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A novel method for the quantification of interfacial tomato stresses during transportation

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Abstract

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Transportation of tomatoes on farm and market roads causes interfacial stresses of tomatoes due to truck dynamics as affected by road and transportation conditions. These stresses may affect the shelf-life of tomatoes if they are high enough to cause damage to the fruit. This paper describes a novel method for the in situ measurement of the stresses during actual transportation of tomatoes, providing the producer information that can assist in taking decisions regarding the use of alternative routes, maintenance of existing routes or changes in packing to prevent excessive stresses onto tomatoes. The process involves measurement of the stresses using a stress-sensor that is recording the interfacial stresses continuously during transportation. These stresses can be correlated to road conditions (quantified through standard road-roughness statistics) and used to subject tomatoes in laboratory conditions to similar stresses to study shelf-life effects of transportation stresses. The paper focuses on the measurement process and first-order data analysis, and excludes a detailed study on the physiological effects of the measured stresses on tomatoes.

Keywords: transportation related stress; shelf-life

Fruit is transported from the farm to the market to enable the producer to sell their products. This transportation process typically consists of a combination of transportation means between the farm where it is harvested and moved to suspensionless trailers, on to the packaging area where it may be packaged into bulk or retail containers, and then on towards the market. The transportation process takes place over a range of road types and conditions. The first section of the route may follow relatively rough farm roads, followed by secondary gravel or paved routes, primary paved routes and ultimately metropolitan streets. The condition of each of these routes causes specific dynamics and vibrations in the vehicle used, as well as the cargo transported (Timm et al. 1996; Jarimopas et al. 2005; Steyn et al. 2012). Over the years, pavement engineers have developed means of measuring the actual condition or roughness of the road, and thus the road condition can be objectively quantified and described (Sayers, Gillespie 1986; Jarim 1992).

Various authors have studied the effects of road conditions on transported agricultural product (O'Brien et al. 1969; Chesson and O'Brien 1971; Singh, Singh 1992; Jarimopas et al. 2005). The majority of these studies have focused on the dynamic response of the vehicle and agricultural cargo during the transportation process, as well as the effect of parameters such as the road condition, vehicle speed and vehicle components (e.g. suspension and tire type) on these dynamic responses. It is understood that these dynamic responses cause possible stresses in the transported product, as it is related to the way it is packed, and thus stresses will develop between adjacent fruit. Several studies have focused on the effect of certain stresses on the shelf-life and/or condition of product (Fisher et al. 1992; Batu 1998; Vursavuş, Özgüven 2004).

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In this regard, methods such as the flat-plate compression test applies force to a tomato and measures the force vs. deflection response of the tomato, providing an indication of the effect of the applied force on the tomato. Product properties such as variety, age and ripeness affect the level of potential damage or deterioration that is caused to the tomatoes (Jackman et al. 1990). However, most of these studies had to link the dynamic effects caused during the transportation process indirectly with the forces applied to the tomatoes.

This paper describes a novel method to enable direct measurement of these interfacial stresses during transportation of the tomatoes on real roads; interfacial stresses refer to the stress exerted by two tomatoes that are in contact with each other. Although the method can be applied to various types of agricultural product, this paper specifically describes the process as followed during transportation of tomatoes in the Limpopo province of South Africa. The author was the Principal Investigator for the California Department of Transportation (Caltrans) study in which the effect of road conditions on truck and freight damage and logistics were evaluated (Steyn et al. 2014, 2015). As a part of the study, transportation of tomatoes by a producer was monitored, with both the road roughness and accelerations generated on the transported tomatoes measured (Steyn 2013). Afterwards, limited studies were conducted in the laboratory where the interfacial stresses developed during simulation of similar accelerations were quantified. The measurement system was subsequently refined for the study in the Limpopo province in South Africa, to such an extent that the interfacial stresses were quantified during the actual transportation of tomatoes.

Tomato transportation. Tomatoes (and other agricultural product) need to be transported between the farm and the market to enable the producer to run a profitable business. Such transportation should be done in a way that is not damaging to the tomatoes, and thus the producer needs to take into account all factors that may affect the conditions of tomatoes during the transportation process. In this regard, the factors that may affect this process are the road conditions, vehicle components (tires, suspension and dimensions), vehicle operating conditions (speed) and packaging of tomatoes. External factors such as the weather conditions when transporting tomatoes (temperature and humidity), the age and ripeness and the variety of tomatoes may also affect their conditions during the transportation process (Mutari, Debbie 2011).

In South Africa the major tomato producers makes use of tractors and suspension-less trailers to transport the tomatoes from the fields to the packaging areas, and rigid or interlink trucks to transport the packaged tomatoes between the packaging area and warehouses or the market. Examples of these types of vehicles are shown in Fig. 1. The South African road network consists of a total of around 750,000 km of roads, of which 158,000 km (21%) are paved and 592,000 km (79%) are unpaved. Both the paved and the unpaved roads are maintained by road agencies. The riding quality of a road is typically measured in terms of the International Roughness Index (IRI), with values of less than 3 m/km indicating very good roads and values greater than 16 m/km indicating roads of unacceptable quality. The riding quality of the paved network is managed to be better than a value of 2.7 m/km in general, while the unpaved road network riding quality varies widely, dependent on material types, local environment, traffic volumes and maintenance schedules (Sayers, Gillespie 1986; Kannemeyer 2014).

The major tomato producer that was involved in this study transports tomatoes between the

Fig. 1. Examples of rigid (a) and interlink (b) trucks for transportation of tomatoes

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Fig. 2. Examples of small boxes (a) and half-bin containers (b) used to transport tomatoes

farm and packaging areas in half-bin containers (Fig. 2b) and between the packaging area and market in small boxes (Fig. 2a). During this transportation, the half-bins and/or small boxes are stacked and fastened to the truck, and very little relative movement exists between the containers and the truck. Tomatoes are packed loose in the containers, and settle down as transportation starts. In a recent study (Steyn, Coetzer 2014) the transportation conditions on a range of roads and road conditions were measured for the tomato producer. Riding quality was quantified and truck vibrations and movements measured. This study is not part of the paper due to the commercial sensitivity of the information and due to ongoing analyses of the data. However, the process used to measure the interfacial stresses during transportation is viewed as novel and beneficial to other researchers and producers interested in determining these effects of transportation conditions on their product, and thus the focus of the paper.

MATERIALS AND METHODS

Stress sensor. Tomatoes that are fitted tightly inside a container exert stresses on each other. These interfacial stresses vary due to factors such as packing density of tomatoes, the ripeness of tomatoes, the height of the container and the stresses and vibrations imparted to the container and its contents due to handling and transportation. An accurate quantification of these interfacial stresses is important for the producer to understand the stress ranges that the tomatoes are subjected to during transportation as excessive stresses can lead to damage initiation of fruit that may affect their shelf-life. Subsequently, a history of inadequate shelf-life may lead to a loss of marketability of tomatoes from a specific producer due to reputation of short shelf-lives.

In order to enable the quantification of the interfacial stresses during transportation in situ, a resistive-based stress sensor was used (Tekscan 5350N and Tekscan 5101; Tekscan, USA, (TEKSCAN 2013)). Application of pressure to the sensor results in a change in the resistance of the sensing element in inverse proportion to the pressure applied. In Fig. 3 an example of the sensors is shown, together with its handles and links to the computer. The sensors are connected through connection handles and a hub to the USB port of a computer. Proprietary (I-Scan, Version 7.60, Tekscan, USA, (TEKSCAN 2013)) software is used to collect the stress data and also to conduct calibration and basic analysis of the data (Tekscan 2013). The proprietary software allows for a range of measurement options to be selected. The more important options are the sensitivity setting of the sensor (used to ensure that the sensor is used within a reasonable and applicable stress range for the application), and the data collection frequency (typically selected between 1 Hz and 100 Hz for the interfacial stress type applications). The sensors are available in a range of dimensions and measurement densities. Two types of sensors were used in the research by Steyn and Coetzer (2014). The BigMat (5350N) (TEKSCAN 2013; Tekscan, USA) sensor has a surface area of 439.9 mm × 480.1 mm and 2,112 sensels (sensel is the designation used for

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Fig. 3. Examples of the sensors with handles and connections to the computer

a single sensor element in the sensor array or the connection locations where the stresses are actually recorded (Tekscan 2013)), while the 5101 sensor (TEKSCAN 2013; Tekscan, USA) has a surface area of 111.8 mm × 111.8 mm and 1,936 sensels. Data from the sensors are generated in raw format. Calibration of the sensors is done through applying known loads to the sensor over at least 80% of the surface are at a range of loads, and storing this data in the calibration mode of the system (a calibration standard method for the type of sensors (Tekscan 2013). Calibration within the expected stress range for the application ensures that the measured data provide correct stress values for further analysis. Collected stress data can then be converted to contact stress values for each of the sensor locations.

Application procedure. Application of the sensors inside the transported tomatoes for measurement of the interfacial stresses is done through careful placement of the sensor in-between the layers of tomatoes during loading of the container (Fig. 4). The system is activated and the collection process of interfacial stresses can be initiated at any stage of the transportation process. Typically, for a complete stress picture, the measurement should be started while the tomatoes are being packed inside the container, as this will enable the whole logistics chain and its effects on the interfacial stresses to be evaluated.

This process provides the *in situ* interfacial stress population for the specific route. However, these data only provide a portion of the information required to determine the potential damage caused to the tomatoes during transportation. The specific effect of the applied stresses still needs to be determined. For this, a sample of tomatoes was subjected to stress application in the laboratory under controlled conditions, while the strain was also measured. The selected stresses were obtained from the actual interfacial transportation stress distributions, with 50^{th} and 90^{th} percentile values of the transportation stresses used as representative stress values. The analysis method used only focused on the differences between interfacial stresses at the 50^{th} and 90^{th} percentile levels, as these were established in preliminary studies as levels at which limited and severe damage would occur to the transported tomatoes (Steyn, Coetzer 2014). Such damages are typical related to colouration due to bruising (on the limited scale) and broken skin (on the more severe scale), and they typically lead to shorter shelve-lives and loss of sales to the producer.

The laboratory test provided the stress-strain properties of the specific type of tomatoes transported, as well as a tomato stiffness value (Steyn, Coetzer 2014). Using these data, the expected strain on the tomatoes can be determined and these data can then be used further in an agricultural analysis to determine the shelf-life of the specific tomatoes. In the study by Steyn and Coetzer (2014) this was done through an analysis of the colour changes in tomatoes over a period of 30 days, comparing the areas where the stresses were ap-

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Fig. 4. Typical placement of the sensors in-between tomatoes during loading of half-bins

plied in the laboratory with no-stress areas. This analysis falls outside the scope of this paper.

This paper focuses on the measurements on one type of tomato ('Topacio'), which constitutes more than 80% of tomatoes grown in the study area. The variability of the tomato stiffness values were quantified in Steyn and Coetzer (2014) through analyses of the coefficient of variation (CoV) of the data and was shown to be relatively low (less than 10% CoV) with a sample size of 30 randomly selected tomatoes.

RESULTS AND DISCUSSION

As indicated, the basic data collected consist of the raw values as measured through the sensor during the collection process. This consists of a matrix of stress data at each time interval. The changes in stress values can be observed in the proprietary software during the logging process to ensure that data are actually being collected and that all sensors are in a functional condition. In Fig. 5 a typical screen with dynamic interfacial stress data is shown. The image shows the instantaneous stresses on the larger image, while the force history of the total force applied to the whole sensor is shown in the plot on the bottom the screen. The colours of the dots are indicative of the stress levels at each of the sensels. Stress data from each of the sensels are stored in a matrix for each of the measurement intervals.

The stress data (matrix of sensel data) are exported in CSV format, enabling further analysis of the data in standard spreadsheets. Before exporting, the data are calibrated for the specific sensor and stress range. Data for each of the time intervals at which the data were collected are exported as a separate matrix of data. These data can then be combined in various ways for detailed analyses. A typical analysis of the interfacial stress data consists of a statistical analysis of the data, focusing on cumulative distribution of the measured stresses at specific intervals or over specific sections of the route followed. In Fig. 6 a typical example of such a cumulative distribution of stresses measured over two road sections are shown. The data indicate that the interfacial stresses occurring in-between tomatoes transported on Road 2 are larger than those for tomatoes transported on Road 1 for all stresses up to at least the 90^{th} percentile. The two sections (A and B) of the two roads are relatively similar (with measured stresses at the 50^{th} and 90^{th} percentile values within acceptable limits for stress damage to the tomatoes), although there are smaller differences in the stress distributions, probably due to slightly smoother and rougher sections of road. The data in Figs 6 and 7 are based on a collection of between 1,936 and 2,112 sensels per sensor collected over a period of at least 10 minutes at a frequency of 4 Hz (N = 4,800,000 data points).

The interfacial stress data distribution (Fig. 6) is then used to determine 50^{th} and 90^{th} percentile data to select the stresses at which the laboratory-applied stresses are used for the controlled shelf-life studies (Fig. 7). No statistical comparisons between the cumulative distributions of the interfacial stresses were conducted at this stage. Comparison between cumulative distributions were only done qualitatively as an overall indication of

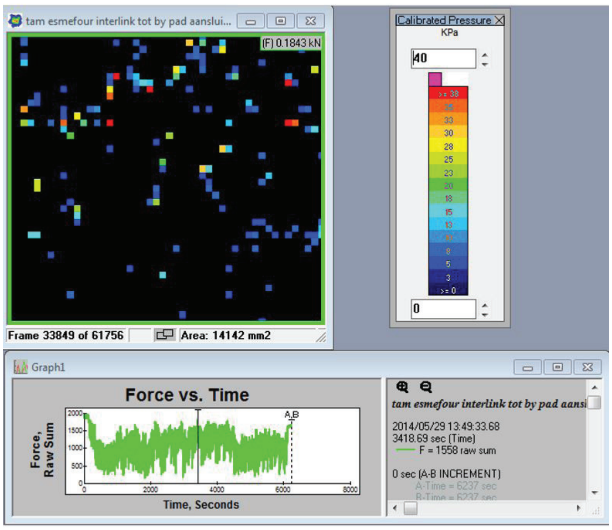

Fig. 5. Typical screen-shot of interfacial stress data during transportation

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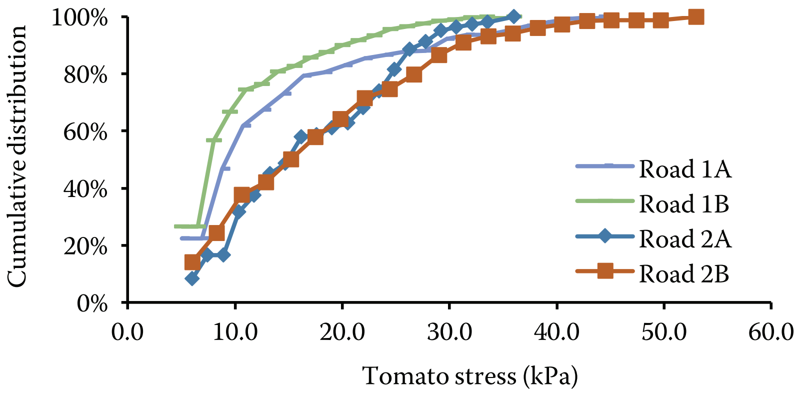

Fig. 6. Examples of a typical cumulative stress distribution for two road sections

the differences between interfacial stresses on different routes, as a more detailed statistical analysis of the cumulative distributions was deemed outside the scope of the initial understanding of the effect of road conditions on interfacial stresses.

Fig. 7 indicates contact stresses measured for a range of different roads followed during one trip, with the smallest and largest 50th and 90th percentile contact stresses for the range of values shown. Differences in interfacial stresses are thus caused by a combination of parameters such as road condition and speed (all measurements were conducted on the same truck, tomatoes and under the same environmental conditions). These contact stresses will typically be used in the stress-strain measurements to develop correlations between road and transportation conditions and shelf-lives in the laboratory. No detailed legend was provided for the 29 data sets in Fig. 7, as the focus of this analysis is on the distribution of all interfacial stresses and the subsequent range of 50th and 90th percentile interfacial stresses. In a current follow-up study more emphasis is being placed on the direct comparison between quantified road roughness and interfacial stresses, for which the individual data sets will be analysed as separate responses to specific road conditions.

The objective of this paper is to present a novel method for measurement of interfacial stresses during transportation. The data and information in the paper tracks the process from installation of the sensors in-between the tomatoes, through the measurement process and the subsequent potential application of the data to determine shelf-life of the tomatoes after being exposed to specific ranges of stresses during transportation. This type of exercise is potentially valuable to tomato producers to enable them identify sections of their transportation sup-

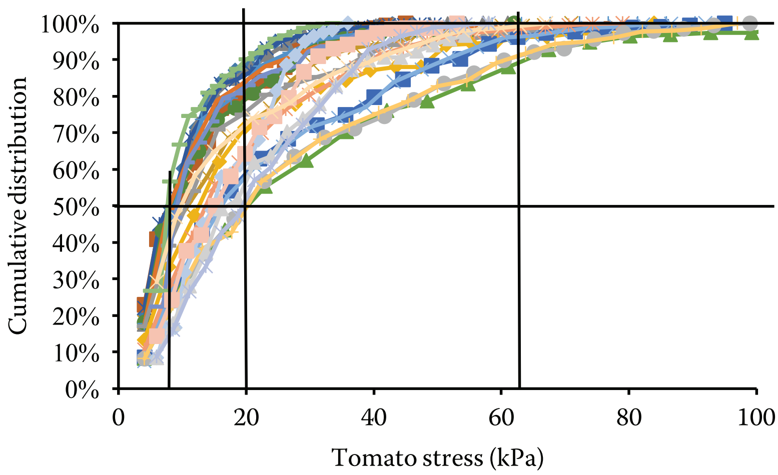

Fig. 7. Cumulative distribution of interfacial stresses with indication of 50th and 90th percentile stresses originating from a suite of road conditions

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ply chain that cause the highest interfacial stresses, and optimising the transportation system (typically through improved road riding quality, use of alternative routes or changes in truck speeds) to decrease these stresses and increase tomato shelf-life.

The information, methodologies and outcomes of the techniques described in this paper are of potential relevance and use to a suite of individual professionals that traditionally interacted to a very limited degree (e.g. built environment/transportation infrastructure engineers and planners in private and public sectors, private sector agricultural producers and transporters, logistics analysts, consultants, and academia). It is envisaged that the ideas would enable a more detailed dialogue between such groups on issues where their professions interact.

CONCLUSION

Based on the information and discussions in this paper, the following conclusions are drawn:

– It is possible to measure the interfacial stresses induced due to transportation of tomatoes *in situ*;
– The interfacial stresses during transportation can be used to evaluate actual stresses, and allow producers to determine possible effects of these stresses on the shelf-life of tomatoes;
– Knowledge of the interfacial stresses during transportation allows producers to adapt their transportation supply chain through the use of alternative routes, improvement in the condition of routes or adapting truck speeds to prevent undue shortening of tomato shelf-lives caused by transportation conditions.

It is anticipated and recommended that the broad potential implications and wider use of the approach presented in this paper be discussed and implemented by the wider transportation infrastructure and agricultural logistics communities to enable improvements in the productivity of transportation of agricultural product through quantified evaluation of the effects of road infrastructure on agricultural product condition. This can be achieved through wider application of the methodology in other agricultural production areas and route networks.

It is further recommended that once confidence is established in the basic measurement technique and outcome of the current basic statistical analysis technique as described in this paper by tomato producers, a more detailed statistical analysis of the cumulative distributions of interfacial stresses should be added to enhance the usability of the collected data.

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