

Corrugated packaging fea compression test engineering essay

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Abstract

Corrugated packages are used extensively for transporting and storing fresh produce in the horticultural industry. These packages are expected to protect products from various static and dynamic mechanical hazards such as drops, impacts, vibration and compression loads. The analysis and prediction of the stacking compression load capacity of corrugated packages is important to study the response of existing packaging to mechanical stress or to design new packages to meet postharvest handling conditions. Good design of vented packaging is important in optimizing the cooling and ventilation uniformity, minimizing quality deterioration of packed produce and maintaining the mechanical integrity of the package. Various experimental and modelling tools are used to investigate the design and mechanical performance of packaging. Experimental studies on mechanical performance of packaging include compression, impact and vibration analysis. Finite element analysis and simulation offers a useful tool for the study and mechanical design of ventilated packaging, taking into account factors such as the shape, location and size of the vent. Advances in information and communication technologies offer new prospects for development of user-friendly software toward integrated design and performance analysis of food packaging. Keywords: Corrugated packaging; FEA; Compression test; Drop test; Vibration test

Introduction

Packaging plays a critical role in the postharvest handling and distribution of fresh and processed food and other biomaterials (Opara, 2011; Pathare,

Opara, Vigneault, Delele, & Al-Said, 2012). Packaging has many other important functions, such as protecting the packaged goods from hazards including contamination in the distribution environment, facilitating transportation and storing of products, and carrying printed information and graphics (Hägglund& Carlsson, 2011). 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 (Castro, Vigneault, & Cortez, 2005; Thompson, Mejia, & Singh, 2010). Ventilation holes in the container maintain an air flow channel between the surroundings and the inside of the containers. This results in reinforcement of the preservation function of the containers (Han& Park, 2007). Vents allow the heat built up by respiration to escape. Ventilated packages should be designed in such a way that they can provide a uniform airflow distribution and consequently uniform produce cooling. The package must have enough vents to provide uniform airflow through the entire mass of produce while providing suitable mechanical resistance (Castro, Vigneault, & Cortez, 2004a; Vigneault& Goyette, 2002; Vigneault& Castro, 2005). A proper package vent design must consider not only the total vent area (Brosnan& Sun, 2001; Castro, Vigneault, & Cortez, 2004b; Smale, Tanner, Amos, & Cleland, 2003; Stanley, 1989), but also the size and the position of each vent to enhance the efficiency of forced air precooling system while still offering an adequate mechanical support for the produce (Vigneault& Émond, 1998). Recent review by Pathare et al. (2012) showed that effective package venting is essential to maximise the efficiency of cooling produce

during forced-air cooling. Corrugated boxes with vents are not as strong as unvented boxes. To minimize the loss in strength, vents should be located away from the vertical corners of the box and generally should not account for more than 5% total box wall area (Kader, 2002). Boxes with greater than 5% venting must be specially designed to provide adequate strength (Thompson, Brecht, & Hinsch, 2002). These studies show that cost-effective design of ventilated packaging for horticultural produce requires careful consideration of conflicting objectives; (a) maintaining the cold chain at high relative humidity, and (b) ensuring mechanical integrity of the package and resistance to impact and compressive loads. Packaging is one of the most important steps in the long and complicated journey of fresh horticultural produce from grower to consumer. Packing and packaging materials contribute a significant cost to the produce industry; therefore it is important that packers, shippers, buyers, and consumers have a clear understanding of the wide range of packaging options available (Pascall, 2010). The types of packaging used to package fresh horticultural produce are wood crates, corrugated shipping cartons polymeric films pouches, bags, baskets, crates, and trays; paper sheets, pouches, etc (Pascall, 2010). Corrugated paperboard can be referred to by many different terms such as corrugate, corrugated, and corrugated fibreboard is manufactured in many different styles and weights. It is the dominant produce container material and will probably remain so in the near future due to relatively low cost and versatility. The strength and serviceability of corrugated paperboard have been improving in recent years. Packages have to withstand significant compression loading conditions during carriage and storage (Viguié et al.,

2011) and corrugated paperboard packages are well known for their good stacking strength (when dry), easy availability and inexpensive cost (Twede & Harte, 2003). Corrugated paperboard is often considered to be the packaging material of the future, and has many advantages, including (Allansson & Svärd, 2001) Low weight. Saves money when transporting Can be entirely customised for the purpose It is strong and stiff compared to its weight Easy to handle Easy to print Recyclable A major drawback of corrugated paperboards is that they can lose much of their strength (indeed, all of its compression strength) when wet (Coles, McDowell, & Kirwan, 2003). Paper and paperboard-based packaging is widely used because it meets the criteria for successful packaging, such as to contain the product, protect goods from mechanical damage and preserve products from deterioration (Kirwan, 2005). Packaging qualities are identified based on several parameters i. e. compression strength, stiffness, tearing resistance, tensile strength, water absorbency and product safety. Factors that are known to influence corrugated paperboard box compression strength include the material properties, the board combining method, the box dimensions, manufacturing defects interior partitions, temperature, humidity, stacking/loading method and time (Twede & Harte, 2003). Several packaging researches had been conducted due to on material used for some fruits with high economic value. Corrugated paperboard is proven to have good properties for material packaging that reduced mechanical damage for apple (Jarimopas, Toomsaengtong, Singh, Singh, & Sothornvit, 2007) and mangosteen (Darmawati, Yulianti, Salokhe, & Soni, 2009; Sutrisno, Sugiyono, & Edris, 2010). In relation with fruits quality, mechanical damage affected

weight loss, firmness and TSS (Anwar, Malik, Amin, Jabbar, & Saleem, 2008; Çakmak, Alayunt, Akdeniz, Aksoy, & Can, 2010). Corrugated packaging plays an important role in the storage and transportation of horticultural fresh produce. The packaging impact a considerable cost to the horticultural industry so any cost savings that can made on packaging will increase the profitability. Cost savings could be made by reducing the quantity of material used in package providing adequate compression strength can be maintained. Design of corrugated box should comprise optimal combination of raw materials, optimal selection of prism type, optimization of overall design of box, and the cost control of packaging (Chen, Zhang, & Sun, 2011). Fresh horticultural packaging design to reduce its mechanical damage during distribution process and to test the packaging design to determine the packaging performance is important. As fresh horticultural produce cool storage and transport conditions provide one of the most demanding environments for corrugated packaging. Conventionally, a product reliability test to prevent impact-induced damage is carried out by a procedure of ' design - prototype - test - redesign' which is highly cost and time consuming. A numerical modelling of the product and its packaging provides an efficient methodology to predict the structural strength during impact (Djilali Hammou, Minh Duong, Abbès, Makhoulouf, & Guo, 2012). Finite element analysis (FEA) simulation offers a useful tool to the mechanical design of ventilated packaging, taking into account factors such as the shape, location and size of ventilated opening. FEA allows to avoid numerous experimental tests and to predict possible failures during the design stage (Djilali Hammou et al., 2012). Combining FEA and Computational fluid dynamics (CFD)

modelling offers a powerful tool for cost-effective ventilated packaging to meet the structural requirements of packaging and cold chain requirements of fresh horticultural produce. The objectives of fresh produce packaging are shelf-life extension, maintenance of natural colour, texture, flavour, and nutrients; reduction in moisture loss and subsequent wilting; limiting disease, infections and infestation; cushioning as a preventative measure against injury during handling and shipping; aid in processing, facilitating transport and help in labelling, advertisement, and marketing (Pascall, 2010). These packages are expected to protect the product from various static and dynamic hazards they experience such as drops, impacts, vibration, compression and climatic conditions. The article provides an overview of the application of corrugated paperboard packaging in the horticultural industry, and discusses the experimental and finite element modelling approaches used to investigate the mechanical design and performance analysis packaging.

Applications of Corrugated Paperboard in Horticultural Packaging – an overview

Corrugated cardboard is an orthotropic sandwich with the surface plies (facing) providing bending stiffness, separated by a lightweight bending core (fluting) that provides shear stiffness (Allaoui, Aboura, & Benzeggagh, 2011). The principal directions are the machine direction (MD), the cross-machine direction (CD), and the thickness direction (ZD). Due to the distribution of the fibres during forming of the sheet and the different drying strains in MD and CD, the MD is usually the stiffest and strongest direction (Stenberg, Fellers, & Östlund, 2001). It comprises a central paper (called the corrugating medium,

or medium) which has been formed, using heat, moisture and pressure, in a corrugated, i. e. fluted, shape on a corrugators and one or two flat papers (called liners) have been glued to the tips of the corrugations (Fig. 1). The ease of recyclability along with its high strength to weight ratio and high printability has made corrugated packages a prime choice for fresh produce packaging. As fresh produce has a rapid spoilage rate, rapid refrigeration is often required. To accommodate this need corrugated packages must be made to withstand frequent changes in temperature and humidity throughout the products lifecycle. The package may be exposed to several environments before arriving at its end use location. These environments include refrigerated storage, followed by rises in temperature and drops in humidity during transport before returning to refrigeration. These changes in temperature and humidity can take a drastic toll on the strength of the package and therefore are a top consideration during package design. Due to long term storage while stacked on pallets, corrugated packages must be made to withstand large amounts of compression forces for extended periods of time. When compressed for long periods, corrugated packages can experience fatigue, creep and even buckling. If the package fails in this manor, severe product damage can occur. To prevent this, the package must be designed with a focus on the vertical sidewalls. Since two-thirds of the packages total strength is derived from the vertical faces it is practical to add material in these areas rather than thickening the top or bottom horizontal faces. One important performance requirement is box stacking strength, which is a function of the edgewise compression strength and bending stiffness of corrugated fibreboard (Urbanik, 2001). Corrugated board

lost its compressive strength when subjected to distribution hazards such as high relative humidity, excessive stacking load, long term storage and uneven stacking pattern (Jinkarn, Boonchu, & Bao-Ban, 2006). Factors Affecting the Mechanical Properties of Corrugated Paperboard Packaging

Corrugated package performance requirements ranges from its appearance, to its mechanical strength and ability to protect its contents. Structure of corrugated board gives it a very high stiffness to weight ratio as well as a high strength to weight ratio. The overall strength and performance of a corrugated package are dependent on many factors, such as the engineering mechanical properties of the components (liner, medium, and adhesive), the manufacturing quality control protocol, machine precision, and the human factor involved in the corrugation process (Rahman & Abubakr, 2004). These properties give corrugated board considerable resistance to compressive forces from stacking and impacts, vibration and fluctuating atmospheric conditions. In order to improve the design and manufacture of corrugated board products, it is necessary to have a clear, technically sound understanding of the contributions of all of these factors to performance (Luo, Suhling, & Laufenberg, 1995). Various shipping and warehousing conditions should also be taken into consideration. These include high long-term compressive forces from stacking, vibrations, impacts, and adverse atmospheric conditions. Due to its structure, corrugated board is resistant to buckling and can be made to exhibit considerable stacking strength, making it an ideal choice for fresh produce industry. Depending on the requirements of a product, corrugated board can be manufactured to have higher compressive strength by adding layers

(Patterson, 2011). Structural performance of a corrugated package is the major factor in its success in the marketplace as shipping requirements have changed the paperboard market from one based on tonnage to one based on performance (Luo et al., 1995). The box compression strength (BCT) constitutes a general measure of the performance potential of a corrugated board package (Markström, 1999). Long term storage while stacked on pallets, corrugated packages must be made to withstand large amounts of compression forces for extended periods of time. When compressed for long periods, corrugated containers can experience fatigue, creep and even buckling. If the package fails in this manor, severe product damage can occur. To prevent this, the package must be designed with a focus on the vertical sidewalls. Since two-thirds of the packages total strength is derived from the vertical faces it is practical to add material in these areas rather than thickening the top or bottom horizontal faces. Knowing more about the fundamentals of compression strength at attributes will lead to higher product performance, which can either reduce the amount of material needed to obtain necessary performance or allow unique design features so that corrugated fibreboard can compete more favourably with other materials (Urbanik & Saliklis, 2003). The strength of corrugated board containers is crucial for preserving the content, while an optimization of corrugated board containers is essential to save money and resources (Biancolini & Brutti, 2003). Stackability is best measured using the box compression test. The strength considerations for cartons and containers are almost always related to stacking strength. The most common way to specify paper /paperboard is by basic weight or grammage (weight per unit area).

Basis weight can play a large role in stacking strength, flexibility, and ultimately cushioning properties. Higher basis weights result in stiffer and stronger board. The edge crush test (ECT) is used to evaluate the compression strength of the corrugated board and expressed as kilonewton per metre (kN/m). BCT is the top-to-bottom compression strength. The box resistance to vertical compression is the parameter that gives the best account of the effects of transport and storage conditions, and of the stackability of the packages (Poustis, 2005). ECT and its relationship to compression and stacking strength play a key role in corrugated fibreboard container performance (Twede & Selke, 2005). Compression strength is not the same as stacking strength. Relative humidity, stacking pattern, and time in the supply chain all reduce a corrugated box's stacking strength. The reduction is less when the contents of the box help to support the load. Mechanical properties of paper based packaging material are sensitive to environmental humidity in actual logistics (E & Wang, 2011). It is well known that crush and compressive strengths of corrugated packaging are seriously affected by moisture (Eagleton & Marcondes, 1994). High humidity storage conditions can severely degrade the strength of a stack of packages in a matter of hours. The corrugated board weakens over time under load, and with the amount of transport and handling. A box under load loses about 40% of its strength in the first 90 days of storage at TAPPI conditions. A third factor is the stacking pattern on the pallet. Since the strength of a box is in its walls and upright edges, perfectly aligned column stacking best uses a box's compression strength. Alignment of the edges and corners creates a support beam structure within a pallet load. If packages are misaligned or an

interlocking pallet pattern is used, stacking strength will be lower. Pallet overhang and wide deck board gaps also reduce stacking strength; since they affect the level surface of the bottom most packages in the stack, which are expected to carry the heaviest load. ASTM D4169 has simplified the effects of humidity, time and alignment into a factor from 3 to 8 (Twede & Selke, 2005). The factor is divided into the predicted compression strength. Stacking loads are determined as (1) where, $SL = \text{Stacking load}$
 $CS = \text{Compression strength}$
 $F = \text{Safety factor}$

Load Resistance of Corrugated Paperboard Package

In supply chain journey, the packages are expected to protect the product from various static and dynamic hazards they experience such as drops, impacts, vibration, compression and climatic (Singh, Singh, & Paek, 2009). Damage can be caused by any of the hazards or a combination of two or more. The shock and vibration experienced by goods result from the vibration of a cargo-carrying vehicle, the shock resulting from the impacts of railroad cars, and the shock caused by the handling (e. g. dropping) of packages, etc (Guo, Xu, Fu, & Wang, 2011). It is important to protect the goods from shock and vibration damage. Impact Load Resistance of Corrugated Paperboard Package

The first of the potential hazards that may be encountered is shock/impact. It occurs when there is a sudden increase in velocity (falling) followed by a sudden decrease in velocity (hitting a surface). It can occur in a range of distribution environments such as manual handling, falling from a forklift or storage area, a sudden stop by a truck or train, and in many other situations. Impact behaviour of materials is usually expressed by peak acceleration and static stress curve. Peak acceleration

means the acceleration transferred to protected product under a certain impact. The less the acceleration is, the chance of damage to impacted products will be lower, and the protection on the products will be better. The peak acceleration and static stress curves are usually concave and upward. The curve has a lowest point. In this point, the material can absorb most energy (Wang, 2009). It is important to determine the potential drop height the packaged product may encounter and the fragility of the product itself, also known as the critical acceleration. The structure and quality of a corrugated board are essential to ensure the protection of the product when the case is dropped. During storage and transportation, products can accidentally fall onto the floor causing some damages during storage and transportation and drop test is used to determine the package ability to retain and protect its contents under a shock due to a free fall (Djilali Hammou et al., 2012). Drop testing is performed for several reasons: (a) to design impact-tolerant, or rugged, portable products, (b) to replicate the abuse that might occur during manufacturing, shipping and installation and, (c) for accelerated life testing (Goyal& Buratynski, 2000). The potential energy of the box in drop testing is the product of the weight of contents and the drop height (Poustis, 2005). Guo et al.(2010) evaluated the dynamic shock cushioning property of corrugated paperboard pads by drop shock tests, and establish the experimental formulas of dynamic cushioning curves. They studied the vibration transmissibility of corrugated paper-board pads at different static loads by vibration tests, and analyze the resonance frequencies, vibration transmissibility and damping ratios. Wang (2009) conducted dynamic cushioning tests by free drop and shock absorption

principle. The effect of paper honeycomb structure factors on the impact behaviour was analyzed. Experiment results showed that paper honeycomb structure factors, including honeycomb cell-wall thickness and length, honeycomb core thickness, and liner material, have a certain effect on the impact behaviour of paper honeycomb sandwich panels. Flexible corrugated paperboards as liners can increase the compression resistance, reduce the acceleration transmissibility, and increase the cushioning properties. A combined honeycomb may become the new trend in the structural cushioning application for packaging.

Vibration Load Resistance of Corrugated Paperboard Package

The second potential hazard is vibration. Vibration is oscillating motion over time. A package will endure vibration when it is transported by truck, rail, or plane. Vibration is often overlooked when considering potential hazards but it can be as damaging as both shock and compression. Fruits and vegetables move randomly in their packages during transportation. Duration and intensity of vibration related to the extent of the repeated force and displacement determine the deterioration of fruits and vegetables (Çakmak et al., 2010). The effects of the transportation on agricultural products depend on the type of packaging (Schulte Pason, Timm, Brown, Marshall, & Burton, 1990); some types of packaging, such as bulk bins, can remarkably amplify vibrations during transportation from the bottom to the top of the shipment column (Chesson & O'Brien, 1971; O'Brien, Gentry, & Gibson, 1965; O'Brien & Guillou, 1969). The vibrations due to transportation are influenced by road roughness, distance, travelling speed, load, and some characteristics of the truck such as the suspension and the number of axles (Berardinelli, Donati, Giunchi, Guarnieri,

& Ragni, 2003). The vibration component of the vehicle with the largest effect during transportation is the vertical vibration because the vibration component in the vertical direction is greater than the others. Hence, the effect of vertical vibration was investigated by neglecting the other vibration components in most studies performed in the past (Singh & Xu, 1993). Several researchers studied damage of packaged fruit subjected to transit vibration (Hinsch, Slaughter, Craig, & Thompson, 1993; Jarimopas, Singh, & Saengnil, 2005; Singh & Marcondes, 1992; Singh & Xu, 1993). Wholesale packaged sweet tamarind is subjected to mechanical loading damage during transportation mainly through vibration (Jarimopas & Sirisawas, 2006). Singh and Xu (1993) reported that as many as 80% of apples can be damaged during simulated transportation by truck, depending on the type of truck, package and position of the container along the column. Other results of tests carried out on apples during transportation confirm the high susceptibility of these fruits to mechanical vibrations and the great influence of the kind of container on damage (Schulte Pason et al., 1990; Timm, Brown, & Armstrong, 1996). Vursavus and Ozguven (2004) evaluated the effects of vibration frequency, vibration acceleration, packaging method, and vibration duration on the mechanical damage during apple transportation. The research was performed in three stages. Firstly, vibration frequency and vibration acceleration were measured on the truck-bed for determining the vibration frequency and acceleration distribution. Secondly, packaging transmissibility and vibration frequency sensitivity for all the packaging methods used in this research were measured. Thirdly, a laboratory vibrator, which simulates the road transportation under laboratory conditions, was

used to obtain some factors influencing the mechanical damage during apple transportation. Apples packed by pattern packing methods produced the lowest damage levels and severe bruise index (EBI) values, followed by the paper pulp tray and volume packaging methods. The paper pulp tray packing method at high vertical acceleration had the highest bruise potential because of apple size variations within counts. Therefore, trays used should be sized to provide a slight clearance in the carton and fruit of similar size should be used in paper pulp tray packaging to reduce bruise damage. The use of top cushioning materials for all of the packaging methods can help in reducing bruising; however, the cost and inconvenience of using them seemed prohibitive. In horticultural fresh produce transportation, the damage to products can be associated with various vibration forces that originate from the transportation method during shipping. Therefore, it is important to know the type and levels of these forces to reduce damage by designing optimum packaging. A complete understanding of these levels helps packaging designers to avoid conditions of either over- or under-packaging. Over-packaging is often attributed to be environmentally unfriendly, whereas under-packaging can result in damage and loss of sale. These levels are also used to develop test methods that are used to test packages being shipped using specific transport methods in different regions of the world (Jarimopas et al., 2005). Bruise damage is caused from impacts, compressions and vibrations, during various operations after harvest. Careful handling and proper packaging have shown to reduce the losses of fruits due to bruising (Singh, Burgess, & Xu, 1992). The choice of container system and packing configuration in the container can greatly affect the bruising of

mangoes and other sensitive fruits during shipping and handling (Chonhenchob & Singh, 2003). Compression Load Resistance of Corrugated Paperboard Package

The third of the potential hazards is compression. Compression occurs when a pushing force reduces the volume of an object. Static compression is a loading force that a package will endure when it is stacked vertically for an amount of time. The force being applied is not moving. A package may also encounter dynamic compression while being transported in the back of a truck. Dynamic compression occurs when there is a moving force being pressed against the object. Dynamic compression is the form of compression that is observed during cushion testing. Corrugated board box strength is most important requirement due to logistic needs, during goods shipping and warehousing, boxes are stacked, so every box has to prevent damaging of its content and of supported boxes (Biancolini, Brutti, & Porziani, 2010). For horticultural fresh produce, packages are usually provided with opening vents. A major function of the ventilation holes in the container is to maintain an airflow channel between the surroundings and the inside of the containers. Strength and ventilation capability are heavily dependent on the geometric location, sizes and shapes of the ventilation holes (Pathare et al., 2012). Mechanical properties can be divided into two categories, those that pertain to rough handling and stacking. Both of these types are difficult to duplicate accurately in the laboratory. As a consequence, the box compression test (BCT) of an empty container has been widely used as a means of evaluating container performance. However, in order to distinguish between factors that govern box performance it is necessary to test the quality of the corrugated board and its components,

maintain good control of conversion operations and environmental influences such as humidity and load duration (Nordstrand, 2003). The most common failure mode for a corrugated box loaded in top-to-bottom compression is post-buckling deflection of its side panels, followed by biaxial compressive failure of the board in the highly stressed corner regions of the box. Local instabilities of the liners and fluting may also interact with the failure progression (Johnson& Urbanik, 1989; Westerlind& Carlsson, 1992).

Corrugated paperboard box strength is affected by design, use and environmental conditions including storage time, humidity, corrugation orientation, location and size of vent holes, and stacking arrangement.

Paperboard loses strength over time when it is supporting weight. This is called fatigue. For example, a box supporting weight for 10 days will have only 65% of its original, laboratory determined strength; after 100 days its strength is only 55% of the original strength (Thompson& Mitchell, 2011).

Compression strength as Stacking strength of a container measured as the maximum load that can be applied to it under specified conditions before it is crushed. Also the compression strength called compression resistance, compressive strength, or crush resistance. Bending stiffness or flexural rigidities is the most important attributes of a corrugated board (Luo et al., 1995). An important example of such requirements is the strength of the container in compression (stacking strength) during high humidity exposure. The packaging must withstand the load during the specified time of storage (Hägglund& Carlsson, 2011). Box compression test to evaluate their structural performance is performed experimentally (Viguié et al., 2011).

Panyarjun and Burgess (2001) tested various long corrugated packages with

different length, cross sectional shapes, flute directions and board strengths in bending. They developed an equation to relate the box compression strength to the various properties of the box. The correlation coefficient for the fit of actual data was about 0.4. Packages having the flutes run around the box had 20% higher compression strength than packages with horizontal flutes. The most significant factor was found to be the board edge crush strength. The result suggests that failure of packages in bending is due to localized crushing of the panel at the point of application of the load, rather than collapse of the whole box. Jinkarn et al. (2006) studied the effects of the carrying slots on the compressive strength of corrugated board panels. The results reveal that corrugated board with circle shape slotting shows the smallest reduction in compressive strength compared to other slotting shapes. Perforated style shows better performance in compressive strength than the true cut slot. Furthermore, compressive strength of the board decrease as the slot position is located away from the centre of the board. Also, the smaller the slot size, the higher the compressive strength. Singh et al. (2008) studied the loss of compression strength in corrugated containers as a function of size, shape and location of ventilation and hand holes. They found that the presence of ventilation and hand holes can cause strength reduction between 20 to 50% in single wall corrugated shipping containers. Vertical holes that are rectangular or parallelogram in shape are better in retaining corrugated box strength as compare to circular holes. Also they found a linear relationship between the loss of strength and the total area of the holes made for venting or handling. This relationship does not stay linear when over 40% of the face material is removed. For practical packaging

applications the strength and stability of packages made from corrugated board are of great importance. Stacking packages on top of each other places the highest load on the box at the bottom, which has to possess sufficient box compression strength for withstanding this load without collapsing. A lasting contribution for the design of corrugated board containers is the design formula proposed by McKee et al.(1963) Attempts for a more accurate prediction of the compression strength of corrugated containers comprise finite element simulations of the whole box (including closure fins) using shell elements that exhibit the same effective orthotropic stiffness as the actual corrugated board, compare (Biancolini& Brutti, 2003; Nordstrand, 2003). A good agreement between simulation results and experimental data was obtained for both the initial buckling load and the limit load, the latter being approximately twice as high as the former for the considered type of box (Biancolini& Brutti, 2003). Urbanik (1996) reviewed the effect of buckling mode and geometry effects on post buckling strength of corrugated containers.

Modelling the load resistance of corrugated packaging

Corrugated paperboard industry has considered FEM as a possible tool for replacing the traditional application of semi-empirical expressions looking for both, improved accuracy in the prediction of box compression strength using numerical simulation of the package (Fig. 2), and extending the analysis to package types as different as possible (Jiménez-Caballero, Conde, García, & Liarte, 2009). However, in spite of similarities to applications in other materials, FEM simulation of corrugated board is a high challenging modelling task due not only to the need of addressing properly the complex

mechanical modelling of paper itself, but also because of phenomena that are directly related to the corrugated structure, as the relationships between local and global instability failure modes. The complicated nonlinear behaviour of paper makes modelling of the mechanical response of corrugated board and structures composed of corrugated board a difficult task (Gilchrist, Suhling, & Urbanik, 1998). Corrugated paperboards are plates with orthotropic material behaviour that means that the cardboard possesses different mechanical properties for each direction of the axes, contrary to materials with isotropic behaviour, whose material properties are independent from the direction. The orthotropic property results from the corrugations of the carton. Depending on the direction of the corrugation, the boards have a different module of elasticity. But to ensure a correct and successful finite element simulation with models, which have an orthotropic behaviour, several material properties are needed (Comba, Belforte, & Gay, 2011). Different approaches for modelling the mechanical strength of paperboard packaging

Corrugated container has to withstand significant compression loading conditions during carriage and storage. BCT is the most currently performed experiment to evaluate their structural performance (Viguié et al., 2011). Some researchers (Nordstrand, 2004; Patel, Nordstrand, & Carlsson, 1997) strengthened their efforts to obtain a description of the buckling and post-buckling behaviour of individual board panels. Nordstrand (2004) used an elastic and orthotropic description of the mechanical behaviour up to the failure. The chosen failure criterion was the Tsai-Wu criterion for a plane stress case, which accounts for anisotropic strengths and different strengths in tension and compression loading situations.

Modelling the static behaviour of corrugated packages One of the earliest models for estimating the compressive strength of corrugated box was developed by Kellicutt and Landt's (1952). It predicts the box compression strength from the design parameter of the box and the overall ring crush strength of linerboards. Equation indicates that the compression strength is directly proportional to the overall ring strength of the linerboards. (2) where,

$BCT = \text{box compression strength}$
 $RCT = \text{overall ring crush strength of the linerboards}$
 $A = \text{flute constant}$
 $BPKL = \text{box perimeter}$
 $B = \text{box constant}$

The simplest reported box compression models have been statistical relationships between box compression strength P and box length L , width W , and depth D . The model most supported by experiments is probably the formula by Maltenfort (1956) derived from an extensive body of 14, 800 compression tests. Although the original experimental design treated L and W as independent variables, there is a benefit to writing the formula in terms of the box perimeter Z and the L/W ratio as inputs. The Maltenfort formula can be put in the form (3) where P is expressed in Newtons and D and Z in millimeters. Equation (1) is useful for examining how the strength P_r of a rectangular box compares to the strength P_s of a square box with an equal perimeter and all other variables remaining the same. The variation of the strength ratio P_r / P_s with L/W applied to the Maltenfort data predicts that treating a rectangular box as square leads to about a 7% strength error around $L/W = 2$. ECT values can be used to predict the box compression strength (BCT). Compression strength of an empty box depends on board's flexural (bending) stiffness, the ECT and the perimeter. McKee et al. (1963) developed a relationship, which is still widely used formula which predicts

the box compression strength.(4)where, D is the dimension of the box (perimeter); FS is the flexural stiffness of the board; ECT is the edge crush test of the board; and K, a, b and c are empirical constants. The McKee formula shows the relationship of compression strength and the dimension of the box, which is the perimeter of the corrugated shipping container.

However, it does not show the relationship between the opening areas, such as hand holes or vent holes, and the compression strength because the compression load intensity is not the same on all points of the perimeter, so a location of hand holes also has an effect on compression strength. Allerby et al.(1985) modified the constant and exponents of McKee's equation to predict the compression strength of packages made of C- flute corrugated fibreboards.(5)Where, BP - box perimeter (m)ECT = edge crush testBSMD =

bending stiffness machine direction (N. m)BSCD = bending stiffness cross machine (N. m)BP = box perimeter (m)Kawanishi (1989) developed an empirical equation to predict the box compression strength of wrap-around and regular slotted cantons. He also included moisture content in his formula for the prediction of compressive strength.(6)where, K = linerboard factorbw.

L = total basis weight of linerboards (g. m⁻²)bw. B = total basis weight of corrugated fibreboards (g. m⁻²)TF = take up factorCC = average corrugation countCK = corrugated fibreboard thickness (mm)BPK = box perimeter (mm)BT = box type factorPR = printed ratioMCSW = sidewall moisture content (%)

More recently, some models have been developed to predict the critical buckling load and the post-buckling response of loaded corrugated panels or containers. Nordstrand (2004) treated the post-buckling behaviour of a corrugated board panel using an elastic, orthotropic description of its

content (%)

More recently, some models have been developed to predict the critical buckling load and the post-buckling response of loaded corrugated panels or containers. Nordstrand (2004) treated the post-buckling behaviour of a corrugated board panel using an elastic, orthotropic description of its

mechanical behaviour up to its failure. The chosen failure criterion was the Tsai-Wu criterion for a plane stress case, which accounts for different and anisotropic strengths in tension and compression loading. Discrepancy between the predicted and experimental results was attributed to the plasticity and the local buckling of the linerboards, which were not considered. Some studies were based on the numerical finite element method. Biancolini and Brutti (2003) used the approach to predict the first buckling mode and the related critical load of a container by assuming an elastic and orthotropic mechanical behaviour for the simulated corrugated board. This approach seems to be successful in predicting the critical buckling load, but is limited because it does not give the box compression strength. Beldie et al. (2001) incorporated in their numerical simulations elastic-plastic behaviour with a flow rule for plastic deformation with kinematic hardening. In this case, the Hill's orthotropic yield function was used. This approach describes the full compression loading curve. Nonetheless, there was a poor agreement between the predicted box compression curve and the observed one. This was attributed to a structural effect of the scores. Urbanik (1996; 1997) proposed a nonlinear material model to predict the compressive strength of the panels and containers. He used a three-parameter hyperbolic tangent equation that characterized by the stress-strain relationship to describe the material nonlinearity. The corrugated structure in his study was taken as an effective homogeneous plate. Their material nonlinearity theory predicted more conservative buckling loads for low width panels and yielded a more accurate and sensitive compressive strength prediction than those using linear material

properties. Viguié et al. (2010b) used a 3D Digital Image Stereocorrelation technique method to analyse the buckling behaviour of box panels during their compression. This technique is highly efficient to provide relevant data on the 3D displacement and strain fields at the surface of the box panels. E and Wang (2011) developed a mathematical model to predict the stress plateau of multilayered corrugated paperboard under flatwise compression in various humidity environments. The model relates the stress plateau to the thickness-to-flute pitch ratio of corrugated core cell, the yield stress of corrugated medium and the relative humidity in surrounding air. A model found in good agreement with the observation. A good correlation is achieved corroborating the feasibility and accuracy of the model with experiments. The proposed method can be used for practical application of the optimum design and material selection of multilayered corrugated paperboard.

Finite element modelling of corrugated package

Finite element analysis (FEA) is a computer simulation technique used mostly by engineers, scientists, and mathematicians (Huebner, Dewhirst, Smith, & Byrom, 2001). The basic principle of FEM is that a complicated structural model can be cut into smaller components, called elements, by using a sub-dividing system in which the differential equations obtain the approximate solution. This numerical analysis uses a complex system of points called nodes which make a grid called a mesh. This mesh is programmed to contain the material properties which define how the migration will occur. Nodes are assigned at a certain density throughout the material depending on the anticipated diffusion levels of a particular area.

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Regions which will present a probability of large diffusion and high concentration gradients usually have a higher node density than those which experience little or no migration. Points of interest may consist of interface between two different layers and high concentration areas. As the number of nodes is increased (higher node density) a more accurate solution is obtained at each point in the model. However, accuracy of the numerical analysis cannot for practical reasons be improved indefinitely. There is an upper limit after which the accuracy of a number of nodes stays practically the same, while computing time increases drastically. Commercial FEA software contains several different element types and material properties so that users can select input variables. There are three fundamental procedures used by commercial FEM software to solve a problem: pre-process or structural modelling; analysis; and post processing. An advantage of FEM software is that it can accommodate complex geometry types, boundary conditions, and loading conditions. While the FEM solution approaches a true solution from underestimated and under conservative results, its numerical approximation may not result in the exact solution (Cook, 1981). Material properties such as Young's modulus, shear modulus and Poisson's ratio used in the FEA (Yoshihara, 2012). To verify predicted solutions, FEM results can be compared to experimental results. By using some finite element models and commercial finite element code ABAQUS, MSC or ANSYS, the mechanical behaviours of corrugated paperboard such as buckling, transverse shear, elasticity, stability, collapse and ultimate failure were studied (Aboura, Talbi, Allaoui, & Benzeggagh, 2004; Gilchrist et al., 1998; Haj-Ali, Choi, Wei, Popil, & Schaepe, 2009; Nordstrand & Allansson,

2003; Talbi, Batti, Ayad, & Guo, 2009). Application of finite element analysis has been developed to predict the behaviour of corrugated board panels and structures. By applying the technical theories of corrugated performance and with good control of calliper (thickness) and board hardness in the box plant, it is possible to predict, accurately, how a corrugated box will perform under a stacking load. Finite element software to predict package performance under load can be applied for test cases, predicting the effect of complex design features such as access (hand) holes (Kirwan, 2005). FEM Applications in Fresh Produce Industry FEM used to predict the behaviour of complex products, like wood pallets, paperboard requires the acknowledgment of several difficult variables. Orthotropic material has material properties, such as stiffness and strength, which differ along three mutually perpendicular axes. When the FEM is employed to predict the deformation of orthotropic material, users need to account for the fact that orthotropic properties make corrugated board much more difficult to model than isotropic materials. Due to the complex structure and properties, it is necessary to verify the FEM modelling results with experimental data. Table 2 presents the example of FEA application in corrugated packaging/paper industry. Masood and Haider Rizvi (2006) proposed several new pallet designs and analysed them by using the FEM and related information of weight, loading and safety conditions. Using FEM analysis and simulation studies they were able to suggest several optimum designs with one-third the weight and all of the functionality of traditional pallets. Weigel (2001) developed a FEA model to research the dynamic interactions between wood pallets and corrugated containers during resonant vibration within the

unit load system. This research resulted in a useful model that was developed to improve the efficiency of the unit load system during transportation and distribution. Biancolini and Brutti (2003) studied the buckling behaviour of corrugated paper packages by experimental and theoretical analysis. Mechanical behaviour of paperboard was first evaluated experimentally, then a local geometry FEM model, able to reproduce with a very good accuracy buckling loads obtained experimentally in the standard edge compression test, was developed. To investigate the buckling of a complete package, a finite element corrugated board was introduced by means of a dedicated homogenization procedure. The FEM model of the package, assembled with this new element, can accurately predict the experimental data of incipient buckling observed during the standard box compression test, despite the few degrees of freedom and the minimal computational effort. Pommier and Poustis (1990) studied the bending stiffness of corrugated board structures using models based on the finite element method and a developed linear elastic analysis code SYSTUS. The corrugating medium defined in the calculation code incorporated trapezoidal mesh structure. The models assumed perfect bonding between the fluting and the liners. To accomplish this, the nodes of the fluting were merged with those of the liners at the points where contact occurred. The finite element code was executed to simulate the movements of the bending-stress test samples. These results were compared to the experimentally measured values for the bending stiffness. They concluded the proposed model was insufficient to determine the terms of the bending flexibility matrix of an equivalent orthotropic sheet. Pommier and Poustis (1989a) employed the

linear elastic finite element method to predict the top to bottom compression strength of a corrugated box. The bending stiffness and shear bending of the board were considered. The shear bending stiffness was measured using an anticlastic bending test. Since all four sides of the corrugated board expand outward under vertical compression, free rotation about the folding ridges of the corrugated sleeve was modelled. The finite element calculations gave results in agreement with their experimental values. Han and Park (2007) used FEA to predict the loss of compression strength due to vent and hand holes. They used actual testing on fifteen different styles of packages and hole patterns. The study used double-walled corrugated packages with dimensions of 41 x 30 x 25 cm and the surface area occupied by the holes was approximately 2% of the total surface area of the vertical faces of the packages. The study reported a compression strength loss of less than 10% based on FEA and experimental data. They also found that an increase in the radius of curvature at both ends of the hand hole provided better stress relaxation and lower stress. The decrease in compression strength of the box could be minimized with identical area of the ventilation holes if the length of the major axis of the ventilation hole is less than $\frac{1}{4}$ of the depth of the box and the ratio of the minor axis to the major axis is $\frac{1}{3}$. 5 - $\frac{1}{2}$. 5, provided that even-numbered holes are located symmetrically. Djilali Hammou et al. (2012) developed an efficient homogenization model for the corrugated cardboard has been developed and implemented into ABAQUS through the user subroutine UGENS. This model has been used to simulate the drop tests of the corrugated cardboard box containing different foam cushion configurations. The FE simulation results agree well with the experimental

results. We have also shown that the corrugated card-board box with the corner foam cushions gives a more damping effect to the shock response of the product. Finite element simulations have been depends on a large number of parameter inputs from the base material. These are all estimates at best, given that paper is a somewhat variable material that will change properties with age, temperature, and humidity, among other factors (Morris, 2011). FEM is now sufficiently mature and capable for the analysis of different performance aspects of corrugated fibreboards (Haj-Ali et al., 2009).

Conclusion

Comprehensive review of the literature showed that importance of mechanical design of corrugated packaging which plays a major role in fresh produce transportation and storage. In horticultural fresh produce transportation, the damage to products can be associated with various vibration forces that originate from the transportation method during shipping. Therefore, it is important to know the type and levels of these forces to reduce damage by designing optimum packaging. Horticultural packaging is subject to a number of different loading conditions in the filling, stacking, transportation, and storage operations. The loads are especially important for corrugated packages that are used as secondary packages to support loads and protect primary packages, which in turn typically are not supporting loads. Packages are often stacked on a pallet. The packages at the bottom are thus subject to a top-to-bottom compressive loading by the overlying packages. Stronger packages use more material and are more expensive, the final design is always a balance between strength and cost,

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with better solutions sometimes evolving out of structural design or the ability to pass some of the stacking load onto secondary containers in the package when possible. The analysis and prediction of the stacking compression load capacity of corrugated packages are essential especially through simulations. FEM is now sufficiently mature and capable for the analysis of different performance aspects of corrugated packaging. A future challenge for research is to develop more sophisticated and standard testing methods that are based on finite element models. Once the roles of liner and medium behaviour in box performance are properly understood, material properties can be evaluated by mill and plant personnel so that attention is given to the properties that govern end-use performance. For example, corrugated containers that are stacked on top of each other will slowly deform with time until one of the packages collapses or the stack falls over. Consequently, the relevance of studying creep behaviour of paper and board is that it can reduce stacking factors in design of corrugated board packages. This is a future goal in the development of a user friendly computer-based tool for strength design of corrugated packaging.