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A Theoretical and Experimental Analysis of the Effects of Suspension and Road Profile on Bruising in Multilayered Apple Packs

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A mathematical model of bruising in impacted multilayered single columns of apples was developed and tested. The model is based on relationships between energy absorbed and bruise volume and calculates the amount of energy absorbed at each interface in the column from energy and momentum considerations using an interactive procedure on a digital computer. The model quantifies the road profile in terms of potholes and bumps and the effects of soft and hard suspensions.

A special rig was designed and constructed to test the theoretical model. Over a limited, but representative range of test conditions, good agreement was found between total bruising and bruise distribution predicted by the model and experimental results. The model successfully predicted that bumps caused more bruising than potholes and that soft suspensions reduced bruising relative to hard suspensions.

1. Introduction

Transport is a major cause of mechanical damage in fruit and vegetables. O'Brien *et al.*[1] report that fruit bruising on trucks has long been a problem and they found that 12–40% of cling peaches were bruised during a journey of 160 miles on trucks having different types of suspension systems. Coursey and Proctor[2] report transport losses of 15% for tomatoes and increased scarring of bananas from 1% to 25·1% after a 45-mile lorry journey. There is clearly a need to understand the factors affecting transport damage.

Considerable literature exists on modelling the dynamic response of vehicles: Schoorl and Holt[3], O'Connor *et al.*,[4] Miller and Swannell.[5] Miller and Swannell[5] report on modelling a single rear axle truck to determine bridge–vehicle interactions. They used experimentally determined suspension characteristics in the model and found good agreement between the model predictions and measured responses. The effects of speed, vehicle load and road surface profile were investigated and it was shown that the most dramatic increase in bridge response resulted from abrupt changes in road profile. Further, it was found that the magnitude of the vertical rise was the major factor in producing this response. This work has obvious implications for the transport of fruit and vegetables; the factors generating bridge response as the vehicle traverses a pothole or bump will also be experienced in modified form by the load the truck is carrying.

Schoorl and Holt[3] showed that, for a multilayered energy absorbing load such as horticultural produce, the road–vehicle–load interactions determine the energy dissipated within the load, and hence the mechanical damage to the produce. A model for predicting bruising in dropped apple columns has been developed and tested for a range of drop heights onto a solid surface and on a programmed shock tester.[6,7] The model is based on the correlation between bruise volume, i.e. volume of discoloured issue, and energy absorbed and calculates the bruise volume at each interface in a multilayered arrangement. There is good agreement between predicted and experimental results and the basic model appears to be sound and robust.

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NOTATION

m	mass
x, y	displacement
$v, \dot{x}, \dot{y}$	velocity
$\ddot{x}$	acceleration
a, c, t	subscripts referring to apple, container and tray respectively
b, f, o	subscripts referring to before collision, after collision and initial condition respectively
i	i^{th} interval
h	drop height
g	acceleration due to gravity
Σm_a	mass of apples already collided
E	energy
V_B	bruise volume (discoloured tissue)
C	bruise resistance coefficient
S	deformation of impact surface
t_B	bruising time
t_i	bruising interval
c, k	damping coefficient and spring constant respectively
f	function
e, d	subscripts excitation and drop tester respectively
P	drop tester period
N	number of apples in column
F	damping force
a, b	constants

This paper reports on the extension of the predictive model to cover potholes and bumps, including the effects of suspension characteristics over a range of loading conditions. The design and commissioning of a special rig to test the extended model is described. Preliminary experimental results are reported and show that the rig performs its intended function and also that the energy model for predicting damage satisfactorily accounts for potholes and bumps.

2. Modelling of multilayered loads under impact

2.1. *Modelling the load*

It has been shown for a variety of produce (apples,[8] strawberries,[9] cabbages[10] and potatoes[11]) that the amount of damage suffered during impact loading is directly related to the energy absorbed. The following arguments could be based on the energy absorbing properties of any of these commodities, but previous experience has shown that consistent and repeatable experiments can be conducted with apples to test theoretical models.[6,7] Further, recent studies on Golden Delicious apples by Chen and Sun[12] showed that bruising was independent of impact momentum and impact velocity in the range 0·9–2·5 m/s, so the bruise volume–energy relationship does not need adjustment for velocity.

There are several other advantages in using apples in experiments: they are regular in shape and size; they can be stored without rapid changes in mechanical properties; damage, i.e. bruising, can be easily measured; and there is a linear correlation between bruise volume and energy absorbed.[8,13,14] In commercial practice apples are either pattern packed with individual pieces arranged in layers or tipped into containers. In pattern packs a limited number of support systems are possible, viz. individual pieces arranged in columns or resting in pockets formed by two or three other pieces to form repeating structures. Randomly tipped apples adopt some combination of these three possibilities. Working with dropped apple packs, Schoorl and Holt[15] showed that total bruising and the distribution of bruising between layers were independent of the packing arrangement. Single columns of apples can thus be used to model more complicated packing arrangements. Three types of packages are commonly in use for apples, fibre board cartons, plastic returnable crates and bulk bins. The rebound characteristics of the package can affect the amount of energy absorbed by the apples[6,7] but only the plastic crates exhibit significant rebound. From observation, the coefficient of restitution for fibre board is very low and likewise the timber base of a bulk bin rebounds little when the bin is dropped. So, to begin with, the load can be modelled with zero rebound.

2.2. *Suspension characteristics*

Vehicle suspension response is generally modelled in terms of mass, spring stiffness and damping. It can be expected that the dynamic response of the vehicle–load combination will be strongly affected by the relative masses of the sprung body (load tray, chassis and associated suspension elements) and of the load, as well as stiffness and damping. A lightly loaded truck will behave quite differently to a heavily laden one. It will thus be necessary to separate the effect of the number of layers from the effect of changing relative mass, i.e. the ratio of load mass to sprung body mass becomes an important variable to include in the model. The mass of the load can of course be changed only in discrete steps, by changing the number of apples in the column, whereas spring stiffness and damping can theoretically be set to any desired value.

2.3. *Potholes and bumps*

As a truck traverses a pothole the force maintaining contact between the various elements is temporarily removed from the suspension and the load as the wheel drops into the hole. In a

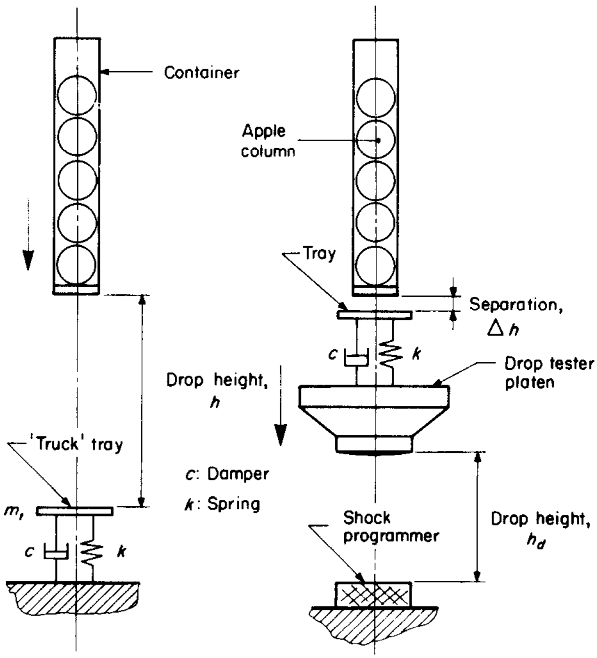

Fig. 1. Idealized load-suspension systems for pothole and bump road profile. (Left) Gravity drop—pothole; (right) base excitation—bump

column of apples the elastic recovery produces small spaces between the pieces and the whole separated column moves down under the influence of gravity.[6] When the wheel hits the bottom of the hole the suspension compresses and the truck body slows, stops and then reverses direction due to spring action. During this time the falling column collides sequentially with the truck body. There is a transformation of energy as kinetic energy is converted into potential energy stored in the spring system and in the load or dissipated in the damper and in individual apples. Energy is dissipated in the apples either by hysteresis or by cell bursting to form a bruise.[16] The relative velocities, and thus the energy transfers, occurring during the various collisions can be reproduced by dropping a column of apples onto a stationary tray and suspension system. The drop height simulates the depth of the pothole.

When a truck wheel strikes a bump the stationary suspension-load system receives a sudden upward displacement, compressing the springs and transmitting motion through to the load. Again there is a transformation of energy resulting in damage to the load and modifying the motion of the truck body. Simulation of the motion of the system requires a controlled upward motion of the suspension base.

To simplify rig construction and subsequent testing of any damage model it was decided not to simulate directly the bump condition but to model a situation where an already falling column of apples receives an upward impact through the suspension system. This allowed an existing drop tester[17] to be used. Impact experienced by a falling load does simulate a real condition, i.e. when a wheel encounters the exit side of a pothole while the load is still dropping. It is argued that if this condition can be adequately described by the model, then the model can be used to predict other bump conditions.

These considerations lead to the conceptual models shown in *Fig. 1*. *Fig. 1 (left)* describes an idealized load-suspension system traversing a pothole and, similarly, *Fig. 1 (right)* describes the special bump case where the wheel encounters the exit side of a pothole.

2.4. *Mathematical development*

Consider a column of apples held in a container falling onto a stationary or moving surface. It has been shown previously[6] that individual apples in the falling column separate by approximately 6 mm due to elastic recovery, and it may be assumed that the separation distance between the bottom apple and the container base is about 3 mm. There will thus be a sequence of collisions, beginning with the impact between the container and the equivalent of the truck body, or tray in the experimental rig. The motion of the tray is affected by this and subsequent collisions as the apples impact one after the other. The motion of the tray is further influenced by its own mass and the characteristics of the suspension. In the case of a bump another input to the system occurs in the form of a displacement of the other (bottom) end of the suspension. For each apple impact the bruising that results depends on the kinetic energy dissipated during that impact. Since each bruising impact is not instantaneous but takes a certain time dependent on the bruise size, velocities of apples and the tray and displacement of the base all change during an individual collision. The mathematical development thus requires the solution over time of the displacement and velocity of each element.

The velocity of the container at impact depends on the drop height. At impact, $t=0$, let displacement $x=0$ then

$$x_{t,0}=v_{t,0}=x_{c,0}=0$$

$$v_{c,0}=\sqrt{2\,gh}$$

$$x_{a,0}(i)=-0{\cdot}006\,(i-0{\cdot}5)$$

$$v_{a,0}(i)=\sqrt{2\,gh}$$

where x = displacement (m), v = velocity (m/s), h = drop height (m), g = acceleration due to gravity (m/s^2), $i = 1, 2, \ldots, n$, n = total number of apples and the subscripts a, c and t refer to apple, container and tray respectively. Applying conservation of momentum and assuming a coefficient of restitution of zero then the velocity of the tray plus container after impact is given by

$$v_{c,f} = v_{t,f} = \frac{m_c\, v_{c,b} + m_t\, v_{t,b}}{m_c + m_t}$$

where m_c = mass of container (kg), m_t = mass of tray (kg) and the subscripts b and f refer to before and after respectively. After this impact the motion of the tray is damped-free vibration and the equation of motion may be written as

$$(m_t + m_c)\, \ddot{x}_t + c\dot{x}_t + kx_t = 0$$

where x_t = displacement of the tray (m), $\dot{x}_t$ = velocity of tray (m/s), $\ddot{x}_t$ = acceleration of tray (m/s^2), k = spring constant (N/m) and c = damping constant (N/m/s). The velocity and displacement of the tray at any time after impact can be solved numerically by applying the Runge-Kutta procedure as follows. The method obviously suits a digital computer. The equation of motion can be rewritten as

$$\ddot{x} + \frac{c}{m}\,\dot{x} + \frac{k}{m}\,x = \frac{1}{m}\,f(t)$$

where $f(t) = 0$. To reduce the equation to a first order one put $\dot{x} = y$, then

$$\dot{y} = -\frac{c}{m}\,y - \frac{k}{m}\,x + \frac{1}{m}\,f(t)$$

Given the initial conditions t_o, x_o and y_o, x and y are solved by finding the increments $\triangle x$ and $\triangle y$ for each time increment $\triangle t$.

The motion of each apple in the column prior to impact is free fall under gravity. For an ith apple its displacement after the tray–container impact is

$$x_a(i) = \frac{1}{2}\,gt^2 + v_{a,o}(i)t + x_{a,o}(i)$$

and it impacts the tray when $x_a(i) = x_t$ and its velocity at impact is $v_{a,\text{impact}}(i) = gt + v_{a,o}(i)$, where g = acceleration due to gravity (9·81 m/s^2). If it is assumed that there is no bounce back after each apple impact, an observation made during previous experiments,[4] the final velocity of the tray, container and apple may be calculated from the conservation of momentum and

$$v_{a,f}(i) = v_{t,f} = \frac{m_t\, v_{t,b} + m_a\, v_{a,b}(i)}{m_t + m_a}$$

where the effective mass of the tray is $m_t + m_c + \Sigma m_a$, where Σm_a is the mass of apples already in contact with the tray. For each impact the motion of the tray can be solved using the Runge-Kutta method, employing the appropriate initial conditions. The whole process is repeated until the apple impacts are completed.

It is assumed that multiple impacts are prevented by arresting the container if it separates from the tray. The energy available for bruising is

$$E = \frac{1}{2}\,m_a\, v^2_{\text{impact}}$$

where E = energy available (J) and v_{impact} is the relative velocity between the impacting apple and the tray.

$$v_{\text{impact}} = v_a - \frac{v_{t,b} + v_{t,f}}{2}$$

since the tray velocity changes during the time taken for bruising. Now since the distribution of bruising between various interfaces is determined on the basis of the time taken for bruising,[6,7] the time taken for bruising as a function of bruise volume can be calculated as follows:

$$\text{bruise volume } V_B\,(\text{ml}) = CE$$

where C = bruise resistance (ml/J) and from experimental results[6] the deformation of the surface of the apple is

$$S = 2{\cdot}52 + 0{\cdot}5\ V_B - 0{\cdot}013\ V_B^2$$

where S = deformation (mm). Assuming constant deceleration, the time taken for bruising is

$$t_B = 0{\cdot}002\ \frac{S}{v_{\text{impact}}}$$

where t_B = bruising time (sec). For any impact the time taken for bruising is thus t_B but for the interface below, which began bruising an interval t_i earlier, the time available is $t_B - t_i$. For the interface below that again the time available is $t_B - 2\,t_i$, where t_i is the collision interval for apples in the falling column. The proportion of energy absorbed on the nth interface is thus

$$= \frac{t_B}{t_B + (t_B - t_i) + (t_B - 2\,t_i) + \ldots}$$

until the next bracketed term goes negative, at which interface it is assumed that, since bruising is complete, collisions further up the column will have no effect. This gives a method of distributing the energy of each impact between the impact surface and any interfaces down the column which are still bruising. The energies absorbed at each interface can be converted to bruise volume and, using an iterative technique again ideally suited to a digital computer, the bruising at each interface in a column of falling apples can be determined.

This model of bruising can be extended to the special bump case by modifying the equation of motion of the tray. The equation can be written

$$m_t\,\ddot{x} + \frac{c}{m_t}\,\dot{x}_t + \frac{k}{m_t}\,x_t = \frac{1}{m_t}\,f(t)$$

$f(t) = kx_e + c\dot{x}_e$, m_t is the effective mass of the tray and the subscript e refers to the excitation produced by the drop tester. $\dot{x}_e$ has been measured previously for the drop tester in use[5] and is given by

$$\dot{x}_e = v\cos\frac{2\pi t}{P},\quad 0 \leqslant t \leqslant \frac{P}{4}$$

$$= 0{\cdot}6\,v\cos\frac{2\pi t}{P},\quad \frac{P}{4} \leqslant t \leqslant \frac{P}{2}$$

$$= -0{\cdot}6\,v \qquad ,\quad t \geqslant \frac{P}{2}$$

where $\dot{x}_e$ = velocity of excitation (m/s), v = velocity of drop tester platen at impact = $\sqrt{2 g h_d}$, h_d = drop tester drop height (m), and P = drop tester period (s). The Runge-Kutta method can also be used for this case.

3. An experimental rig to test the bruising model

3.1. *Design parameters and constraints*

For both potholes and bumps the total bruising and distribution of bruising in columns of varying numbers of apples will depend on the bruise resistance of the fruit and the impact conditions. The impact conditions for a given energy input can be described in terms of N, number of apples in the column; m_a/m_t, ratio of mass of apples to mass of tray; k/m_t, ratio of spring stiffness to mass of tray; and c/m_t, ratio of damping constant to mass of tray. A rig was designed so that N could be varied holding the ratios m_a/m_t, k/m_t and c/m_t nominally constant.

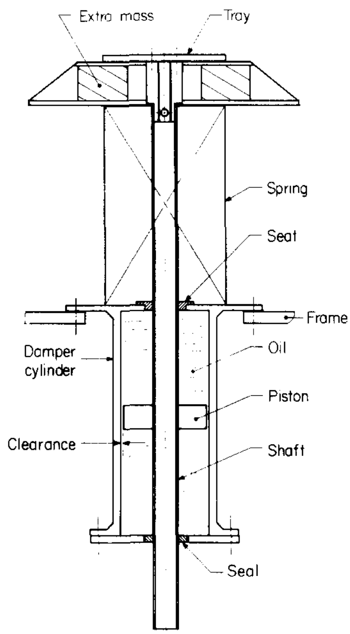

Fig. 2. Arrangement of test rig suspension units comprising load tray, spring and damper

Most apple packs are five-layered although bulk bins may contain ten or more layers so that provision is needed for testing single columns comprising nine to ten apples. To cover this range and to permit investigation of the effect of N, columns of apples 1, 3, 5, 7 and 9 high have been used. An apple mass of 0·15 kg was assumed and several different containers were constructed to maintain m_a/m_t approximately constant since the suspension system responds to the combined apple and container mass. The ratio m_a/m_t is a measure of vehicle–load interactions. Miller and Swannell[5] use a ratio of 1·6 as the full load condition. A maximum value of 2 and a minimum value of 0·5 have been adopted for this rig. There are obvious constraints on the value of this ratio in our case since the minimum spring mass, m_t has to be kept below the mass of a single apple. Similar constraints appear in determining suitable spring stiffness and damping figures.

Typical suspension values for transport vehicles quoted by Page[18] yield $k/m_t = 140$ and $c/m_t = 0{\cdot}74$, but these were found to require unrealistic, large spring deflections for our rig. The suspension characteristics were thus defined primarily by the bruising behaviour of the apples. A compromise had to be reached between a stiff spring, which would give the maximum amount of bruising, and a soft spring which allows significant movement of the spring mass in response to the sequential apple impacts. Five separate suspension units were proposed, arranged as shown in *Fig. 2*. The units each incorporate a helical spring, an oil-filled piston and cylinder type damper and a removable tray top which has provision for adding extra mass. Five different springs, spring stiffness k, $2\,k$, $3\,k$, $4\,k$ and $5\,k$, five different dampers with three different oil viscosities giving damping in the range c to $20\,c$, and adjustable tray mass were selected as design targets to give a suitable range of experimental conditions. A computer program, based on a limited version of the bruising model developed earlier in this paper, was then used to estimate values for k and c which would give easily measured bruise volumes over a range of impact conditions. The resulting planned test conditions for both gravity drop (pothole) and base excited (bump) options are shown in Table 1, where $k = 600$ N/m and $c = 5{\cdot}69$ N/m/s. The drop height for the gravity drop tests was expected to be about 0·45 m with possible changes to produce acceptable bruise volumes in more or less bruise-resistant fruit. The computer program also predicted acceptable bruise levels with a drop tester drop height of 0·30 m combined with a container drop height between 0·340 and 0·380 m, i.e. a separation, $\triangle h$, between container and tray of between 0·040 and 0·080 m.

TABLE 1

Planned test conditions for testing bruising model applied to potholes and bumps

	$m_a/m_t = 2{\cdot}0$					$m_a/m_t = 1{\cdot}0$					$m_a/m_t = 0{\cdot}5$				
No. of apples in column N	1	3	5	7	9	1	3	5	7	9	1	3	5	7	9
Apple + container mass m_a (kg)	0·30	0·60	0·90	1·2	1·5	0·30	0·60	0·90	1·2	1·5	0·30	0·60	0·90	1·2	1·5
Tray mass m_t (kg)	0·15	0·30	0·45	0·60	0·75	0·30	0·60	0·90	1·2	1·5	0·60	1·2	1·8	2·4	3·0
Spring constant	k*	$2\,k$	$3\,k$	$4\,k$	$5\,k$	k	$2\,k$	$3\,k$	$4\,k$	$5\,k$	k	$2\,k$	$3\,k$	$4\,k$	$5\,k$
Damping constant	c†	$2\,c$	$3\,c$	$4\,c$	$5\,c$	$2\,c$	$4\,c$	$6\,c$	$8\,c$	$10\,c$	$4\,c$	$8\,c$	$12\,c$	$16\,c$	$20\,c$

*$k = 600$ N/m; †$c = 5{\cdot}69$ N/m/s.

3.2 *A description of the test rig*

The rig is shown in the bump simulation configuration in *Fig. 3*. The rig consists of a suspension unit (1), containing an apple column (2), guide wires and frame (3) on a base (4). The base excitation is provided by the motion of the platen of the drop tester (5) which is guided in the drop tester main frame (6). The drop tester platen rebounds from a rubber shock programmer (7) and is arrested at the top of the rebound by a pawl and rack system (8). Quick release mechanisms (9 and 10) ensure simultaneous release of the drop tester and apple column respectively. The whole structure is mounted on a large seismic mass. One of the five suspension units is shown separately consisting of a tray (11), the helical spring (12) and an oil-filled damper (13). A metre rule attached to the right-hand column of the drop tester indicates the scale of the test rig.

Calibration of the assembled suspension units showed considerable variations from the specified spring constant and damping values. While the specified materials and wire diameters were

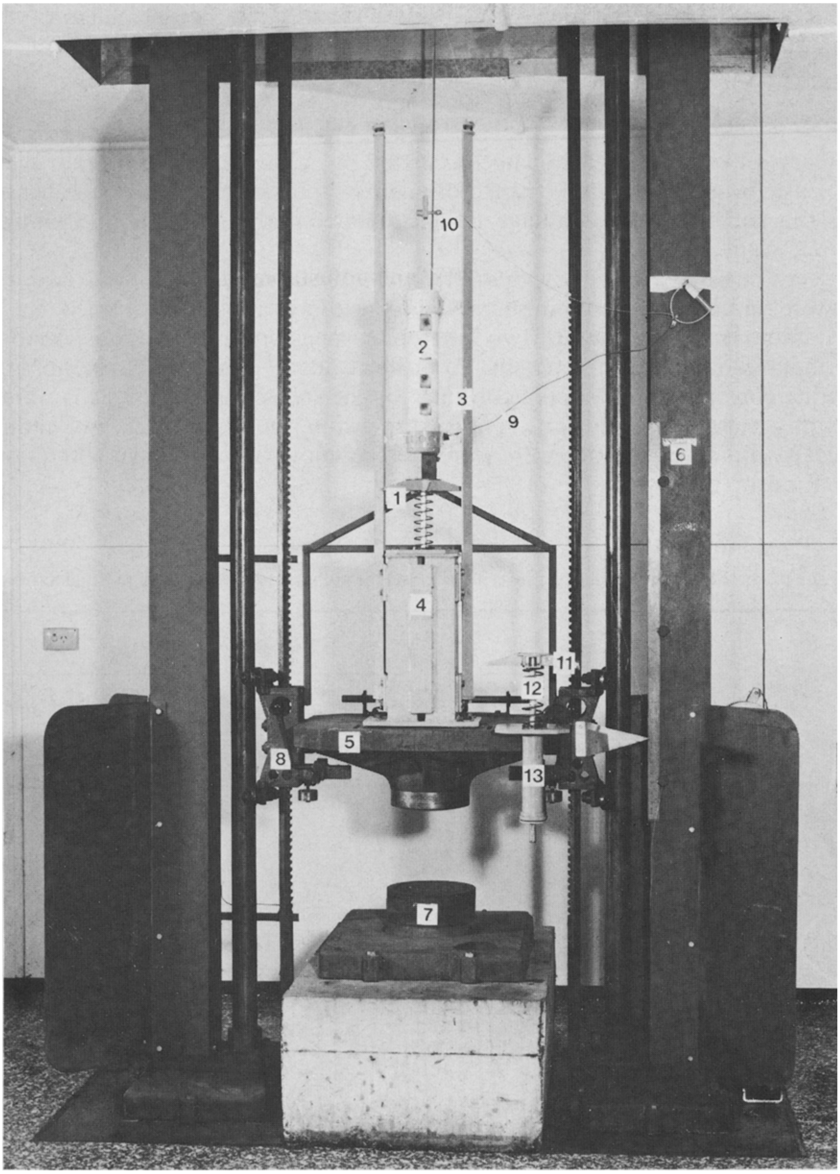

Fig. 3. Test rig mounted on drop tester for bump simulation

used by the spring manufacturer, some variations in spring diameter occurred. It was found that the damping force was best described by a relation of the form $F = a + b\,\dot{x}_t$, where F = damping force, $\dot{x}_t$ = velocity of tray and a and b are constants, i.e. a frictional component exerted considerable influence on the action of the damper. While this had been expected at the design stage, the magnitude of the effect could not have been predicted with any confidence. Consequently, damping values have had to be "fine tuned" by modifications to the length of the pistons for some of the dampers. Even with this tuning, final values vary significantly from planned ones so that tests of varying apple numbers cannot, at the moment, be carried out under identical dynamic conditions. This is not a serious disadvantage since the aim of the design and construction of the rig is to test the bruising model. However, it does perhaps limit the usefulness of the rig as a transport simulator.

4. Experimental bruise volumes and model predictions

A preliminary set of experiments has been carried out to test the operation of the rig and to validate, at least for a representative range of energy inputs, the ability of the bruising model developed in this paper to predict damage under simulated pothole and bump conditions.

4.1. *Experimental methods and results*

Potholes were simulated by dropping single columns of five apples constrained in a light, tubular, paper container onto the trays of two different suspension units. The suspension units had different spring and damper characteristics to produce "soft" and "hard" responses; calibrated values of spring constant and damping constant for the soft suspension, unit 1, were 1335 N/m and 22·18 N/m/s respectively and for the hard suspension, unit 2, were 2676 N/m and 36·82 N/m/s respectively. Bump conditions were simulated by mounting these same units on the drop tester platen for drop tests.

TABLE 2

Measured and predicted bruise volume and bruise distribution for potholes and bumps with soft and hard suspension

Road profile	*Suspension type*	*Interface number*	*Bruise distribution*			
			Experiment		*Prediction*	
			Bruise vol. (ml)	*% distribution*	*Bruise vol. (ml)*	*% distribution*
Pothole	1 (soft)	5	1·1	8·5	2·5	15·1
		4	2·1	16·1	3·0	17·8
		3	2·6	19·7	3·1	18·6
		2	3·3	24·8	3·1	18·6
		1	4·1	30·8	5·0	29·9
	Total		13·3	100·0	16·8	100·0
	2 (hard)	5	2·9	12·8	3·9	13·6
		4	3·3	15·0	5·0	17·4
		3	3·6	16·3	5·5	19·0
		2	5·8	26·2	5·3	18·6
		1	6·6	29·7	9·0	31·4
	Total		22·2	100·0	28·7	100·0
Bump	1 (soft)	5	2·2	12·7	2·3	12·1
		4	2·0	11·5	2·9	15·2
		3	3·2	18·7	3·5	18·0
		2	4·5	26·5	3·9	20·3
		1	5·2	30·6	6·7	34·5
	Total		17·0	100·0	19·4	100·0
	2 (hard)	5	3·4	11·4	3·9	11·7
		4	4·1	13·8	5·5	16·3
		3	7·4	24·8	6·6	19·6
		2	7·9	26·5	6·6	19·6
		1	7·0	23·5	11·0	32·6
	Total		29·7	100·0	33·6	100·0

The bruise resistance of the Granny Smith apples selected for the experiments was 9·88 ml/J, standard deviation 1·30 ml/J. Average mass of the apples was 0·163 kg and the ratio of apple mass to tray mass was $m_a/m_t = 2{\cdot}0$. For the pothole condition a drop height of 1 m was found to produce easily measured bruises for both suspensions. Bump conditions were simulated using a drop tester drop height of 0·3 m with a separation between apple container and tray of 0·080 m. It should be noted that these drop heights are not meant to simulate road profiles directly but model the combination of vehicle speed and bump or pothole height.

The experimental results are given in Table 2. Interface 1 refers to the contact between the bottom apple in the column and the apple container base, interface 2 refers to the surface contact between the second apple and the bottom apple and so on up the column. Bruise volume on each interface, total bruise volume in the whole column and the distribution of bruising on each interface as a percentage of the total volume are listed in Table 2 for pothole and bump conditions using soft and hard suspensions.

4.2. *Predicted bruise volume and bruise distribution*

The mathematical model of bruising developed in section 2 was programmed on a PDP 11/10 mainframe computer. The flow chart for the calculations follows that given by Holt and Schoorl,[7] considerably extended to include the effects of suspension characteristics and base excitation. The input data included calibrated suspension data, measured drop tester platen motion, experimental bruise resistance and it was assumed that individual apples in the falling column separated by 6 mm (section 2.4). Predicted interface bruise volume, total bruise volume and bruise distribution results are tabulated alongside the experimental results in Table 2 for bumps and potholes with soft and hard suspension.

4.3. *Discussion of results*

Total bruise volume figures show that bumps cause greater bruising than potholes. For both soft and hard suspensions a drop height of 1 m for the pothole simulation resulted in less bruising than a drop height of 0·380 m for the bump condition. During a bump the suspension base is driven upwards while the column of apples is still falling. Impact velocities are considerably increased leading to greater energy absorption. The total bruise volume figures also show the difference in bruising between soft and hard suspensions. For both pothole and bump conditions the soft suspension dissipates more energy than the hard suspension, leaving less energy available for bruising. The effect is marked with the soft suspension giving 40% less bruising. The bruise distribution results show that bruising is highest on the bottom interfaces and progressively decreases up the column for all test conditions.

In general there is good agreement between predicted and experimental results. The model successfully predicts the relative bruising from pothole and bump conditions and the differences between soft and hard suspensions, about 40%. Predicted bruise distribution figures also follow the experimental trends. In all cases the predicted total bruise volumes are higher than corresponding experimental values, showing that the model over-estimates the energy absorbed in the column. This is to be expected since the model does not take into account frictional losses between the apples and the container and ignores bouncing and rotation of individual apples.

5. Conclusions

An energy model of the bruising process in impacted multilayered single columns of apples has been developed. The model quantifies the effects of potholes and bumps and the effects of soft and hard suspensions.

A special rig to test the theoretical model has been designed and commissioned and preliminary experiments over a representative range of conditions have shown good agreement between model predictions and experimental results.

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