Analysis and evaluation of a fruit bin for apples

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Abstract A fruit bin is an essential part of apple harvesting, storage, and transport. The lateral pressure distribution on the bin walls by apples in the bin are not well understood, thus making it harder to predict the behavior of the vertical walls of the bin. In this study, a bin was loaded with apples and deflections of the base and a vertical wall were experimentally measured and then modeled using finite element methods to understand typical static load distribution. One of the factors determining the accuracy of an analytical model is accurate representation of load distribution on the structure. A mathematical model was used to validate the lateral pressure distribution applied by the apples on the vertical walls and the bottom plate of the bin. The effect of unit weight of an apple and the angle of repose of apples on load distribution in the bin has been analyzed. Angle of repose is found to be a significant parameter for the lateral pressure distribution on the bin walls. A nonlinear lateral pressure distribution was observed along the depth from top to bottom of the bin. The resulting finite element model allows for comparison of deformation behavior of fruit bins constructed with a variety of materials, such as plywood, wood plastic composites, or a thermoplastic polymer. Although this study dealt with bins for apples, the sensitivity analyses for a range of unit weights and angles of repose for apples makes the analysis results versatile for use with other kinds of fruits and vegetables that fall within the reported range of unit weight and angle of repose.

Keywords Apple bin · Fruit bin · Angle of repose · Plywood · Finite element modeling

Introduction

The apple export in the U.S., which controls 15 % of the world market share, was valued at over \$600 million in 2008 (USDA, Foreign Agricultural Service 2008). Bins or crates are used for storage and transportation of different types of vegetables and fruits, including apples. Therefore, a bin design that minimizes any damage to the fruit during storage or transportation is critical. Substantial research has been performed to characterize apple bruising and the response of apples to the pressure of storage (Lewis et al. 2008; Roudot et al. 1991; Lu and Abbott 1996); however, even after 45 years of considerable research on apple impact damage, there is still a lack of understanding regarding the load distribution within a fruit bin due to a lack of validation of models, poor agreement between test conditions, and a lack of supplementary research (Zeebroeck et al. 2007). Realistic representation of load distribution on the walls of a fruit bin is critical for accurate modeling and designing of bins, especially when considering alternative materials for bin construction.

While functional design is focused on the volume and shape of the bin, structural design is necessary to ensure that its stability and strength is adequate for all types of loading it is expected to experience. Little has been published on the modeling of wood-based fruit bins. Early designs of steel bins were analyzed considering both static and dynamic loads to prepare guidelines for structural design (Xavier 1979). While the static load was assumed to result from the lateral pressure of the stored material, a dynamic loading condition was considered to evaluate the state of flow of the material inside the bin during filling and discharging. Powell et al. (1980) investigated the pressure distribution of stored potatoes on the vertical walls of large bins. The validation of the study was based on Rankine's theory for a semifluid material. The pressure distribution curve along the

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depth from top to bottom of the bin found in their study was identical to that of Rankine's theory, but the pressure values were somewhat larger. The Rankine's theory states that the stress condition in the material is primarily dependent on the angle of repose of the corresponding material (Das 2005). The angle of repose is the steepest angle of descent relative to the horizontal plane when material on the sloped face is on the verge of sliding (i.e., between 0 and 90°) (Fig. 1). Angle of repose is regarded as one of the most important physical parameters in characterizing the segregation behavior of granular materials (Jullien et al. 1993; Zhou et al. 2002). The angle of repose is highly correlated with the size and shape of the material in addition to the density of the material (Zhou et al. 2002). In a typical apple bin, as the apples are randomly placed, the angle of repose will vary. Studman and Geyer (2002) modeled the apples as circular objects in two-dimensional analysis and as spherical objects in three-dimensional analysis, and concluded that the maximum load on an apple at the bottom layer of the stack could be as high as 3–7 times greater than the average load due to its self weight.

The objectives of this study were to model and evaluate the pressure distribution of stored apples on the vertical walls of a typical apple bin for two physical parameters of apple (unit weight and angle of repose), validate the pressure distribution model, and finally model and evaluate bin wall and floor deflections under static loading. Lateral load distribution on the bin walls due to apples was estimated from the modified Rankine's theory developed by Powell et al. (1980). The computed pressure was then considered in the finite element (FE) simulation of the vertical wall and bottom floor of a bin. FE model was validated from the deflection measurements of the vertical wall and the bottom floor of a bin loaded with apples. Accurate representation of load distribution and prediction of bin behavior will assist in considering alternative materials for bins or bin design modifications.

Load distribution in an apple bin

In a bin filled with apples, the bottom floor will be subjected to uniform pressure while the vertical walls will experience

Fig. 1 Angle of repose of stacked apples

horizontal pressure that is minimum at the top and maximum at the bottom (Fig. 2). Although the horizontal pressure distribution along the depth of the wall is depicted as linear, in actuality it is nonlinear and depends on several factors such as shape of the apples, their unit weight, angle of repose, stacking characteristics, and the wall height of the bin.

The pressure at the bottom is determined from the total weight of apples inside the bin and the floor area. No research has been conducted on the vertical distribution of horizontal pressure on the walls of an apple bin. However, in a study to determine the pressure exerted on a storage bin of potatoes (Powell et al. 1980), the horizontal pressure was expressed as a function of the unit weight of potatoes, the angle of repose of the potatoes, and the height of the wall. Based on the study on potatoes by Powell et al. (1980), the load and pressure distribution of apples on the bin walls can be characterized by Eqs. 1 and 2 following Rankine's theory for a semi fluid material.

$$P = \frac{\gamma h^2}{2} \frac{1 - \sin \theta}{1 + \sin \theta} \quad (1)$$

$$p = \frac{2P}{h} \quad (2)$$

where

- P total pressure against a unit width of the wall, kN/m
- γ unit weight of the material kg/m³
- h height of material inside the bin from bottom, m
- θ angle of repose of the material (Fig. 1), degree, and
- p pressure against the wall, kPa

While apples and potatoes might have different sizes and shapes, their moisture content and unit weight depends on their maturity and cultivar. The average moisture content of apples and potatoes on a wet basis has been reported to be

Fig. 2 Load distribution on the bottom floor and the vertical walls of a bin loaded with apples

Fig. 3 **a** Three dimensional view of an apple bin, **(b)** plan view, **(c)** section X-X, **(d)** beam cross-section and **(e)** column cross-section

84.4 % and 77.0 %, respectively (Donsi et al. 1996), while another study reported the moisture content of an apple to range between 81.1 % and 85.1 % (Kheiralipour et al. 2008).

A range of unit weights for apples has been reported by a number of researchers, and was reported to vary from 684 kg/m³ to 883 kg/m³ (Kheiralipour et al. 2008; Meisami-asl et al. 2009). Meisami-asl et al. (2009) have determined the angle of repose for apples on three different surfaces: galvanized steel (20.0°), glass (26.3°), and plywood (26.8°). In contrast, for potatoes, the unit weight and angle of repose were reported to be 673 kg/m³ and 37° (Powell et al. 1980). Due to these similarities in the physical properties of potatoes and apples, the mathematical model described by Eqs. 1 and 2 was used to calculate the horizontal pressure on the vertical walls of the bin, and the calculated pressure was used in the FE modeling and analysis.

Apple bin geometry in FE modeling

The apple bin modeled, was 1,220 mm square and 629 mm high in dimension (Fig. 3). The test bin was constructed of plywood bottom plate and vertical walls, with triangular cross-section solid wood posts in the four corners, and rectangular cross-section solid wood stringers supporting the bottom plate

under the bin. Walls and the bottom plate were connected to the posts and stringers with nails. The top cross sections of the four corner posts of the bin were covered with 1.59 mm steel plates.

Mechanical properties of bin materials

The mechanical properties of solid timber vary from species to species and within a species by grade. Plywood properties

Table 1 Mechanical properties of plywood and solid wood

Material	Modulus of elasticity (GPa)	Poisson's ratio	Shear modulus ^d (GPa)
Plywood (parallel to grain) ^a	8.62		3.32
Plywood (perpendicular to grain) ^a	4.33		1.67
Solid wood ^b	16.40	0.430	
Even ply plywood ^c	8.68	0.415	

^a Plywood specimens from apple bin tested

^b Dinwoodie 2000

^c Gerrard 1987

^d Calculated using Eq. 6

Fig. 4 Location of dial gages and load cells to measure deflections and loads during loading of the bin with apples

are dependent on the ply species, grade, and lay-up configuration. In this research, to accurately model the bin material properties for the FE model, plywood specimens from the bin walls were tested in flexure and modulus of elasticity values were determined following ASTM D3043 guidelines (ASTM 2006). Modulus of elasticity values in directions parallel and perpendicular to the grain are given in Table 1. Typical material properties of Douglas-fir-larch (DF-L) even-ply plywood (for comparison) and Douglas-fir solid timber (for properties of four corner posts and bottom stringers) are also listed in Table 1. Modulus of elasticity of solid timber and plywood listed in Table 1 is in the longitudinal direction for both materials. For even-ply plywood, the modulus of elasticity is the same in both longitudinal and transverse directions (Gerrard 1987).

Shell elements were used for modeling the bottom plate and the vertical walls of the bin. In the FE analysis the required material properties for orthotropic shell material are modulus of elasticity in the x -, y -, and z -directions, Poisson's ratio, and shear modulus in the x - y , y - z , and z - x directions. For the apple bin plywood, moduli of elasticity in the x - and y -directions were determined through experiments. Because of the close resemblance of flexural modulus of elasticity determined from the tests and those reported by Gerrard (1987), the modulus of elasticity in the z -direction was adopted from Gerrard's (1987).

To be consistent with the constitutive relationship of stress-strain for orthotropic materials, the Poisson's ratio was approximated to satisfy Eqs. 3, 4, and 5 (ADINA 2010; Jones 1975):

$$|v_{ji}| < \left(\frac{E_i}{E_j} \right)^{\frac{1}{2}}, \quad i, j = x, y, z \quad (3)$$

$$v_{xy}v_{yz}v_{zx} < 0.5 \left(1 - v_{xy}^2 \frac{E_x}{E_y} - v_{yz}^2 \frac{E_y}{E_z} - v_{zx}^2 \frac{E_z}{E_x} \right) \leq 0.5 \quad (4)$$

or

$$v_{xy}v_{yz}v_{zx} \frac{E_x}{E_z} < 0.5 \left(1 - v_{xy}^2 \frac{E_x}{E_y} - v_{yz}^2 \frac{E_y}{E_z} - v_{zx}^2 \frac{E_z}{E_x} \right) \leq 0.5 \quad (5)$$

where ν is the Poisson's ratio, E is the modulus of elasticity, and x , y , and z represent the three material directions. The shear modulus required for FE analysis was estimated using Eq. 6 (Morozov and Vasiliev 2003):

$$G_{xy} \geq \frac{E_x}{2(1 + \nu_{yx})} \quad (6)$$

where G is the shear modulus or modulus of rigidity.

Experimental evaluation of fruit bins

An experimental investigation was performed to measure the deflection of the bin walls and bottom plate when loaded with apples. A traditional used plywood bin, obtained from a local orchard, was tested to validate the FE model. Bin was instrumented (Fig. 4) with dial gages and load cells to measure

Table 2 Experimentally measured deflections at predetermined locations on the bins and corresponding loads

Load (kg)	Deflection				Load	
	VWL1 (mm)	VWL2 (mm)	BPL1 (mm)	BPL2 (mm)	Load Cell 1 (kg)	Load Cell 2 (kg)
92	0.00	0.13	1.37	1.47	22	24
226	0.43	1.02	2.82	3.20	55	56
392	3.05	2.67	4.78	7.65	97	102

Fig. 5 Results of the FE analysis showing (a) the deflected shape, (b) displacement in x-direction, (c) displacement in y-direction, and (d) displacement in z-direction

vertical and horizontal deflections at predetermined points on the bin and loads under two of the opposing posts of the bin. The dial gage and load cell readings were recorded simultaneously. Horizontal deflections were measured at 25.4 mm from the top edge of a vertical wall (Dial Gage 1) and at the mid-point of the same vertical wall (Dial Gage 2). Vertical deflections were measured underneath the bottom plate at a location that is 606 mm from the front vertical wall and 914 mm from the side vertical wall (Dial Gage 3), and at a location that is 457 mm from the front vertical wall and 305 mm from the vertical side wall (Dial Gage 4).

After zeroing the dial gages and load cells, apples were slowly loaded into the bin using buckets. Dial gage and load cell readings were recorded at three different loads of apples in the bin (Table 2). Based on their locations, dial gages 1, 2, 3, and 4 were labeled as Vertical Wall Location 1 (VWL1), Vertical Wall Location 2 (VWL2), Bottom Plate Location 1 (BPL1), and Bottom Plate Location 2 (BPL2).

FE analysis of apple bin

The apple bin was modeled using the ADINA finite element software package. Taking advantage of the symmetry at the centerline, only half of the bin was modeled. Nine-node

Fig. 6 Maximum (a) deflection and (b) effective stress from FE analysis with the change in angle of repose (bin load of 392 kg and apple unit weight of 960 kg/m³)

Fig. 7 Maximum (a) deflection and (b) effective stress from FE analysis with the change in unit weight of an apple (bin load of 392 kg and angle of repose of 15°)

shell elements were used for modeling the vertical walls and the bottom plate. Corner posts and the stringers underneath the bottom plate of the bin were modeled as beam elements. In practice, a bin is loaded with approximately 454 kg of apples. Previous studies indicate that unit weight and angle of repose for apples could vary. Thus, a sensitivity analysis was performed for unit weight varying from 640.0 kg/m³ to 960.0 kg/m³ and the angle of repose ranging between 15° and 35°, to determine the influence of critical physical parameters of apple on maximum loading on the bin wall. As there was some slip at the joints in the apple bin due to its use over time,

for a meaningful comparison of the experimental and the analytical results the bottom plate and vertical wall of the bin were modeled separately with distributed loads for 92, 226, and 392 kg of apples in the bin. Because apple bins are stacked on top of each other during transportation and storage, FE analysis of a bin was also performed with a bin carrying 454 kg of apples and three additional bins with each carrying the same weight stacked on top of it. To analyze the influence of stacked bins, the stringers underneath the bottom bin were supported over the entire length since in storage the bottom bin is placed on the ground.

Analysis of a single bin - influence of unit weight and angle of repose

A single apple bin, supported at the four corners of the bin, was modeled for evaluation of the relationship between bin deformation and unit weight of apples and angle of repose. A bin load of 392 kg was picked to conduct a sensitivity analysis for angle of repose. The deflected shape of the bin and the displacements in the *x*-, *y*-, and *z*-directions for an angle of repose of 15° and a unit weight for the apples of 960 kg/m³ are shown in Fig. 5. The deflected shape shown in Fig. 5(a) is magnified by a factor of 97.

Analysis of maximum bin deflection and effective stress as a function of angle of repose (Fig. 6) indicates that vertical wall outward deflection and effective stress decreases significantly with the increase in the angle of repose. This result is expected since a small angle of repose leads to an increased tendency for the apples to spread laterally. Variations in the angle of repose had little effect on the bottom plate deflections, which is also expected since that plate is most affected by the weight of the apples. As expected, the maximum deflection in the *x*- and *y*-direction was found in the vertical wall while the maximum deflection in the *z*-direction was observed in the bottom plate and the maximum effective stress was found in the vertical wall (see Fig. 2 for bin axes orientation).

When analyzing the influence of varying unit weight, the angle of repose was held constant at 15° as that angle was

Fig. 8 Deflection contour in the (a) *x*-direction (vertical wall), and (b) *z*-direction (bottom plate) of an apple bin with 392 kg of apples

Fig. 9 Comparison of experimental and analytical deflection results of an isolated vertical wall and the bottom floor for different loads in the apple bin at (a) Vertical Wall Location 1, (b) Vertical Wall Location 2, (c) Bottom Plate Location 1, and (d) Bottom Plate Location 2

shown to yield the highest lateral pressure on the vertical walls. The change in maximum deflections due to the variation of apple unit weight is shown in Fig. 7. Comparing Figs. 6 and 7, it could be surmised that the relationship between the deflection and angle of repose is nonlinear, while the relationship between the deflection and unit weight is approximately linear. In addition, the angle of repose has a greater influence on bin behavior under load than the unit weight of an apple.

Validation of experimental results

The FE model was validated by the experimental results of the apple bin by comparing the measured displacements with the model predictions from analysis of the isolated vertical wall and bottom floor. This was necessary to minimize the affects of loose connections at the bin joints and preexisting damage to the bin provided by the local orchard. At constant apple unit weight, minimum angle of repose leads to maximum deflection of the vertical wall, whereas maximum angle of repose results in maximum deflection of the bottom plate of the bin. Thus, these two critical combinations of loadings were considered when modeling the load distribution of the vertical wall and bottom floor. Figure 8 represents the deflection contours from a typical FE analysis of the individual sidewall and bottom plates. Comparison of analytical and experimental displacements at the four

predetermined locations points (VWL1, VWL2, BPL1, and BPL2) on the tested bin indicates a good correlation (Fig. 9). This indicates that the assumptions for material properties, the kinematics of the plate behavior, and the loading patterns were reasonable. Both from the experiments and analysis, the deflection trends are identical for vertical wall and bottom plate, which is nonlinear and linear respectively. While error in prediction is greater at maximum bin load level, the differences in deflection values at intermediate and minimum bin load levels are not significantly different for both the vertical wall and the bottom plate. Large variation at higher load levels could be due to poor quality of the bin tested. As the bin was

Fig. 10 Nonlinear horizontal pressure distribution along the depth of a vertical wall in a typical apple bin

used on a regular basis, any additional play in the joints could have been included in the deflection readings of the bin wall and the bottom plate.

FE analysis of stacked bins

FE analysis was also performed considering the apple bins stacked over one another as it is regarded as the most critical loading condition for the bin. The stacked condition was modeled by imitating equivalent load or weight from the top bins to the bottom bin. It was assumed that each of the apple bins was carrying 454 kg of apples and that three bins were stacked above the bottom one. Two stacking conditions were analyzed. For the first condition, the stringer directions of the top bins were assumed to be parallel to the direction of the stringers of the bottom bin; in which case, the maximum deflection in the x -, y -, and z -directions were 2.24 mm, 2.54 mm, and 1.70 mm, respectively. In the second condition, where the stringers of the top bins were assumed to be perpendicular to the stringers of the bottom bin, the maximum deflections in the x -, y -, and z -directions were 2.39 mm, 2.54 mm, and 1.70 mm, respectively. It should be noted that the maximum deflection in the z -direction was not in the bottom plate but in the vertical sidewall, which is due to additional concentrated load at the mid point on the top edge of the vertical wall caused by stacking of the bins. The difference in the deflection is not very significant for the stacked bin compared to the single bin since most of the loads from the top bins are directly transferred to the corner columns of the bottom bin.

Horizontal pressure on vertical wall of the bin

Horizontal pressure applied by the apples was not analyzed separately. However, the horizontal pressure distribution applied to the vertical wall of the bin calculated using Eqs. 1 and 2, was shown to provide a similar deflection pattern as in FE analysis. Typical horizontal pressure exerted by apples on bin vertical walls computed using these equations is shown in Fig. 10. The horizontal load distribution varies nonlinearly with maximum load applied at the bottom of the vertical wall. Naturally, maximum load at the bottom of the bin along with the gravity load from apples on the top results in apples at the bottom of the bin bruising more readily than those at the top.

Conclusion

A finite element model of a typical apple bin was developed and analyzed. Apart from the unit weight of stored material, it was found that angle of repose of stacked apples in a bin has a significant effect on the load distribution. A model to describe

the horizontal load distribution on a vertical wall was validated using a combination of FE and experimental analysis. Finite element method along with the method to represent horizontal load distribution on the bin walls can be used to appropriately design bin prototypes with other materials, fasteners, joint types, and geometries. There are numerous possibilities for design optimization including changing the cross section of the members and use of alternative materials and connections. Analytical models, such as the one used in this study, will be useful to examine the influence of bin geometry and material on the bin structural behavior. Although stresses were not analytically estimated, they can be computed and compared to study the influence of change in member material (such as natural fiber wood-plastic composites) or geometry. For accurate modeling, it is critical to know how the load is distributed on a structure. This study provides an insight into appropriately representing the load distribution on the walls of an apple bin using Rankin's method. Further research is also required for dynamic loading during filling, discharging and transporting apples in the bins. Dynamic analysis is required to determine both apple bruising characteristics and design optimization of bin materials under more complex loading conditions.

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