FINITE ELEMENT MODELLINGMECHANICAL LOADING-PUMPKIN PEEL AND FLESH

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Abstract
Finite element (FE) models of uniaxial loading of pumpkin peel and flesh tissues were developed and validated using experimental results. The tensile model was developed for both linear elastic and plastic material models, the compression model was developed only with the plastic material model. The outcomes of force versus time curves obtained from FE models followed similar pattern to the experimental curves however the curve resulted with linear elastic material properties had a higher difference with the experimental curves. The values of predicted forces were determined and compared with the experimental curve. An error indicator was introduced and compared for each case. Root Mean Square Error (RMSE) values were calculated for each model and compared. The results of modelling were used to develop material model for peel and flesh tissues in FE modelling of mechanical peeling of tough-skinned vegetables. The results presented in this paper are a part of a study on mechanical properties of agricultural tissues focusing on mechanical peeling methods using mathematical, experimental and computational modelling.
Keywords: Mechanical properties, , peel and flesh tissues, tough skin vegetables, Root Mean Square Error, error indicator.

1. Introduction

Reducing the volume of loss and waste created during post harvesting and processing stages of agricultural products can increase food availability globally [1]. Applying Finite Element (FE) methods in modelling industrial operations is a new trend among researchers, particularly in the food and beverage industry. Researchers focus on determining and optimizing the best possible conditions and highest quality of products possible under conditional variables. These methods are mainly used to analyze created stress versus strain on food materials when they undergo external loading, which is usually difficult to use common experimental methods [2]. Computational models are capable of predicting the outputs of operations even before manufacturing the equipment [3]. Considering the advantages of these methods and software, there are limitations which need to be well thought-out. Material modelling, boundary conditions, dimensions and geometric aspects are some of these crucial parameters [4]. Due to the complexity of industrial operations, it is necessary to simplify the models in order to reduce the computational time and error. The response of food materials under loading differs in terms of damage on different sections and magnitude of the load; specifically under large deformations the damage created is high due to the soft nature of tissue. This paper details the research carried out in development of FE models of the mechanical loading process of pumpkin peel and flesh samples. Tensile and compression tests are two common methods of evaluating mechanical response of food materials under loading. In order to select an appropriate material model, results of compression and tensile tests [5-9] were used to develop FE model. The model development was designed to present the response of peel and flesh samples. The model has been constructed to create a numerically stable and efficient representation of tough-skinned vegetable response under deformation. The model was developed using the LS DYNA v971 [10] program which is utilized in large deformation static and dynamic behaviors of materials [11].

1.1. Response of material

Response of structure under loading is an important aspect in modelling and simulation of any engineering system. This response can be classified as linear or non-linear, which is highly related to the type of structure and operations that have been modelled. Linear response is defined as a direct relationship between stress and strain values [12], which is normally limited to a very low rate of load for a short period of time related to the softness of material. In a real world operation the response to the loading process is usually non-linear. In the case of agricultural and food materials, the linear response of materials is limited only to the small deformation condition, while the raise in the deformation value leads to non-linear behaviors of materials [13-17]. Although an elastic portion is usually considered as response of material to simplified mechanical loading tests, even this portion is restricted to the deformation condition, value of yield stress and the limit of elasticity. In this study the material behavior is considered to be nonlinear and the failure criterion was used to develop FE models. The bio-yield and rupture points of samples obtained from experimental results were considered effective parameters in the modelling procedure.

1.2. Material Model Evaluation Using Experimental Results

Some of the important parameters to be considered in FE modelling are the level of moisture content, variety and ripening stage. FE modelling of their response in mechanical operations is a challenge. It is important to select an appropriate material model which exhibits similar properties of materials in both elastic and plastic regions. LS DYNA system is used in this study to develop the model. In terms of material modelling the main concerns were the accuracy of the FE model behavior under loading in comparison with the experimental results. Stress versus strain and force versus deformation were the parameters to compare the results of modelling with the empirical outcomes. In order to evaluate the material response to the external loading, two compression and tensile models were developed and the results of simulations were validated using the experimental tests results. A linear plasticity model with the capability of inputting elastic and plastic section details has been chosen to create the material model. The bio-yield stress was used as a point in which the failure starts in the tissue structure, and the details of plastic section of stress strain curve were entered as the guide for plastic changes in material. Piecewise-linear plasticity formulation (MAT_24) is one of the available material types in the LS DYNA package which classifies material response to elastic and plastic sections. In the elastic zone, material's modulus of elasticity (E) is the main parameter and the limit of elasticity is defined by Yield stress. The other option available is to define 8 points after yielding as effective plastic stress and effective plastic strain values, to define the actual stress versus strain curve in plastic region. After yielding the tangent modulus of material is required for the material model. However when the stress versus strain curves is input as the effective plastic stress and strain data, defining the values of tangent modulus were not required [10].

Failure phenomenon was another essential parameter to be defined and considered. This failure breaks the cell walls and creates elastic and inelastic deformations in agricultural crops such as apple, which have been defined as bio yield point by Mohsenin [18]. For the harder materials such as kernels this phenomenon creates cracks that can be visible or invisible on the surface of grain, in meat however it has been defined as the tearing and separating that happens in the connected parts of tissues [18]. For agricultural materials the failure is directly related to the cell wall resistance to the applied load. Plastic deformation basically is known as a state of failure in material structure [19] which can happen due to various changes on structure of tissue such as cleavage, slip and bruise [20]. There are different failure criteria depending on the type of material and external loading. In this study the Yielding stress (Von Mises Criterion) has been considered as the main factor of causing failure in the material. In this failure condition mainly deviatoric stress creates the changes rather than the hydrostatic stress [19]. Based on experimental results the Von Mises failure criterion is more accurate than the Tresca failure criterion [21].

2. Material Model

Experimental results [5, 6] were used to develop and validate the FE model using both elastic and plastic properties of tissue. The Picewise-Linear-Plasticity model uses the Cowper Symonds model with the following formulation for scaling the strain rate [10]:

$$\sigma_y(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p) = \sigma_y^s(\varepsilon_{eff}^p) + SINGY.\left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{1/p} \qquad \text{Equation 1}$$

Equation 1 is used in dynamic case where the $SINGY > 0$, however for static problems when the $SINGY = 0$ the model will apply the following solution:

$$\sigma_y(\varepsilon_{eff}^p, \dot{\varepsilon}_{eff}^p) = \sigma_y^s(\varepsilon_{eff}^p)\left[1 + \left(\frac{\dot{\varepsilon}_{eff}^p}{C}\right)^{1/p}\right] \qquad \text{Equation 2}$$

In Equation 2, the $SINGY$ is the Yield stress, ε_{eff}^p and $\dot{\varepsilon}_{eff}^p$ are effective strain and strain rates, and $\sigma_y^s(\varepsilon_{eff}^p)$ is the static stress. Nonlinearity and large strains happening in small stress condition in mechanical loadings of food materials [18], the reason of selecting material Picewise-Linear-Plasticity model (MAT_24) for FE model was the possibility of applying both elastic and plastic behaviors of tissue with failure criteria at the bio-yield point.

2.1. Model development

Compression and tensile models were developed based on the size and dimensions of the samples in experimental tests on Jap variety of pumpkin [5, 6]. The following assumptions were considered: The compression loading process happens with the constant rate of 20 mm/min, Tensile samples were dog bone-shaped with a narrow section in the middle. The length of samples was 40 mm with a width of 10 mm, Shell element was selected for the tensile model and the thickness of samples was 3 mm according the experimental dimensions of samples. The material is assumed to be homogenous and moisture content assumed to be constant, accordingly the unit consistency in LS DYNA the system of units: tonnes, mm, s, N, Mpa and N.m [22] was selected for all the models. The flesh and peel samples had different heights according to the experimental specimen dimensions. Material properties were obtained from the empirical results. Both flesh and peel were developed using solid element and triangular mesh models. A cylindrical model of flesh and peel samples with diameter of 40 mm were developed for compression test. The height of peel and flesh samples were 5 mm and 34.44 mm respectively. The values of stress versus strain curve were input for the material model. The elastic modulus was considered to be the slope of stress-strain curve. Poisson's ratio value for flesh samples was obtained from experimental tests [5, 6]. Poisson's ratio value for flesh considered 0.43, for peel samples however the Poisson's ratio was considered as the value determined for unpeeled samples (0.33) [7]. A set of nodes was defined on the bottom surface of the model and fixed support was applied at this area limiting the transactional and rotational movement in X, Y and Z directions. The compressive movement also modelled as a displacement-time as applied on a set of nodes on the top side of samples which moved in a negative direction of Z axis. The termination was applied as the time that the compressive loading experiment has been stopped. A motion type (Prescribed-Motion-Set) was applied for a set of nodes that was defined on top surface of the samples with the displacement in Z direction and the load curve obtained from experimental tests. The termination time for all models was considered to be the termination time of experimental tests with the time step of 0.1 s.

A fully integrated element type was applied for the FE model, which is commonly used for plasticity problems in LS DYNA software [11]. A displacement was applied on a set of nodes defined on one side of the model; a fixed boundary condition was applied on this set. The motion (Prescribed-Motion-Set) was applied on a set of nodes defined on the free side of the model. The motion assumed to be a displacement in X direction and the detail of elongation versus time was obtained from experiments. Stress versus strain curve has been calculated using the results of the force-extension curve obtained from experimental tests from literature [5, 6].

True stress and true strain values were used in the modelling [23]:

$$\sigma_t = \sigma(1+e) \qquad \text{Equation 3}$$

$$\varepsilon_t = \ln(1+e) \qquad \text{Equation 4}$$

In Equation 3 and Equation 4, $\sigma_t, \varepsilon_t, \sigma$ and e are true stress, true strain, engineering stress and engineering strain respectively. Termination time was obtained from experimental testing and the time step was 0.1s.

3. Results and Discussion

Finite element models with a non-linear elasto-plastic material type for pumpkin tissues were developed assuming that material is isotropic and homogenous. Models were created and simulated based on the following performance criteria: the FE models of compression and tensile loadings are numerically compatible with the experimental and the material model selected for each model should accurately represent the mechanical behaviors of tough-skinned vegetables under loading. The performance criteria were employed to facilitate developing an accurate FE model for each part. Results of FE models were compared with the results of experimental compression and tensile tests [5, 6], an error indicator values were defined based on the following description:

$$e_{force} = \frac{|F_{exp} - F_{FE}|}{|F_{exp}|} \times 100 \qquad \text{Equation 5}$$

In Equation 5, e_{force}, F_{exp} and F_{FE} are error indicators for the force predicted, experimental force value and FE predicted force value. An error percentage was determined for each FE set of results, the individual differences between experimental values and values predicted by model.

3.1. Development and Validation of Finite Element Model of Tensile Test

Existing FE modelling studies in literature mainly used linear elastic material model for development and validation of their models [2, 13, 24-31]. In this study it was decided to create and validate a tensile model with elastic material type in order to be able to compare the results with available literature. Afterward, models of tensile and compression tests were developed using plastic material model.

The displacement versus time curve was applied up to the elastic limit for the loading and as mentioned before, the stress versus strain relationship assumed to be linear with the slope equal to elastic modulus value. The density, elastic modulus and Poisson's ratio of tissues were determined from experimental study (Table 1) [7].

Table 1: Mechanical properties of samples input for the tensile model.

	Density (ton/mm^3)×10^{-9}	Elastic Modulus (Mpa)	Bio-Yield Stress (Mpa)	Poisson's Ratio
Peel	0.903	25.02	1.5	0.33
Flesh	0.934	7.63	0.58	0.43

The models were solved and the outcomes of force versus time were determined as shown in Fig. 1. The maximum stress happened in the narrow middle section of the samples, which is the section where rupturing happened in experimental tensile tests as well. This was expected as the cross sectional area is smaller than the sides of sample, and as a result the value of stress will be higher on the middle section in comparison with the sides. Maximum tensile load reached 22.8 N, which was comparable and slightly higher than the experimental value 20.21 N for peel samples. The results of force in flesh samples were 7.4 N slightly lower than the experimental value was 7.8 N. The difference between errors for the predicted value from the FE model and the actual experimental values were calculated as error percentage values and the percentage of error versus time curves was determined for both samples as is shown in Fig. 1(b).

Table 2: RMSE and maximum load predicted by FE model using linear elastic material properties.

Linear Elastic Material		RMSE	Maximum Force (N)
FE	Peel	1.06	22.8
	Flesh	0.39	7.87
EXP	Peel	-	20.21
	Flesh	-	7.47

The Root Mean Square Error (RMSE) values also were determined to compare the accuracy of the FE models, the RMSE values for peel and flesh samples were 1.03 Mpa and 0.36 Mpa respectively.

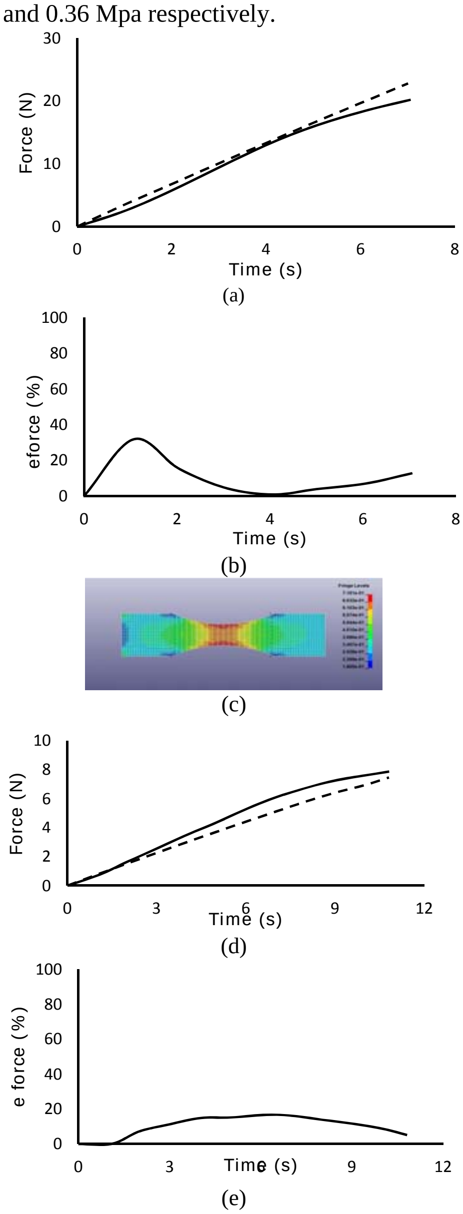
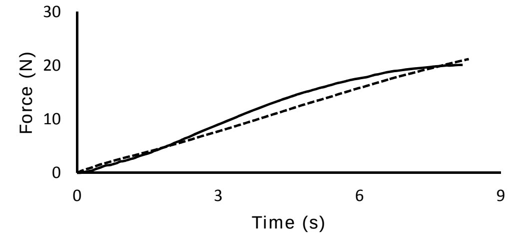


Fig. 1: Tensile force versus time for peel samples (a), error percentage between FE predicted (- - -)and experimental (—–) values (b) and (c) the stress distribution resulted from FE model, (d) and (e) results of flesh model.

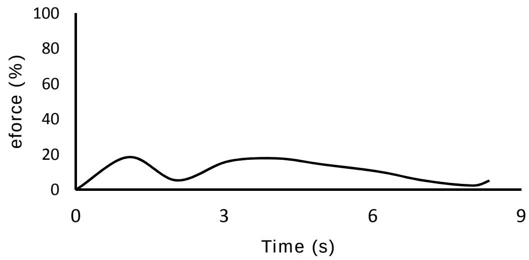
These RMSE values show the difference between the FE predicted value with the actual values observed in experimental tests. Values of error shown in Fig. 1(b) showed that the maximum difference between predicted and experimental value happened where the experimental curve bends, while the FE results is a linear line regarding the material type selected. Maximum error value was 31% for peel samples. The results of stress for flesh samples with elastic material properties showed the maximum error near the force peak value which was 16% (Fig. 1(b)).

The comparison between FE and experimental test shows a better agreement for smaller deformation; similarly it is reported by Dintwa et al. [32] for tomato under compressive loading. Where the results of the FE model showed a very close result under smaller deformation (less than 0.2 mm), the error values for flesh samples were much lower than the error percentage for peel samples, according to the shape of experimental curve. For flesh samples, under smaller deformation the difference between predicted values was lower while for peel samples, smaller errors appeared under larger deformation (see Table 2 and Fig. 1). There was a better correlation observed between experimental and FE results for flesh samples in comparison with peel samples where the percentage of error and RMSE were lower. This indicates the development of permanent plastic deformations are starting to occur and the stress versus strain relationship is changing to a nonlinear. As is mentioned before regarding the curved shape of peel samples, the first section of peel results was less linear than the flesh samples, which were flatter than peel samples. The modulus of elasticity, density, Poisson's ratio, bio yield stress, and the true stress versus strain curve were input as material properties (see Table 1**)** for material selected (Piecewise-Linear-Plasticity model). This material model is a failure-based material type which requires the details of yielding point and the effective plastic stress versus strain curves. The curves in Fig. 2 feature a force versus time curve resulted from FE modelling; the differences between experimental values and predicted values with FE in two different cases have also been presented. Root Mean Squared Error also was calculated for the obtained results and shown in Table 2 and Table 4. The RMSE was also 0.44 Mpa which is lower than the values determined for FE with the experimental input model (1.36 Mpa). For the first two seconds of the loading, the FE model results followed a close pattern with the experimental curve Fig. 2(a) and the maximum predicted values of force was higher than the experimental results.

The results of FE models for flesh samples have been presented in Fig. 2. The maximum force predicted by the FE model was 8.53 N and the RMSE was 0.18 Mpa and error indicator factor for peel samples showed the maximum error of 18.5%.



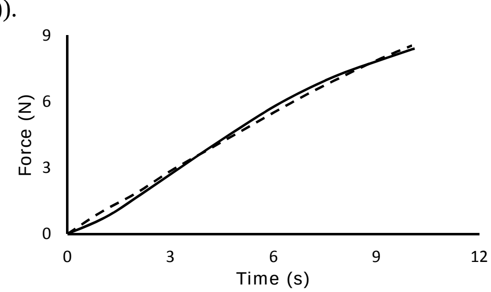
(a)



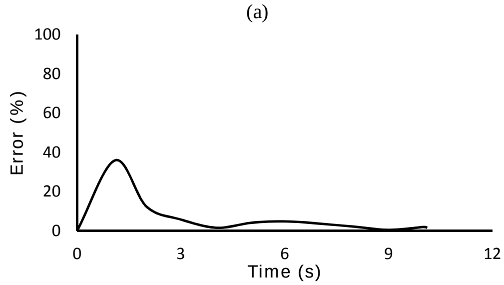
(b)

Fig. 2: Results of FE model (- - -) with experimental (—) input properties, and percentage of error for peel samples under tensile loading.

The comparison between peel results showed that both predicted maximum load values for peel samples were higher than the experimental values. The maximum error for FE model of flesh sample was over 35%, which happened in under 2 seconds of test (see Fig. 3(a)).



(a)



(b)

Fig. 3: Results of FE model (- - -) with experimental (—) and the error percentage for flesh samples under tensile loading.

3.2. Development and Validation of Finite Element Model of Compression Test

The geometry for compression model was developed based on experimental sample size [5, 6]. Poisson's ratio value for flesh samples was calculated using the results of experiments from literature, for the peel samples Poisson's ratio assumed to be 0.33 equal to the value calculated for unpeeled samples under uniaxial compression [5, 6].

The results of experimental tests were used to develop stress versus strain curves for both samples (Fig. 4). Bio-yield point was defined for the samples as a point where the compressive force value decreases or stays unchanged with the increase in deformation value and elastic modulus was defined as the slope of curve in that limit (see Table 3**)** for material properties of tissue).

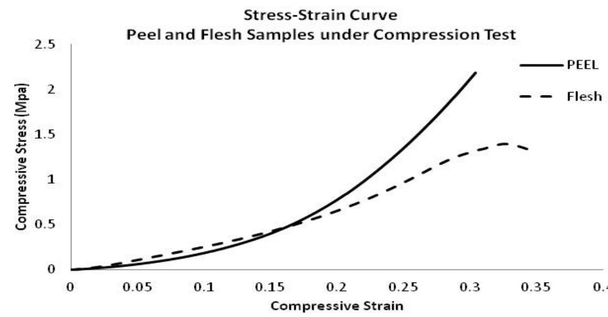


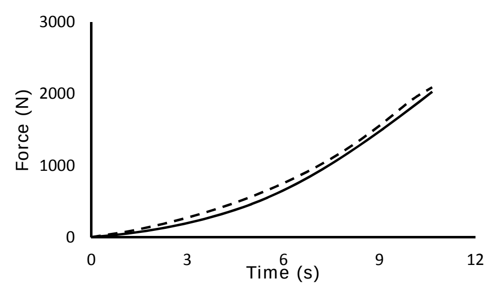
Fig. 4: Stress versus strain for peel and flesh samples obtained from experimental study under compressive loading.

Force versus time results have been presented in Fig. 5, the first curve (a) in Fig. 5 shows the results of FE modelling test for peel samples.

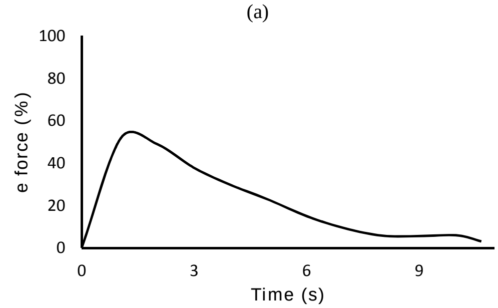
Table 3: Material properties were defined for peel and flesh samples under compressive loading obtained from experimental study.

Material	Density (ton/mm^3)	Elastic Modulus (Mpa)	Bio-Yield Stress (Mpa)	Poisson's ratio
Peel	0.903×10^{-9}	2.59	2.18	0.33
Flesh	0.934×10^{-9}	4.19	1.39	0.434

The input data was obtained from experimental results and included the density, elastic modulus, Bio-Yield stress and the effective plastic stress versus strain curve.



(a)



(b)

Fig. 5: Force versus time curve resulted from FE model (- - -), and comparison with experimental (——) results for peel samples.

The failure criterion, the effective stress and effective strain were required in order to consider the material behaviours after yielding happens where failure in materials is assumed to occur.

Fig. 5 (b) represents error indicator for predicted values for force in comparison with experimental values for FE. As it has been shown, the errors were higher for the first 2 seconds of test while the error values dropped gradually after a peak and reached minimum after 8 seconds. Despite the difference between percentages of error during the model running time, FE curve results had a similar pattern in comparison with experimental curve. The Root Mean Squared Error (RMSE) value for experimental based FE was 16.77 Mpa. The values for peel samples were 76.8 Mpa for FE.

Table 4: Comparison between FE and experimental results and RMSE values for tensile ad compression tests.

Tensile	RMSE		Maximum Tensile Load (N)	
	Peel	Flesh	Peel	Flesh
FE	1.36	0.18	21.19	8.53
Experimental	-	-	20.14	8.39
Compression	**RMSE**		**Maximum Compressive Load (N)**	
	Peel	Flesh	Peel	Flesh
FE	76.98	16.77	2088.81	1073.68
Experimental	-	-	2026.658	1176.19

The error calculated for experimental based FE model is higher for the first 20 seconds of compression loading test, while the error percentages are lower after 20s (Fig. 6).

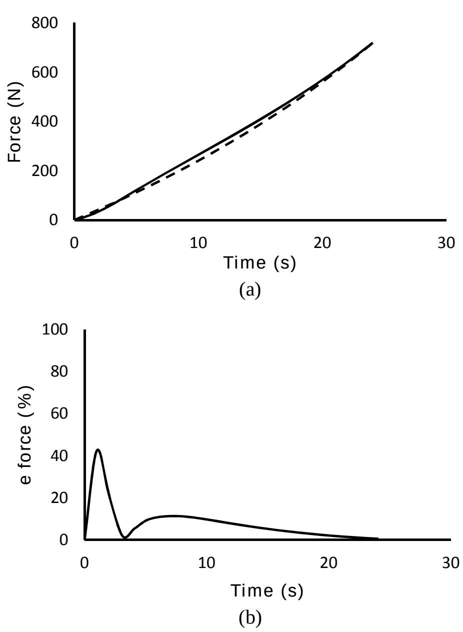


Fig. 6: Force versus time curve resulted from FE model (- - -) and comparison with experimental (——) for flesh sample.

(a) Results of FE with experimental input, (b) the error percentages for FE model with experimental input.

The error indicator had a peak for both peel and flesh samples in the first 2 seconds of the test with 42%, while the error value in peel results was much higher than the flesh. The high error observed was due to the curve shape of force versus time diagram (see Fig. 5(b)).

The FE results also showed a stress distribution from the top to the bottom where the force is applied on top of the cylindrical samples; the same pattern was observed for peel samples. This phenomenon was similar to what happened in experiments; damage was observed as crushed layer of tissue on the side of samples where load was applied was higher and the deformation was clear.

The RMS Error for compression model was lower for flesh samples (Table 4**).** Maximum predicted force values were higher than the experimental values for peel samples for both FE models, while the flesh results were both lower than the experimental values.

4. Conclusion

The predicted values for force in the tensile model with linear elastic material properties were 22.8 N and 7.4 N where the experimental data was 20.21 N and 7.8 N for peel and flesh respectively. In general, the outcomes of FE model followed a linear line as expected regarding the type of material was chosen. For the tensile model with linear plastic material model (Piecewise-Linear-Elasticity) where the plastic deformation of tissue was considered, maximum load was predicted 21.19 N and 8.35 N while the experimental values were 20.14 N and 8.39 N for peel and flesh respectively. As mentioned in the previous sections, the force-deformation curve for food and agricultural materials are usually different from other engineering materials. The curve resulted from FE model was similar to the experimental curve in terms of pattern on force versus time curve. The linear plastic (Picewise-linear-Plasticity) model illustrated better outcomes however the models were developed for one deformation rate according to the experimental condition. Further studies on rate of deformation can provide clearer details of tissue behavior.

In compression model the maximum compressive load was determined by FE model 2088 N and 1073 N for peel and flesh respectively while the experimental values were 2026 N and 1176 N for peel and flesh respectively. The maximum stress in both tensile and compression models occurred on the expected region were the highest deformation and rupturing on the tissue surface.

This study is one of the few attempts on modelling actual behaviors using FE approach, however it is recommended to apply this method for other types of tissues where mechanical properties of material plays an important role in reducing volume of unwanted deformation on tissue during post harvesting and processing operations. The outcomes of this study can be used in investigating behaviors of food products under mechanical loading when new processing equipment are designed.

References

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