Journal of
Food Process Engineering

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Journal:	*Journal of Food Process Engineering*
Manuscript ID	JFPE-2018-Jun-0449
Manuscript Type:	Original Article
Date Submitted by the Author:	01-Jun-2018
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Determination of Time Dependent Stress Distribution on a Potato Tuber during Drop Case

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ABSTRACT

Realistic representation of time-dependent internal stress progression and deformation behaviour of a potato tuber during a sample drop case has been studied in this paper. A reverse engineering approach, compressive tests, slow motion camera records and finite element analysis (FEA) were employed to analyse the drop case deformation behaviour of a sample potato tuber. Simulation results provided useful numerical data and stress distribution visuals. The numerical results are presented in a format that can be used for the determination of bruise susceptibility magnitude on solid-like agricultural products during drop case. The visual observations revealed that slow motion camera images and simulation printouts were in good correlation. The modulus of elasticity of the potato specimens was calculated from experimental data to be 3.12 [MPa] and simulation results showed that the maximum equivalent stress was 0.526 [MPa] on the tuber. This value for stress indicates that bruising is not likely on the tuber under a pre-defined drop height. In order to test the simulation accuracy, empirical and simulation-based estimates for total energy in this drop case were compared. The relative difference between empirical and simulation results was 1.27 %. This study provide a good "how to do" guide to further research on the utilisation of (FEM)-based time-dependent simulation approach in complex mechanical impact based damaging analyses and industry focused applications related to solid-like agricultural products such as potato.

KEYWORDS: Potato tuber, potato bruising, drop test simulation, finite element analysis, explicit dynamics

Practical Application: The engineering simulation based "how to do" pathway presented in this study is a scientific novelty because the explicit dynamics simulation technique for potato tuber damage under drop case and its visual verification has been limitedly introduced in the literature. This study present deeper analysis on material model description, slow motion camera records, time dependent non-linear stress analysis and FEM based Explicit Dynamics Simulation procedures. This study aims to represent a realistic non-linear deformation case of the tuber which is very complicated to obtain through physical and/or empirical expressions. As a further step from other literature studies, this research has presented a novel realistic time-dependant non-linear drop test simulation based on physical compressive material test data. The findings have been prepared in a form which may be used as input parameters in design studies for solid-like agricultural products (such as potato tubers) processing machinery systems used in food/agricultural industries.

INTRODUCTION

Mechanical damaged caused by external impact cases such as self-collision, drop and component impacting that occur in agricultural production phases such as harvesting, post-harvest and transportation operations can be considered the main causes for most damage of solid-like agricultural products. Therefore, economic losses due to mechanical drop/external impact/collision based damage to the products become a problem to be solved for the fruit and vegetable industry (García *et al.,* 1995; Van Zeebroeck *et al.,* 2003, 2007; Berardinelli *et al.,* 2005; Prusky, 2011; Celik, 2011, 2017; Abedi and Ahmadi, 2013; Komarnicki *et al.,* 2016). Specifically, bruising due to drop case in harvest and post-harvest operations is a serious problem and this type of bruising is one of the major causes of consumer complaints and an economic loss to the industry. Solid-like products may experience internal bruising during drop case and this is an undesired phenomenon since such bruising may propagate in time during storage or transportation. Conversely, this type of bruising may not be noticeable at first sight just after the drop case. Because understanding and/or determining the internal bruising in solid-like agricultural products such as potatoes is very problematic issue. Determination of internal stress distribution which is associated with drop case is a complicated phenomenon due to the biological cell formation of the organic product and the rapid deformation progression during drop or external impact cases, as the bruise is a type of subcutaneous tissue failure without rupturing the skin of the solid-like product (Mohsenin, 1986). In order to prevent such damage and losses, the bruises caused due to the internal deformation progression during drop case, should be carefully analysed. To do this, in addition to several experimental methods, numerical methods based computer simulations can also be employed as an efficient auxiliary solution for prediction of the stress progression that occurs during the drop case. Engineering simulation techniques have provided very good understanding for complex engineering problems in various engineering fields since the 1950s. These techniques have furthermore been designated as part of an effective, unique solution to the practical, complicated issues experienced in agricultural engineering (such as drop/impact conditions of solid-like agricultural products) (Sitkei, 1986).

Nowadays, one of the most popular numerical methods based engineering simulation analysis tools in use is the finite element analysis (FEA) (Khoei, 2015). The finite element method (FEM) is very useful and promises an easy to use interface in next generation engineering analysis software for modelling non-linear material deformation. Therefore, use of this method and computer application will be very useful for the deformation analysis of agricultural products. Due to the organic structure of the agricultural products, most of them give viscoelastic response under mechanical deformation (Mohsenin, 1986). In fact, the deformation mechanism of an agricultural product under dynamic loading (such as drop or impact) is highly nonlinear. In this context, the explicit solution technique has been underlined as being invaluable in solving time-dependent nonlinear loading events such as drop test applications. Computer aided explicit dynamics simulation system is designed to simulate nonlinear structural mechanics applications and the studies indicated that, in complicated applications, explicit methods are more applicable and the explicit dynamics technique provides an alternative powerful problem-solving ability (Wakabayashi *et al*., 2008; SolidWorks Doc. 2010; Lee, 2012; Wu and Gu, 2012; ANSYS Doc. 2016). Therefore, in this study, drop case of the potato tuber was considered as a nonlinear structural mechanics application covered by the explicit dynamics system. This study aims to describe and understand the bruising occurrence caused by stress progression under dynamic drop case of a sample potato tuber by means of advanced engineering simulation and physical drop test. A reverse engineering approach, compressive material tests, slow motion camera records and FEM-based explicit dynamics simulations have been utilised to analyse the drop case bruising event for the potato tuber. The following sections detail the study procedures and related discussions.

MATERIALS AND METHOD

Material Testing Procedure

The structure of solid-like agricultural products such as potatoes present an understandable example for reverse engineering, deformation simulation and slow motion camera recording described in this paper. The potato tuber specimens handled in this study were randomly selected from the shelves of a supermarket. The tubers were kept in a cold storage unit. The material properties such as density, elastic modulus and bio-yield points are material parameters required to conduct the deformation analysis. An experimental procedure was set up in order to measure and calculate some of these parameters. Experimental studies were conducted within the Biological Material Test Laboratory of the Department of Agricultural Machinery and Technology Engineering, Akdeniz University, Antalya, Turkey. Basic compression tests were utilised and cylindrical specimens (specimen dimensions: 20 x 25 [mm]) extracted from whole potato tubers were used in the physical compression tests. A universal compression test device, which has a loading capacity of 2000 [N], was employed and the test data collected using a computer-aided data acquisition system. The specimens had tested for the same moisture content (85.25 ± 2.81%, wet-base, 10 specimens) at a room temperature of 20 ºC. Each of the compression tests were carried out for 10 specimens. The ASAE S368.4 W/Corr. 1 DEC2000 standard (R2012) describes the compression tests applicable for food materials. The nominal compression travelling speed of 2.5–30 [mm min^{-1}] in the tests for most hard fruits and vegetables are suggested by this standard. Therefore, a compression tool travelling speed of 5 [mm·min^{-1}] was set up in all tests. The data sampling rate was 10 [Hz] during the tests. End of the testing procedures, the force-deformation curves obtained from the test results of the potato specimens are graphically exhibited. Testing details and the graphical representations are shown in Figure 1.

(Figure 1. The testing set up and the graphical test results)

Solid Modelling Procedure

The potato tuber which was used in the physical drop test and digitised for the simulation study was selected randomly from non-damaged test specimens. 3D CAD data of the tuber was created through a reverse engineering approach in order to simulate an accurate and realistic drop case with a realistic tuber model. A NextEngine-2020i 3D desktop laser scanner was used in the digitisation of the potato tuber. The scanned data were processed by Scan-StudioHD and SolidWorks 3D parametric design software tools. Finally, surface refined solid model of the tuber was obtained. Some dimensional properties of the digitised potato tuber were measured in the CAD software. Measured dimensional properties and solid modelling details are given in Figure 2.

(Figure 2. Solid modelling of the potato tuber)

Slow motion camera set-up and simulation procedure

Dropping an object on the planar surface is a stereotypical application for drop test studies (hence the name) and this phenomenon is basically concerned with the effect of the impact of a component with rigid or flexible planar surfaces. In this study a drop case scenario was set up for a sample potato tuber. The drop height for the tuber was set at 1 [m]. The scenario was physically investigated, recorded and then it was simulated through a FEM based explicit dynamics simulation strategy. A slow motion camera (Kodak motion corder analyser SR-series) was used to record the physical drop case (Kodak product, 1998). Dropping moments were screened by using 3000 [fps] resolutions with 128 x 120 screen frame size and a black & white screen. In the simulation, a potato tuber was allowed to make freefall impact onto a planar stainless steel surface from a predefined drop height under standard gravity. The input velocity (V) at impact in the simulation set up was calculated from; $V=(2\cdot g\cdot h)^{1/2}$, where g is the gravitational constant [m·s^{-2}] and h is the drop height [m]. An explicit dynamics module of the ANSYS Workbench commercial FEM code was employed to run the scenario. The tuber model used in the simulation was assumed to be whole homogeneous flesh structures. The simulation settings with frictionless (nonlinear) contact definitions and an idealised linear elastic material model for the solid models were defined in the simulation pre-processor steps. This drop case problem in the simulation set up was considered as a time dependent engineering problem. Standard gravity (9.8066 [m·s^{-2}]) was described in the simulation. Single moisture content of the potato tuber (85.25 ± 2.81%, wet base, 10 specimens) was assumed. Finite element models (mesh structure) of the solid models used in the simulation were obtained with an identical uniform meshing strategy. Initial impact moment, deformation progression, rebound period in contact and fully non-contact moment after impact energy absorption durations and capacity of the computing platform were considered in the simulation solve time and the drop case simulation was solved for 0.35 [s]. The solving platform was a mobile workstation of Dell Precision M4800 Series (Intel Core™ i7-4910MQ CPU @ 2.90GHz, NVIDIA Quadro K2100M-2GB, and Physical Memory Total: 32 GB). The simulation scenario, experimental set up, boundary conditions, material properties and mesh structure details of the tuber models are shown in Figure 3.

(Figure 3. The dropping scenario, experimental set up and mesh structure details)

RESULTS AND DISCUSSION

Compression test results for the cylindrical specimens allowed us to draw the force-deformation curve of the potato tubers, and the modulus of elasticity and bio-yield point were calculated from these test data as 3.12 [MPa] and 1.05 [MPa] respectively. Finney and Hall (1967), reported a mean value of elasticity modulus for Russet Rural tubers of 3.75 [MPa] (543 [psi]), obtained by compressing cylindrical cross sections of the potato specimen. Timbers *et al.* (1965) reported a mean value of 3.99 [MPa] (579 [psi]) for elasticity modulus of Netted Gem potatoes in similar tests. These values are reasonably close to the values calculated for the tuber's modulus of elasticity through physical tests in this study. Absolute difference between these values has been accepted as reasonable as the different kind of tubers and moisture content of the specimens were used in the tests. The simulation results provided a clear understanding of internal deformation of the tuber during the drop case which is very elusive to represent through physical tests. Applicable numerical data and deformation screens were successfully extracted from the FEA study.

In addition to the slow motion camera's records, numerical outputs demonstrated time-dependent stress and contact force progressions on the potato tuber during predefined drop case conditions, however, accuracy of the simulation is another important issue. In an explicit dynamic simulation, two outputs from the simulation are suggested to be checked in order to test the accuracy of the mesh structure and accuracy of the numerical results: hourglassing/hourglass energy progression and total energy activity summary. In this regard, the literature indicates that hourglass energy should be under 5~10 % of internal energy and conservation of total energy should be expected (Chotika *et al* 2001; Elitok *et al* 2006; Björkmon 2010; Dilek and Gedikli 2014; ANSYS Doc. 2016). In this study, all results obtained from the simulation indicate that the conservation of the energy state was stable. In order to validate this, comparison calculation of the empirical and simulation results for total energy were carried out. The relative error was calculated as 1.27 %. Simulation energy summary also revealed that the hourglass energy was under 5~10 % of internal energy values in the simulation. Thus, it would not wrong be to say for this simulation study that element size used in the mesh structure is appropriate, the reliability of the mesh structure is satisfactory and the simulation results are trustworthy. Energy conversation summary and comparison of the potential energy calculations are given in Figure 4.

(Figure 4. Simulation energy activity summary and verification)

The tuber's drop case was visually exhibited and compared with simulation printouts, where the simulation steps were compared with screens taken from the slow motion camera. This comparison indicated that the simulation and the camera's screens worked in unison with each other. Figure 5 illustrates the equivalent (Von Mises) stress, contact force response progressions with graphical representations and screens of the slow motion camera's screens for the drop case. These representations indicate that there were non-linear progression in deformation characteristics against time during the drop case. In the graphical and visual demonstration given in Figure 5, at the first contact moment (scenario solve time (SST): 0.00 [s]), the transfer of the kinetic energy to internal and contact energy begun and contact force between the tuber and the steel plate arose to the maximum at the SST of 0.004 [s]. This contact moment was also the maximum stress moment, i.e. the moment where the maximum level of the drop energy was absorbed by the tuber. After this moment, the tuber body proceeded to rebound. In the following duration, at a SST of 0.010 [s], total travel distance (total displacement) from initial contact point was maximum. Last contact between the tuber and the platform was as at 0.030 [s] and the simulation was ended at a SST of 0.035 [s]. The maximum equivalent stress value in the global screen (impact platform and tuber) was obtained on the platform as 0.572 [MPa] from the simulation at a time of 0.004 [s] (just after initial contact case). The maximum equivalent stress value on the tuber was 0.526 [MPa] which was obtained at the same time step of 0.004 [s]. The contact force was 675.98 [N] at the maximum stress moment. After this moment, the tuber travelled (bounced) and its last contact with the platform resulted in 0.160 [MPa] and 183.35 [mm] equivalent stress value and total travel distance (total displacement) from the initial contact point respectively.

It should be underlined that bruising behaviour and bruise area/volume of the organic materials can change under different drop conditions (different drop height, product moisture content etc.) and orientations. In the study, the start point of the possible bruising was assumed as the tuber bio-yield stress point of 1.05 [MPa] and any region which experiences a stress over this magnitude described as bruised region, however, these numerical results revealed for this study that the tuber did not experience bruising as the maximum stress value (0.526 [MPa]) during the drop case of the tuber was lower than its experimental yield point (1.05 [MPa]). This is an important indicator in order to understand and describe deformation behaviour and bruising characteristics of the potato tubers under drop case events. As a final result, it is noted that the tuber behaved like an elastic mass under 1 [m] drop height with random dropping orientation on the steel material based impact platform and no bruising was experienced. In this case, it should be noted that the impact angle and mass of the tuber has an important role in bruise occurrence in addition to the other drop conditions mentioned above, it means that the stress magnitude can change due to the drop angle of the tuber even for the same drop height and impact platform.

(Figure 5. Simulation results)

CONCLUSION

In all disciplines of engineering, it is a very important issue to make a visual investigation of physical events of materials in order to understand and analyse their deformation behaviour under highly dynamic loading cases such as material dropping cases and this can be more complex for agricultural products because of their organic inner structure. Generally, physical experiments do not allow for scanning of what arise inner structure of the specimen under the highly dynamic conditions most especially during a very rapid bruising progression of agricultural products at impact. However, engineering simulations can be very serviceable in that process. The major aim of this work was to describe the stress progression of a sample potato tuber under a single drop case by means of a FEM-based explicit dynamics simulation technique. In this context, the aim of the study has been successfully targeted. The contact force and equivalent stress progressions of the tuber during drop case has been visually and numerically revealed. Simulation results (visual print outs and numerical data) exhibited reasonable deformation behaviour of the tuber. In addition to the numerical results, dynamic deformation behaviour of the tuber was successfully simulated and validated through real time slow motion camera records. The camera records and simulation print outs were in union. The simulation results revealed that the potato tuber in drop case did not experience bruising under pre-defined boundary conditions as maximum stress magnitude on the tuber (0.526 [MPa]) was lower than the material bio-yield point (1.05 [MPa]). This was also seen on the physical tuber sample used in the experimental drop test. In fact, similar impact like deformation cases are very common in related agricultural production phases. In this point, the results obtained here may be helpful for a greater understanding of the complex deformation response of solid-like agricultural products such as potato tubers. To have a deeper understanding is imported as well understood deformation cases are a good source for designing more efficient agricultural machinery and equipment. This study contributes to further research in the use of drop test simulation techniques in difficult deformation analysis related to solid-like agricultural products such as potato tubers.

ACKNOWLEDGEMENTS

This study was part-supported financially by the Scientific Research Fund of Akdeniz University (Turkey). Additionally, the authors wish to acknowledge the UK EPSRC-supported Engineering Instrument Loan Pool at Rutherford Appleton Laboratories for the loan of the slow motion camera equipment utilised in this research carried out at the Lancaster Product development Unit, Engineering Department, Lancaster University (UK).

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FIGURE CAPTIONS

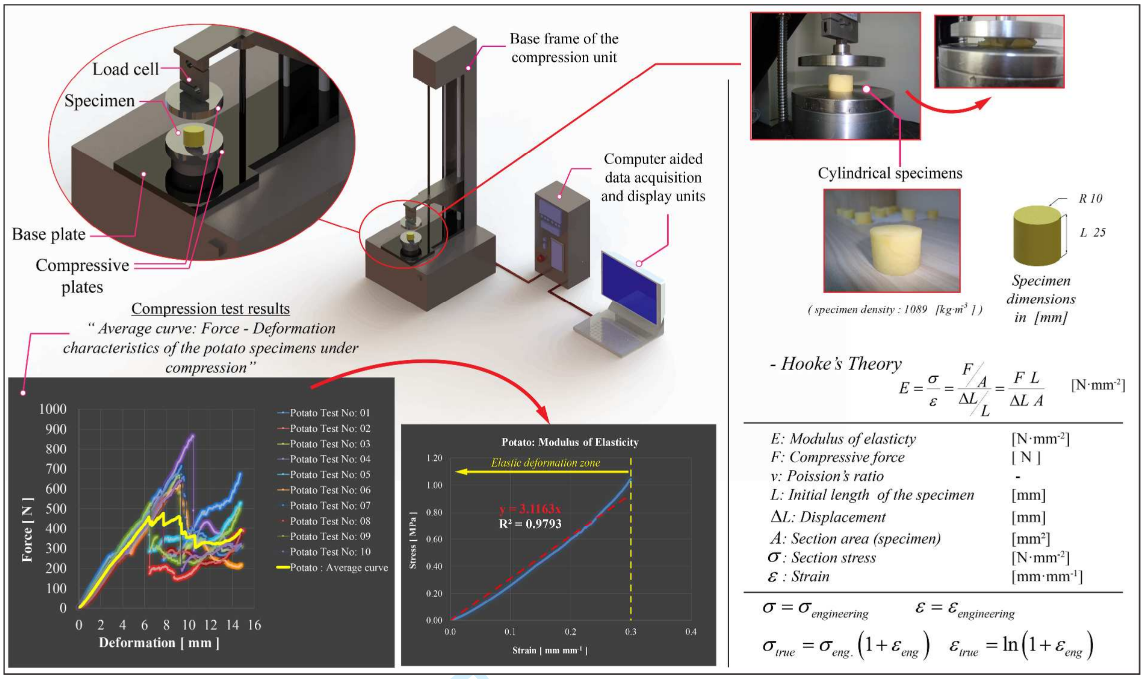
Figure 1. The testing set up and the graphical test results

Figure 2. Solid modelling of the potato tuber

Figure 3. The dropping scenario, experimental set up and mesh structure details

Figure 4. Simulation energy activity summary and verification

Figure 5. Simulation results

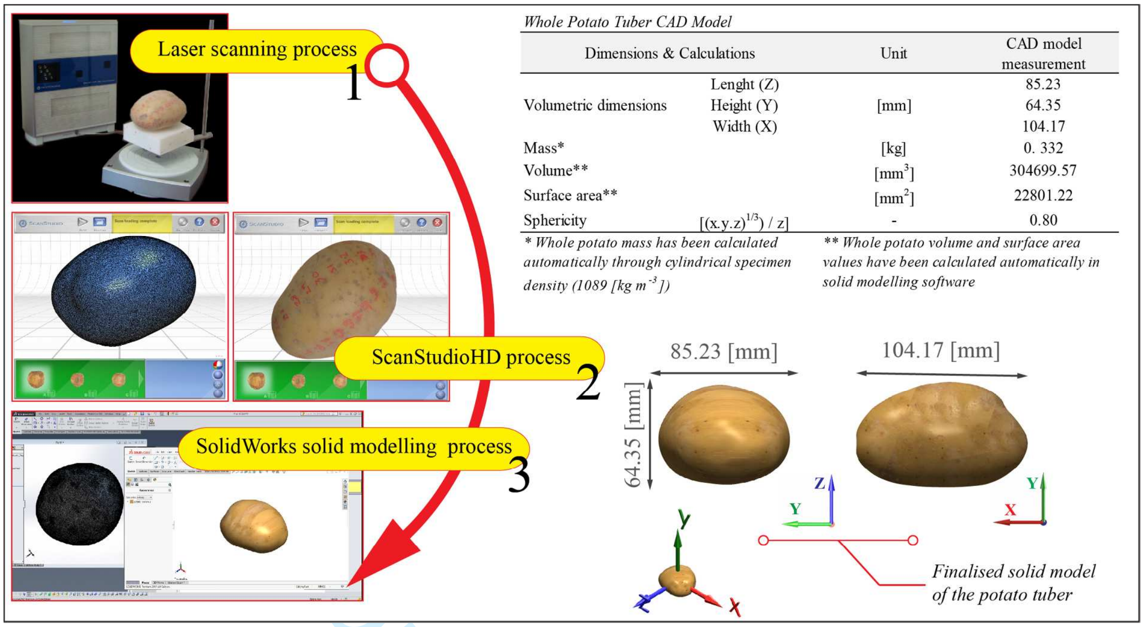


$$E = \frac{\sigma}{\varepsilon} = \frac{F/A}{\Delta L/L} = \frac{F\,L}{\Delta L\,A} \quad [\text{N}\cdot\text{mm}^{-2}]$$

$$\sigma = \sigma_{engineering} \qquad \varepsilon = \varepsilon_{engineering}$$

$$\sigma_{true} = \sigma_{eng.}\left(1+\varepsilon_{eng}\right) \qquad \varepsilon_{true} = \ln\left(1+\varepsilon_{eng}\right)$$

Figure 1. The testing set up and the graphical test results



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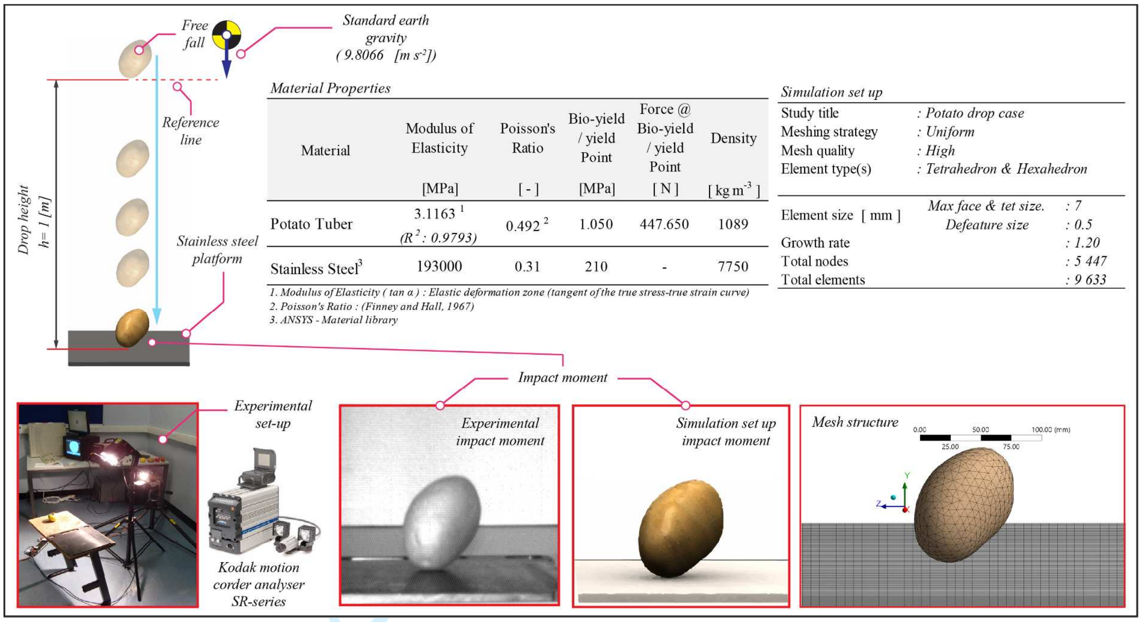

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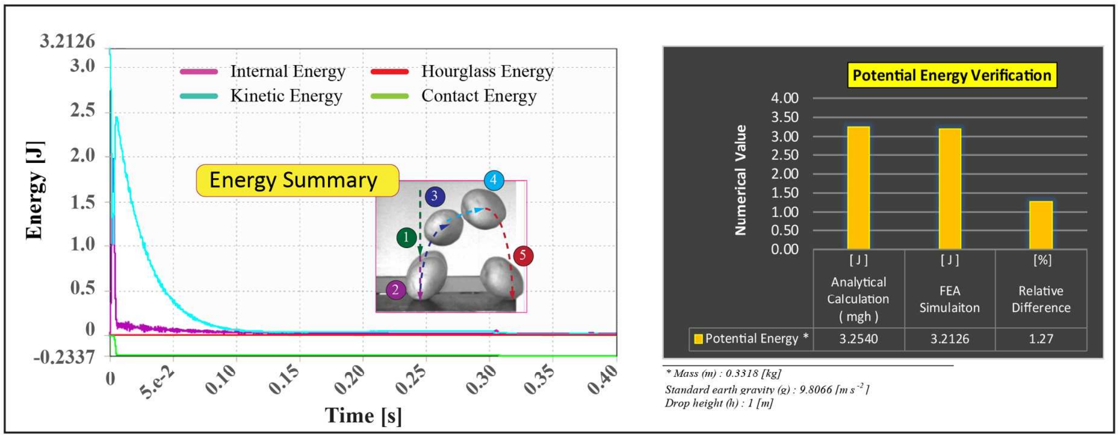

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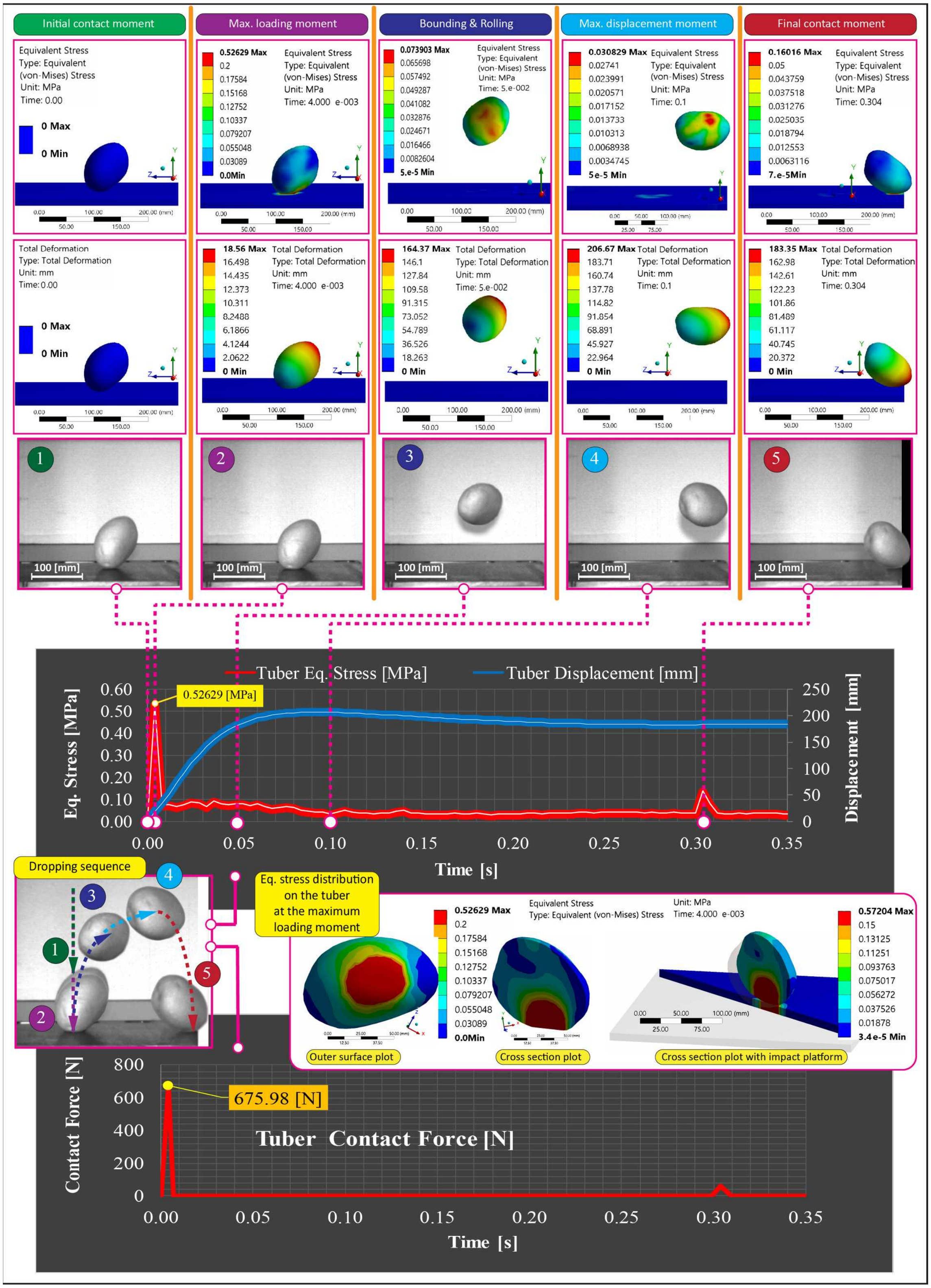

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