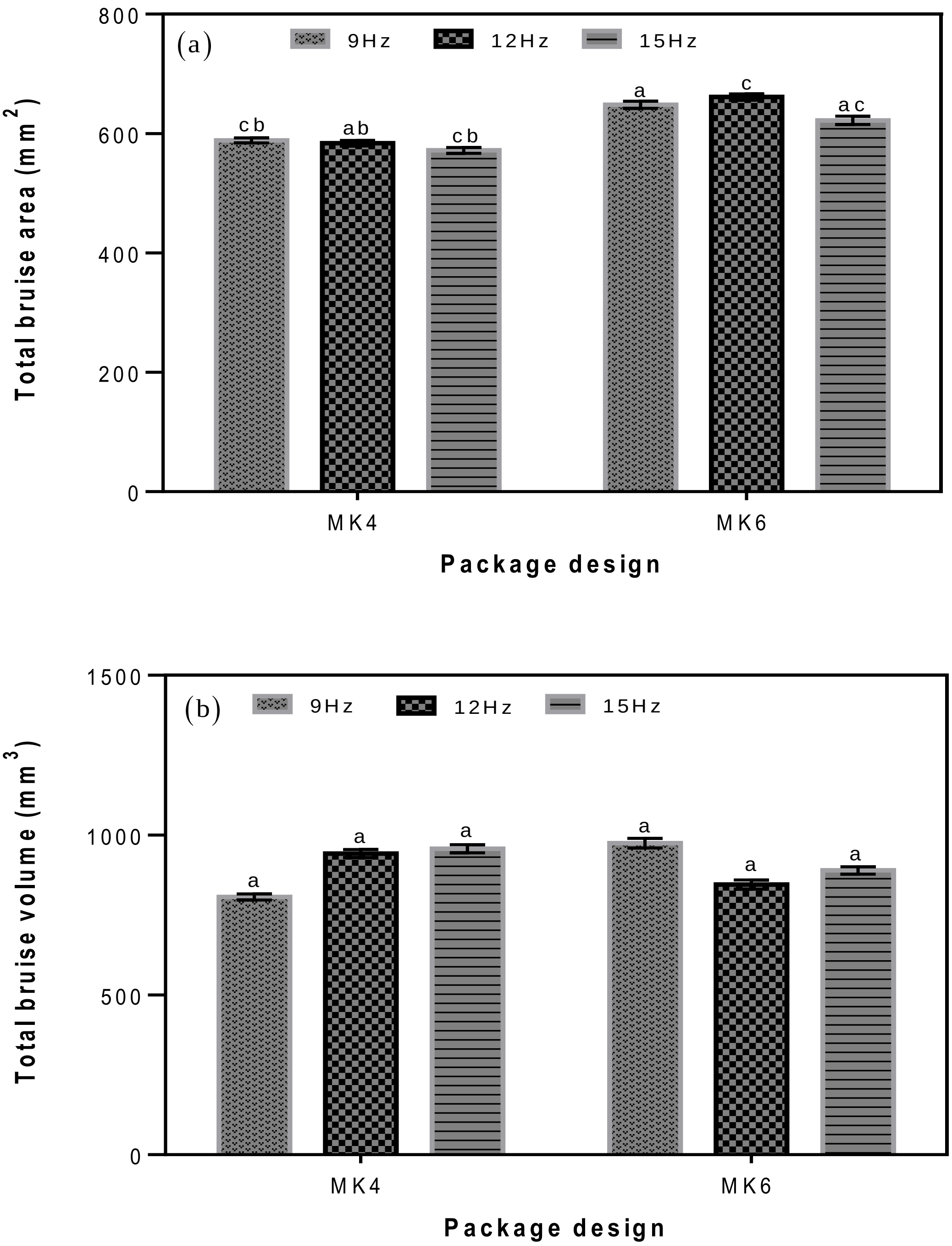


Figure 4.8: Total apple bruising (a) Bruise area (b) Bruise volume.

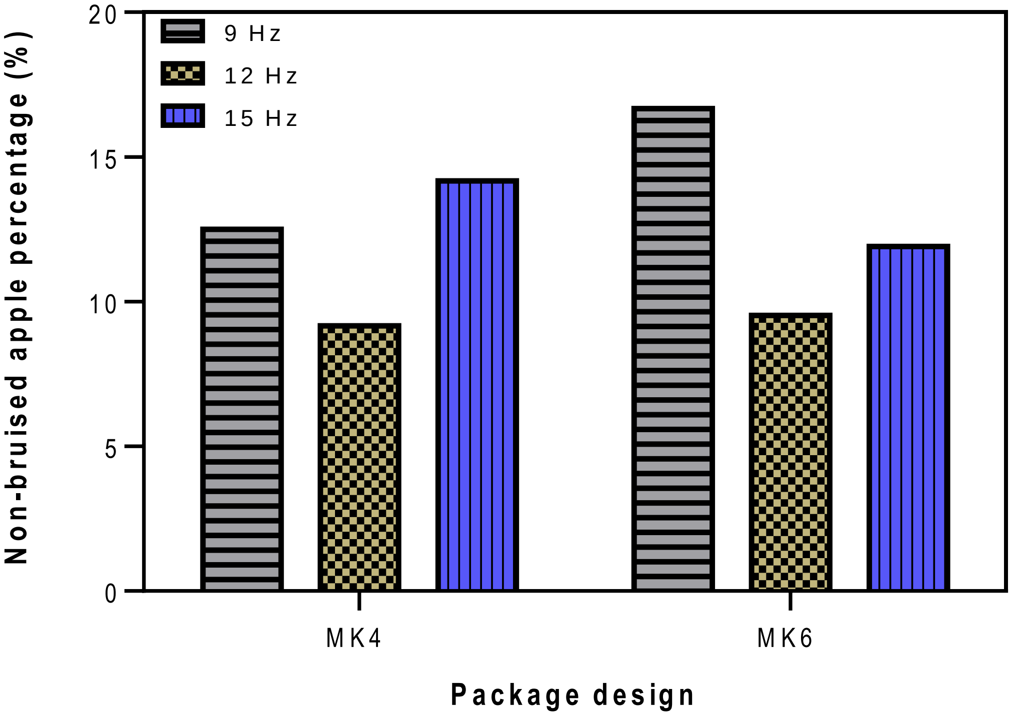


Figure 4.9: Non-bruised apples at different frequencies.

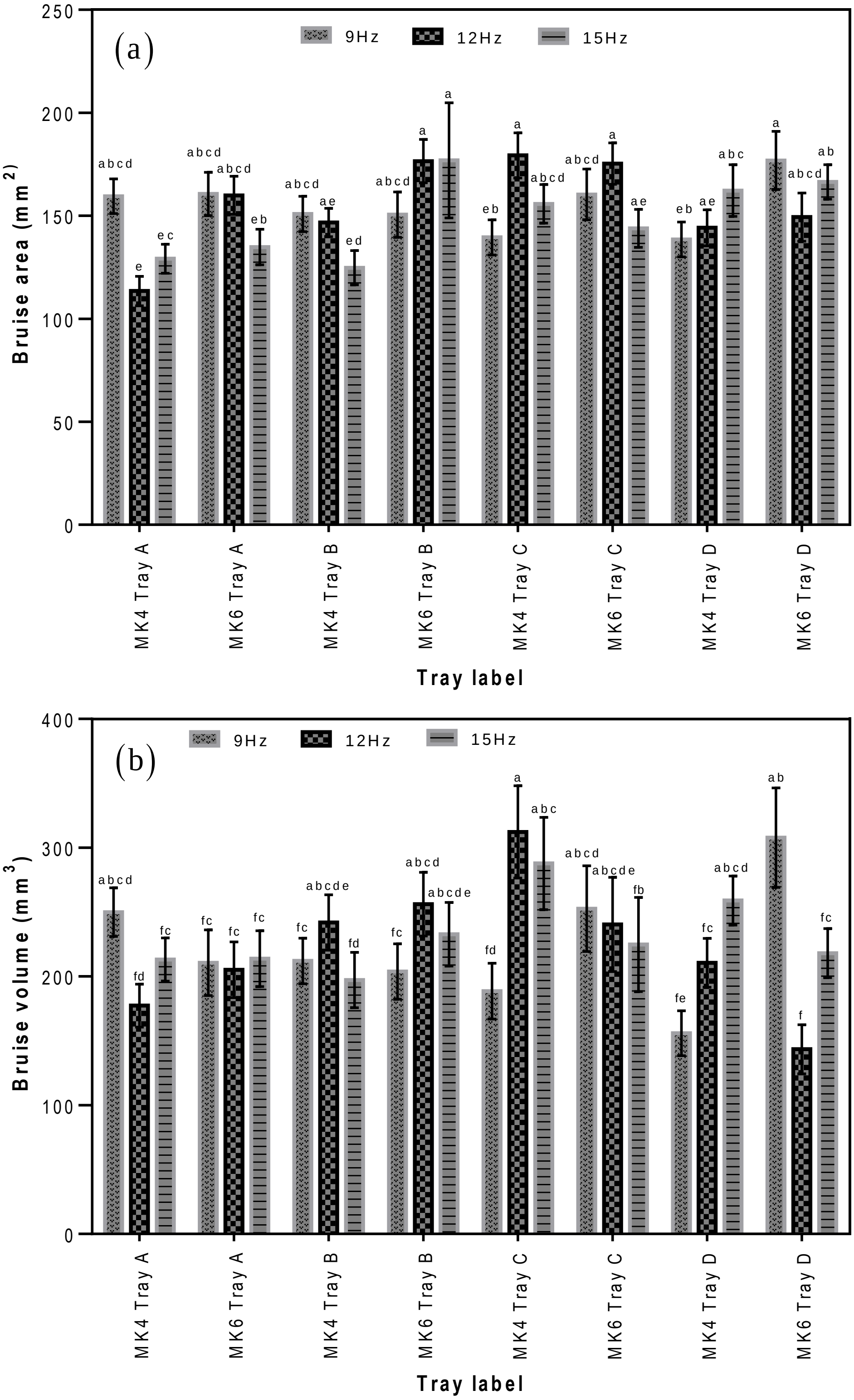


Figure 4.10: Spatial variation of bruise inside the different package designs (a) Bruise area; (b) Bruise volume.

Chapter 5 Investigating the mechanical properties of fresh produce packaging material: experimental and modelling approaches

Keywords: paper grammage, corrugated paperboard, elasticity modulus, edgewise compression test, relative humidity.

Abstract

Paper and paperboard are the most widely used packaging materials in the world. The combination of corrugated medium (fluting) and linerboard can be varied to design a corrugated paperboard package in relation to specific mechanical properties of the paper and paperboard. Tensile tests were performed on five different paper grammages (175 $\mathrm{g/m^2}$, 200 $\mathrm{g/m^2}$, 225 $\mathrm{g/m^2}$, 250 $\mathrm{g/m^2}$, and 300 $\mathrm{g/m^2}$) in the principal directions of the paperboard (machine direction, and cross direction) at standard condition (23℃ and 50% RH) and transport refrigerated condition (0℃ and 90% RH). At the same environmental conditions, edgewise compression tests were performed on the corrugated paperboard. Results showed that the responses of the paper and paperboard to the mechanical properties were affected by the environmental conditions. At the refrigerated condition, the modulus of elasticity strongly decreased in the range of 20 - 53% for all the paper grammages. The modulus of elasticity in the machine direction (MD) was observed to be highest for all the paper grammages, but no significant difference was observed in the thickness direction. The buckling behaviour of the experimental edgewise compression test of the corrugated paperboard was compared with numerical results. The finite element model of the corrugated paperboard could accurately predict the experimental value of the incipient buckling load with an error of 0.4% and 5.5% at the standard condition and refrigerated condition respectively.

5.1 Introduction

Paper and paperboard are sheet materials obtained from an interlaced network of cellulose fibres obtained from cellulosic material such as wood, cotton or linen (Marsh & Bugusu, 2007; Haslach, 2000). Paper is an important and one of the most complex engineering materials, especially due to its response to moisture, loads and to temperature (Bandyopadhyay et al., 2000; Haslach, 2000). However, paper and paperboard have long been the main packaging material for various products and goods (Chonhenchob et al., 2012; Marsh & Bugusu, 2007; Twede & Selke, 2005). The reliability of paper and paperboard packaging in the fresh fruit industry is extremely important (Raheem, 2012; Kibirkštis et al., 2007), where packaging plays a continuously increasing role (Mahalik & Nambiar, 2010; Marsh & Bugusu, 2007; Pré 1992; Smith et al., 1990).

The most important application of paper and paperboard is in corrugated paperboard packages (Beldie et al., 2001; Gilchrist et al., 1999). Corrugated paperboard is inexpensive and lightweight, having a high strength – to – weight and stiffness – to – weight ratios making the material the best choice for the manufacturing of packages for the transportation of products (Biancolini, 2005). Paper and paperboard are orthotropic in nature with different mechanical properties in the three principal directions (Jiménez-Caballero et al., 2009; Baum et al., 1981) (Figure 5.1). Corrugated paperboard is an orthotropic sandwich structure consisting of the surface plies known as liners, providing bending stiffness, separated by a lightweight bending core (fluting) that provides shear stiffness (Figure 5.2). The machine direction (MD) and the cross direction (CD) are the two main directions characterising this material. MD corresponds to the direction of manufacturing of the material while CD corresponds to the transverse direction. However, to refer to the out-of-plane direction, that is the direction through the thickness, a third direction ZD is introduced (Allaoui et al., 2011; Talbi, et al., 2009; Aboura et al., 2004). The analysis of the structural components of the paperboard and investigation of the strength and stiffness properties are very crucial in the design of paperboard packages (Biancolini et al., 2005; Biancolini, 2005). Understanding these properties reduce the damage to the product due to lateral crushing and compression loads from stacking. Furthermore, buckling may be avoided by knowledge of these properties (Talbi, et al., 2009; Biancolini, 2005) and understanding the response of paperboard packages is an important step in designing of packages.

Biancolini et al. (2005) identified the proper combination of paper for corrugated board as a factor that can affect package design and also highlighted the uncertainties involved in the process of design due to the variation in the mechanical properties of paper. In the study by Haslach (2000), the complexity of paper was discussed. The author further stated that the structural performance of paper is dependent on time with reference to moisture content, load, and temperature whether constant or variably combined. Several authors have also studied the effect of varied loads and exposure to moisture on the strength of paper and paperboard (Navaranjan et al., 2013; Kibirkštis & Kabelkaitė, 2006; Alfthan, 2004; Sørensen & Hoffmann, 2004; Larotonda et al., 2003; Sørensen & Hoffmann, 2003; Bandyopadhyay et al., 2000). Despite the complexity of the paper structure, the advent of numerical models such as finite element analysis (FEA) have proven to provide adequate confidence to use it as a design tool (Delele et al., 2010; Jiménez-Caballero et al., 2009). Corrugated paperboard is regarded by several authors as a structure (Haj-Ali et al., 2009; Biancolini, 2005; Beldie et al., 2001), a sandwich (Nordstrand, 1995) or as monolithic material (Aboura et al., 2004). Irrespective of the approach, knowledge of the mechanical components is vital as the sandwich structure is influenced and governed by the behaviour of the components. In the study by Gilchrist et al. (1999), a finite element model was developed for different corrugated board configurations. The authors found reasonable results that correlated well with the experimental assessments. Experimental measurements were reported to be consistent with numerical results in the study by Biancolini et al. (2010). The authors developed two finite element models by using homogenised elements to represent the entire geometry of the corrugated board. Results were also compared with simplified formula and a good correlation was observed. The stiffness properties of corrugated board were evaluated by Biancolini (2005), using the finite element method based on a comprehensive micromechanical model to represent a small section of the corrugated board.

The structural performance of corrugated packages is dependent on numerous factors including the quality of the input cellulose fibre, the mechanical properties of the liner and the fluting and the structural properties of the combined board (Pathare & Opara, 2014; Zhang et al., 2014; Biancolini et al., 2010; Rahman & Abubakr, 2004; Biancolini & Brutti, 2003). Knowledge about these fundamental attributes can improve the package structural performance, by either minimising the amount of material utilised for making corrugated paperboard packages or by allowing for unique and improved designs to enable competition with other materials. The main objective of this study was to investigate the engineering properties of packaging materials for fresh produce.

5.2 Materials and methods

5.2.1 Paper and paperboard sample

Five different virgin paper samples with different grammage were used in this study. Four of the paper samples were used as liners while the remaining one was used as fluting material and combined to form a corrugated paperboard. The thickness of the paper samples is usually not constant because of the fibrous structure of the material and the small imperfections as a result of the manufacturing process. A digital thickness micrometre (Figure 5.3) was used to measure the thickness of the paper and paperboard samples. Ten samples of each grammage type were measured. The thickness of the paper samples used in the study is shown in Table 5.1.

5.2.2 Material characterisation

The elastic modulus of the paper sample (flute and liners) was obtained by performing tensile tests. Since paper is made of oriented wood fibres, the stiffness and strength properties are anisotropic. In most cases, the fibre orientation is approximately symmetric, indicating that the stiffness properties can be assumed to be orthotropic, i.e. three symmetry planes for the elastic properties can be found. Due to the orthotropic nature of the material, the in–plane properties were determined by orienting the paper in the machine direction (MD) and the cross direction (CD). The out of plane (thickness direction, ZD) modulus of elasticity was estimated using Equation 5.1 (Beldie, 2001; Persson, 1991). The tensile tests were done according to the standard ISO 1924 – 2: 2008. The Instron Model 4444 Tensile testing machine (Norwood, MA, USA) was used (Figure 5.4). Rectangular samples of 180 × 15 mm were cut with a guillotine and tested under a constant displacement velocity of $20 \pm 5\ \mathrm{mm/min}$. The samples were conditioned for 48 hours in a versatile environmental chamber (model MLR – 352H) at 23℃ and 50% RH and at the refrigerated cold storage condition for fresh produce, 0℃ and 90% RH. Ten replicates of each of the grammage type were tested.

$$E_{ZD} = \frac{E_{MD}}{200} \tag{5.1}$$

where E_{ZD} is the modulus of elasticity in the thickness direction and E_{MD} is the modulus of elasticity in the machine direction.

The shear modulus was evaluated by performing tensile tests on paperboard samples oriented at $45°$ to the machine direction. The shear modulus (G_{LT}) was approximated using Equation 5.2 according to Biancolini & Brutti (2003) using $E_{45°}$ obtained for the $45°$ rotated stiffness matrix.

$$G_{LT} = \left[\frac{2\nu_{LT}}{E_{MD}} - \frac{1}{E_{MD}} - \frac{1}{E_{CD}} + \frac{4}{E_{45°}}\right]^{-1} \tag{5.2}$$

where $E_{45°}$ is the elasticity modulus in the $45°$ direction, G_{LT} is the shear modulus, ν_{LT} is Poisson’s ratio. Poisson’s ratio was approximated and set according to the values used by Biancolini & Brutti (2003) for a similar material namely 0.33 for the flute paper and 0.34 for the liners.

5.2.3 Corrugated paperboard strength test

Edgewise compression test

The in-plane compressive strength of corrugated paperboard is evaluated usually by the Edgewise Compression Test (ECT), otherwise known as the Edge Crush Test. The Edge Crush Test was performed using the FEFCO No. 8 Standard for rectangular corrugated paperboard samples that were cut to 100 mm long and 25 mm wide using the Edge Crush Tester (Messmer 937 model, Figure 5.5). The corrugated paperboard used for the test was a single wall of type “C” flute. The corrugated paperboard used is made from Kraft paper with a paper grammage of 250 $\mathrm{g/m^2}$ for both inner and outer liners and a paper grammage of

175 $\mathrm{g/m^2}$ for the flute (corrugated medium). The corrugated paperboard was inserted between two compression platens with no waxed edges or mechanical support beyond the initial vertical alignment at a constant speed of 12.5 $\pm$ 0.25 $\mathrm{mm/min}$ until instability occurred. The maximum force that the sample could resist before failure was recorded. To obtain the value for the ECT, the maximum force was normalised by the length of the sample using Equation 5.3 as described by McKee et al. (1963).

$$ECT = \frac{F_b}{L} \tag{5.3}$$

where ECT $(\mathrm{kN/m})$ is the value of the Edgewise Compression Test, F_b (N) is the force at which buckling occurred, and L (mm) is the length of the corrugated paperboard. Ten replicates of the paperboards were tested.

Simulation of the ECT of corrugated paperboard

Geometry modelling

To accurately model the corrugated paperboard, the numerical simulation must be able to represent the physical model. The corrugated paperboard dimensions used in the finite element model are shown in Figure 5.6. The fluting was approximated by modelling its shape as a sine wave (Figure 5.7).

Finite element modelling

The corrugated paperboard was modelled using the detailed geometry of the liners and the flutings. The finite element analysis was performed with the commercial code SimXpert/Nastran (MSC Software Corporation, California, USA). In order to accurately model the geometry in a finite element model, some basic assumptions were made. The behaviour of paperboard material is orthotropic and the material properties obtained from the tensile test for the liners and the flute were used as input parameters in the finite element models. The model was approximated as linear elastic. Linear quadrilateral shell elements were used for the ECT models and they were oriented properly so as to capture the actual pattern of the paperboard of liners and the flutings. The mesh size used was 0.5 mm. The model of the ECT was according to the standard FEFCO No. 8 with a rectangular (100 mm × 25 mm) shaped corrugated paperboard. The aim was to model the boundary condition (Figure 5.8) as closely as possible to the experimental setup. A fixed constraint (x, y, and z) was applied to the bottom of the model and at the outside edges close to the top where the model is clamped. The total load function was used to distribute a load of 1 N evenly across all the nodes. A linear buckling analysis was performed on the ECT model in order to determine the most likely buckling shape and estimate the critical buckling load. The material properties of the paperboard combination are shown in Table 5.2.

5.2.4 Statistical analysis

The statistical tests were performed using Statistica (v. 11.0, Statsoft, USA). The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p < 0.05$ considered statistically significant. Graphical representations were made using GraphicPad Prism 6 software (GraphicPad Software, Inc. San Diego, USA). Error bars on the figures indicated standard error of the mean. The letters on the error bars were used to show the statistical difference. Means with the same letters are not statistically different.

5.3 Results and discussion

5.3.1 Effect of paper grammage and environmental condition on paper properties

Typical characteristic stress–strain curves for both the liner and the flute paper is shown in Figure 5.9. The stress–strain curves were used for the characterization of paper behaviour under tension. The linear part of the curve which precedes the non–linear part is in general, dependent on the cellulose fibre, the moisture content and the hydrogen bonds (Allaoui et al., 2009). The modulus of elasticity in the machine direction was observed to be more significant than the other directions for both the liner and the flute paper. A similar observation was reported by Allaoui et al. (2009). The apparent and natural difference between the machine direction and the other directions was reported in the study by Salminen (2003) to be due to the straining behaviour of the MD which is less plastic and ductile. Also, due to the orientation and the distribution of the fibres during the forming of the paper sheets in the machine direction, the paper has the ability to resist a higher stress and is usually stiffest in the machine direction (Pathare & Opara, 2014; Stenberg et al., 2001). The elasticity moduli of the different paper grammage at two different environmental conditions are shown in Table 5.3. The machine direction showed the highest elasticity modulus for paper grammage of 200 $\mathrm{g/m^2}$ at the standard condition while the lowest under the same condition was observed for paper grammage of 175 $\mathrm{g/m^2}$ with a reduction of about 41%. The same trend was observed in the machine direction at the refrigerated condition with about 42% reduction. However, the paper grammage of 250 $\mathrm{g/m^2}$ showed the lowest elasticity modulus in the machine direction. For all the paper grammages in the principal directions under both the standard and the refrigerated conditions, the decrease in the elasticity modulus from the highest to the lowest was in the range of 27 - 54%.

In the study by Vishtal & Retulainen (2012), it was reported that the presence of moisture in paper materials softens the material and changes the behaviour of the stress-strain curve of paper fibres by reducing the elastic modulus and tensile strength. It was observed that on changing the conditions from standard to refrigerated, for the principal directions, the elasticity moduli decreased in the range of about 20 - 53% for all the paper grammages (Table 5.3). Allaoui et al. (2009) observed similar results and reported that the elastic modulus of paperboard decreased with about 50% in the cross direction and about 30% in the machine direction, when the relative humidity was increased from 50% to 90%. The equilibrium moisture content of paper is closely linked to the relative humidity of the surrounding environment (Pathare & Opara, 2014). When the RH of paper material alternates, the paper fibre absorbs moisture from or releases moisture to the environment. Furthermore, when paper material absorbs moisture, the water content increases significantly and the bond of the cellulose fibre of the paper material breaks, greatly affecting the mechanical properties (Pathare & Opara, 2014; Zhang et al., 2011; Hung et al., 2010; Allaoui et al., 2009). There was a significant difference in the elastic moduli at all directions between the standard condition and the refrigerated condition for all the paper grammages except for the thickness direction. This may be due to the preferential orientation of fibres in the plane of the paper (Stenberg et al., 2001). Paper fibre experiences shear stresses when the tensile loads do not line up to the orientation of the in–plane fibre of the paper (Stenberg et al., 2001). As expected, the shear modulus was higher at the standard condition than at the refrigerated condition (Figure 5.10). Paper grammage 175 $\mathrm{g/m^2}$ had the highest shear modulus in the MD at the standard condition. This paper grammage is suitable for the fluting in a corrugated paperboard as the purpose of the fluting is to carry shear stresses and to keep the facings (liners) of the board apart.

Substantial knowledge of the mechanical properties of paper is very important because the strength properties of paper can aid in the design of paperboard packages (Pathare & Opara, 2014; Vishtal & Retulainen, 2012). Furthermore, mechanical properties of paper, especially at varied conditions (Pathare & Opara, 2014; Morris, 2011) can be used as input parameters in numerical models such as the finite element method of paperboard packages (Yoshihara, 2012). This can help to predict the mechanical behaviour of corrugated paperboard packages such as buckling, transverse shear, stability, collapse, elasticity and ultimate failure (Haj-Ali et al., 2009; Talbi et al., 2009; Guo et al., 2008; Nordstrand & Allansson, 2003; Nordstrand & Carlsson, 1997).

5.3.2 Effect of environmental condition on corrugated paperboard ECT

The ECT value can be used as an indicator to determine the quality of corrugated paperboard. Furthermore the ECT value is usually used to evaluate the compression strength of the corrugated paperboard in the direction of the medium and its resistance to crushing (Pathare & Opara, 2014; Twede & Selke, 2005). The experimental and the numerical ECT values of the investigated corrugated paperboard are shown in Table 5.4. It was observed that the simulation of the ECT accurately predicted the experimental ECT values and the differences between the experimental results and the simulation results were 0.4% and 5.5% for the standard and the refrigerated conditions respectively. The influence of the environmental factors between the standard condition and the refrigerated condition was observed as the strength of the corrugated paperboard reduced by 38% experimentally and was as high as 41% with the FEA results. A similar study has shown that the edge compression strength of a corrugated paperboard reduced by 19% when the relative humidity was gradually increased from 30% to 90% (Zhang et al., 2011). Figure 5.11 shows the first global buckling mechanism of the FEA model for the standard and refrigerated conditions. The ECT value can be used by packaging industries to predict and estimate the strength of a corrugated paperboard package from the package geometry and the paperboard properties using the well-known McKee formula (McKee, 1963). The requirement for the strength of corrugated paperboard packages are greatly influenced by changes in environmental conditions such as temperature and relative humidity (Bronlund et al., 2014; Dongmei et al., 2013). Therefore, package designers must accommodate these factors in designing corrugated paperboard packages to withstand frequent changes that may occur throughout the life cycle of the package and for long-term storage.

5.4 Conclusion

The current study investigated the tensile properties of five different paper grammages and edgewise compression test (ECT) of corrugated paperboard at standard condition (23℃ and 50% RH) and refrigerated condition (0℃ and 90% RH). The ECT was also investigated by finite element analysis to evaluate the structural performance of the corrugated paperboard. The experimental tensile tests showed a variation in properties in the principal directions of the paperboard, indicating the orthotropic nature of the paper material. The machine direction had the highest elasticity modulus because the paper fibres are oriented in the machine direction during forming of the paper sheets. The elasticity modulus for all the directions was observed to be sensitive to the environmental conditions with a reduction as high as 53% at the refrigerated conditions compared to the value obtained at the standard conditions. The ECT value also reduced with about 41% at the refrigerated conditions. The developed FEA model accurately predicted the incipient buckling load of the corrugated paperboard. The accuracy of the model was validated by comparing the experimental ECT values. An excellent agreement was observed between experimental ECT results and the numerical results. The experimental results and the simulation results differed by 0.4% and 5.5% for the standard and the refrigerated conditions respectively. The tensile properties might be useful for the selection of the best combination of papers for liners and fluting to obtain maximum strength of the corrugated paperboard and can also be used as input material properties for the FEA model. The numerical tool can be utilised by package designers to optimise corrugated paperboard packages thereby improving the overall strength and lowering the cost.

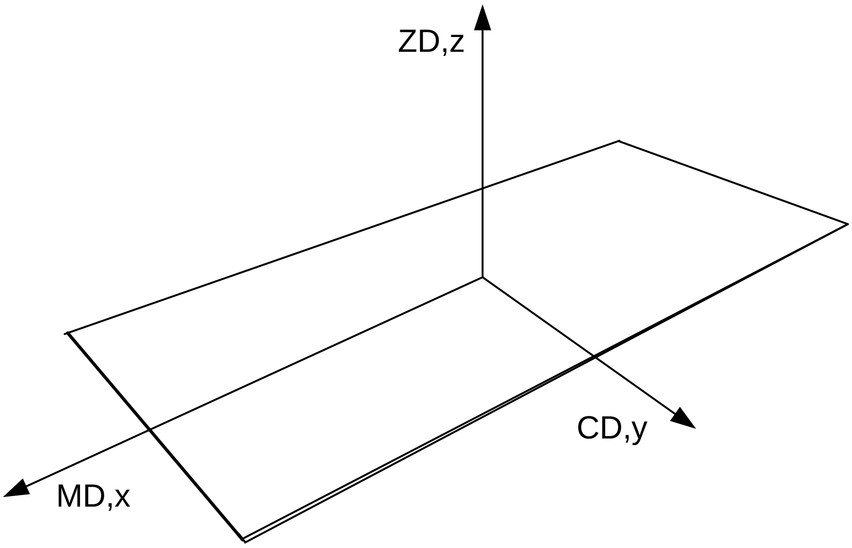


Figure 5.1: Principal material directions of paperboard.

Figure 5.2: Corrugated paperboard panel geometry.

Figure 5.3: Paper thickness measuring instrument.

Table 5.1: Thickness for all the paper samples.

Paper sample	**Grammage** $\left(\frac{\mathbf{g}}{\mathbf{m^2}}\right)$	**Thickness** $(\mathbf{mm})$
Liner	200	0.266±0.0012
	225	0.362±0.0013
	250	0.355±0.0018
	300	0.425±0.0023
Flute	175	0.289±0.0015

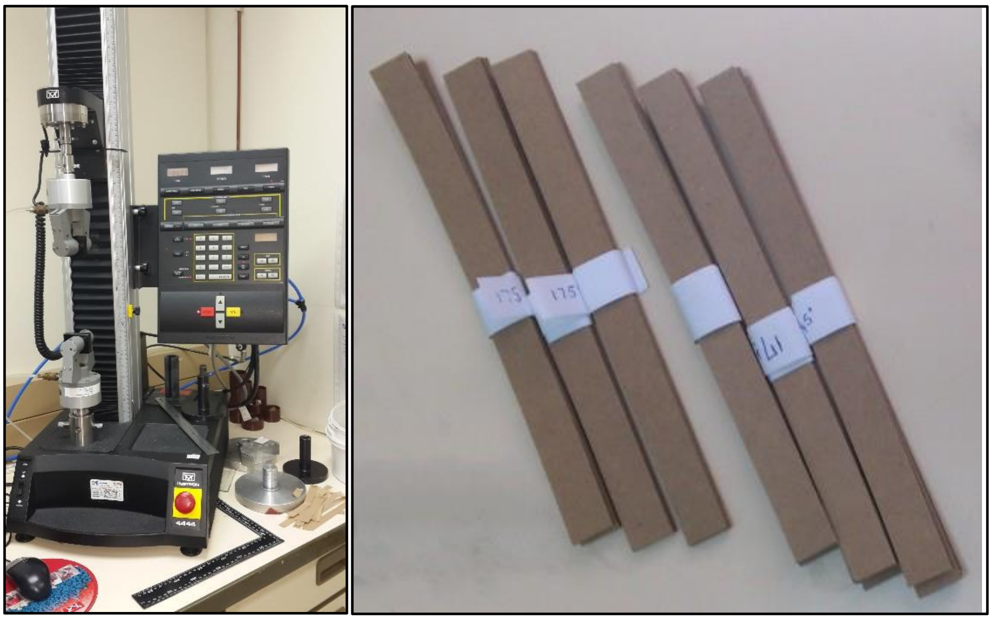


Figure 5.4: Tensile testing machine and paper sample.

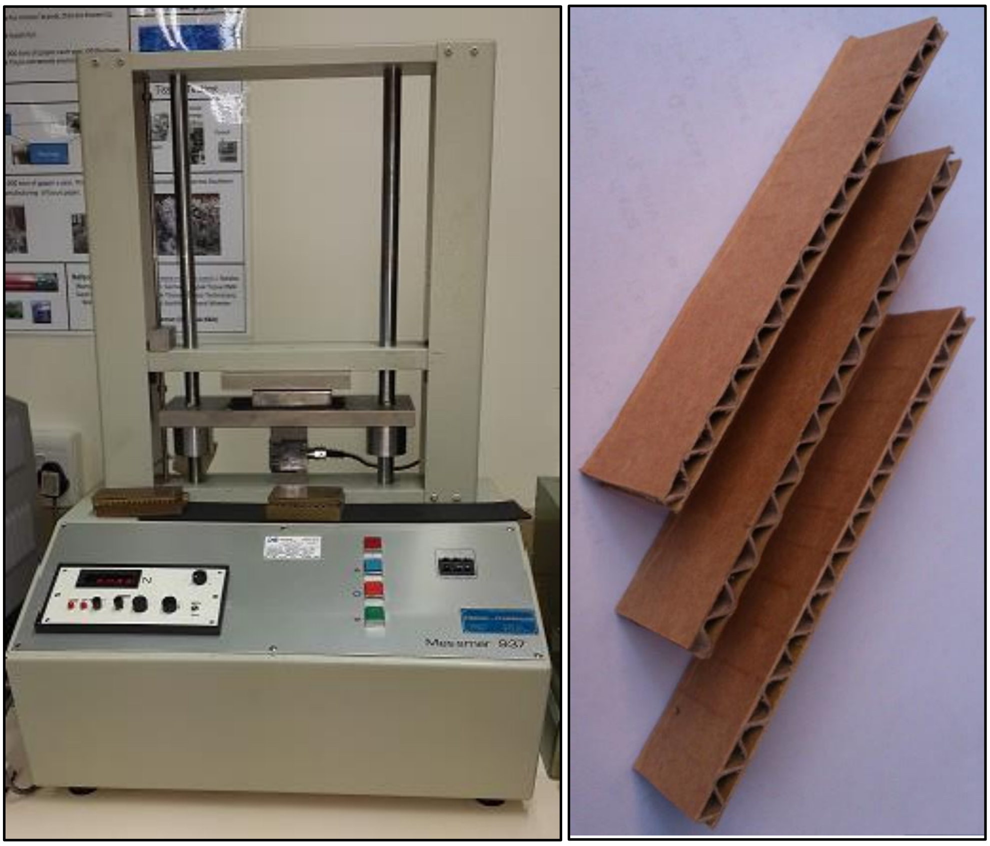


Figure 5.5: Edgewise compression test machine and the corrugated paperboard sample.

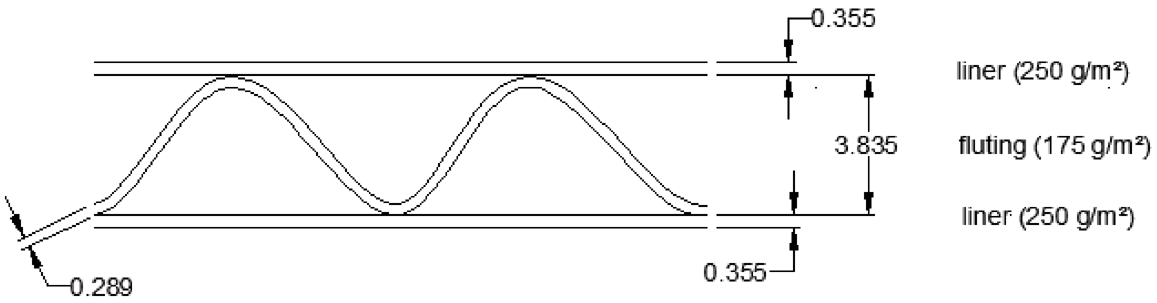


Figure 5.6: Dimension of the corrugated paperboard.

Figure 5.7: Approximate sine wave flute.

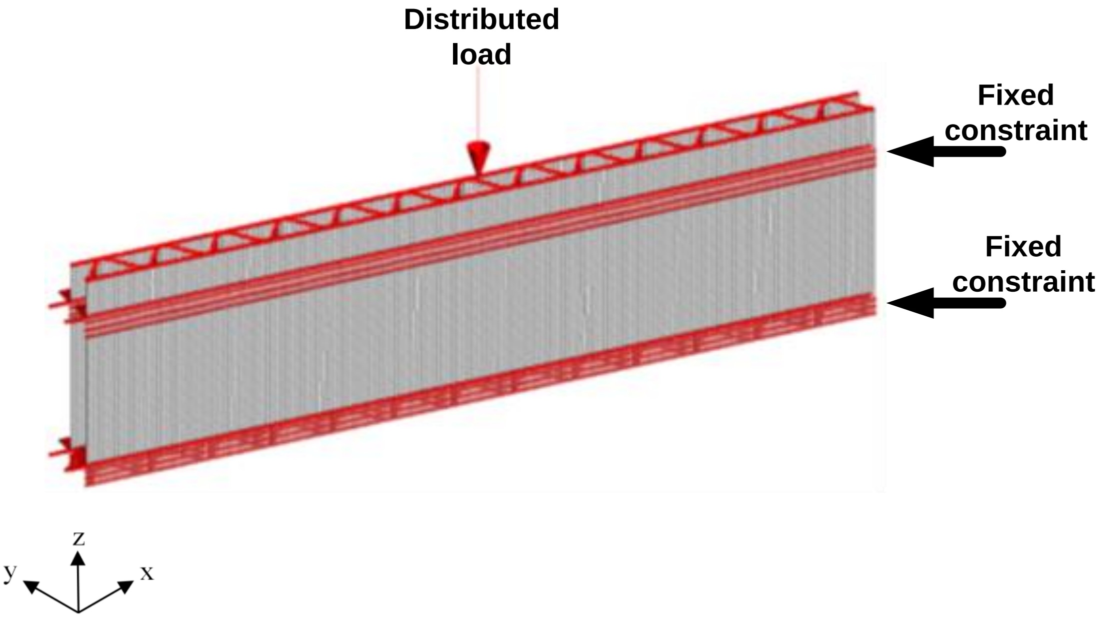


Figure 5.8: The finite element model setup for the ECT.

Table 5.2: Material properties used for finite element analysis (FEA).

Properties	Standard condition		Refrigerated condition	
	Liner	Flute	Liner	Flute
Elasticity modulus (MD) (MPa)	2194	2160	1198	1491
Elasticity modulus (CD) (MPa)	359	456	220	306
Poisson’s ratio	0.34	0.33	0.34	0.33
Shear modulus (MPa)	565	1890	338	301

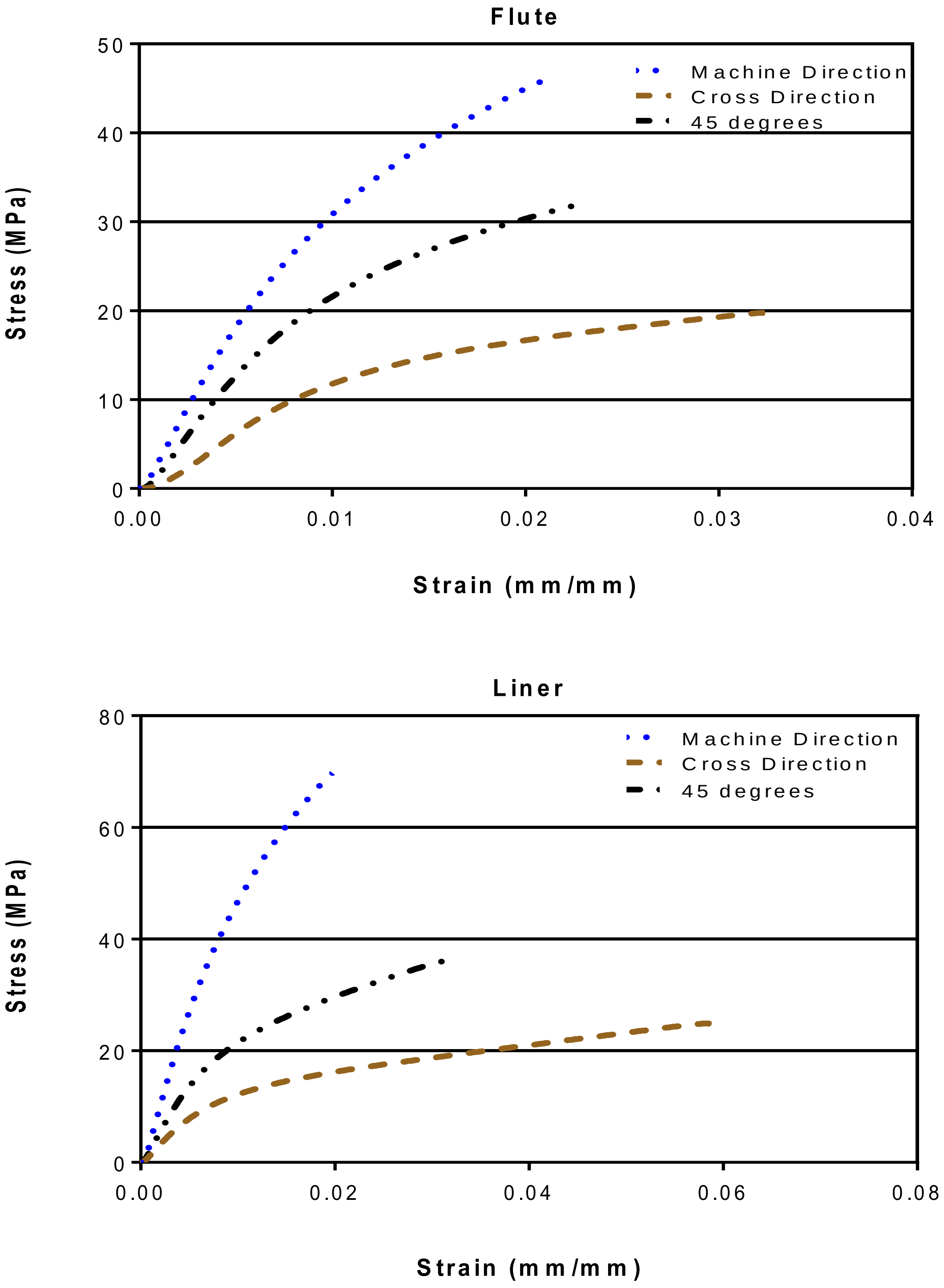


Figure 5.9: Typical stress–strain curve.

Table 5.3: Elasticity modulus at two different conditions.

Paper grammage $\left(\frac{g}{m^2}\right)$	Elasticity modulus (MPa)							
	Machine direction (MD)		Cross direction (CD)		Thickness direction (ZD)		45 degrees	
	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**	Standard condition*	Refrigerated condition**
175	2155.57 ± 31.92^{e}	1491.34 ± 27.49^{g}	456.13 ± 16.93^{op}	306.22 ± 4.37^{st}	10.78 ± 0.16^{v}	7.46 ± 0.14^{v}	1385.69 ± 18.40^{h}	587.31 ± 8.63^{n}
200	3670.47 ± 69.75^{a}	2592.38 ± 36.73^{d}	331.64 ± 3.15^{sr}	262.29 ± 1.91^{ut}	18.35 ± 0.35^{v}	12.96 ± 0.18^{v}	950.43 ± 13.73^{k}	689.88 ± 8.50^{m}
225	3044.75 ± 43.43^{b}	1445.48 ± 26.31^{g}	430.67 ± 6.49^{qp}	273.61 ± 2.66^{ut}	15.22 ± 0.22^{v}	7.23 ± 0.13^{v}	1122.23 ± 22.39^{j}	498.33 ± 6.61^{o}
250	2193.48 ± 37.15^{e}	1198.62 ± 16.75^{i}	358.78 ± 7.32^{sr}	220.38 ± 2.00^{ut}	10.97 ± 0.19^{v}	5.99 ± 0.08^{v}	850.54 ± 13.38^{l}	514.11 ± 3.65^{o}
300	2858.05 ± 24.22^{c}	1597.30 ± 24.90^{f}	378.64 ± 6.20^{qr}	231.64 ± 2.44^{ut}	14.29 ± 0.12^{v}	7.99 ± 0.12^{v}	869.63 ± 14.18^{l}	522.89 ± 8.04^{o}

*** (23℃ and 50% RH)**

**** (0℃ and 90% RH)**

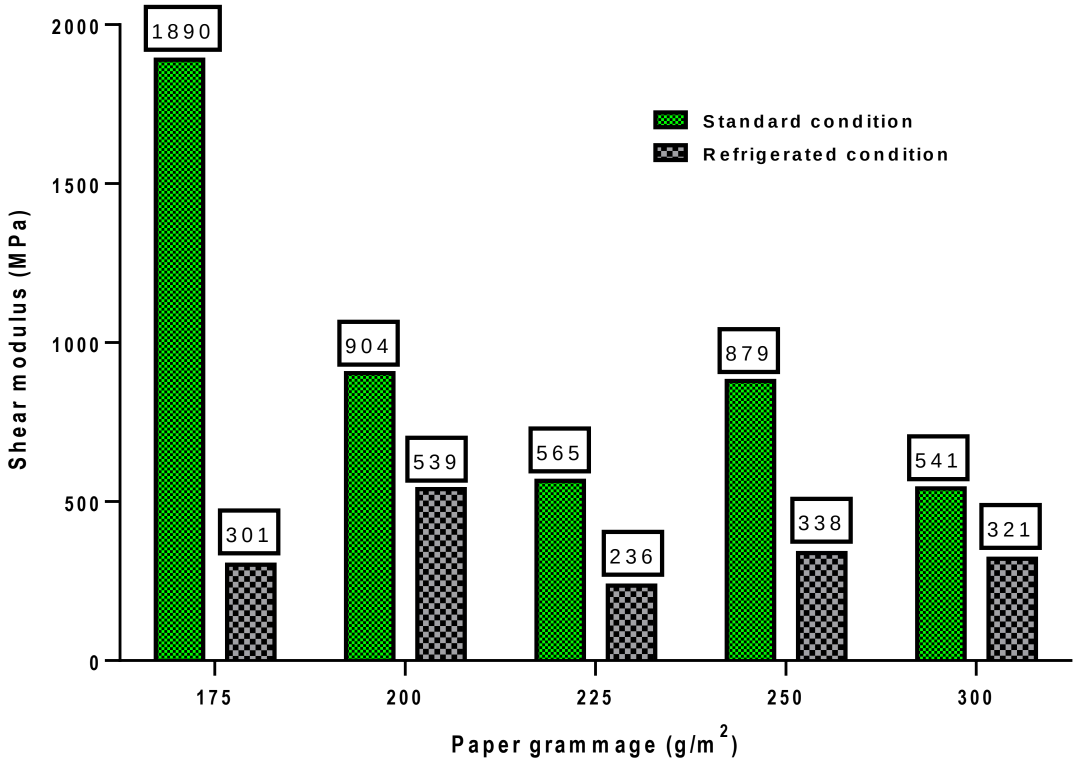
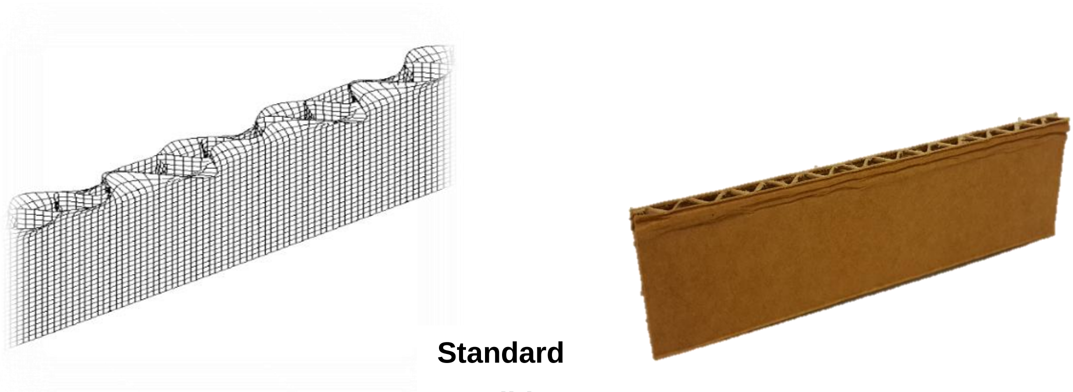


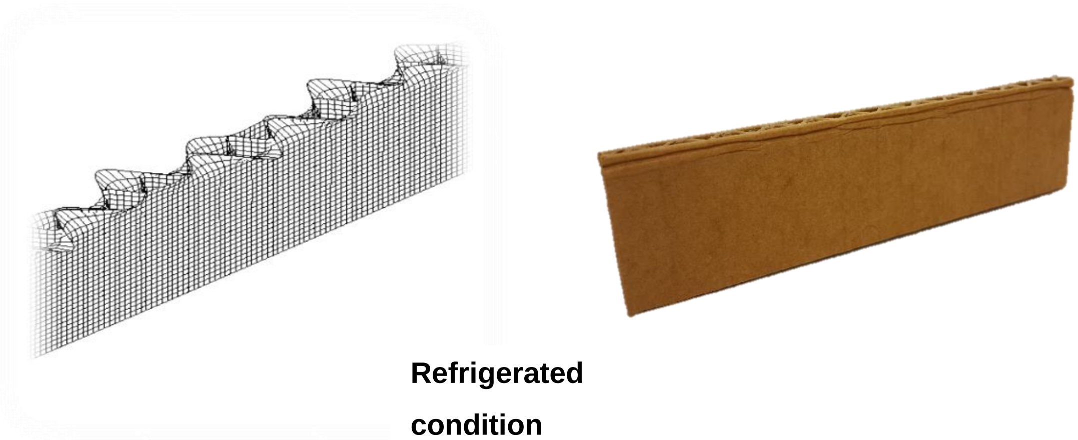
Figure 5.10: Shear modulus at different conditions.

Table 5.4: Edgewise compression test values.

Environmental condition	**Experimental $\left(\frac{\text{kN}}{\text{m}}\right)$**	**Numerical $\left(\frac{\text{kN}}{\text{m}}\right)$**
Standard	7.94	7.91
Refrigerated	4.91	4.64



Standard condition



Refrigerated condition

Figure 5.11: Detailed failure mechanism FEA model for ECT simulation and the actual mechanism.

Chapter 6 Compression strength of ventilated corrugated paperboard packages and fruit susceptibility to compression damage inside packaging: modelling and experimental approaches

Keywords**:** FEA, buckling load, ventilated packaging, compression damage, relative humidity, temperature

Abstract

Fresh produce such as apples are susceptible to mechanical damage during postharvest handling. Ventilated corrugated paperboard (VCP) packages that are used extensively in the fruit industry cold chain are designed to minimize produce damage and to maintain adequate airflow needed to ensure optimum heat transfer from produce to cold air. Under such cold chain conditions, the packages may experience mechanical failure due to excessive compression loads under high relative humidity condition, which in turn may also lead to bruise damage of produce. The objectives of this study were to; investigate the compression strength of two VCP package designs (MK4 and MK6) numerically using FEA, validate the model with experimental conditions and assess the susceptibility of fruit to mechanical damage when loaded inside the packages. The FEA results were in good agreement with the experimental results with a difference of 4.7% for MK4 package and 8.2% for MK6 packages. 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 package designs when stored at low temperature (0℃ and 90% RH) compared to standard conditions (23℃ and 50% RH). Both the incidence and susceptibility to bruise damage were affected by package design, with more fruit bruising occurring inside the MK6 package than the MK4 package design. Irrespective of package design, the highest and lowest bruise incidence of bruise damage occurred at the top and bottom layers of the package, respectively.

6.1 Introduction

The packaging of fresh fruit remains vital in 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 (Lu et al., 2012; Lu et al., 2010; Van Zeebroeck et al., 2007). During handling, transportation and storage, fruits and vegetables experience various loading conditions, which may be static, dynamic or a combination of both (Opara & Pathare, 2014; Lewis et al., 2008). In spite of the handiness and use of different packaging designs in fruit handling, these conditions lead to mechanical damage (Knee & Miller, 2002) resulting in postharvest loss of fresh fruits (Opara & Pathare, 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). However, mechanical damage is responsible for extensive rot or decay of fresh fruits and vegetables. About 30% to 40% of produce may be lost due to mechanical damage in the distribution chain between grower and the consumer (Barchi et al., 2002). A Clear understanding 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 et al., 2010; Dewulf et al., 1999; Roudot et al., 1991; Jones et al., 1991).

Several researchers have catergorised the loadings causing mechanical damage into compression, impact and vibration forces (Opara & Pathare, 2014; Kitthawee et al., 2011; Lewis et al., 2008; Opara, 2007; Jarimopas et al., 2007; Robertson, 2005; Knee & Miller, 2002; Bollen et al., 1999; Brown et al., 1993; Vergano et al., 1991; Ruiz Altisent, 1991; Brusewitz et al., 1991; Armstrong et al., 1991). As noted by Brown et al. (1993), fruits are exposed to compression via forces applied through contact by the picker, tree limbs, fruit to fruit contact due to overfilled cartons or carton stack height or by an operator forcing cartons into a tight spot, etc. Vibration forces occur during transportation and are difficult to avoid (Opara & Pathare, 2014). When the cartons reach resonance (their natural frequency equals the forcing frequency of the conveyance), severe mechanical damage is inherent. Impact forces are usually high, occurring in an extremely short duration and impact results from dropping produce or packaged produce on an insufficiently cushioned surface during mechanical handling of fresh produce. Bruise, permanent damage and lower quality produce are effects of impact forces (Eissa et al., 2012). These forces are difficult to eliminate during extensive production and distribution of horticultural produce (Gołacki et al., 2009).

Mechanical properties of fruits and vegetables are those having to do with the behaviour of the produce under applied forces, describing how the action of forces on packaging during transportation and handling result in mechanical damage of the produce (Babarinsa & Ige, 2012). Studies have been done on the mechanical damage to horticultural produce due to compression loading; (Kılıçkan & Güner, 2008; Khan & Vincent, 1993b; Holt & Schoorl, 1977) apples, (Vursavuş & Özgüven, 2004) apricot, and (Babarinsa & Ige, 2012) tomatoes. As reported by Robertson (2005), one of the major requirements for packaging of fresh horticultural produce is the ability to prevent mechanical damage, particularly resulting 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, cartons, bulk bins, and palletized containers. Ventilated paperboard package is the most widely used type of package for the packaging and distribution of a wide variety commodities ranging from fruits and vegetables, industrial products and consumables (Pathare et al., 2012; Hung et al., 2010). Stacking the packages on top of each other during transportation causes the bottom package to experience the highest load. Therefore, the bottom package must possess adequate and sufficient compression strength for withstanding the load without collapsing (Daxner et al., 2007). Recently, several authors have studied package behaviour using finite element analysis (FEA) (Beldie et al., 2001; Biancolini & Brutti, 2003; Han & Park, 2007). However, it is crucial to validate numerical results with experimental results (Delele et al., 2010)

Pommier & Poustis (1989) studied the top to bottom compression strength of a corrugated paperboard box using a linear elastic FEA. The authors found that the numerical analysis was in agreement with experimental values. Similarly, Biancolini & Brutti (2003) investigated the compression strength of corrugated board packages and found a good agreement with experimental results. Singh et al. (2008) investigated the loss of compression strength in ventilated paperboard cartons as a function of size, shape and location of ventilation and hand holes. The authors concluded that the presence of ventilation and hand holes can cause strength reduction between 20 to 50% in single wall corrugated shipping packages, with the shape of the hole being critical to loss of compression strength. In their study of compression performance of boxes with various shapes and sizes of vent holes using FEA, Han & Pack (2007) determined the appropriate pattern and location of vent holes. The authors reported the appropriate shape of vent hole to be vertical oblong shape, symmetrically located at about the centre of the front and rear faces. Furthermore, a good agreement with experimental results was reported.

Paperboard packages are used under various atmospheric conditions. In the study of Allaoui et al. (2009), the most severe relative humidity was 90%, corresponding to cold storage in cold room with forced moisture. The knowledge of the behaviour of paperboard packages under this condition will help in good optimisation of the material.

With several studies on the response of various horticultural produce, including apples and ventilated paperboard package, little is available on the susceptibility of fruits in the packaging. The objectives of the study were to investigate the strength of packages using

FEA simulation, validate the efficiency of the model, investigate the effectiveness of ventilated paperboard packages in protecting apples and the susceptibility of apples to mechanical damage caused by compression inside Bushel MK4 and MK6 ventilated corrugated paperboard packages.

6.2 FEA simulation

6.2.1 Materials and their properties

Two ventilated corrugated paperboard packages used for apple packaging, Bushel MK4 and MK6, were selected (Figure 6.1). The corrugated paperboard used for the package was a single wall of type “C” flute. Other flute types are A, B, E and F flutes. The corrugated paperboard used for manufacturing the packages is made from Kraft paper with a paper grammage of 250 $\mathrm{g/m^2}$ for both inner and outer liners and a paper grammage of 175 $\mathrm{g/m^2}$ for the flute (corrugated medium). The basic physical and material properties are shown in Table 6.1. Poisson’s ratio was approximated and set according to the values used by Biancolini & Brutti (2003) for similar material (0.33 for the flute and 0.34 for the liners).

6.2.2 Modelling approach

In order to accurately model the corrugated paperboard, the numerical simulation must be able to accurately represent the physical model. The package was modelled as a composite structure consisting of three layers where a solid core was created (Figure 6.2). The material properties of the liners remained the same as shown in Table 6.1. The equivalent properties for the solid core were calculated using the procedure suggested by Biancolini et al. (2010) and Biancolini (2005). This procedure provides a means of approximating a sandwich structure as a homogenous material and the stiffness matrix can be calculated if the function describing the sandwich pattern is known. The fluting of the corrugated paperboard was approximated as a sine wave (Biancolini et al., 2010). The equivalent plate bending stiffness formula for the corrugated core used to calculate the ABD matrix of the laminate is shown in Table 6.2 (Biancolini et al., 2005). The ABD matrix serves as a connection between the applied loads and the associated strains in the laminate. It essentially defines the elastic properties of the laminate. The mechanical properties used for calculating the equivalent core properties were those of the flute material with a paper grammage of 175 $\mathrm{g/m^2}$.

The equivalent core and liner properties used for the model are shown in Table 6.3. The procedure for calculating the equivalent core properties is shown in Appendix A. The FEA was performed with the commercial code SimXpert/Nastran (MSC Software

Corporation, California, USA). The bottom of the package was completely constrained while a uniformly distributed load of 1 N was applied at the top of the package. A constraint was applied at the top of the package to allow translation in the z-direction while preventing translation in the x and y directions. Rotation was allowed about the x-axis in the direction of the length of the package and about the y-axis in the direction of the width of the package. The model was assumed as linear elastic. Linear quadrilateral shell elements were used for the box compression test (BCT) model and the boxes were oriented properly so as to capture the actual pattern of the paperboard of liners and the core. The mesh size used for the model was 4 mm. A linear buckling analysis was performed on the BCT model in order to determine the most likely buckling shape and estimate the critical buckling load.

6.3 Experimental design and procedure

6.3.1 Fruit supply

‘Golden Delicious apples were purchased from Two-a-Day packhouse in Grabouw, Western Cape, South Africa $(34°48'14''\mathrm{S}, 19°02'50''\mathrm{E})$. Fruit with uniform size and maturity based on background colour, firmness and free from physical defects were used for the experiments. The apple variety was selected because of its susceptibility to bruising, and bruises and abrasion are easily visible. Mean diameter and mass of the apples were 65 ± 2.0 mm and 148.7 ± 7.0 g, respectively.

6.3.2 Packaging materials and preparation

The experiment was conducted using two ventilated paperboard package designs used for handling apples in international trade; Bushel MK4 and Bushel MK6. Both package designs consist of inner and outer boxes separated by four pulp trays (Figure 6.3). For each package design, fruit were placed on tray layers resulting in gross package mass of 18 kg and 13.3 kg, respectively, for the MK4 and the MK6 package designs. MK4 package is designed to hold 120 apples per package, 30 apples per layer while MK6 is designed to hold 84 apples per package, 21 apples per layer. The trays were labelled A to D, starting with the bottom tray. The apples were placed carefully with the flower stalk axis horizontal and in the same direction in the moulded pockets of the trays. The test packages were preconditioned prior to compression testing, in accordance with the requirements of the ASTM D4332 standard. Conditioning was done in a versatile environmental chamber (model MLR – 352H). The initial and the final weight of each packages were measured using an electronic weighing balance (ML3002.E, Mettler Toledo, Switzerland). The weight gain or loss by the packages were determined using the method described by (Andrés et al., 2014; Akbarpour et al., 2009):

$$W\ (\%) = \frac{W_i - W_f}{W_f} \times 100 \tag{6.1}$$

where W is the weight loss or gain, W_i and W_f are the initial weight (g) of the packages before conditioning and the final weight (g) of the package after conditioning respectively.

6.3.3 Compression test

The compression test measures the compressive strength of the package. The Lansmont compression tester-squeezer was used (Figure 6.4). The compression test was performed in accordance with the ASTM D642 Standard. The packages were compressed by applying a continuous motion of the platen of the compression tester at a speed of 12.7 ± 2.5 mm/min until failure was reached. A preload of 222 N was applied on the test packages. The preload removes the initial transient effects. Ten replicates for both package designs were used for the compression test. Empty packages were compressed at two environmental conditions; the standard condition for compression testing (23℃ and 50% RH) and the refrigerated cold storage condition for fresh produce (0℃ and 90% RH). Compression bruises were produced by compressing the packages filled with apples after storing for two days at a temperature of 0℃**.** Five replicates for both package designs were used for the compression of the filled packages.

6.3.4 Bruise measurement and analysis

The apples were left prior to evaluation at room temperature (20 – 22℃; 65 – 68% RH) for 24 h after compression for full development of the bruise and for the bruise to become apparent. The method described by Lu et al. (2010) was used to determine the bruise area and bruise volume, assuming an elliptical shape for the bruises (Opara & Pathare, 2014; Bollen et al., 1999). Bruise width and depth were measured using a pair of a digital Vernier calliper $(\pm 0.01\ \mathrm{mm})$. The measurement for the bruise depth was done after the bruised apple was cut perpendicular along the major axis of the bruise width.

Bruise area (BA) was calculated by:

$$BA = \frac{\pi}{4} w_1 w_2 \tag{6.2}$$

where w_1 and w_2 are the bruise width along the major and minor axes (mm).

Bruise volume (BV) was calculated by:

$$BV = \pi \frac{d_b}{24}\left(3w_1w_2 + 4d_b^2\right) \tag{6.3}$$

where d_b is the depth of the bruise (mm). Figure 6.5 shows a typical bruise on the apple and a cut section through bruised tissue while Figure 6.6 shows the bruise dimensions.

6.3.5 Statistical analysis

The experimental data were treated with one-way analysis of variance (ANOVA) at 95% confidence level and with the differences at $p < 0.05$ considered statistically significant. The statistical tests were performed using Statistica 11.0, Statsoft, USA. Graphical presentations were made using GraphicPad Prism software (GraphicPad Software, Inc. San Diego, USA). Error bars on the figures indicated standard error of the mean. The letters on the error bars were used to show the statistical difference. Means with the same letters are not statistically different.

6.4 Results and discussion

6.4.1 Simulation results of the packages

The buckling location for both MK4 and MK6 package is shown in Figure 6.7. This shows that buckling originated from the centre of the long side (length) of the package for both package designs. Localised crushing of the faces usually results to package failure (Panyarjun & Burgess, 2001). The width of the package was observed to be more resistant to buckling. The buckling loads were 5948.40 N and 6396.10 N for the MK4 and the MK6 package design, respectively, indicating about 7% difference. The total area of the vent on the long side of MK4 and MK6 were 5007 mm^2 and 4241 mm^2, respectively The higher buckling load observed for MK6 package can be attributed to the higher ratio of vent area on the long side to the length compared to MK4 The box length and vent area were 395 mm and 3.9% (MK6) and 495 mm and 3.8% (MK4), respectively. In addition, the higher length-to-height ratio on the MK4 package contributed to the lesser buckling load observed on the package. The length-to-height ratio of the MK4 and MK6 packages are 1.86 and 1.45 respectively. In their study of effect of ventilation and hand holes on the loss of compression strength in corrugated boxes, Singh et al. (2008) reported that increase in the amount of material removed for ventilation resulted to loss in the strength of the corrugated boxes (Singh et al., 2008).

6.4.2 Compression strength of empty packages

Figure 6.8 shows a typical force–deformation curve of both MK4 and MK6 package designs at the two environmental conditions. The compression strength of MK6 design was higher than the compression strength of MK4 package design at both environmental conditions (Table 6.4). There was a significant difference between the two environmental conditions for both package designs. The compression strength of MK6 package design was 12% higher than MK4 package design at standard condition while at refrigerated condition, MK6 package design was 19% higher than MK4 package design. The high compression strength in the MK6 package could be attributed to the amount of vent area and the vent shape. Singh et al. (2008) also observed that there is a linear relationship between the loss of strength and total vent area. The vertical oblong vent shape were the best option for ventilated corrugated packages when considering the mechanical integrity (Singh et al., 2008; Han & Park, 2007). Comparing the length of the oblong shape vent holes on both package designs, MK6 package had a shorter vent hole than MK4 package contributing to the large compression strength observed for MK6 packages. Similar trend was shown in the study of Han & Park (2007). The authors concluded that the length of vent holes should be less than 25% of the depth of the package.

During compressive load, buckling occurs and it is usually produced by the maximum bending moment around the centre face of the package. The location of a vent hole or hand hole at the centre of the face results to a substantial decrease in the compression strength of the package (Han & Park, 2007; Jinkarn et al., 2006). The presence of a hand hole at the centre of the side face of MK4 package contributed to the reduced compression strength. The presence of vent holes on a package is important for cooling (Thompson et al., 2002), although ventilation openings decrease mechanical strength (Pathare et al., 2012). The design of ventilated corrugated packages should be such that it provides adequate cooling to the fruit and still maintains the structural integrity. Although unvented corrugated packages are stronger than ventilated corrugated packages, however to reduce the loss of strength in ventilated corrugated packages, the location of the air vents should be such that they are far from the vertical corners of the packages (Vigneault et al., 2009; Kader, 2002). Furthermore, the ventilation area greater than 5% of the total wall area of the package must be adequately designed to provide sufficient strength (Thompson et al., 2002). Air vent lesser than 5% of the total wall area of be package will consequently increase the cooling rate and cooling time of the product (Thompson, 2008). Usually horticultural products packed in ventilated corrugated paperboard packages depends on the package walls to prevent mechanical damage to the packaged products inside the package. Therefore, maintaining and retaining the strength of the package walls is ultimately important during postharvest handling, storage and transportation.

The performance of paper-based packaging materials such as the compression strength, tensile properties, folding endurance, dimensional stability are generally affected by moisture content of the packaging materials, directly influenced by the environmental conditions (Rhim, 2010; Parker et al., 2006; Sorensen & Hoffmann, 2003; Bandyopadhyay et al., 2002; Marcondes, 1992). Figures 6.9 and 6.10 show the effect of absorbed or released moisture after environmental conditioning on the compression strength at different environmental conditions; (23℃ and 50% RH) and (0℃ and 90% RH) respectively. The effect of conditioning resulted in either a weight gain or weight loss. A decrease in compression strength of the ventilated corrugated paperboard package was observed with an increase in weight of the package due to the absorbed moisture from conditioning by mimicking cold storage condition for fresh produce. A similar occurrence was observed when the packages released moisture when conditioned at standard conditions. It was also observed from Figures 6.9 and 6.10 that the maximum compression strength was strongly dependent on the weight gain or loss for both MK4 and MK6 package designs as a result of conditioning. The coefficient of determination (R^2), for MK4 package design was 0.7218 and 0.8832 while R^2 for MK6 package design was 0.9213 and 0.8779 at standard and refrigerated conditions respectively. The water content of paper material increases appreciably and breaks the bonds between cellulose fibres by increasing the moisture content (Allaoui et al., 2009). Twede & Selke (2005) reported that high humidity storage condition can reduce the strength of packages in a matter of hours. A similar trend was observed in various paper based packaging materials. Mechanical properties such as elastic moduli, yield stress and tensile strength of paper decreased substantially at high humidity (Bandyopadhyay et al., 2002). The study by Sorensen & Hoffmann (2003), also reported that the static compression strength of moulded paper tray was significantly affected by moisture absorbed or dissipated and decreased with increased moisture.

When comparing the maximum compression strength values obtained from the experimental study with the buckling loads obtained from the finite element model for both MK4 and MK6 packages. There was a good agreement between the numerical values and the experimental values. Although the model predicted lower values, the difference with experimental values was about 4.7% and 8.2% for MK4 and MK6 packages respectively. The difference observed between the experimental and the numerical results may be due to the fact that the model assumed the package material to be perfectly bonded together. However, in reality, this is not the case.

6.4.3 Effect of package design on compression bruising of apples

Mechanical damage due to compression during handling and storage can result from overfilling, allowing too great a product depth or if a package is not strong enough to support package stacked on top of it (Opara & Pathare, 2014; Sharma & Nautiyal, 2009; Kader, 2002). Package dimensions and fruit volume must be matched carefully to avoid overfilling. The results in Figure 6.11 shows the total apple bruise area and volume for MK4 and MK6 package designs, after being subjected to a compression load. Apple bruising in the MK6 package design was observed to be more than the MK4 package design for both bruise area and volume. The bruise area in the MK6 package was about 94% higher than the bruise area in MK4 package. Similarly, a higher bruise volume of about 56% was observed in MK6 package when compared to MK4 package. There was a significant difference in the total apple bruising between the different package design (MK4 and MK6) for the bruise area and the bruise volume. MK4 package had 21% of non-bruised apples while MK6 package had 16% of non-bruised apples (Figure 6.12). The maximum compression strength of MK4 package design filled with apple fruits shown in Figure 6.13 was observed to be higher than MK6 package with about 18%, although there was no significant difference observed. This indicated the ability of the MK4 package to provide more protection to the fruit during handling and storage than the MK6 package. More bruise damage observed in the MK6 package can be attributed to the low compression strength of the filled package with apple fruit. Minimising bruising due to compression ensures the quality of the fruits (Opara & Pathare, 2014). The results obtained can be used by designers of packaging materials, processing plants and handlers of apple fruits to reduce mechanical damage, especially due to compression (Babarinsa & Ige, 2012).

6.4.4 Effect of fruit position inside the package on apple bruising

A spatial variation of bruising was observed between the two package designs (MK4 and MK6). Figure 6.14 shows the result of the bruise area and the bruise volume of the corresponding tray positions inside MK4 and MK6 packages. A significant difference was observed between tray A and tray D (bottom and top trays respectively), for both package designs. The bruise area and volume for both package designs decreased from the top tray (tray D) to the bottom tray (tray A). The spatial bruise damage in MK6 package was observed to be higher than MK4 package. The bruise area at tray D in MK6 package was about 200% more than MK4 package while the bruise volume at tray D in MK6 package was about 140% more than MK4 package.

6.4.5 Package damage

An ideal and good package should be able to protect the product by minimising mechanical damage. Compression damage to horticultural products are mostly caused by improper packaging and inefficient package performance triggered by; package over-packing, too high stacking and weak packaging. A subjective evaluation of both package designs (MK4 and MK6) was done after the compression test of the filled packages. For both package designs, there was a visible damage on the packages (Figure 6.15). Although the trays were cracked in both package designs, it was observed that the trays absorbed energy due to compression thereby minimising the damage to the apple fruit. Therefore, reducing the damage on the package and the apple fruit packed inside requires that the load on the package be kept below the maximum compression strength.

6.5 Conclusion

This research investigated the compression strength of two ventilated corrugated paperboard (VCP) packages (MK4 and MK6 package designs) numerically and experimentally. Furthermore, apple bruise susceptibility was investigated under compression load inside the package. Compression tests on empty packages were performed at two different environmental conditions; standard condition (23℃ and 50% RH) and refrigerated condition (0℃ and 90% RH). The reliability of the model was validated by experimental data. The difference between the numerical and experimental values was about 4.7% and 8.2% for MK4 and MK6 packages, respectively. The compression strength for both MK4 and MK6 packages decreased in strength with 16% and 11% respectively as the environmental condition was changed from standard to refrigerated condition. A high correlation was observed between change in weight and compression strength of both package designs. Apple fruit inside MK6 package incurred more bruise damage than the apple fruit inside MK4 package with a difference of about 64% and 44% in bruise area and volume respectively. It can be concluded from this research that the type of package have a great effect on the bruise damage incurred by the apple fruit. This research provides possible guidelines to packaging designers in minimising the mechanical damage due to compression.

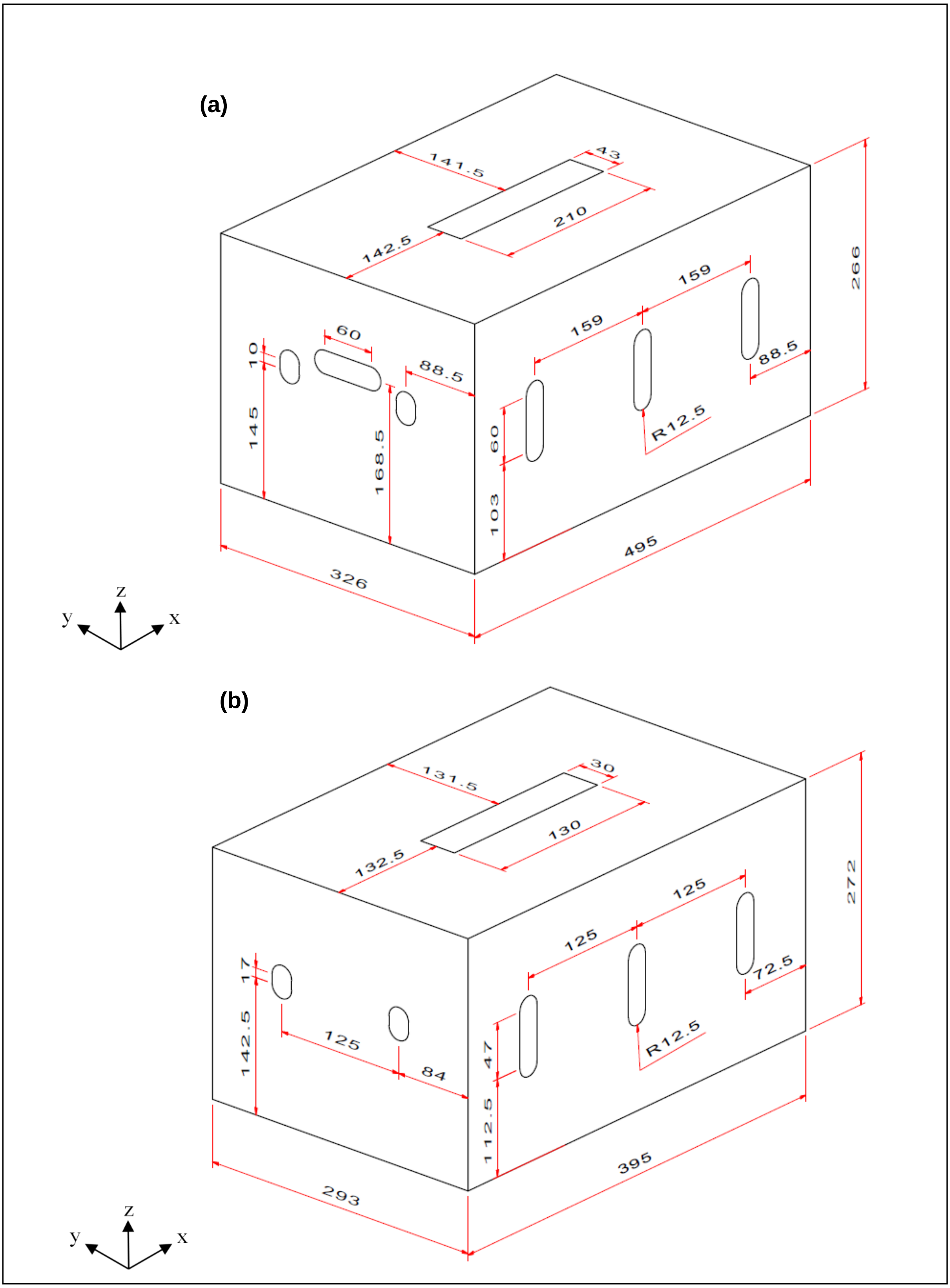
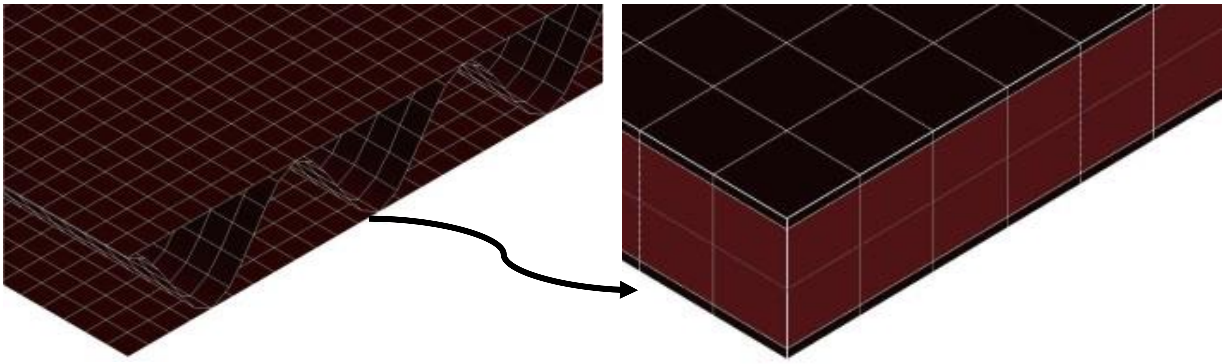


Figure 6.1: Geometry and dimensions of the (a) MK4 and (b) MK6 packages in mm.

Table 6.1: Physical and material properties of the liner and flute used in the ventilated corrugated paperboard package.

	Thickness (mm)	Elasticity Modulus (MPa)		Poisson's Ratio	Shear Modulus (MPa)
		MD	CD		
Liner	0.355	2194	359	0.34	565
Flute	0.289	2160	456	0.33	1890



Detailed **Composite**

Figure 6.2: Finite element modelling approach.

Table 6.2: Equivalent core stiffness.

A	Theoretical value	D	Theoretical value
$\mathbf{A_{11}}$	$\dfrac{E_{11}t}{1+6(1-\nu_{12}\nu_{21})\left(\dfrac{f^2}{t^2}\right)\left(\psi^2-\dfrac{\psi}{2\pi}\sin(2\pi\psi)\right)}$	$\mathrm{D}_{\mathbf{11}}$	$\dfrac{E_1t^3}{12(1-\nu_{12}\nu_{21})}\psi$
$\mathbf{A_{22}}$	$E_2t\psi$	D_{22}	$\dfrac{E_1t^3}{12(1-\nu_{12}\nu_{21})}\psi+\dfrac{1}{2}E_2tf^2$
$\mathbf{A_{12}}$	$\nu_{12}\mathrm{A}_{11}$	D_{12}	$\nu_{12}\mathrm{D}_{11}$
$\mathbf{A_{33}}$	$G_{12}\dfrac{t}{\psi}$	D_{33}	$G_{12}\dfrac{t^3}{12\psi}$

where ψ is the wave number (flute length per liner length), t is the corrugated sheet thickness, f is the amplitude of the flute.

Table 6.3: Material properties for the three layers used for the FEA.

	Liner	Core
Elasticity modulus (MD) (MPa)	2194	644
Elasticity modulus (CD) (MPa)	359	588
Poisson's ratio	0.34	0.362
Shear modulus (MPa)	565	1432
Thickness (mm)	0.355	3.835

Figure 6.3: Packaging types used (A) Tray arrangement inside MK4 Package; (B) MK4 Package; (C) Tray arrangement inside MK6 Package; (D) MK6 Package.

Figure 6.4: Lansmont compression tester.

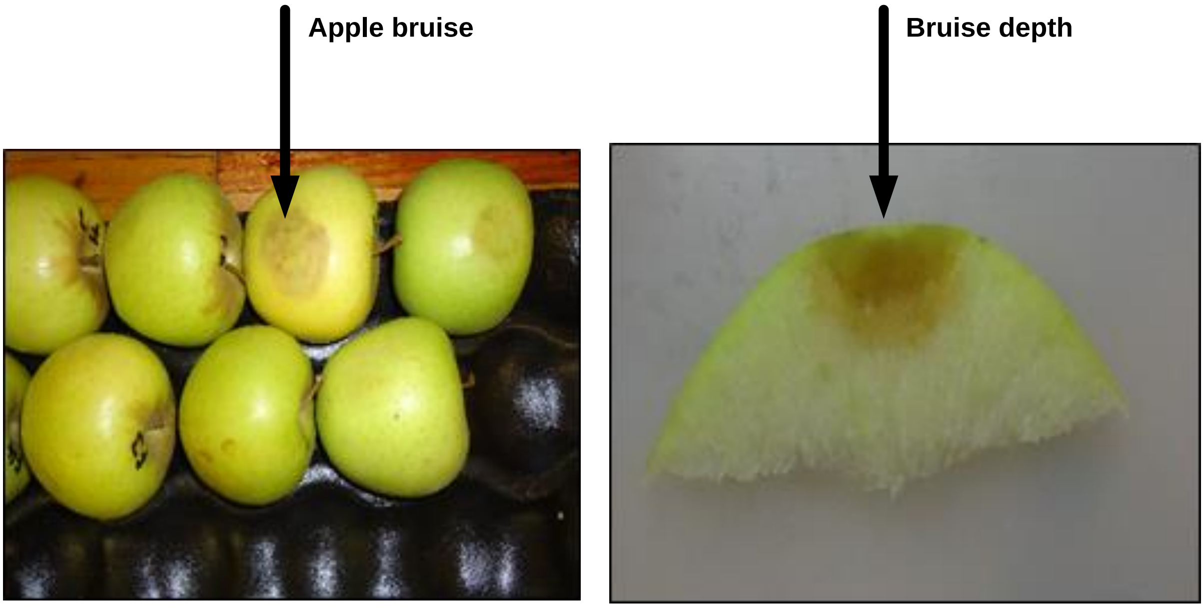


Figure 6.5: Typical bruising on apple after compression.

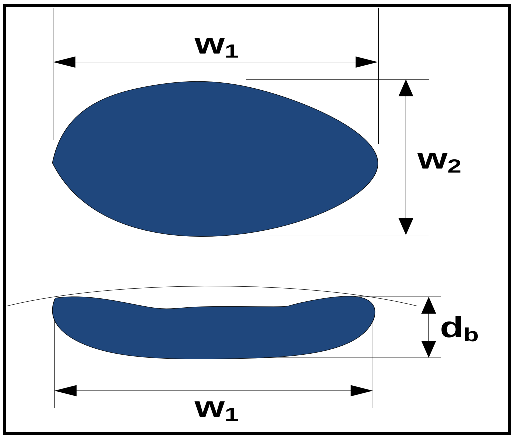
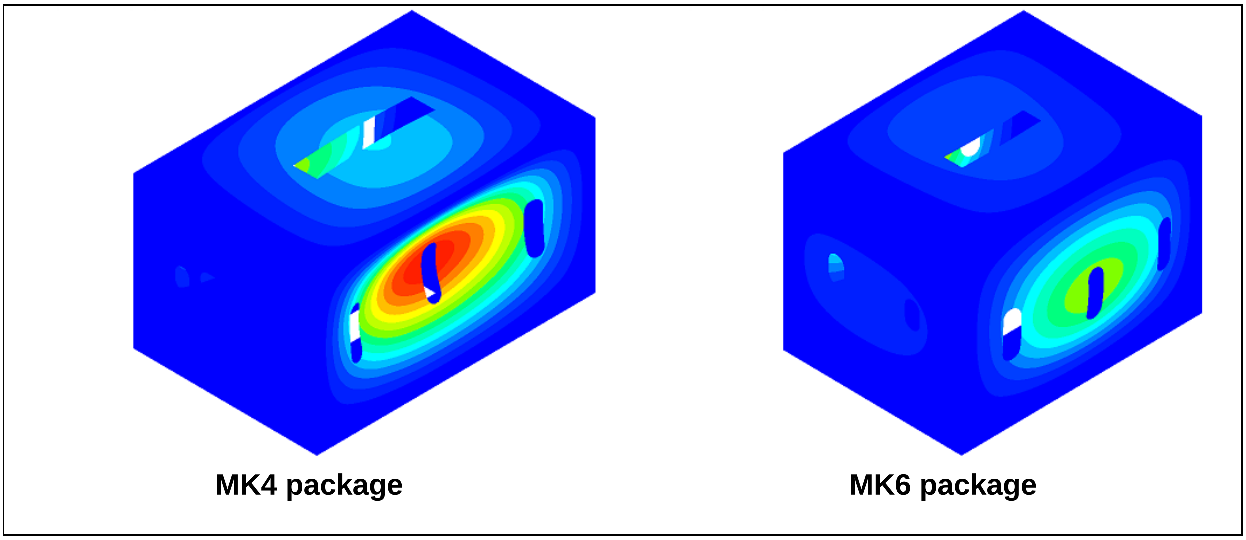


Figure 6.6: Elliptical bruise thickness method for bruise determination.



MK4 package

MK6 package

Figure 6.7: Buckling location on the packages.

Table 6.4: Maximum compression strength of the empty package in Newton (N)

	Standard condition (23℃ and 50 RH)	Refrigerated storage condition (0℃ and 90 RH).
MK4 package	6240.85 ± 160.96^{b}	5254.31 ± 152.11^{c}
MK6 package	6965.48 ± 124.04^{a}	6231.75 ± 146.69^{b}

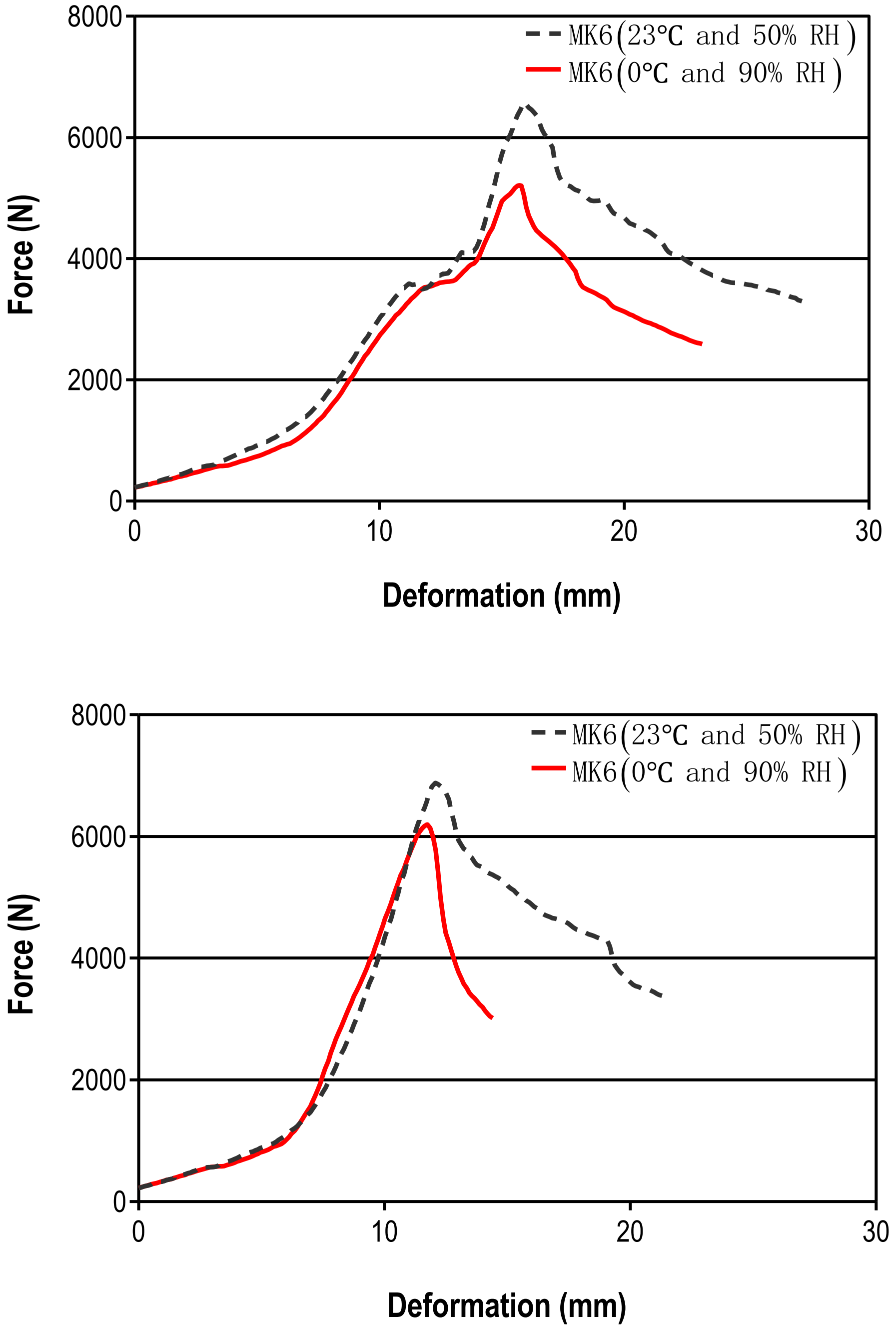


Figure 6.8: Typical force–deformation curve for both package designs.

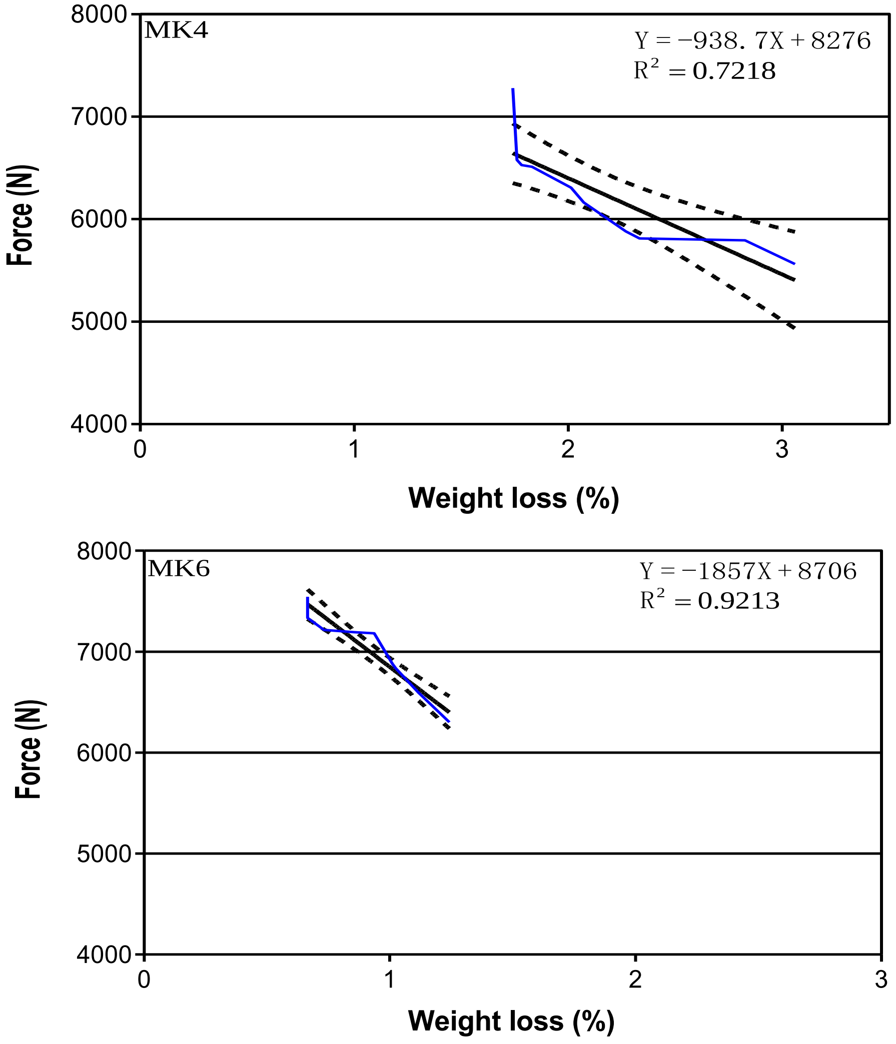
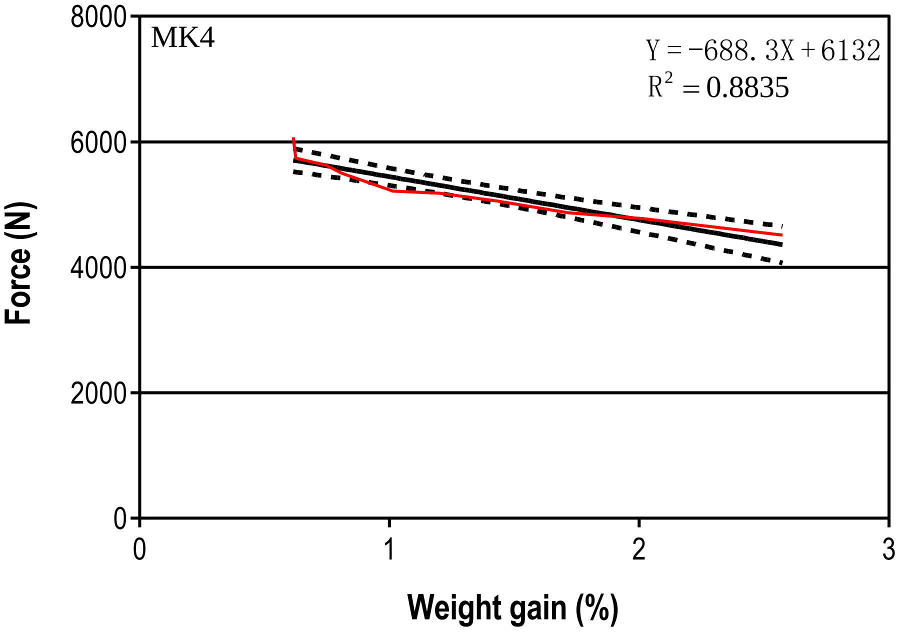


Figure 6.9: Environmental condition effect on compression at 23℃ and 50% RH resulting to a weight loss in the package and the two dotted lines represents 95% confidence interval. The solid black line shows a curve fitting.



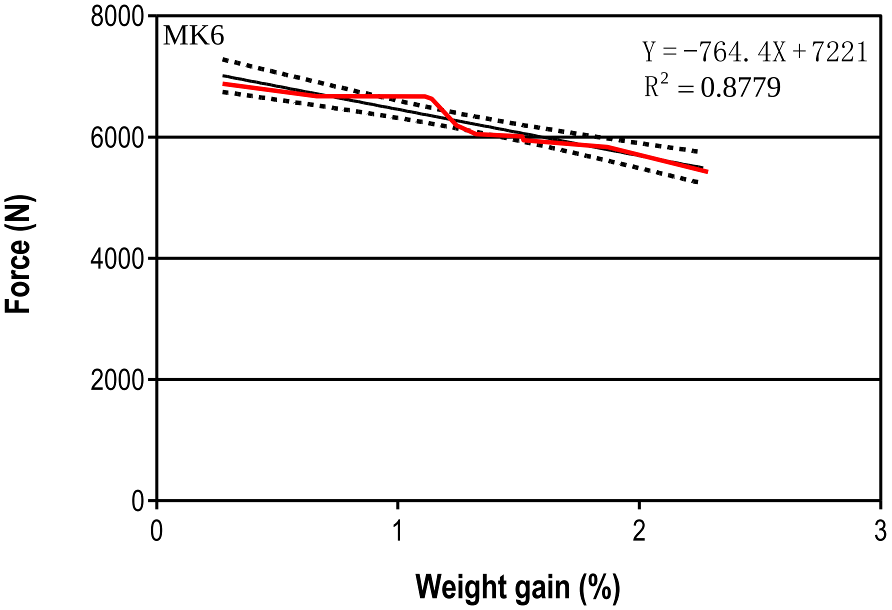


Figure 6.10: Environmental condition effect on compression at 0℃ and 90% RH resulting to a weight gain in the package and the two dotted lines represents 95% confidence interval. The solid black line shows a curve fitting.

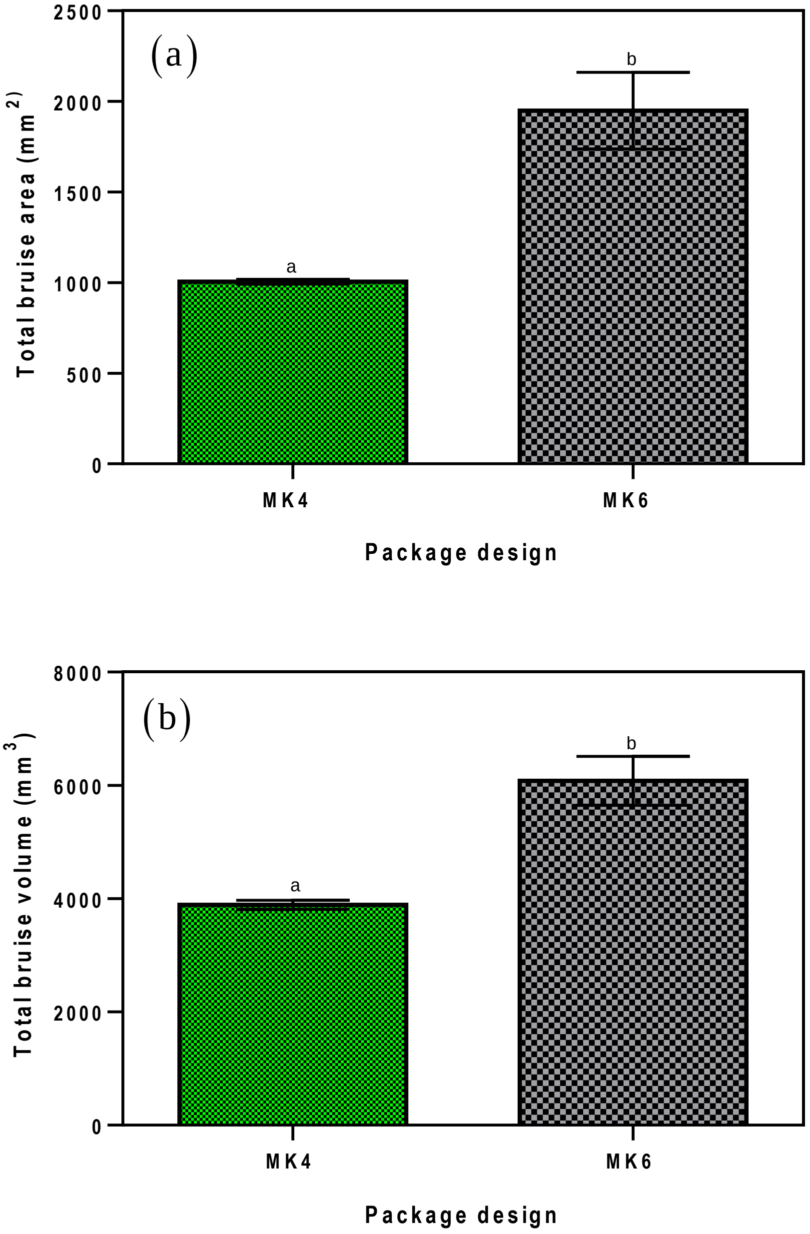


Figure 6.11: Total apple bruising (a) Bruise area (b) Bruise volume.

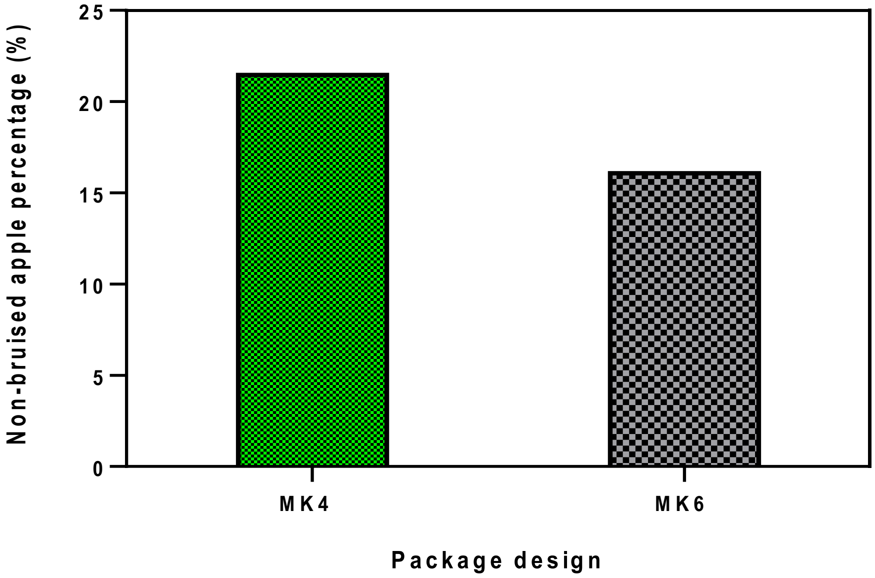


Figure 6.12: Non-bruised apples.

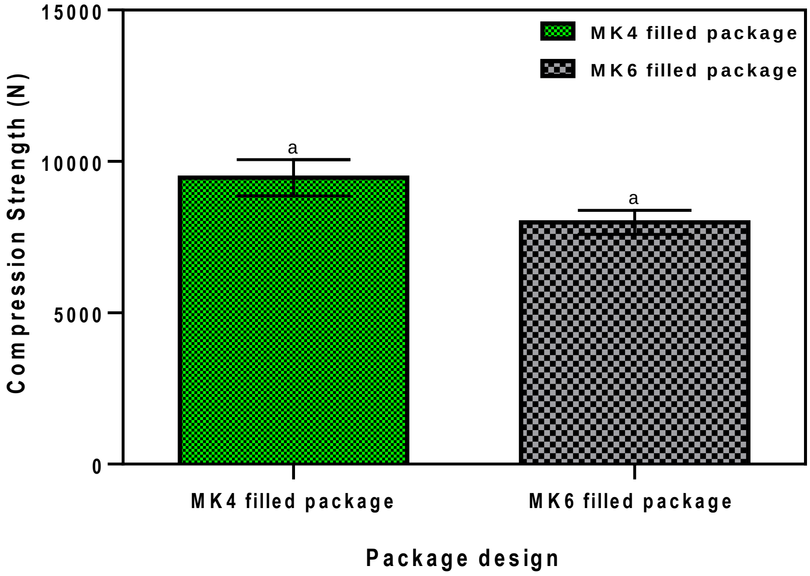


Figure 6.13: Compression strength of package filled with apple fruit.

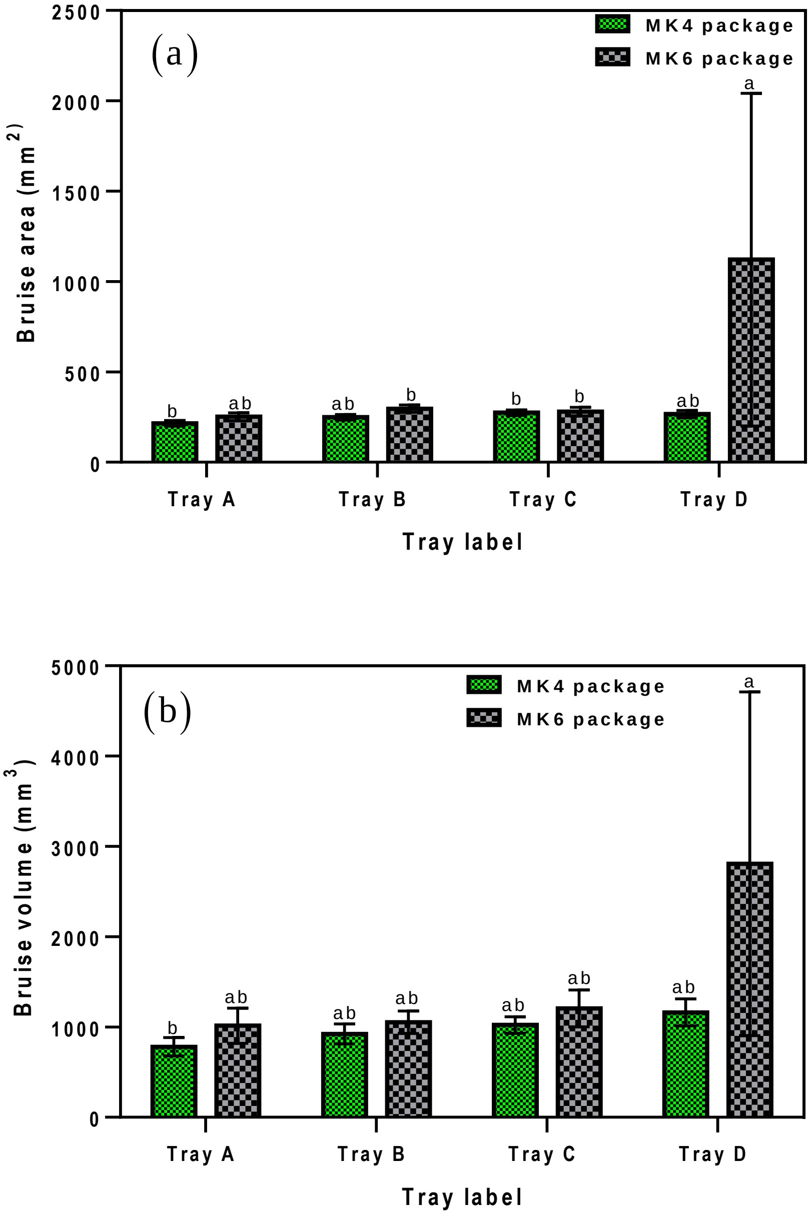


Figure 6.14: Spatial variation of bruise inside the different package designs (a) Bruise area (b) Bruise volume.

Figure 6.15: Package damage after compression.

Chapter 7 Numerical investigation on the effects of design parameters on the strength of ventilated corrugated paperboard packages

Keywords: Ventilated packaging, buckling load, vent, FEA

Abstract

Ventilated corrugated paperboard packaging are used for transporting fresh horticultural produce through a distribution system that requires the packages to maintain adequate airflow between the surroundings and the inside of the packages. The packages protect the packaged produce from mechanical damage due to impact, drop, compression and vibration loads. Due to the presence of vent holes on the packages, the mechanical integrity of the packages are compromised. This research was initiated to investigate the buckling behaviour of two designs of ventilated corrugated paperboard packages (Bushel MK4 and MK6) using finite element analysis (FEA). The model was applied to study the effects of vent height, shape, orientation, number and area. With an increase in vent area from 2% to 7%, buckling load decreased by 8% for the MK4 package and by 12% for MK6 package. 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 also showed that vent number, orientation, and shape affected the buckling of the packages. Rectangular vent holes better retained the strength of the packages compared to circular vent holes for both MK4 and MK6 packages. Irrespective of the vent design parameters studied, MK6 package had higher buckling load than MK4 package. The results obtained will enable package designers develop better and more efficient packages. To optimise vented packages, there is a need to balance studies on the mechanical strength with airflow distribution inside the packages.

7.1 Introduction

The role of packaging in the postharvest handling and distribution of fresh and processed food is very crucial (Pathare & Opara, 2014; Pathare et al., 2012). Packaging protects the packaged product, facilitates transportation and storage of the products as well as advertises the packaged product (Marsh & Bugusu, 2007). Paperboard packages have been used extensively and forms part of a continually growing food packaging industry (Beldie et al., 2001). However, in supply chain journey, these packages are exposed to static and dynamic loads (Singh et al., 2009). The internal pressure of the package within a stack and the pressure from the surroundings result in the static loads while shock and vibration experienced during transportation lead to the dynamic loads (Beldie et al., 2001). Any of these loads or a combination can lead to damage on the package and the packaged produce (Pathare & Opara, 2014).

Corrugated paperboard is a sandwiched structure comprising of a corrugated core called fluting and two facing liners (Figure 7.1). 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 (Figure 7.1) (Talbi et al., 2009; Biancolini, 2005). Corrugated paperboard is used for the production of shipping containers due to its economical and efficient material characteristics (Talbi et al., 2009; Han & Park, 2007). Ventilated corrugated paperboard packaging is widely used in postharvest handling of fresh horticultural produce due to the ability to promote rapid and efficient cooling with a minimal amount of internal packaging material (Thompson et al., 2010; De Castro et al., 2005). 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 configurations of the vent holes such as the size, shape and location, which must be taken into consideration to enhance cooling while still providing sufficient mechanical strength (Pathare et al., 2012; Émond & Vigneault, 1998).

During transportation and storage, stacking packages on top of each other causes the bottom package to experience the highest load. Therefore, the bottom package must possess adequate and sufficient compression strength for withstanding the load without collapsing (Daxner et al., 2007). Improving the package designs continually have resulted in better packages which in turn provides better protection to the packaged produce. However, optimal package designs remain a challenge in the packaging industry (Biancolini et al., 2005). It is therefore crucial to optimise the packages to increase the strength and essentially safe money and resources (Biancolini & Brutti, 2003).

The formula developed by McKee (1963) and experimental procedures have been a lasting contribution to the design of corrugated paperboard packages. However, the need for a more accurate prediction of the compression strength of corrugated paperboard packages has led to the use of finite element analysis (FEA). FEA has been considered as a possible tool to replace the tedious, time consuming experimental analysis of package strength (Delele et al., 2010). The top to bottom compression strength of a corrugated paperboard box was studied by Pommier & Poustis (1989) using a linear elastic finite element analysis. The authors found that the numerical analysis was in agreement with experimental values. The mechanical behaviour of paperboard packages subjected to static compression load was studied by Beldie (2001) using FEA. The authors modelled the paperboard as an orthotropic, linear elastic-plastic laminate. Results in the study showed that the low stiffness of the upper and lower corners of the package led to the low initial stiffness of the package. In another study by Biancolini & Brutti (2003), FEA was used to investigate the buckling behaviour of corrugated paperboard packages. The reliability of the FEA was checked by experimental studies and good agreement was found.

Han & Park (2007) investigated the design parameters such as vent holes on corrugated paperboard boxes using FEA. Different designs of vent holes were studied by considering the stress distribution and stress levels on the package. The authors concluded that vertical oblong-shaped vent holes, symmetrically placed within a certain distance to the left and right from the centre is the most appropriate shape. Furthermore, the FEA simulation of the study revealed a strong agreement with laboratory experiments. Singh et al. (2008) reported that rectangular or parallelogram vertical openings better retained the mechanical strength of a package in comparison with a circular opening. However, in contrast, Jinkarn et al. (2006) concluded that the mechanical strength of a package was least reduced by circular openings. The objective of this research was to apply the validated FEA model reported in Chapter 6 of this thesis to investigate the effects of vent geometrical design parameters on the strength of two ventilated corrugated paperboard packages commonly used in the South African fresh fruit industry, usually referred to as Bushel MK4 and Bushel MK6. The design parameters examined included vent height, shape, orientation, number and area.

7.2 Materials and their properties

Two ventilated corrugated paperboard packages used for apple packaging, Bushel MK4 and MK6, were selected (Figure 7.2). The inside of both package designs consist of four pulp trays where the apple fruit are placed carefully with the flower stalk axis horizontal and in the same direction in the moulded pockets of the trays. The corrugated paperboard used for the package was a single wall of type “C” flute. Other flute types are A, B, E and F flutes. The corrugated paperboard used for manufacturing the packages is made from Kraft paper with a paper grammage of 250 $\mathrm{g/m^2}$ for both inner and outer liners and a paper grammage of 175 $\mathrm{g/m^2}$ for the flute (corrugated medium).

7.3 Finite element modelling

In order to accurately model the corrugated paperboard, the numerical simulation must be able to accurately represent the physical model. The package was modelled as a composite structure consisting of three layers where a solid core was created (Figure 7.3). The equivalent core and liner properties used for the model are shown in Table 7.1. The finite element analysis was performed with the commercial code SimXpert/Nastran (MSC Software Corporation, California, USA). The bottom of the package was completely constrained while a uniformly distributed load was applied at the top of the package. A constraint was applied at the top of the package to allow translation in the z-direction while preventing translation in the x and y directions. Rotation was allowed about the x-axis in the direction of the length of the package and about the y-axis in the direction of the width of the package. Linear quadratic elements were used for the box compression test (BCT) model and the boxes were oriented properly so as to capture the actual pattern of the paperboard of liners and the core. A linear buckling analysis was performed on the BCT model in order to determine the most likely buckling shape and estimate the critical buckling load. The validated model of the original package in Chapter 6 of this thesis was applied to study the effects of vent height, shape, orientation, number and area on the strength of the packages.

7.4 Simulation results

7.4.1 Effect of vent height on the strength of packages

The effect of the height of vent holes was studied, maintaining the vent area of the original packages (MK4 and MK6) and keeping the vent area and location on the width intact. An increase in length of the vent holes resulted in a decrease in the buckling load. Typical buckling location of the longest and the shortest vent holes studied are shown in Figure 7.4. A strong correlation was observed between the length of the vent holes and the buckling load with R^2 values of 0.8215 and 0.9717 for MK4 and MK6 packages respectively (Figure 7.5). As reported in the study by Han & Park (2007), the appropriate length of the vent holes should be less than a quarter of the depth of the package and that the ratio of width to length of the vent holes should be from 0.29 to 0.4. Reducing the height of the vent hole below a quarter of the depth for the MK6 package increased the buckling load obtained for the original MK6 package by 3.8%. However, for the MK4 package a reduction of about 0.5% was observed. This can be attributed to the fact that the ratio of the width to length of the vent height did not satisfy the aforementioned condition reported by Han & Park (2007).

7.4.2 Effect of vent shape on the strength of packages

The effect of vent shape (circular and rectangular) on the strength of both MK4 and MK6 packages was studied by changing the oval vent shape on the length side of the original packages, maintaining the vent area and keeping the vent holes on the width side intact. The buckling location is shown in Figure 7.6. The circular vent holes on the MK4 package reduced the buckling load of the package when compared with the original package by 4.2 N, indicating a 0.07% reduction, while for the MK6 package, there was a decrease of 47.3 N, indicating a 0.7% reduction. The result is in agreement with a study by Jinkarn et al. (2006) where the authors compared the effect of different vent shapes on the compressive strength of corrugated board panel and found that circular openings resulted in the least reduction in compression strength. It is important to consider the cooling effects of vent shape on the cooling of fruit inside the packages. The apple fruit on middle trays will be cooled faster than the top and bottom trays because the air will be concentrated in the middle of the package. The vent holes on the package should be able to provide a uniform airflow distribution (De Castro et al., 2004b).

The length and width of the rectangular vent hole studied was determined by retaining the width-to-length ratio of the original package for both MK4 and MK6. This ratio was within the limits recommended by Han & Park (2007). The authors suggested that the ratio of width-to-length of the vent hole should range from 0.29 to 0.4. The rectangular vent hole on the long side of the MK4 package (maintaining the vent area of the original package) increased the buckling load of the package by 176 N, indicating a percentage increase of 3%, while for the MK6 package the strength increased by 429 N, indicating a percentage increase of 7%. The result obtained was in agreement with the study by Singh et al. (2008). The authors reported that the shape of vent hole is critical in the loss of strength of the package. It was concluded that rectangular vent hole oriented in a vertical position better retained the strength of the package when compared to circular vent hole.

The design of vented packages to maintain a balance between the mechanical integrity of the package and adequate airflow distribution inside the package is crucial (Pathare et al., 2012). Previous studies have shown that the shape of vent holes plays a less significant role in the cooling efficiency of horticultural produce (Delele et al., 2013; Pathare et al., 2012; Baird et al., 1988). Furthermore, Delele et al. (2013) observed a slightly lower pressure drop with the rectangular vent hole when compared with the circular vent hole with no significant effect of the shape of vent holes on the cooling rate and temperature uniformity. The reported differences on the impacts of vent shape on the mechanical integrity and cooling performance of ventilated packages highlights the need for optimal design approaches which integrates both performance criteria, including cost-effectiveness.

7.4.3 Effect of vent orientation on the strength of packages

The effect of vent orientation was studied by positioning the original vertically aligned oval vent holes at $45°$ and $0°$ (oriented horizontally) on the length side of the packages. The buckling locations on vent holes oriented at $45°$ and $0°$ (oriented horizontally) on the length side of the original MK4 and MK6 packages used in this research are shown in Figure 7.7. An increase in buckling load was observed for both package designs when the vent holes were oriented at $45°$, which means that the packages were more resistant to compression load. The buckling load for MK4 package increased by 62.1 N, an increase of about 1% when compared with the buckling load of the vertically oriented oval vent hole on the original package. For the MK6 package, the buckling load increased by 150 N, an increase of about 2% when the vent holes were oriented at $45°$. In contrast to the study by Han & Park (2007), who reported that vertically oriented oval vent hole is the most appropriate, this study showed a slight increase in strength when the vent holes were oriented at $45°$. When the vent holes were oriented horizontally, a decrease of about 4% in the buckling load was observed for the MK4 package while the buckling load increased with 6.5% for the MK6 package when compared with the buckling load of the vertically oriented oval vent hole on the original package. The decrease observed in the MK4 package as compared to the increase in the MK6 package, may be attributed to the length of MK4 package (495 mm) which is longer than MK6 package (395 mm).

7.4.4 Effect of vent number on the strength of packages

The buckling location for 1, 2 and 4 vent holes on the long side of the package are shown in Figure 7.8. For a constant vent area when compared with the original package with 3 vent holes (Figure 7.2), the buckling load increased with one vent hole by about 6.3% and 7.7% for MK4 and MK6 packages, respectively. However, there was a decrease in buckling load when the vent hole was increased to two of about 6.2% and 1.3% for MK4 and MK6 packages, respectively. An increase of about 91 N (1.4%) in the buckling load was observed when the vent hole was increased to four for the MK6 package. However, MK4 package had a reduction in buckling load of about 13 N, indicating a percentage reduction of 0.2% when compared with the original packages with three vent holes. Although the package with one vent hole had the highest buckling load, the uniformity in cooling will be compromised as the packaged produce will not be properly cooled. Studies have shown that airflow uniformity increased with vent number (Delele et al., 2013; Dehghannya et al., 2011; De Castro et al., 2005). Furthermore Delele et al. (2013) reported that the temperature uniformity inside the package increased with an increase in vent number. A study by Thompson et al. (2008) recommended that the vent holes should be placed 60 – 70 mm away from the edge of the package to maintain the mechanical strength of the package. Also, increasing the number of vent holes results in the use of relatively small vent holes which can cause blockage of vents by the packaged produce (Delele et al., 2013; Dehghannya et al., 2011).

7.4.5 Effect of vent area on the strength of packages

Vent areas of 2, 3, 4, 5, 6 and 7% of the length side of the packages were evaluated. The buckling load decreased with an increase in vent area (Figure 7.9). The buckling load for the smallest vent area was 6237.70 N, indicating a percentage increase of about 5%, while the buckling load for the largest vent area was 5736.10 N, indicating a percentage decrease of about 4% for the MK4 package. For the MK6 package, the buckling load for the smallest vent area was 6880.90 N, indicating a percentage increase of about 8%, while the buckling load for the largest vent area was 6059.10 N, indicating a percentage decrease of about 5%. The buckling location for the smallest and largest vent holes studied for both package designs are shown in Figure 7.10. A linear relationship was observed between buckling load and ventilation area with R^2 values of 0.9786 and 0.9863 for MK4 and MK6 packages respectively. A similar trend was observed by Singh et al. (2008) who reported a linear relationship between the total area of the vent holes and reduction in buckling load.

Furthermore, the mechanical resistance of the package as well as protection to the packaged produce is dependent on the percentage of ventilation area on the wall surface of a package (Pathare et al., 2012; Vigneault & Émond, 1998). Concurrently, the percentage of ventilation openings is an important factor that affects the cooling efficiency of a package (Pathare et al., 2012; De Castro & Vigneault, 2005). Delele et al. (2013) and Dehghannya et al. (2011) observed a uniformity in cooling airflow inside a package with an increase in vent area. In the 2-D model of ventilated package for vent areas 2.4, 7.2 and 12.1% conducted by Dehghannya et al. (2011), the authors concluded that the highest vent area exhibited the lowest cooling heterogeneity while for the lowest vent area, the highest cooling heterogeneity was observed. However, excessive vent area could compromise the mechanical strength of the package. Delele et al. (2013) observed no significant difference in the cooling time when the vent area was increased from 7% to 9% and from 7% to 11%. The authors concluded that increasing the vent area above a certain value does not necessarily increase cooling rate of the packaged produce, rather the mechanical strength of the package could be compromised. Therefore, a proper package must be designed in such a way as to provide adequate mechanical support to the packaged produce (Vigneault & Émond, 1998), consequently enhancing cooling efficiency and maintaining uniform airflow distribution inside the package (Pathare et al., 2012).

7.5 Conclusion

A validated finite element analysis model of two ventilated corrugated paperboard packages used in the South African fresh fruit industry (Bushel MK4 and MK6) was applied to study the effects of vent design parameters. The effects of vent height, shape, orientation, number and area were analysed. An increase in vent height and vent area reduced the strength of the package. Increasing the vent height on the length side from 66 to 166 mm reduced the buckling load by 7% for MK4 package, while increasing the vent height from 52 to 172 mm for MK6 reduced the buckling load by 22%. Increasing the vent area of the length side from 2% to 7% of the total wall surface area, the buckling load reduced by 8% and 12% for MK4 and MK6 packages respectively. When compared to the buckling load of the original packages with oval vent holes, the rectangular vent holes better retained the strength of the package as compared to circular holes with an increase in buckling load of 3% and 7% for MK4 and MK6 respectively. Vent holes oriented at 45° increased the buckling load by 1% for MK4 package and 2% for MK6 package. A 4% decrease in buckling load occurred for MK4 package with vent holes oriented horizontally, while the buckling load increased with 6.5% for the MK6 package. Packages with two and four vent holes had a reduced buckling load. The results obtained from this research indicated the increasing potential of finite element analysis to enhance optimisation of ventilated corrugated paperboard packages. This can assist package designers develop more efficient packages that will balance the need for adequate mechanical strength and provide optimum airflow inside the package.

Figure 7.1: Structure of a corrugated paperboard.

Table 7.1: Material properties for the three layers used for the FEA.

	Liner	Core
Elasticity modulus (MD) (MPa)	2194	644
Elasticity modulus (CD) (MPa)	359	588
Poisson’s ratio	0.34	0.362
Shear modulus (MPa)	565	1432
Thickness (mm)	0.355	3.835

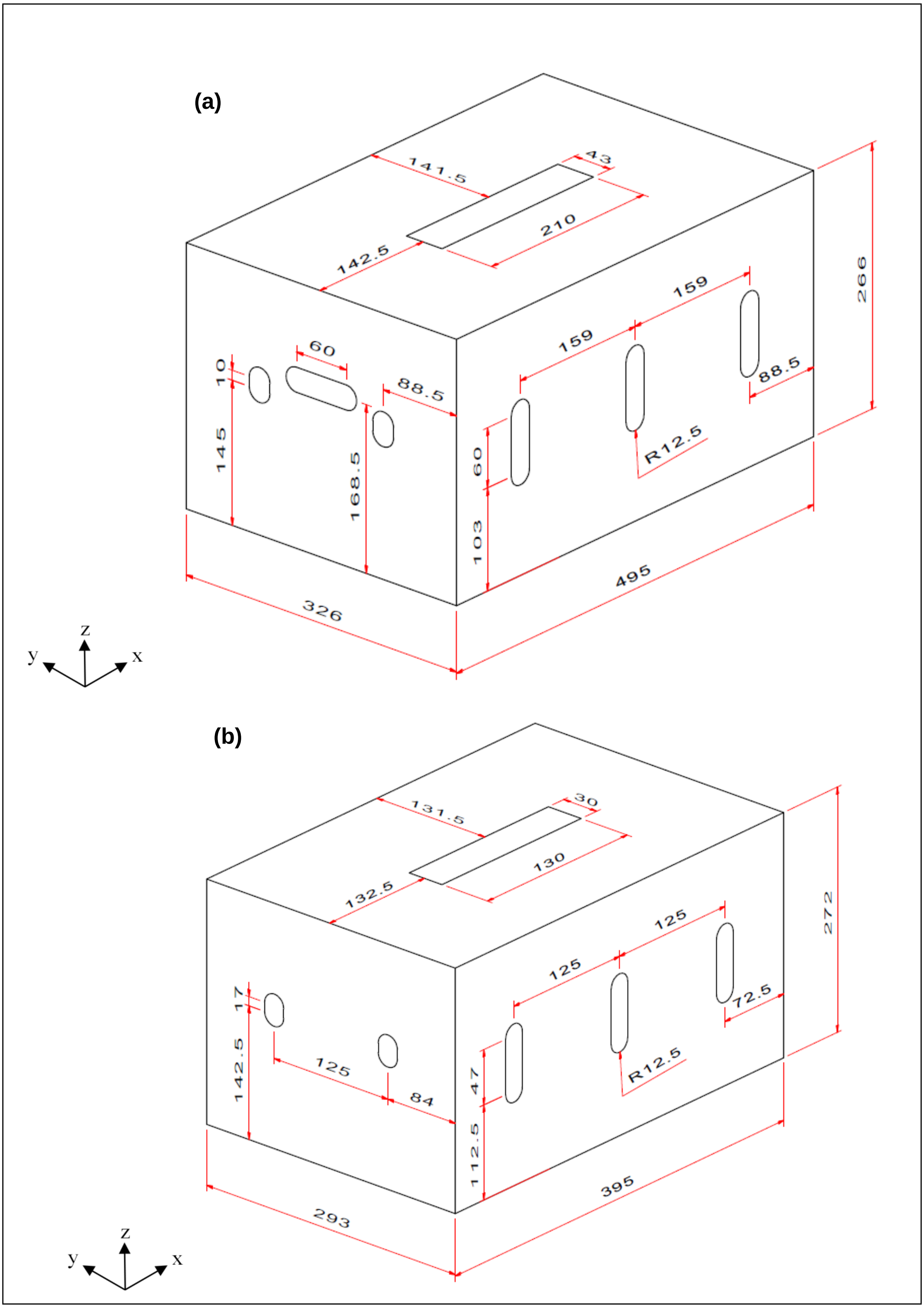
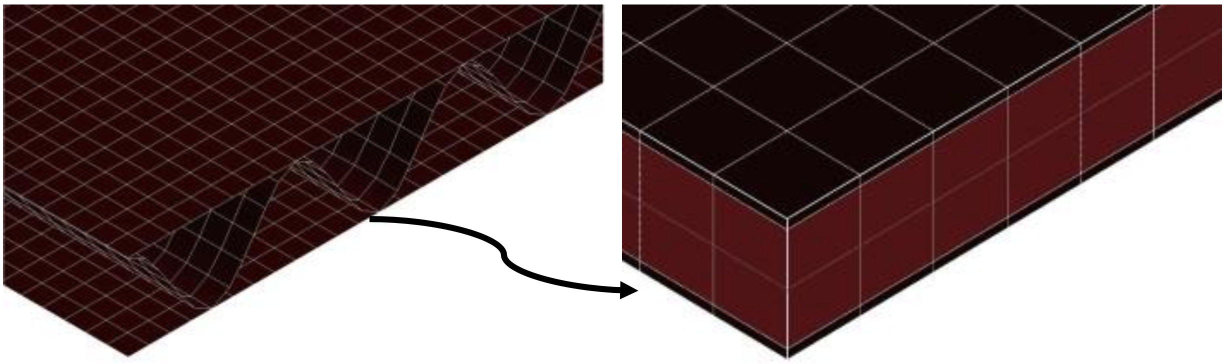


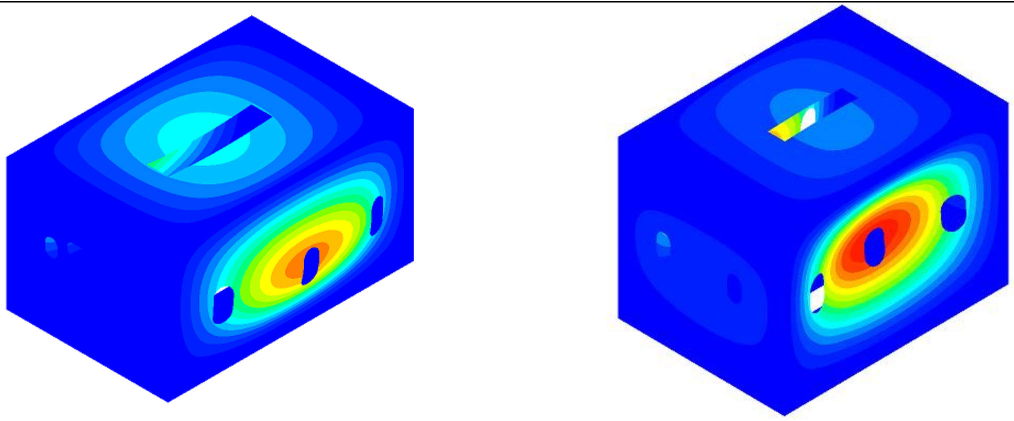
Figure 7.2: Geometry and dimensions of the (a) MK4 and (b) MK6 packages in mm.



Detailed

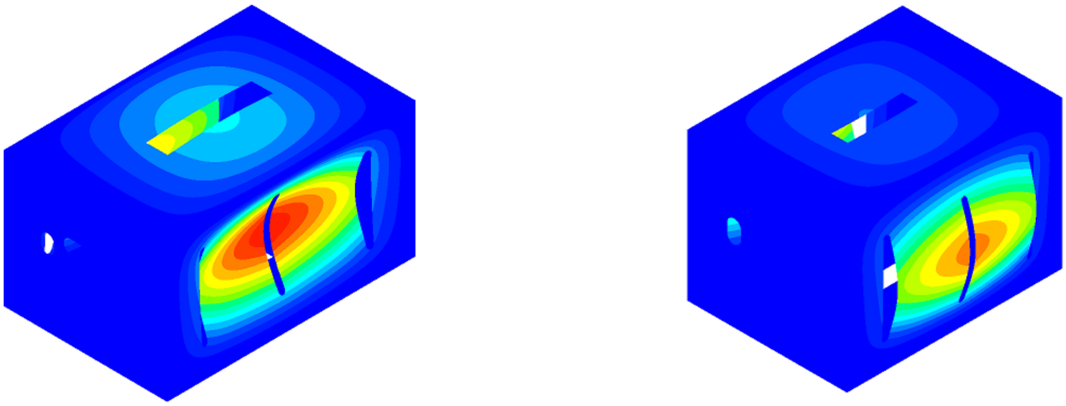
Composite

Figure 7.3: Finite element modelling approach.



MK4 shortest vent height (66 mm)

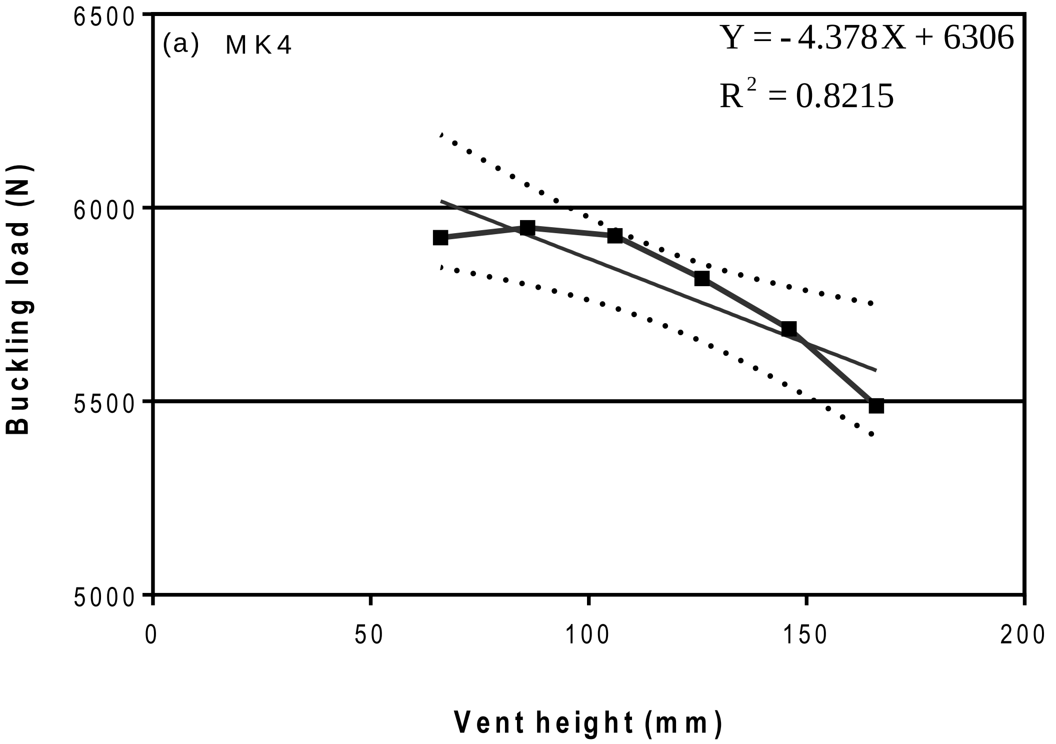
MK6 shortest vent height (52 mm)



MK4 longest vent height (166 mm)

MK6 longest vent height (172 mm)

Figure 7.4: Typical buckling location for the shortest and longest vent heights studied.



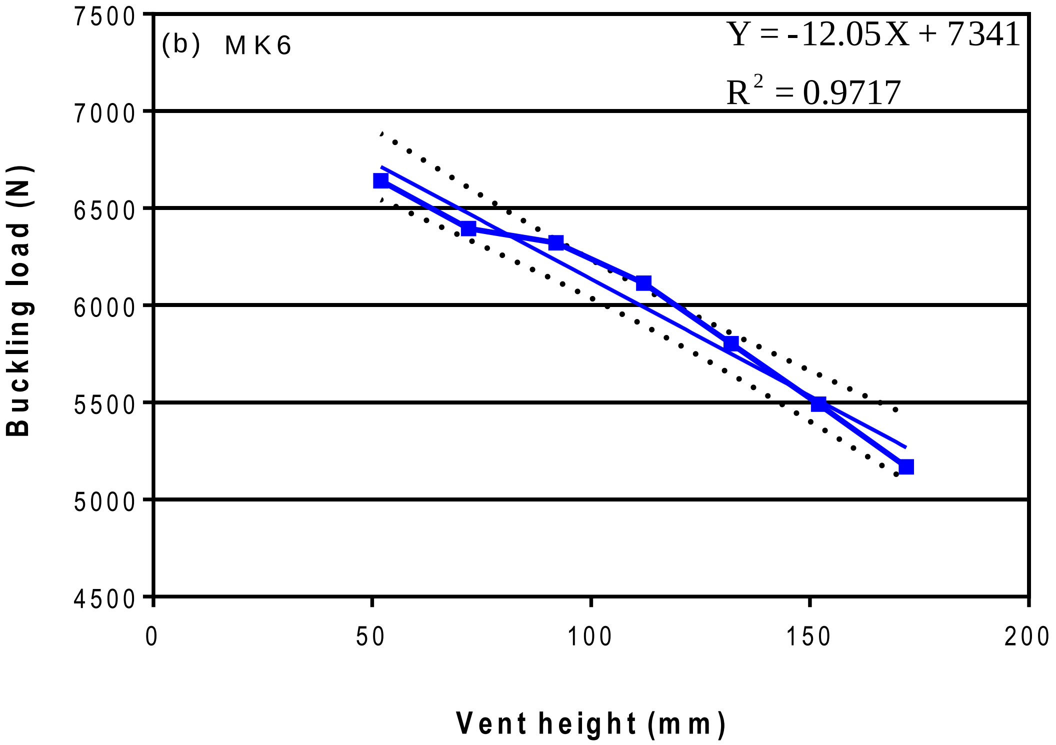
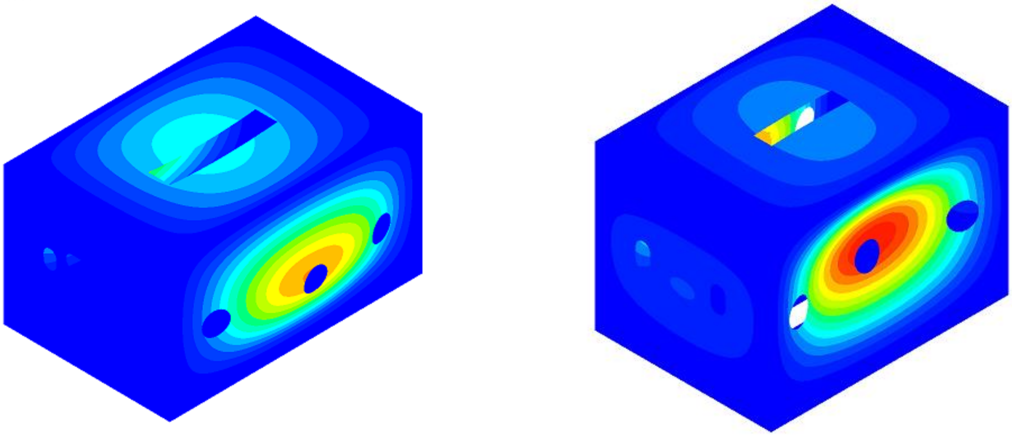
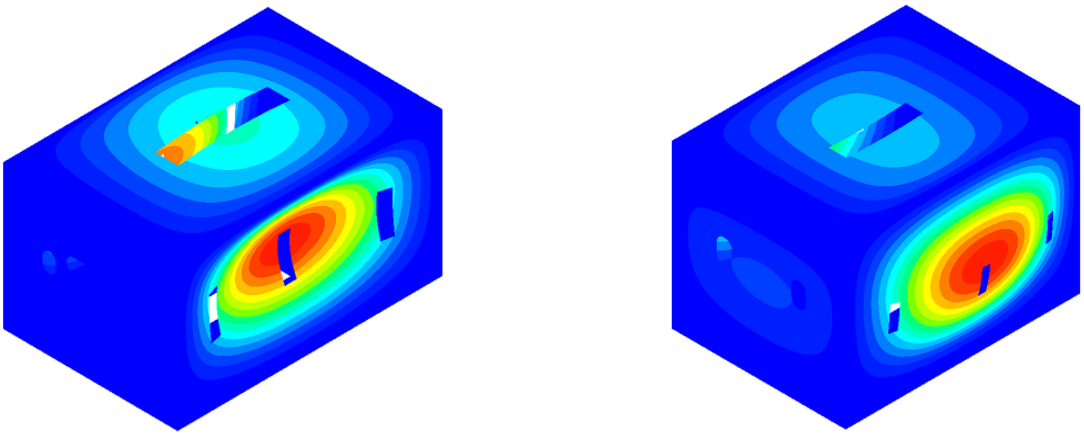


Figure 7.5: Effect of vent height on buckling load, for the (a) MK4 package and (b) MK6 package and the two dotted lines represents 95% confidence interval. The solid straight lines show a curve fitting.



Circular ventilation holes for MK4

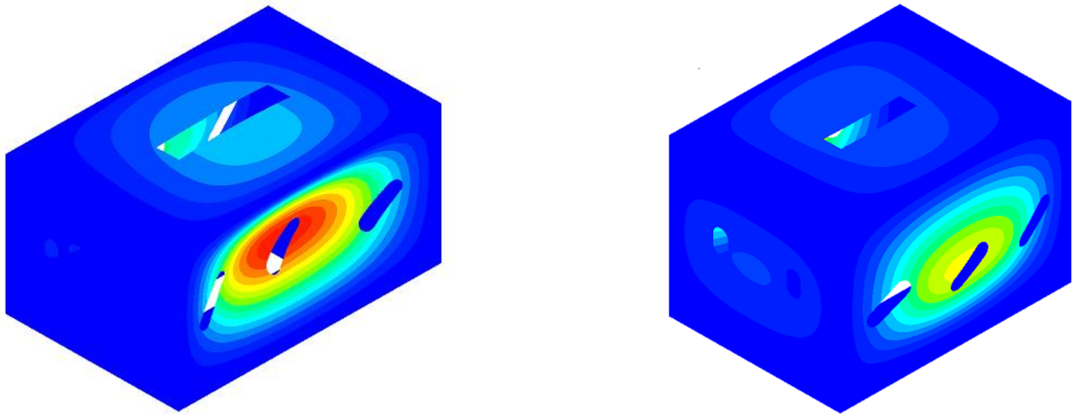
Circular ventilation holes for MK6



Rectangular ventilation holes for MK4

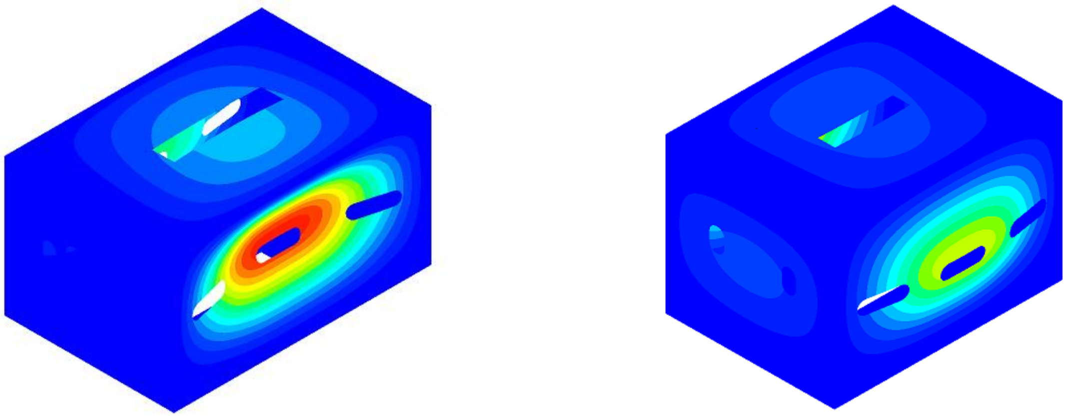
Rectangular ventilation holes for MK6

Figure 7.6: Buckling location for different vent shapes.



Vent holes oriented at 45° on MK4 package

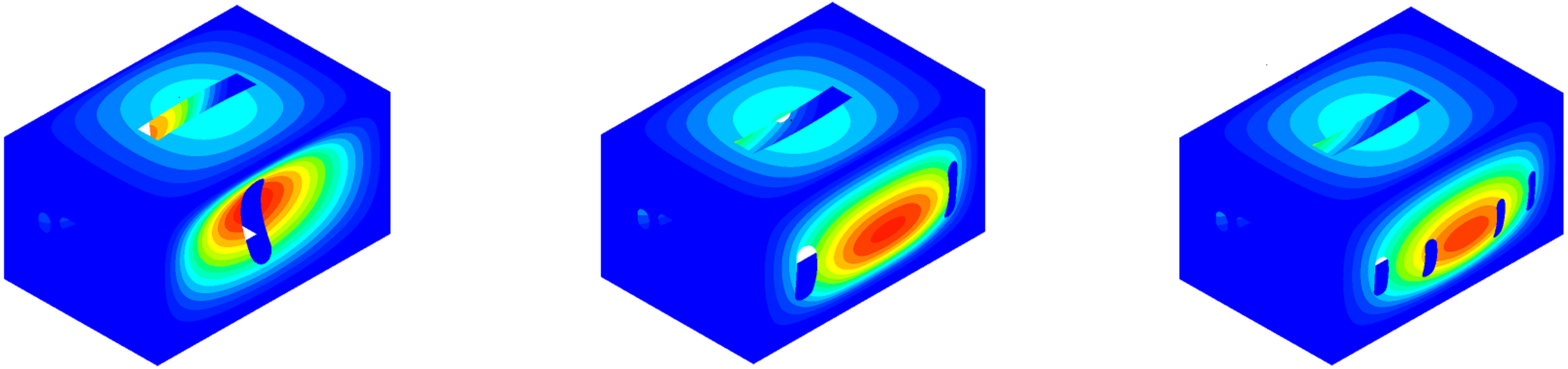
Vent holes oriented at 45° on MK6 package



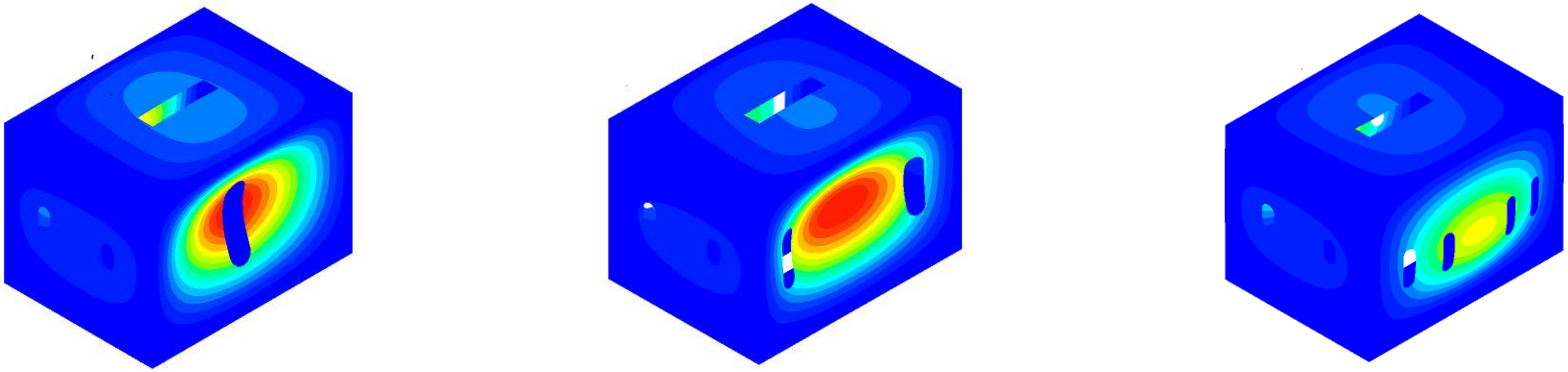
Vent holes oriented at 90° on MK4 package

Vent holes oriented at 90° on MK4 package

Figure 7.7: Ventilation holes oriented at different angles.

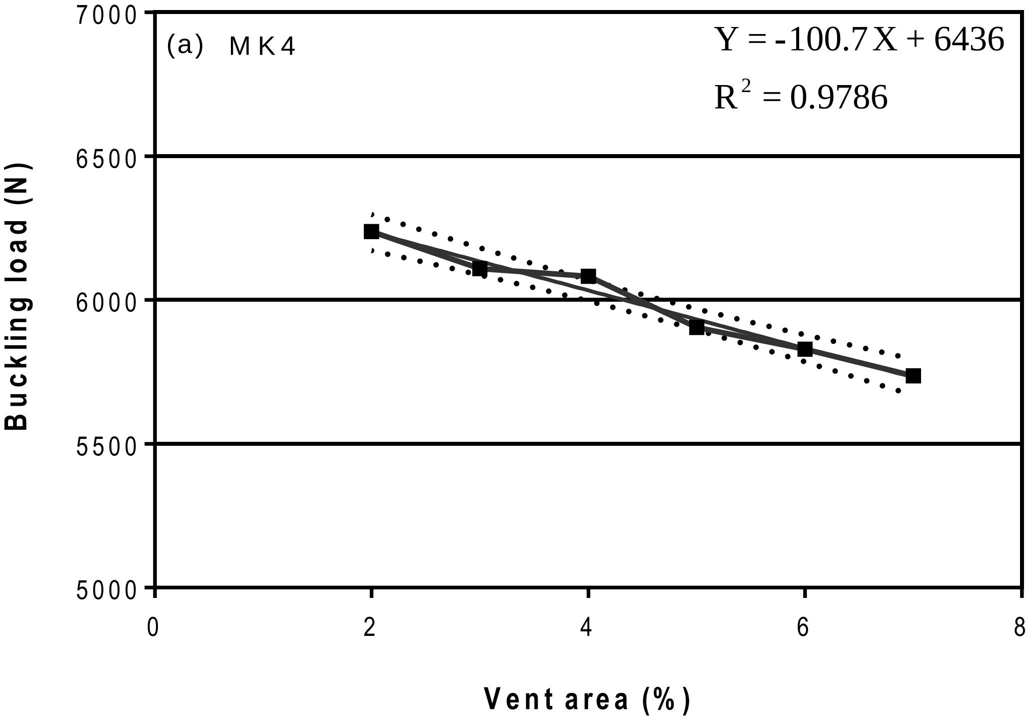


MK4 package with one vent hole **MK4 package with two vent holes** **MK4 package with four vent holes**



MK6 package with one vent hole **MK6 package with one vent hole** **MK6 package with one vent hole**

Figure 7.8: Buckling location for different number of vent holes.



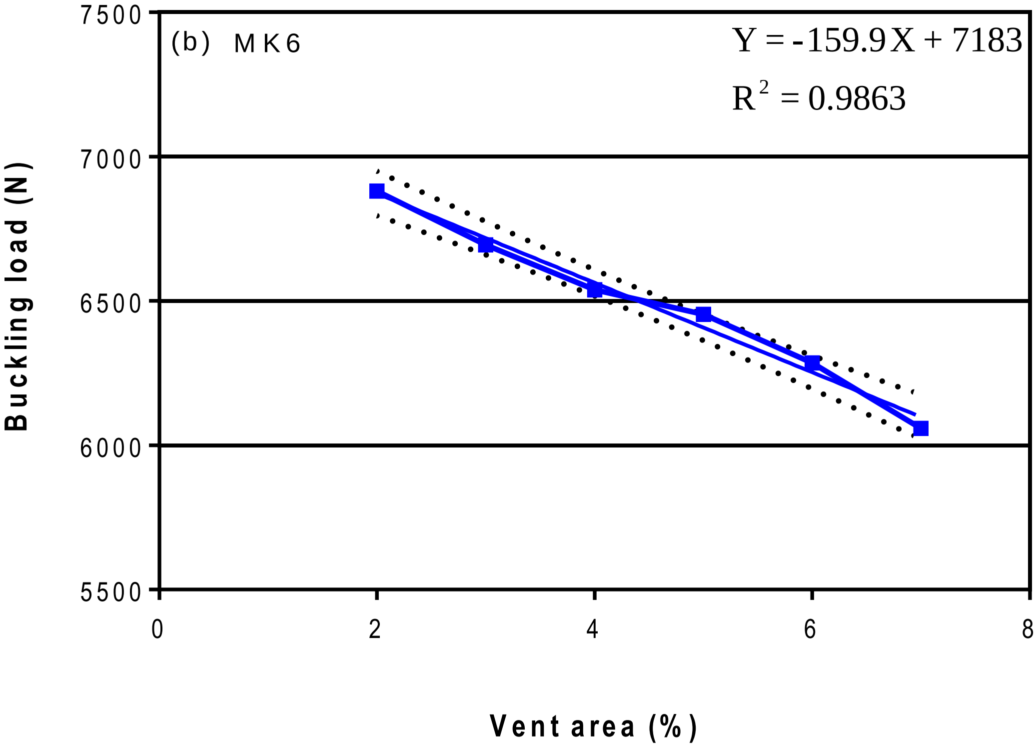
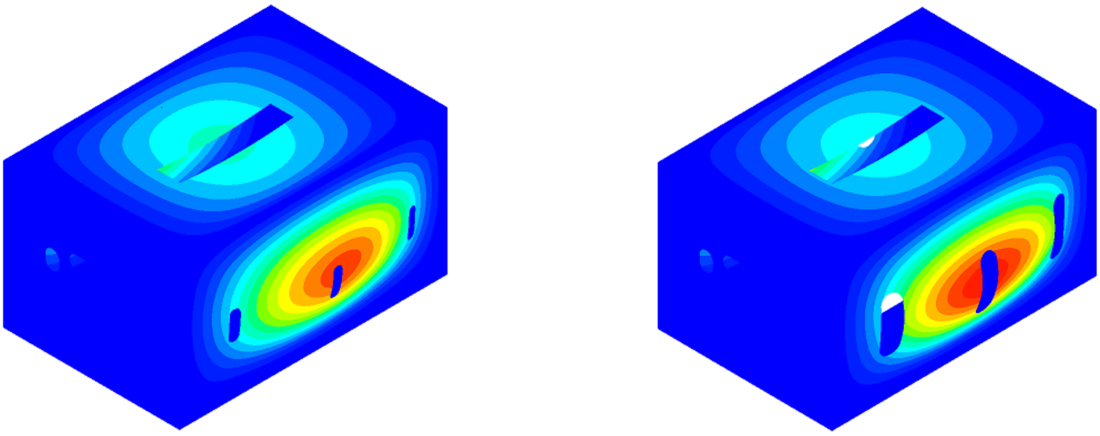
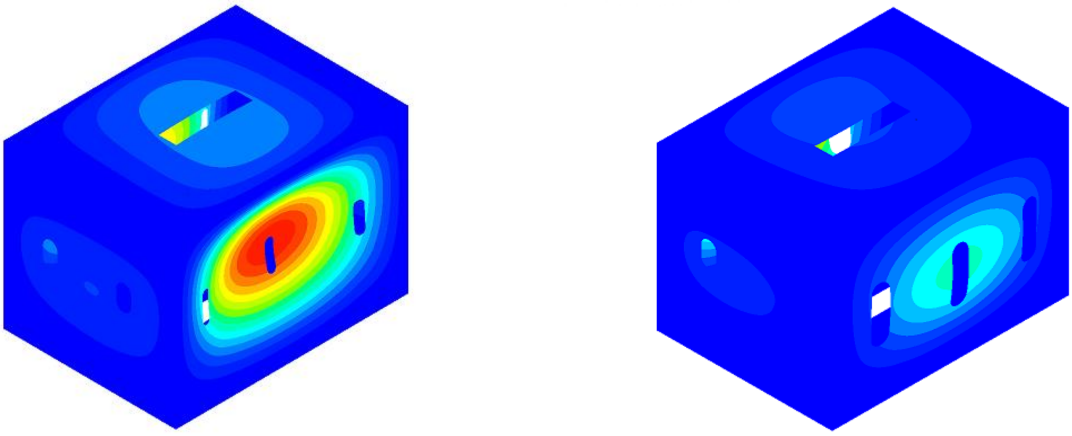


Figure 7.9: Buckling load for different ventilation openings and the two dotted lines represents 95% confidence interval. The solid straight lines show a curve fitting.



MK4 package at 2% vent area **MK4 package at 7% vent area**



MK6 package at 2% vent area **MK6 package at 7% vent area**

Figure 7.10: Bulking location at 2% and 7% vent area.

Chapter 8 General conclusion

The role of packaging is crucial in the postharvest handling and distribution of fresh and processed food and other biomaterials (Pathare et al., 2012). Packaging protects the packaged product from hazards that may arise during distribution and facilitates the transportation and storage of the product (Pathare & Opara, 2014; Jonson, 2000). Ventilated corrugated paperboard packages are used extensively for storage and transportation of fresh produce in horticultural industry due to the ability to promote rapid and uniform cooling (Thompson et al., 2010; De Castro et al., 2005).

During the postharvest journey, these packages are faced with hazards such as compression, drop, impact, and vibration which leads to mechanical damage on the package and the produce (Singh et al., 2009). Mechanical damage on horticultural produce becomes apparent as bruising and is the most common mechanical damage affecting the produce by reducing the quality to the end-users (Opara & Pathare, 2014), which consequently affects the purchasing price (Harker, 2009) and reduces the income for the fruit and vegetable industries (Opara & Pathare, 2014).

Therefore, a proper package design of ventilated packaging is paramount in maintaining a balance between uniform airflow distribution, efficient cooling and mechanical integrity of the package to offer adequate protection to the produce (Pathare & Opara, 2014). This research was aimed at developing a validated finite element model to assist in the mechanical design, and performance evaluation of fruit packaging by investigating the resistance of the packages to the forces they are subjected to and characterising the bruise susceptibility of the fruit inside the packages.

The South African fruit industry utilises various variations in apple package designs, majority of which make use of internal packaging. The susceptibility of apple fruit to impact damage on two ventilated corrugated paperboard (VCP) packages was evaluated by dropping MK4 and Econo package designs at heights 30 and 50 cm. Results obtained showed that both the incidence and susceptibility to bruise damage of the apples were affected by package design and drop heights. The apple fruit inside the Econo package had over 50% higher incidence and more than 66% higher susceptibility than the apple fruit inside MK4 package. This indicated that the energy being transferred to fruit in the MK4 package was less than the energy absorbed by fruit in the Econo package. Furthermore, drop heights had significant effect on the level of damage to the fruit as the damage increased with an increase in height irrespective of the package designs. The incidence and susceptibility of apple fruit to bruising increased significantly by about 50% when the package drop height increased from 30 to 50 cm. Results were in agreement with the study by Lu et al. (2012), who reported an increase in bruising as drop height increased. Impact damage was found to be significant at the bottom of both packages than at the top. Placement of force absorbing materials such as polypropylene foams or bubble wraps at the bottom of the package will reduce the bruise damage incurred by the fruit and also minimise economic loss of the fruit due to downgrading or rejection by consumers (Van Zeebroeck et al., 2007). Further research can be done on impact on the package strength by considering factors such as; impact due to forklift putting pallet down, momentums effect of forklifts acceleration on pallets and packages, and the straps binding packages together on pallets.

To better understand the performance of the VCP packages, a simulated transport study under laboratory conditions was used to assess the performances of two VCP packages; MK4 and MK6 package designs at three frequencies; 9, 12 and 15 Hz. The results obtained showed apple bruising in the packages were affected by package design and frequencies after four hours of excitation. Regardless of the package design, packaging transmissibility was more than 100%. This indicated that both package designs vibrated at higher acceleration level than the shaker. The MK6 package, at a frequency of 12 Hz had the greatest packaging transmissibility of 243%. This was within the most critical level of frequencies between 3 and 15 Hz reported by Vursavufi & Özgüven (2004) for a corrugated package with pulp trays containing apple fruit. The highest bruise area of the fruit was observed in the MK6 package at the frequency of 12 Hz where the packaging transmissibilty was greatest. Irrespective of the package designs, the top layer was prone to bruise damage. A similar trend was reported by Zhou et al. (2007) and Slaughter et al. (1993) on pears when subjected to vibration Therefore, the use of cushioning materials for both package designs can help in minimising bruising.

Further research was done on investigating the mechanical properties of the packaging material. Tensile properties of five paper grammages were determined at two different environmental conditions; standard condition (23℃ and 50% RH) and refrigerated condition (0℃ and 90% RH). For all paper grammages tested, a significant decrease in modulus of elasticity of up to 53% was observed at refrigerated condition when compared with the standard condition. A similar trend was observed by Allaoui et al. (2009). The authors reported that the elastic modulus of paperboard decreased with about 50% in the cross direction and about 30% in the machine direction, when the relative humidity was increased from 50% to 90%. This suggested that the presence of moisture in paper materials softens the material and changes the behaviour of the stress–strain curve of paper fibres by reducing the elastic modulus and tensile strength (Vishtal & Retulainen, 2012). The greatest modulus of elasticity was in the machine direction (MD). Edge compression test (ECT) value for the corrugated paperboard was obtained experimentally and numerically at both environmental conditions. Results obtained from the tensile test were used as input properties in the finite element model of the edge compression test. The finite element model of the corrugated paperboard could accurately predict the experimental value of the incipient buckling load with an error of 0.4% and 5.5% at the standard condition and refrigerated condition respectively. The ECT value can be used as an indicator to determine the quality of corrugated paperboard. In addition, ECT value is usually used to evaluate the compression strength of the corrugated paperboard in the direction of the fluting and its resistance to crushing (Pathare & Opara, 2014; Twede & Selke, 2005).

To better understand the performance of the VCP packages, the compression strength of two VCP packages; MK4 and MK6 package designs were studied numerically and experimentally. Material properties obtained from the tensile test were used as input properties in the FEA model. Empty packages were compressed at two environmental conditions, which were the standard condition (23℃ and 50% RH) and refrigerated condition (0℃ and 90% RH). Apple filled packages were subjected to compression load and the susceptibility of the fruit to bruise damage was determined. The FEA results were in good agreement with the experimental results with a difference of 4.7% for MK4 package and 8.2% for MK6 package. Results showed that the compression strength decreased by about 16% and 11% for MK4 package and MK6 package respectively, when the environmental condition was changed from standard to refrigerated condition. The decreased compression strength observed at the refrigerated condition may be attributed to the increased water content of the paper material which breaks the bond between the cellulose fibres (Allaoui et al., 2009). MK4 package provided more protection to the apple fruit than MK6 package with a difference of about 64% for the bruise area and 44% for the bruise volume. Irrespective of the package designs, more bruise damage occurred at the top layer inside the packages.

The validated model on the compression strength of the two VCP packages; MK4 and MK6 package designs was applied to study the effect of vent height, shape, orientation, number and area on the buckling load. Increase in vent height reduced the buckling load of the packages with R^2 values of 0.8215 and 0.9717 for MK4 and MK6 packages respectively. An increase in the vent area from 2 to 7% reduced the buckling load of MK4 package by 8% while for MK6 package by 12%. A strong correlation was observed between the vent area and the buckling load with R^2 values of 0.9786 and 0.9863 for MK4 and MK6 packages respectively. In relation to the buckling load of the original packages with oval vent holes, rectangular vent holes better retained the strength of the package as compared to circular holes with an increase in buckling load of 3% and 7% for MK4 and MK6 packages respectively. A similar observation was reported by Singh et al. (2008). Vent holes oriented at 45° increased the buckling load for both package designs. When compared with the three vent holes on the original package, packages with two and four vent holes had a reduced buckling load. Furthermore, more research on development of robust FEA model considering factors such as stacks of packages will help improve optimising the packages for better performance.

In conclusion, the study has provided better understanding of the mechanical performance under impact, compression and dynamic loads of the commonly used packaging designs in the South African fruit industry. The study has also demonstrated the potential of finite element analysis to enhance optimisation of the mechanical performance of ventilated corrugated paperboard packages. By combining this approach with computational fluid dynamics (CFD) analysis and modeling of the airflow, heat and mass transfer inside the package, the approach offers tremendous opportunities to simultaneously optimise the integrated performance of ventilated horticultural packages in maintaining the cold chain and protecting produce and package against physical damage.

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Appendix A: Corrugated core homogenisation

A.1 Briassoulis procedure

The Briassoulis procedure provides a way to approximate a sandwich structure as a homogeneous material. The stiffness matrix of a structure can be calculated if a function describing the sandwich pattern is known.

In this case the flute of the corrugated cardboard can be approximated as a sine wave (Biancolini et al., 2010). The ABD matrix of the laminate as well as the derivation of the individual properties was obtained as shown in Table 6.2. The material constants used are the properties of the flute material.

Due to the fact that the laminate is symmetrical, all the B_{ij} components are equal to zero. Once the ABD matrix is known, the laminate stiffness can be determined as shown by Gibson (2012).

$$A_{11} = Q_{11}t$$

$$A_{12} = Q_{12}t$$

$$A_{22} = Q_{22}t$$

$$A_{33} = Q_{33}t$$

$$D_{11} = \frac{Q_{11}t^3}{12}$$

$$D_{12} = \frac{Q_{12}t^3}{12}$$

$$D_{22} = \frac{Q_{22}t^3}{12}$$

$$D_{33} = \frac{Q_{33}t^3}{12}$$

Finally, the stiffness matrix can be used to calculate the equivalent material properties:

$$Q_{11} = \frac{E_x}{1 - v_{xy}v_{yx}}$$

$$Q_{12} = Q_{21} = \frac{v_{xy}E_y}{1 - v_{xy}v_{xy}}$$

$$Q_{22} = \frac{E_y}{1 - v_{xy}v_{yx}}$$

$Q_{33} = G_{xy}$

The x and y directions refer to the machine and cross directions, respectively.

A.2 Computer program

Matlab was used to calculate the equivalent properties as shown below:

```
%% Matlab Calculation of the equivalent core for the flute.
%% Equivalent flute properties calculation
clear all; clc
%% Flute material properties
E1 = 2.160*10^9;            % Elasticity Modulus (MD)
E2 = 456*10^6;              % Elasticity Modulus (CD)
G12 = 1.890*10^9;           % Shear Modulus
nu12 = 0.33;                % Poisson's ratio
nu21 = E2*nu12/E1;

%% Flute geometry properties
tliner = 0.000355;              % Liner thickness
t = 0.0003835 - 2*tliner;       % Flute thickness
f = t/2;                        % Amplitude
psi = 1.32;                     % Wave number used for the ‘C’ flute

%% Calculation of ABD matrix (Biancolini et al., 2010)
A = zeros(3);
A(1,1) = E1*t/(1 + 6*(1-nu12*nu21)*(f^2/t^2)*(psi^2-
psi/2/pi*sin(2*pi*psi)));
A(1,2) = nu12*A(1,1);
A(1,3) = 0;
A(2,1) = A(1,2);
A(2,2) = E2*t*psi;
A(2,3) = 0;
A(3,1) = 0;
A(3,2) = 0;
A(3,3) = G12*t/psi;

B = zeros(3);

D = zeros(3);
D(1,1) = E1*t^3*psi/(12*(1-nu12*nu21));
D(1,2) = nu12*D(1,1);
D(1,3) = 0;
D(2,1) = D(1,2);
D(2,2) = E2*t^3/(12*(1-nu12*nu21)+1/2*E2*t*f^2);
D(2,3) = 0;
D(3,1) = 0;
D(3,2) = 0;
D(3,3) = G12*t^3/12/psi;

%% Calculation of equivalent properties (Gibson, 2012)
nuxy = A(1,2)/A(2,2)
nuyx = A(1,2)/A(1,1)
Ex = A(1,1)*(1-nu12*nu21)/t
Ey = A(2,2)*(1-nu12*nu21)/t
Gxy = A(3,3)/t
```