



THE CONKER SHELL: A BIOMIMETIC INSPIRATION FOR THE DESIGN OF LOAD-MITIGATING STRUCTURES?

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Date: June 10, 2020

I hereby declare that, except where specifically indicated, the work submitted herein is my own original work.

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Abstract

Load mitigating structures provide protection by reducing the loads transmitted to the protected object. This is made possible through their excellent energy absorption ability. A major design challenge is providing lighter structures without compromising energy absorption capability. To this end, research based on engineered designs has yielded significant progress towards overcoming this challenge. However, fruit peels and nutshells in nature may also provide some insight into this problem as they are capable of withstanding large impact loads when they drop from a tree. Their structures can inspire more the effective use of materials to achieve outstanding mechanical properties. The conker shell may possess such a capability, but the relationship between the structure and function of the shell would need to be understood.

This report presents research aimed at operating within the framework of biomimetic design to determine if the conker shell is a biological model for the design of load mitigating structures. The work involved six work packages. Firstly, because of the widely varying physical properties of the conker fruit, statistical analysis of the physical properties of the fruit was carried out to adequately describe the typical conker population. Following this, investigation of the conker shell microstructure under a microscope was carried out to determine the structure of the shell and aid in identifying a suitable material model to explain its mechanical behaviour under quasi-static loading. The next three work packages involved quasi-static compression of the fruit, the seed and the shell respectively. They were completed to ascertain their quasi-static mechanical behaviour and determine how the mechanical properties of the seed and the shell influence the mechanical behaviour of the whole system (the fruit). In addition, the loading rate and loading direction dependency of the fruit's mechanical behaviour were investigated. Finally, drop tests were carried out on the fruit to determine its mechanical behaviour under dynamic loading as well as ascertain the protective capability of the shell.

The results show that: (i)the fruit behaves similarly to an elastic spherical solid in compression with a Young's modulus of 1.11 ± 0.56 MPa, (ii)the seed behaves similarly

to a linearly elastic strut in compression with a Young's modulus of 4.16 ± 0.66 MPa and (iii) the shell behaves similarly to a closed-cell foam with a Young's modulus of about 0.5 MPa. The strength of the fruit linearly increases with loading rate while its strength and stiffness depend on loading direction. Also, considerable loads were transmitted to the seed during impact.

The results suggest that the seed is the primary load-bearing member of the fruit system and acts to withstand high loads under dynamic conditions with the shell providing limited energy absorption. This is shown by the loading rate dependency of the fruit. The loading direction dependency of the fruit suggests that it has potential as inspiration for the design of structures with a favoured orientation of loading and this can be an area of further research.

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1 Introduction

1.1 Background and Motivation

Load mitigating structures absorb energy during impact through deformation, reducing transmitted loads and accelerations. This in turn reduces the amount of damage to the protected object. The consequences of impacts can be dire. In 2014, 3,090 cyclists were killed or seriously injured in the UK, of which 45% suffered severe head injuries [1]. Load mitigating structures play a crucial role in ensuring structural integrity as well as safety. For example, helmet use can lead to a 42% reduction in the risk of fatal injuries and a 69% reduction in the risk of head injuries [2]. A major design challenge is producing lighter load mitigating structures without compromising their energy-absorbing ability. While there has been much research carried out on achieving this based on engineered designs, a new source of innovation gaining prominence is nature. The importance of emulating nature has been recognized because organisms in nature provide sustainable solutions to challenges. Some of which are similar to those faced by humans.

Most natural (or biological) materials are complex composites with mechanical properties that are often outstanding, considering the weak constituents from which they are assembled [3]. They often prove to be lightweight compared to human technology with the same capabilities. The process of identifying potential strategies in nature and emulating them in designs to achieve a sustainable future constitutes biomimetic design. Biomimetic design begins with the problem definition. In this report, we focus on the design of a structure that mitigates impact loading. This human challenge is then expressed as a biological challenge: ‘How does nature withstand impact?’. The next step is to discover an organism that exhibits a strategy relevant to the challenge and use it as a biological model. Then, the underlying principles behind the biological strategy are abstracted in design terms and emulated to develop a final design that is evaluated.

Fruit peels and nutshells, in general, provide good biological models for the design of load mitigating structures. This is because they can withstand large impact forces, relative to their size, following a drop from a tree. They have the primary structural function of protecting the inner fruit. The study of the relationship between their structure and function has not been carried out except on e.g. Pomelo peel, the macadamia nutshell and the green coconut shell. These studies were aimed at providing a relationship between the structure of the peel or shell and the outstanding impact properties, thereby making a case for their selection as biological models for impact load mitigating structures. Such studies may be advantageous in inspiring innovative designs of load mitigating structures and should be extended to other fruits such as the conker fruit.

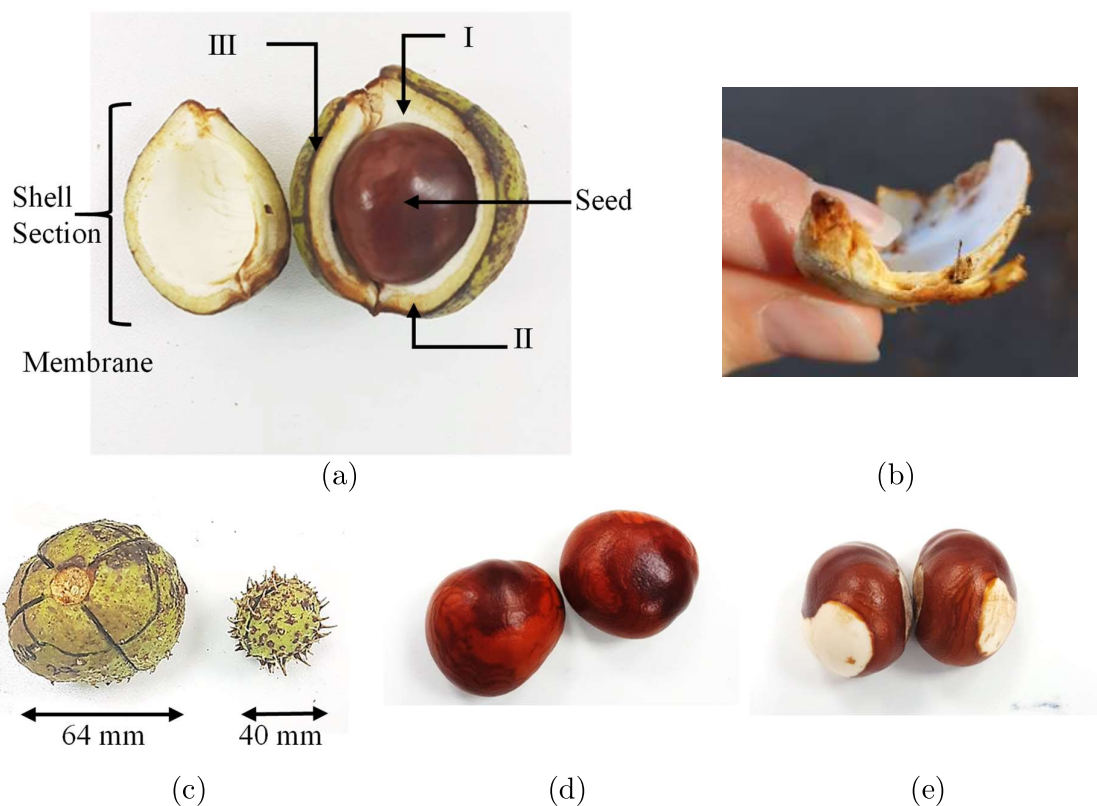


Figure 1.1: Conker fruit (a) Annotated components (b) Membrane (Courtesy of Dr Christelle Abadie) (c) Varying physical properties (d) Seeds of mature fruit (e) Seeds of immature fruit

The Horse chestnut (common name: Conker, scientific name: *Aesculus hippocastanum*) grows on trees that reach a height of over 30 m [4]. Its components are illustrated in Figure 1.1. It consists of a layered shell with an inner membrane and distinct layers as shown in Figure 1.1(a) and 1.1(b). The shell is covered by a green, often spike-covered, skin typically marked by three ridges. The shell encloses up to three seeds. In the following, the whole system (seed and shell) is referred to as the fruit. The size of the fruit can vary from about 10 mm to 120 mm, weighing about 50 g on average. Its seeds possess medicinal properties and boast a glossy brown colour when ripe as in Figure 1.1(d) but are either completely white or possess white patches when unripe (Figure 1.1(e)). It grows within temperate regions; cultivated in streets and parks including in the United Kingdom.

The conker was chosen because it has a high potential for energy absorption. The shell protects the seeds during impact following a considerable drop of about 30m. Assuming the conker fruit weighs about 50 g, this corresponds to an impact energy of about 15J, which is considerable given its size.

1.2 Design of Load Mitigating Structures.

In general, the performance of load mitigating structures is evaluated by the magnitude of peak force or acceleration transmitted. A crucial attribute of a load mitigating structure is its shock-absorbing properties which convert the kinetic energy to thermal energy through plastic deformation. Load mitigating structures come in several forms such as the crush zones in vehicles [5], foams [6], honeycomb structures [7], composite plates and sandwich panels. They are used in various applications such as within the automotive industry, aerospace industry and sports industry. Given the breadth of this field, only the literature concerning bicycle helmets was reviewed. This is because these are one of the most commonly used load mitigating structures, and they also possess a similar spherical geometry. When compared with a conker fruit, the helmet can be likened to the conker shell while the wearer's head can be likened to the conker seed.

With the threat of climate change, cycling presents a sustainable alternative to fuel-powered vehicles. Additionally, in the context of COVID-19, the need for social distancing has curtailed the use and operation of public transport services around the world. With this, cycling has increasingly been adopted by commuters. With more cyclists on the road, the need for efficient safety measures is increasingly crucial.

1.2.1 Load mitigation in the Bicycle Helmet

In bicycle helmets, load mitigation is usually provided by polymeric foams. Polymeric foams can be described as either open-cell or closed-cell. An open-cell foam consists of a network of struts which form cell edges as in Figure 1.2(a) while a closed-cell foam consists of solid membranes that close-off the cell faces shown in Figure 1.2(b). The closed-cell expanded polystyrene (EPS) being the most commonly used. According to Ashby and Gibson [8], the mechanical properties of a foam depend on its structural features such as the relative density, $\frac{\rho^*}{\rho_s}$ and the extent to which the cells are open or closed. These properties are also dependent on the cell-wall properties such as the solid density, ρ_s , Young's modulus and yield strength. Another key property is the densification strain which is the strain at which cell walls crush together. It can be estimated from the relative density using Equation 1.1.

The study of the mechanical properties of EPS foam and its deformation has been carried out extensively e.g. [6], [9], [10]. The typical stress-strain curve is depicted in Figure 1.2(c). A cubic cell model of its structure which is similar to that of an open-cell foam except for the presence of cell walls is illustrated in Figure 1.2(d). The stress-strain curve consists of three regions: (i) the linear elastic region at low strains, (ii) plastic collapse (plateau) region and (iii) densification region. The plastic collapse region has a curve with increasing slope due to the air compression within the cells of the sample. This is followed by a steep rise in stress indicating densification. EPS employs plastic collapse as the main mechanism for energy absorption, therefore most of the energy is absorbed in this region. The stress-strain relationship in this regime can be described by Equation 1.2 according to Gibson and Ashby [8].

$$\epsilon_D = 1 - 1.4 \frac{\rho^*}{\rho_s} \quad (1.1)$$

$$\sigma^* = 0.05 E_s \frac{\rho^{*2}}{\rho_s} + \frac{p_o \epsilon}{(1 - \epsilon - \frac{\rho^*}{\rho_s})} \quad (1.2)$$

Where σ^* is the stress, E_s is the Young's Modulus of the cell wall material, $\frac{\rho^*}{\rho_s}$ is the relative density of the foam, p_o is the internal fluid pressure. ϵ is strain and ϵ_D is densification strain. The second term on the right-hand side depicts the contribution from internal gas pressure, and this is what gives the stress-strain curve its rising slope.

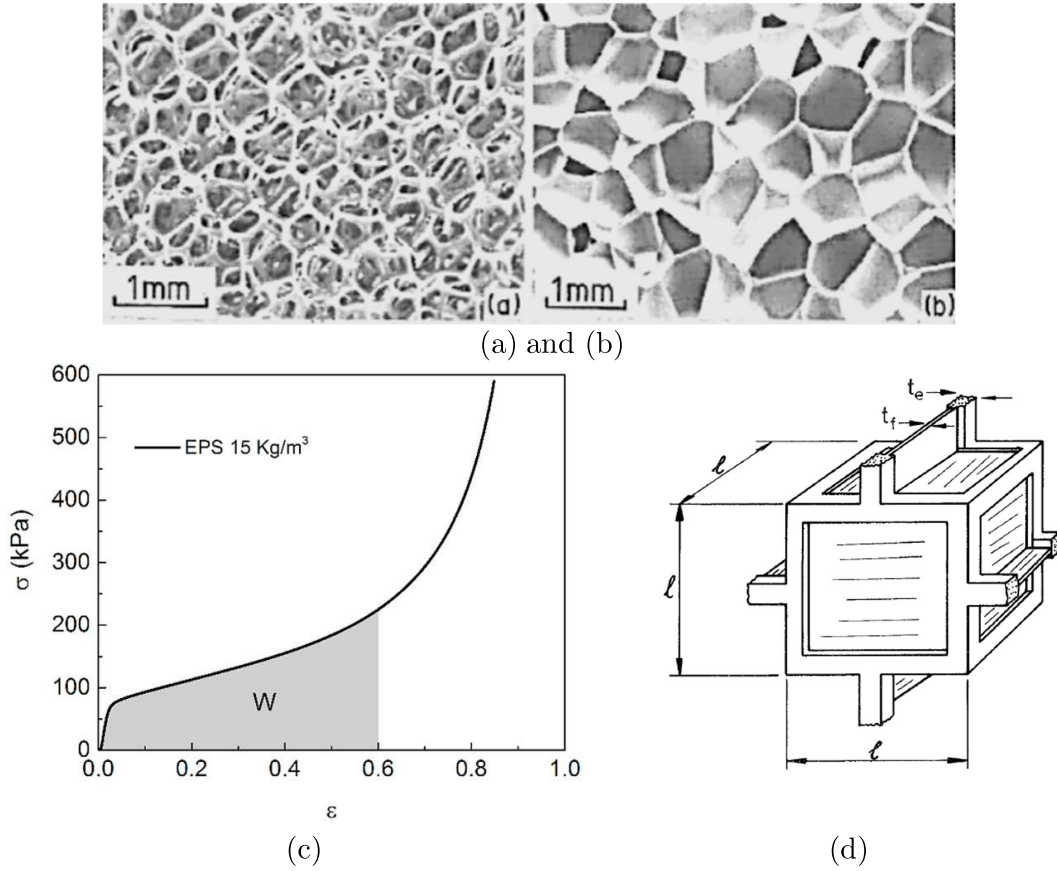


Figure 1.2: Foam structure and behaviour [8], [9] (a)Open-cell foam structure (b) closed-cell foam structure (c)Compressive stress strain curve for typical EPS (d) A cubic cell model for a closed-cell foam, showing the edge thickness, t_e , and the face thickness, t_f

1.2.2 Bicycle Helmets Safety Standard [12]

BS EN 1078 is the most commonly used safety standard for bicycle helmets in the British/European market [11]. This test is carried out on a head form and helmet set-up weighing about 5 kg. To test the shock-absorbing capacity, dropped-weight tests using both a flat anvil and a kerbstone anvil are carried out. The shock-absorbing capacity is measured according to the peak deceleration experienced by the head form, which must not exceed 250g, where g is 9.81 m/s^2 . This is for an impact velocity of 5.42 m/s and 4.57 m/s when impacted with a flat and kerbstone anvil respectively. This level of deceleration corresponds to a maximum threshold load of 12.15 KN. The acceleration is measured using a tridirectional accelerometer in the head form centroid.

This test set up suggests that adequately determining the shock-absorbing capacity of the conker shell would require measurement of the acceleration of the seed within during a dropped impact. However, this cannot be done without causing irreparable damage to the specimen, so literature on drop testing was further reviewed to see if this can be estimated in some other way.

1.2.3 Drop Testing

Drop tests can either be free-fall where the sample is dropped from a height or dropped weight, where a weight is dropped unto the sample. In engineering testing, the dropped-weight test is more commonly used for the characterisation of dynamic properties. In dropped-weight tests, the key measurements are the impact energy and the energy absorbed during impact, the acceleration and force during impact as well as the force transmitted through the sample. The impact energy can be calculated from the velocity that is measured either from the distance travelled between two photosensors [13] or by using an optical laser measurement system [14], for example. The energy absorbed can be calculated using similar systems or measured from the change in potential energy during impact using a high-speed camera and video analysis software. The force and acceleration during impact can simply be measured using a load cell and accelerometer

attached to the impactor while the force transmitted through the sample is usually measured using a load cell upon which the sample is mounted.

N.J. Mills [15] provided a relationship between the force transmitted by a bicycle helmet foam liner that yielded during impact, F , the liner crush displacement, x , the yield stress, σ_y and the radius of curvature, R , shown in Equation 1.3. Considering the contact geometry in Figure 1.3, it was assumed that the liner crush was much less than the radius of curvature, and this equation only applies when the strain is increasing. This study showed that the force transmitted during impact could be estimated from mechanical properties of the helmet under quasi-static loading, and this principle proves useful for this research.

$$F = 2\pi R\sigma_y x \quad (1.3)$$

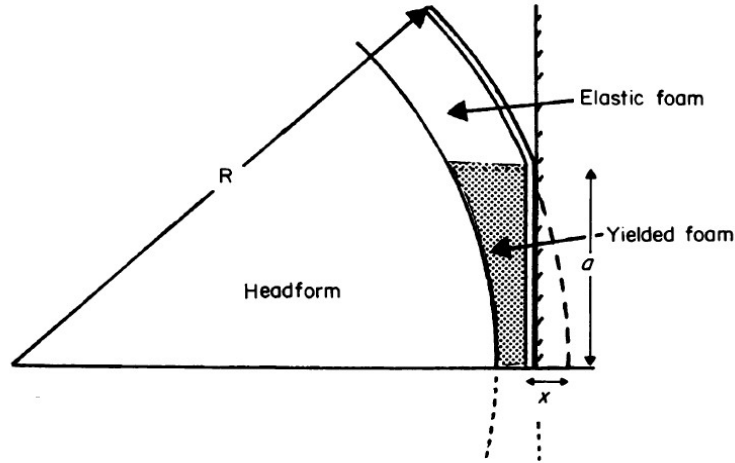


Figure 1.3: Contact geometry between a flat surface and the helmet [15].

1.3 Mechanics of Fruits

Testing of fruits and nuts is primarily carried out within the food and agricultural industry. In agriculture, the study of the mechanical properties of fruits is built on reducing mechanical damage (bruising) along the value chain as well as in the design of both harvest and post-harvest machinery.

1.3.1 Compressive Loading

In agriculture, the compressive behaviour is described in terms of the onset of rupture of the fruit with the rupture force, rupture energy and rupture deformation being the key parameters [16], [17]. To better understand the interaction between the fruit and a surface, various mechanical models have been employed [18]. Specifically, the model most associated with the interaction of a fruit with a flat surface is the Hertzian contact model which has been used successfully to estimate the Young's Modulus of elasticity of the fruit e.g. [19], [20], [21].

1.3.1.1 Hertzian Contact Model for Spherical Contact

This model describes the case of contact between two spheres or a sphere and the surface of a half-space. It has the following assumptions:

- 1) The surfaces are smooth and non-conforming
- 2) The contact area is small compared to the size of the bodies
- 3) And the bodies are isotropic and elastic

For the contact geometry illustrated in Figure 1.4 in which a rigid sphere is in contact with an elastic half-space, the relationship between the applied load and deformation is shown in Equation 1.4.

$$F = \frac{4ER^{\frac{1}{2}}}{3(1-\nu^2)}d^{\frac{3}{2}} \quad (1.4)$$

Where F is the applied load, E is the Young's Modulus of the elastic half-space, d is the deformation, R is the radius of the sphere and ν is the Poisson's ratio of the elastic half-space.

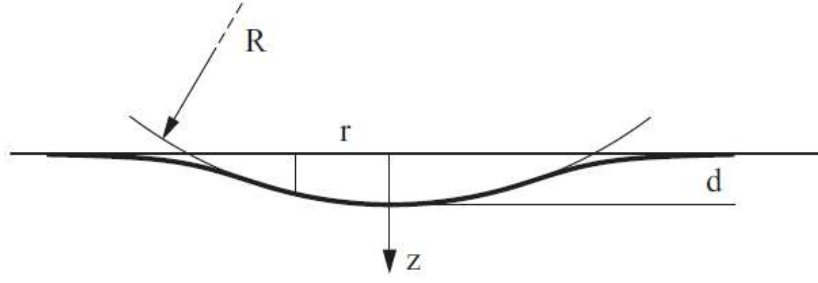


Figure 1.4: Contact between a rigid sphere and elastic half space [22]

1.3.2 Impact loading

In the agricultural industry, impact testing is essential because collisions of the fruits with surfaces and other fruits commonly occur in post-harvest activities. It usually aims to evaluate force-deformation behaviour of the fruit, thereby, requiring measurement of force, deformation, time of impact and coefficients of restitution [23]. It is categorized into drop tests and pendulum tests, although the focus of the literature review was on drop tests. The drop test procedure is similar to that used in engineering testing; however, its focus is on evaluating mechanical damage and designing cushioning materials for handling and transport. Once again, the Hertzian theory of contact can be applied in modelling impact in fruits. It describes the interaction between a sphere and a thick plate during impact. This is provided that the initial velocity is low corresponding to drop heights of 2 cm-40 cm [23]. According to W.J. Stronge [24], the relationship between peak load and maximum compression of the sphere during impact is illustrated in Equation 1.5.

$$\delta_c = \left(\frac{15m(1 - \nu^2)}{16E\sqrt{R}} \right)^{\frac{2}{5}} V_o^{\frac{4}{5}} \quad (1.5)$$

Where δ_c is the maximum compression during impact, m is the mass of the sphere and V_o is the impact velocity.

1.3.3 Material Characterisation of Fruits in Biomimetics.

In recent years, studies have been carried out on characterising fruits as biomimetic models. The Pomelo fruit (scientific name: *Citrus Grandis*) being the prime example.

It is a large citrus fruit (can weigh up to 2 kg) with a thick peel. A study by Siedel et al. [25] showed that the fruit has the potential to dissipate up to 90% of its impact energy in the fruit wall and pulp when dropped from a height of 6 m. Another study by Fischer et al. [26] focused on the mechanical testing of the peel of this fruit. It also proposed the design a functionally graded foam that mimics the peels cellular structure and tested it. They carried out a structural analysis of the peel and observed a gradual transition between the exocarp and mesocarp, which are the outer and middle layer of the fruit. They hypothesised that this lack in abrupt change reduced the risk of delamination during impact as there is a transition in physical and mechanical properties across the layers. Tensile tests were carried out, which yielded a Young's modulus value between 0.39 and 0.98 MPa. Because of this low value, it was concluded that the ability to dissipate large amounts of energy must be as a result of the structural composition of the peel. However, these studies do not consider the compressive behaviour of the peel or the possible load sharing and interaction between the peel and the pulp.

Contrary to the Pomelo peel, which from a material point of view can be interpreted as an open-pored foam whose struts are pressurized and filled with liquid [27], the green coconut is also another fruit that has been considered as a biological model. The green coconut shell from a material point of view is similar to a fibre-based composite with distinct composition in each layer. Graupner et al. [28] carried out a free-fall drop test on the coconut, unnotched Charpy impact test on the pericarp and tensile tests on the fibres of each layer of the pericarp. The analysis of the individual components of the coconut pericarp revealed a remarkable impact performance and a decrease in strength and stiffness from the outer exocarp to the inner mesocarp. This suggests a gradient in mechanical properties across the layers.

1.4 Objectives

As per the biomimetic design process described in Section 1.1, this project sets out to discover a biological model for impact that can inspire lighter impact mitigating structures with the study of the mechanical behaviour of the conker fruit at its core.

The question to be answered is: ‘Can the conker shell inspire the design of better impact mitigating structures?’ To achieve this, six key work packages (WP) were completed, as per below:

- **WP1: Physical Property Characterisation** – There is a large range in physical properties of the conker population e.g. Figure 1.1(c). Because of this, statistical analysis is needed to outline the typical physical properties that accurately describe the conker population.
- **WP2: Shell Microstructure Characterisation** – It is likely that the structural properties of the shell dictate its mechanical behaviour. Therefore, this work package aims at observing the structure of the shell on the micro-scale and macro-scale. The structure type is inferred by comparison of microstructure with those illustrated in the literature.
- **WP3: Quasi-static Compression of Fruit** – The behaviour of the fruit under quasi-static loading can inform on the behaviour under dynamic load. This series of tests aim at determining the mechanical behaviour of the seed and shell system under quasi-static loading as well as investigating dependence on physical properties, loading rate and loading direction. This also provides insight into the interaction between the shell and the seed.
- **WP4: Quasi-static compression of Seed** – It is recognised that the seed may play a significant role in the behaviour of the whole fruit. Therefore, this work package seeks to determine the mechanical properties of the seed and infer its contribution to the behaviour of the system.
- **WP5: Quasi-Static compression of Shell** – The shell is considered to be the most crucial component for energy absorption. As it is the compressive deformation that dictates energy absorption, this work package aims to determine the behaviour of the shell under quasi-static compression and infer its energy absorption capabilities.
- **WP6: Drop test** – It is recognised that the behaviour under quasi-static conditions may not adequately reflect real-life impacts. This work package aims to

determine the mechanical behaviour of the fruit during impact as well as test the limits of the energy absorption capacity. Free-fall drop tests are crucial for determining mechanical behaviour under dynamic loading while dropped weight tests are required to determine the energy required for rupture during impact. However, due to the design of the test set-up, friction between the impactor and the drop tower greatly affected results causing analysis of the dropped-weight test results not to be carried out.

The overall objective of this project is to determine the mechanical behaviour of conker fruit and its components under quasi-static and dynamic loading conditions and the factors affecting their behaviour.

2 Apparatus and Experimental Testing

Due to the timing of the conker season that ranged from the middle of August to the beginning of October, an internship was completed over the summer break from August 12th to October 2nd to complete a comprehensive test programme and collect the data needed for the 4th year project. None of the data was analysed during the internship. The analysis of the data is what constituted this 4th-year project.

2.1 Sample Collection

Samples were collected primarily from two locations within the Cambridge area: Midsummer Common close to the city centre and the lane between Gravel Hill Farm and Huntingdon road in Eddington, Northwest Cambridge. Conker fruits were picked directly from the trees on the morning of testing. To aid picking, a variable-length fruit picker was acquired with a 0.9 m collapse length and a fully extended length of 2.4 m. Therefore, the heights from which conker fruits were picked from ranged from about 1 m to about 5 m (given the height of the gatherer was 1.8 m). Both cracked and uncracked conker fruits were collected (as the shells of older conker fruits do start to crack before falling).

Care was taken to ensure only mature conkers were collected by not picking conkers that required considerable force to be plucked. A further check of the conker seed colour was achieved post-testing (see Section 1.2). In the experiment, the conker fruits tested were chosen so that about 90% of the conkers had a mass between 35 g and 70 g.

2.2 Determination of Physical Properties

Testing was carried out on three kinds of specimens: whole fruits, seeds and shell sections. To determine the size of each specimen, linear dimensions of characteristic lengths were measured using Vernier callipers to an accuracy of 0.01 mm, and the mass of each specimen was measured using an electronic balance to an accuracy of 0.01 mm. The specific measurements taken depended on the kind of specimen as well as the kind of test.

Because of the nature of the ellipsoidal geometry of the conker fruit, there exist three main dimensions measured for each sample, the length, major diameter and minor diameter, illustrated in Figure 2.1. Moreover, the geometric mean of these quantities was calculated as it was a useful property for analysis. Similar measurements were made for the seeds tested as well. The average thickness of the shell was also measured. Finally, the spike level was measured qualitatively based on the length of spikes to determine if the mechanical properties are affected by the presence of spikes. It was measured on a scale of 0 to 4 as illustrated in Figure 2.2 with 0 meaning completely smooth (no spikes at all) and 4 meaning very long spikes.

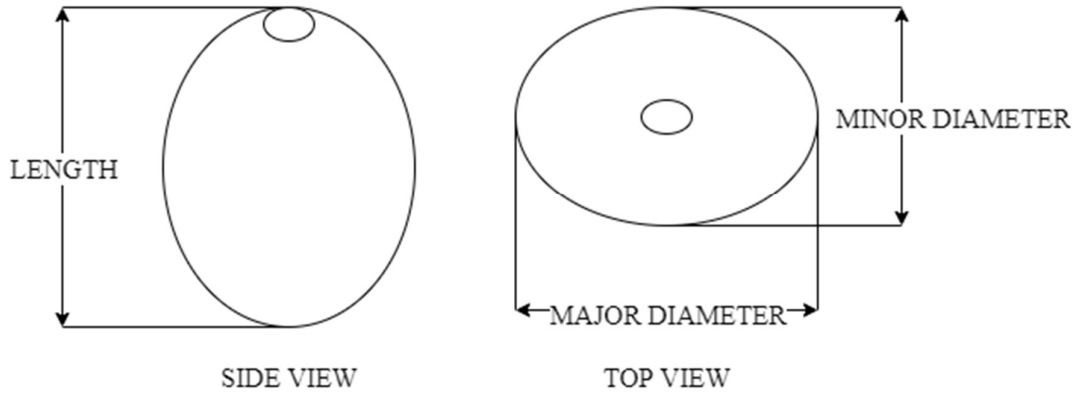


Figure 2.1: Major Dimensions used to characterise the Conker fruit



Figure 2.2: Spike level

2.3 Quasi-static Testing and Analysis Procedure

All quasi-static tests were carried out using the Instron 5544 machine in the downstairs bioengineering lab with a 2 KN loadcell and a preload of 1 N. These tests were carried out to determine the quasi-static behaviour of all components of the conker fruit. The results of three classes of tests carried out were analysed– the whole fruit crush, seed crush and shell crush. These tests are illustrated in Figure 2.3.

2.3.1 Whole fruit crush (WC1, WC2, WC3, WC4, WC5, WC6)

This class of tests was carried out on an entire uncracked mature fruit. The fruit was compressed along its length, as shown in Figure 2.3(a) until failure. Although most of the tests were carried out at a displacement rate of 10 mm/min (WC1), some tests were carried out at 2 mm/min (WC2), 5 mm/min (WC3) and 15 mm/min (WC4) to determine the effect of loading rate on the mechanical behaviour. To determine the effect of loading direction on the mechanical behaviour, some fruits were loaded along

the major (WC5) and minor (WC6) diameters at 10 mm/min. The mechanical behaviour was expressed in terms of Young's modulus, failure load and failure strain.

2.3.2 Seed crush (NC)

In this test, the seed of the conker fruit was crushed along its length as in Figure 2.3(b) similar to the whole fruit at 10 mm/min until failure. This was done to characterise the mechanical behaviour of the seed. The mechanical behaviour was also expressed in terms of Young's modulus, failure load and failure strain.

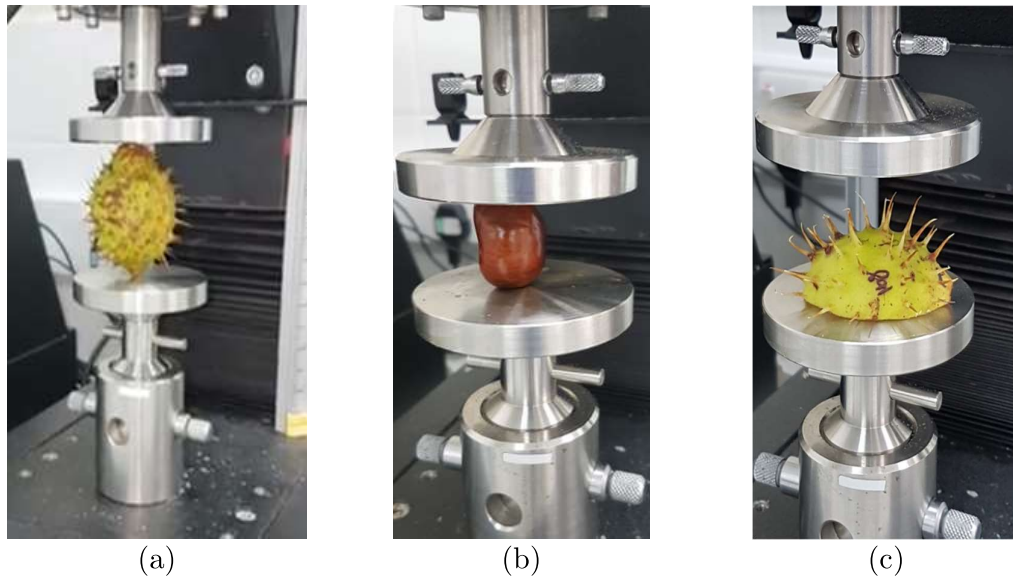


Figure 2.3: Testing Configuration (a)Fruit compression (b)Seed compression (c)Shell compression

2.3.3 Shell crush test (SC1, SC2)

Specimens were obtained by using a scalpel to cut the shell along the ridges and extract the portion between the ridges. This specimen was crushed between two flat plates as shown in Figure 2.3(c). Specimens were selected from both untested and tested conker fruits. Specimens were tested until a load of 2 KN was reached as the failure load exceeded this value. The microstructure was characterised and expressed in terms of relative density.

2.4 Drop testing

Drop testing was carried out to ascertain the energy absorption ability of the shell during impact as well as to estimate the impact energy required for failure of the conker.

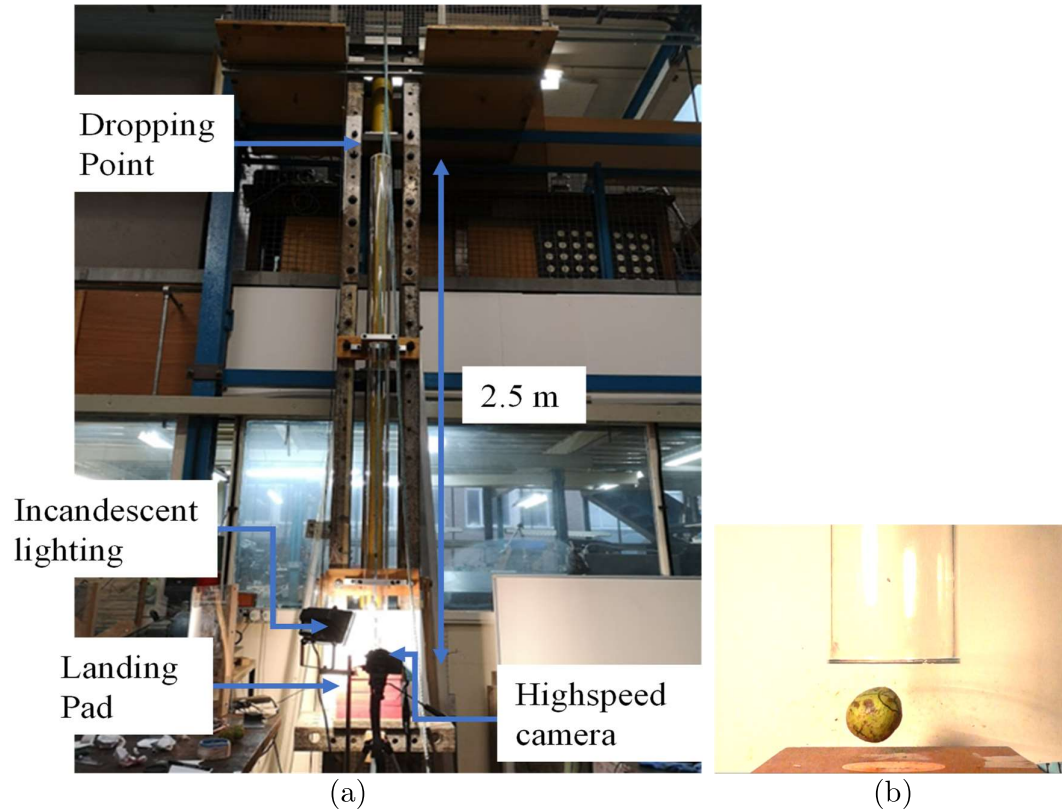


Figure 2.4: Drop test (a)Set-up (b)Landing pad

2.4.1 The experimental Set-up

The drop test set up in Figure 2.4(a), consisted of the drop tower, a highspeed camera to capture a video of the impact, incandescent lighting to improve picture quality and a rubber landing pad (Figure 2.4(b)). The drop tower in the Mechanics research lab was used to carry out the drop tests on the entire fruit. It consisted of a 2.5 m long and 95 mm interior diameter Perspex tube. The Sony RX10 ii camera with a maximum frame rate of 1000s^{-1} was used for capturing the impact within a 2-second duration. The Tracker software was used to derive data for displacement, velocity, acceleration and energy absorption. Markings were made on the conkers to provide more distinct points for tracking.

2.4.2 Free-fall dropped test (DT1)

Free-fall drop tests were carried out on fruits dropped from a height of 2.5 m above the landing pad. The fruits were dropped by hand from the top with the help of the lab technician on a ladder.

2.5 Microscopy

The Olympus SZX16 stereomicroscope in the upstairs bioengineering lab was used to study and capture the structure of a fresh conker shell. A thin slice of the shell cross-section was placed under the microscope. Images of the entire cross-section at 0.7x to 1.55x magnification were captured. The structure of each layer at 11.5x magnification was also captured. Images were only captured before oxidation of the specimen had progressed considerably.

In February, further attempts at characterising the microstructure of the shell were carried out. For this instance, frozen samples were moved from the freezer to the fridge in the downstairs bioengineering lab and left at a temperature of about 4°C for about 16 hours during which the samples were able to defrost.

2.6 Test Programme

The summary of all the tests carried out during the internship is outlined in Table 2.1. Further information on the testing procedures and apparatus can be found in [29].

Table 2.1: Testing Programme for Summer Internship

Instron tests			
Type	Test No.	Properties	No. of tests
N-S crush	WC1	LR=10	50
	WC2	LR=2	5
	WC3	LR=5	5
	WC4	LR=15	5
Major crush	WC5	LR=10	5
Minor crush	WC6	LR=10	5

Seed crush	NC1	LR=10	20
Hemisphere crush with seed*	HC1	LR=10	14
Hemisphere crush without seed*	HC2	LR=10	20
Shell crush	SC1	LR=10	20
Cyclic shell crush*	SC2	LR=10, 2 loading cycles	2
		Subtotal	151
Drop Tests			
Type	Test No.	Properties	No. of tests
Free-fall	DT1	-	102
Dropped weight	DT2	M=50 g	10
	DT3	M=150 g	2
	DT4	M=250 g	3
	DT5	M=350 g	6
	DT6	M=450 g	5
	DT7	M=550 g	2
	DT8	M=650 g	2
		Subtotal	132

Test* - tests whose results were not analysed.

The data of the highlighted tests were not analysed because the test set-ups and sample preparation methods significantly affected the outcomes of the experiments leading to inconsistent results.

3 Fruit Population Characterisation

3.1 Physical Properties of Population

Table 3.1 summarises the physical properties measured during the experiment and the number of samples used for each measurement. The mass of the whole fruit ranged from 13.2 g to 122.5 g with a mean of 48.4 g. The shell mass ranged from 10.5 g to 58.7 g having with a mean of 27.5 g. On average, the length of the fruit is the largest dimension with a mean of 49.4 g compared to 46.1 g and 42.5 g for the major and minor diameters, respectively. The same principle applies to the seed as well. For this project, when estimating a mean diameter for the fruit modelled as a sphere, the geometric mean value was used. On average, the shell is thickest on the at the top and thinnest at the middle belt. This may be because the fruit connects to the stalk at the top therefore, more material is required to ensure a stronger connection at this point.

Table 3.1: Physical Properties of the population

Measurement	Population	Mean	Standard Deviation
Whole Mass (g)	304	48.4	11.7
Seed Mass (g)	172	21.4	7.1
Shell Mass (g)	172	27.5	5.8
Length (mm)	297	49.4	4.8
Major Diameter (mm)	297	46.1	4.7
Minor Diameter (mm)	297	42.5	3.3
Geometric Mean Diameter (mm)	297	45.9	3.6
Seed Length (mm)	60	33.3	2.0
Seed Major Diameter (mm)	60	30.2	2.6
Seed Minor Diameter (mm)	60	24.0	2.5
Shell Thickness (mm)	173	6.9	1.2
Spikiness	284	1.9	1.3

The distribution of these physical properties was expected to follow a normal distribution which expresses natural variability. This was true for the length, the diameters and shell thickness (a typical distribution illustrated in Figure 3.1(b)). However, this did not apply to the mass (Figure 3.1(a)) as its distribution skewed to the right when compared to the normal distribution fit. This is because it was intended that the samples collected would range from 40g to 60g. Therefore, most of the samples outside this range were discarded with fruits below this range, having a higher likelihood of being discarded.

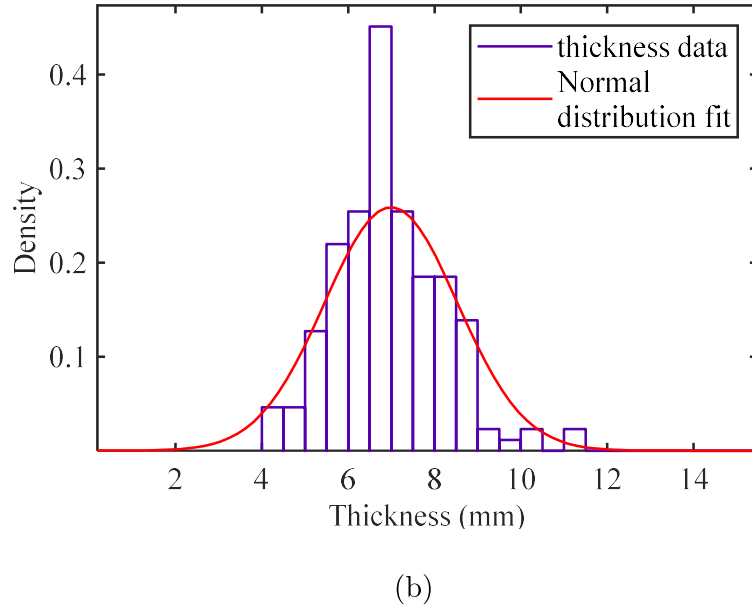
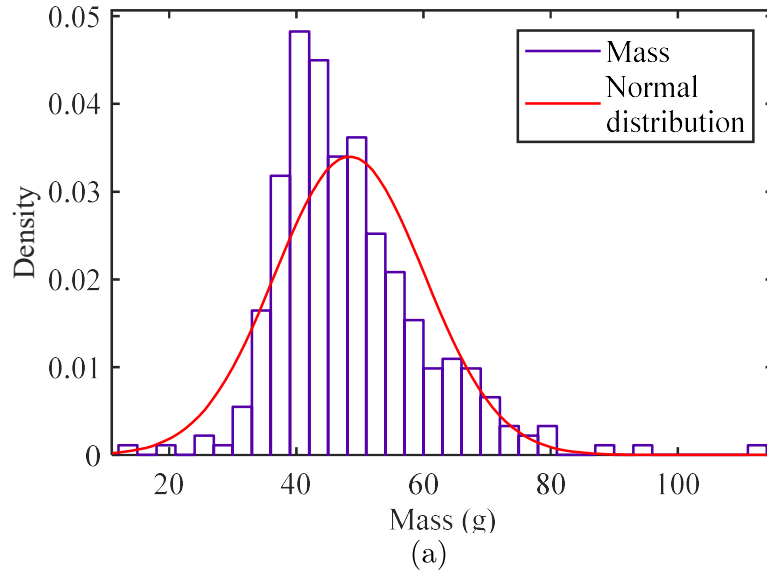


Figure 3.1: Distribution of physical properties of the conker population (a) Distribution of mass (b) Distribution of thickness

3.2 Relationship between Physical Properties

The dependency of thickness on the size was investigated. This was done to verify if the shell thickness can be estimated by considering the size of the fruit. These quantities were plotted against each other as illustrated in Figure 3.2. As shown, there is no correlation between thickness and the size of the fruit

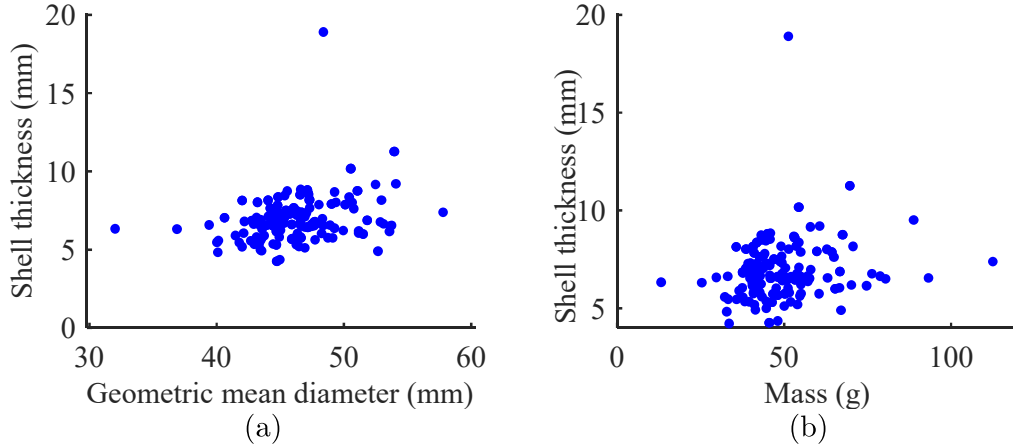


Figure 3.2: Dependence of internal properties on external properties (a) Shell thickness against fruit diameter (b) Shell thickness against fruit mass

4 Investigation of Shell Microstructure

As shown in Figure 4.1(a), the conker shell resembles a composite consisting of four distinct layers of cellular material. These are the inner membrane (I), the middle layer (II), the outer layer (III) and the spiky green skin (See Figure 1.1(a)). The membrane can easily be peeled off while the other layers are inseparable.

A close up of the inner, middle and outer layers are shown in Figures 4.1(b), 4.1(c) and 4.1(d) respectively. It was observed that each of these layers comprised of a fluid-filled cellular structure with distinct morphologies. Figure 4.1(e) shows the captured structure of the shells of defrosted samples. The observed structure, when compared with the structure of an open-cell foam (Figure 1.2(a)) and closed-cell foam (Figure 1.2(b)), its structure is similar to that of open-cell foam. However, the samples were severely degraded on defrosting. The green skin turned brown and the shell could no longer hold its fluid with a light touch immediately causing the seepage of the fluid. This could have greatly affected the structure of the shell.

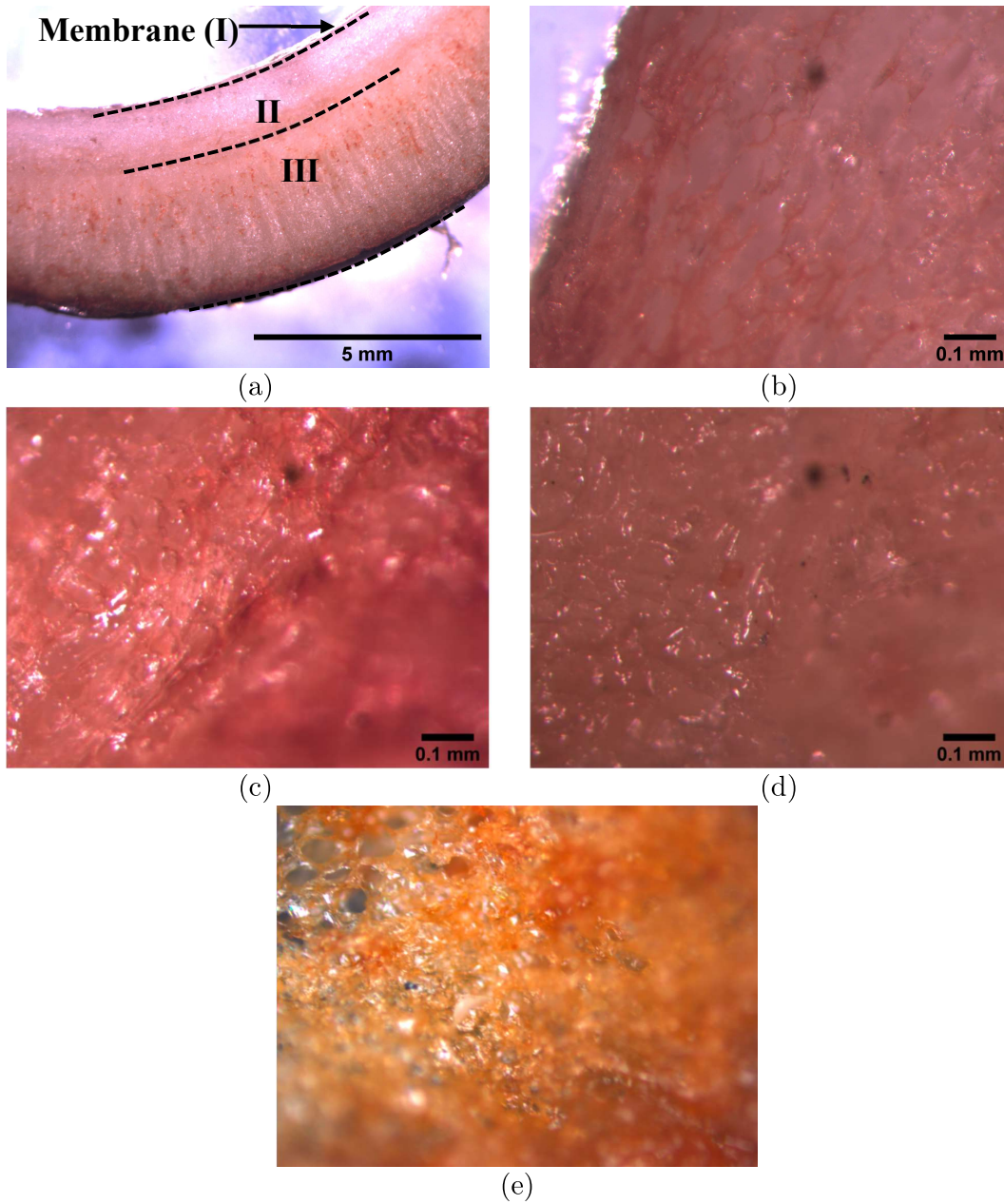


Figure 4.1: Conker Shell Structure (a) Layers of conker shell (b) Close-up of membrane (c) Close-up of middle layer (d) Close-up of outer layer (e) Magnified shell microstructure

5 Quasi-Static Characterisation of Mechanical Properties

5.1 Mechanical Behaviour of the Conker Fruit (WC1-WC6)

5.1.1 Deformation Behaviour

A typical force-deflection curve until failure for the WC1 test is illustrated in Figure 5.1(a). At the point of failure, there is a significant drop in load at a given deflection following crack propagation that initiated at the top and travelled along a ridge. There is an apparent strain-hardening response demonstrated by a percentage increase in deflection leads to a higher percentage increase in load. This is due to the near-spherical form of the fruit. As the load increases, the true area of contact between the fruit and the compression plates increases which consequently reduces the compressive stress increase on the fruit. Therefore, to achieve the same amount of deflection (due to the same amount of compressive stress), a higher load is required.

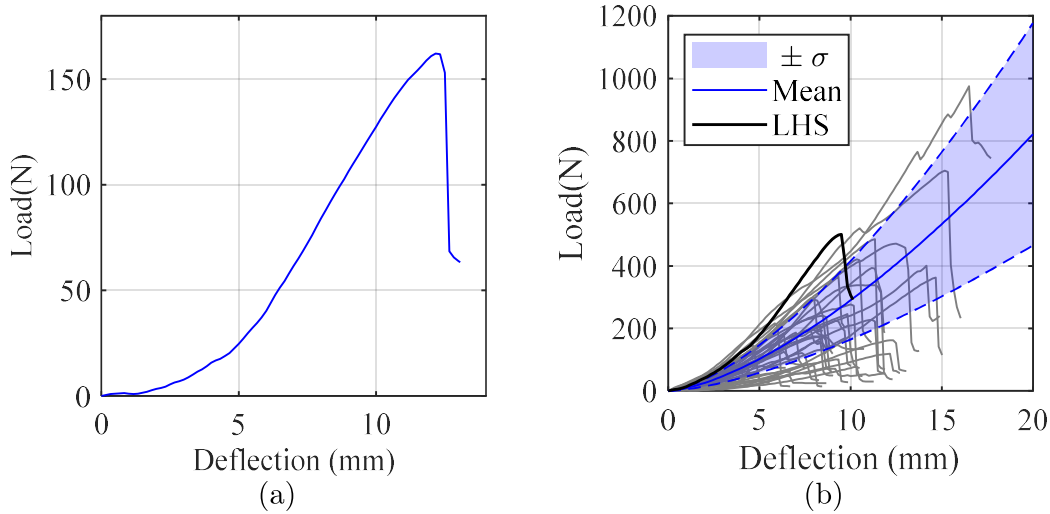


Figure 5.1: Fruit compression force deflection curve (a)Typical curve (b) Curves for all samples, mean curve with dispersion and curve in (a) highlighted

In terms of strength of the fruit, the failure load varies widely from 48.6 N to 974.7 N and the average was calculated as 248.1 ± 185.0 N respectively. Due to the range in lengths of the samples from about 40 mm to 70 mm, the failure strain, taken as the

ratio of the failure deflection to the length of the sample, rather than failure displacement was used to characterise strength. It came to an average of 0.18 ± 0.06 . Because of this wide range of mechanical performance, it was hypothesised that this was due to the wide range of physical properties (Section 3.1). Therefore, an investigation of mass and geometry effects on mechanical behaviour was proposed in Section 5.1.3.

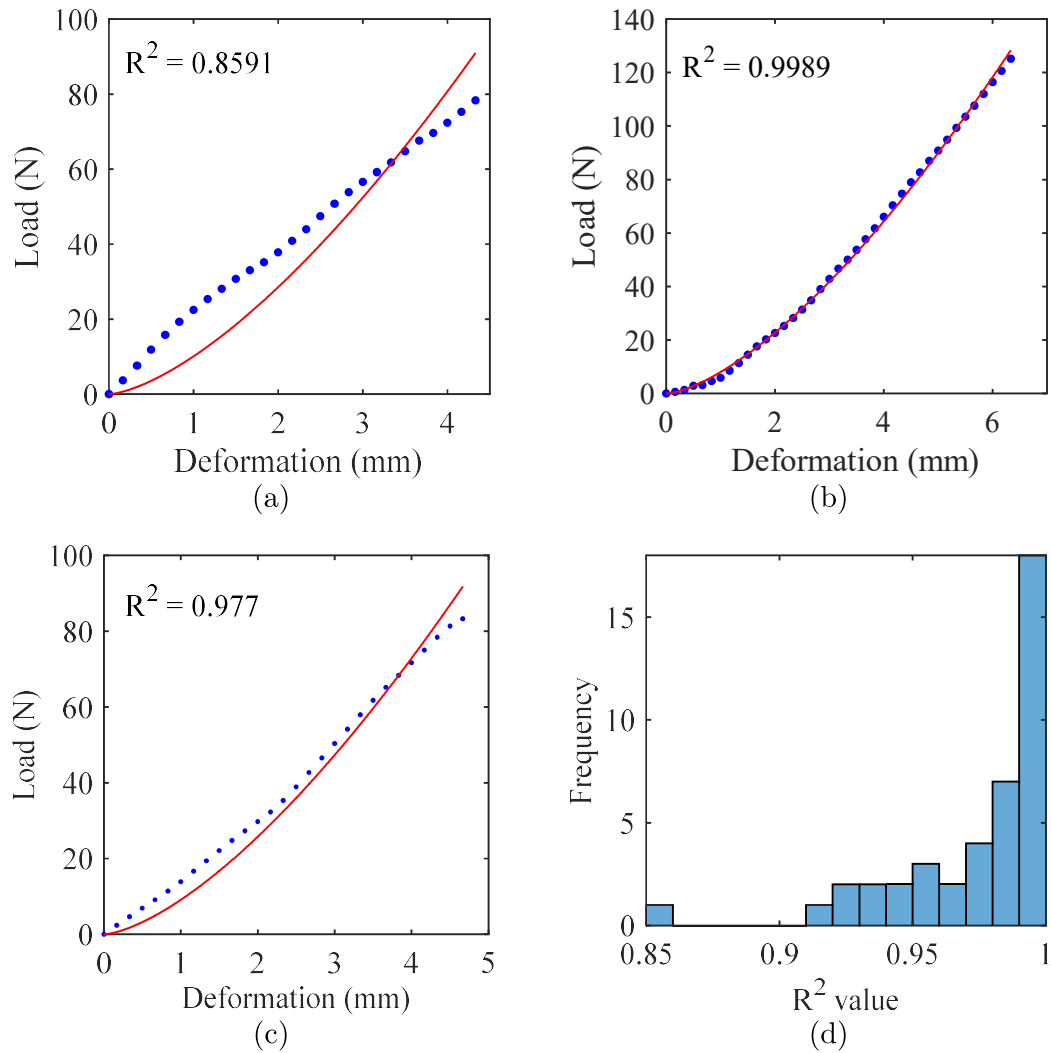


Figure 5.2: Fit of WC1 data to Hertzian Model (a)Worst fit (b) Best fit (c) Average fit (d)Distribution of r-squared value

5.1.2 Investigation of Stiffness

The Equation 1.4 can be adapted to depict the relationship between compression load and deflection of a sphere being compressed by rigid plate and was fit to the force-deflection data. The fruit was assumed as a sphere with the radius being half of the geometric mean diameter. A Poisson's ratio of 0.4 was assumed as it is a value commonly used when analysing mechanical properties of agricultural produce [20]. The r-squared value to characterise the quality of the fit was calculated.

The data was in good agreement with the model as illustrated in Figure 5.2 with an average r-squared value of 0.972 and over 80% having a value greater than 0.95. This suggests that the fruit obeys the Hertzian contact model and behaves similarly to an elastic spherical solid in compression. From this, the Young's Modulus of each sample was calculated. Thus, the estimated mean Young's Modulus was 1.11 ± 0.56 MPa, and these are illustrated in Figure 5.2(b). However, the second assumption of the Hertzian contact model, as in Section 1.4.1.1 states that the contact area must be small compared to the size of the sphere. This could not be measured directly during the experiment but would require a tactile sensor and measurement system to be accomplished.

5.1.3 Mass and Geometry Effects

The effect of fruit size on the failure load, failure strain and Young's modulus was investigated. There was no apparent correlation between the mechanical properties and the mass and length as illustrated in Figure 5.3 and 5.4. There was a similar result for the major diameter and minor diameter. However, the data exhibit a linear upper bound when the failure load and failure strain are plotted against the dimensions of the conker. This suggests that smaller fruits are more likely to fail at a higher load than larger fruits. This may be due to a natural mechanism to allow the healthiest seeds to be dispersed easily.

This lack of correlation may be due to the lack of consideration of moisture content. It can be hypothesised that the lower the moisture content, the lower the failure load. Moisture may have been lost by evaporation while the fruit is maturing. From

experience, it was apparent that conker fruits that have been mature for longer have lower moisture as conkers picked close to the end of the season had a dryer feel. It may be that the shell is pressurised by the fluid, so the loss of moisture leads to stress concentrations at obvious defects in the fruit such as the ridges along the surface and the stalk connection at the top providing points of weakness which make it easier to rupture the fruit.

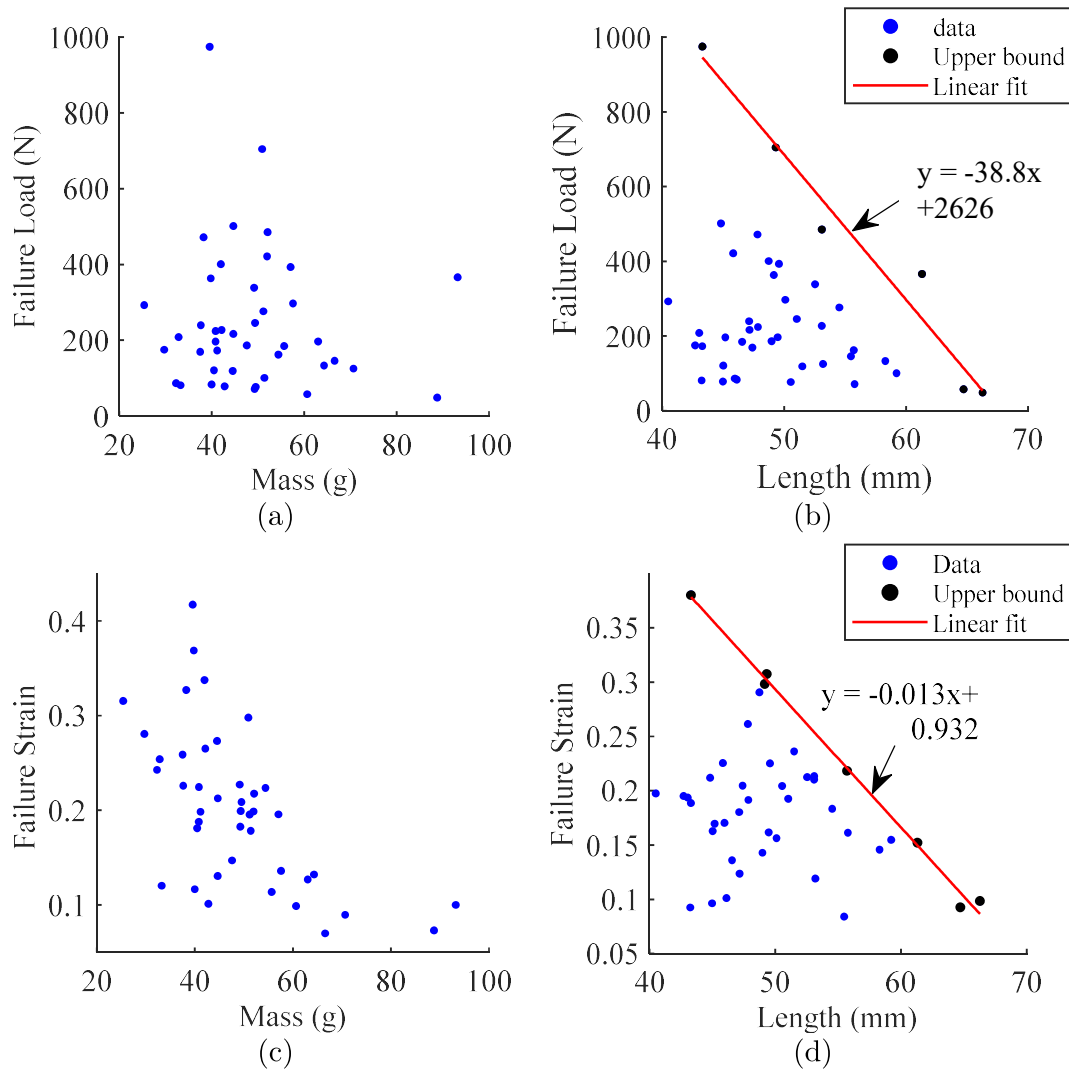


Figure 5.3: Dependence of strength on physical properties (a) Failure load against mass (b) Failure load against length (c) Failure strain against mass (d) Failure strain against length

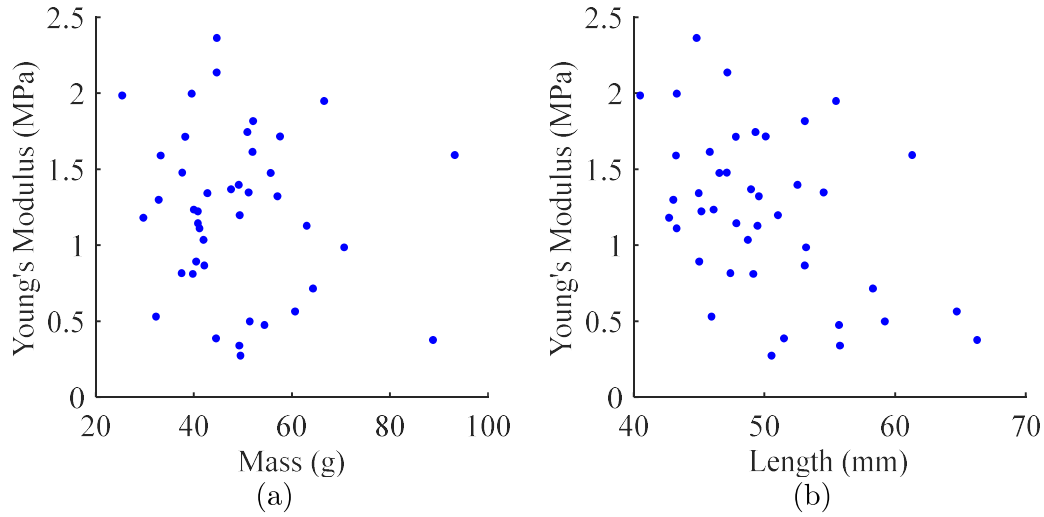


Figure 5.4: Young's Modulus dependence on physical properties (a) Young's modulus against mass (b) Young's modulus against length

5.1.4 Loading Rate and Loading direction effects

The results of investigating the effect of loading rate and loading direction on the failure load, failure strain and Young's modulus are illustrated in Figure 5.5. Figure 5.5(c) illustrates the relationship between Young's Modulus and loading rate. There seems to be no correlation suggesting that stiffness is independent of loading rate. On the other hand, failure load and failure strain in Figures 5.5(a) and 5.5(b) increase linearly with failure strain suggesting that the fruit would exhibit higher strength under dynamic conditions.

Figure 5.6 compares the Young's modulus, failure strain and failure load with loading direction expressing each quantity as a ratio of the corresponding result along the lengthwise direction. It shows that the fruit is weakest along the lengthwise direction, strongest along the minor diameter but stiffest along the major diameter. The difference in failure load and strain may be due to the geometry of the conker which would lead to varying areas of contact when loaded along different directions. For loading along a certain direction, the area of contact is dependent on the curvature at the point of contact which in turn, is dependent on the dimensions of the conker along the other two perpendicular directions. For example, when loading along the lengthwise direction,

the area of contact would be dependent on the major diameter and minor diameter. As seen in Section 3.1, the length is typically greater than the major diameter. Therefore, the area of contact along the minor diameter is the largest because it is dependent on the largest dimensions. This leads to the stress applied at a given force being the lowest compared to the other two directions requiring a larger force to be applied for failure to occur at a given stress. Hence, this explains why it is strongest along this direction. The opposite is true for compression along the length.

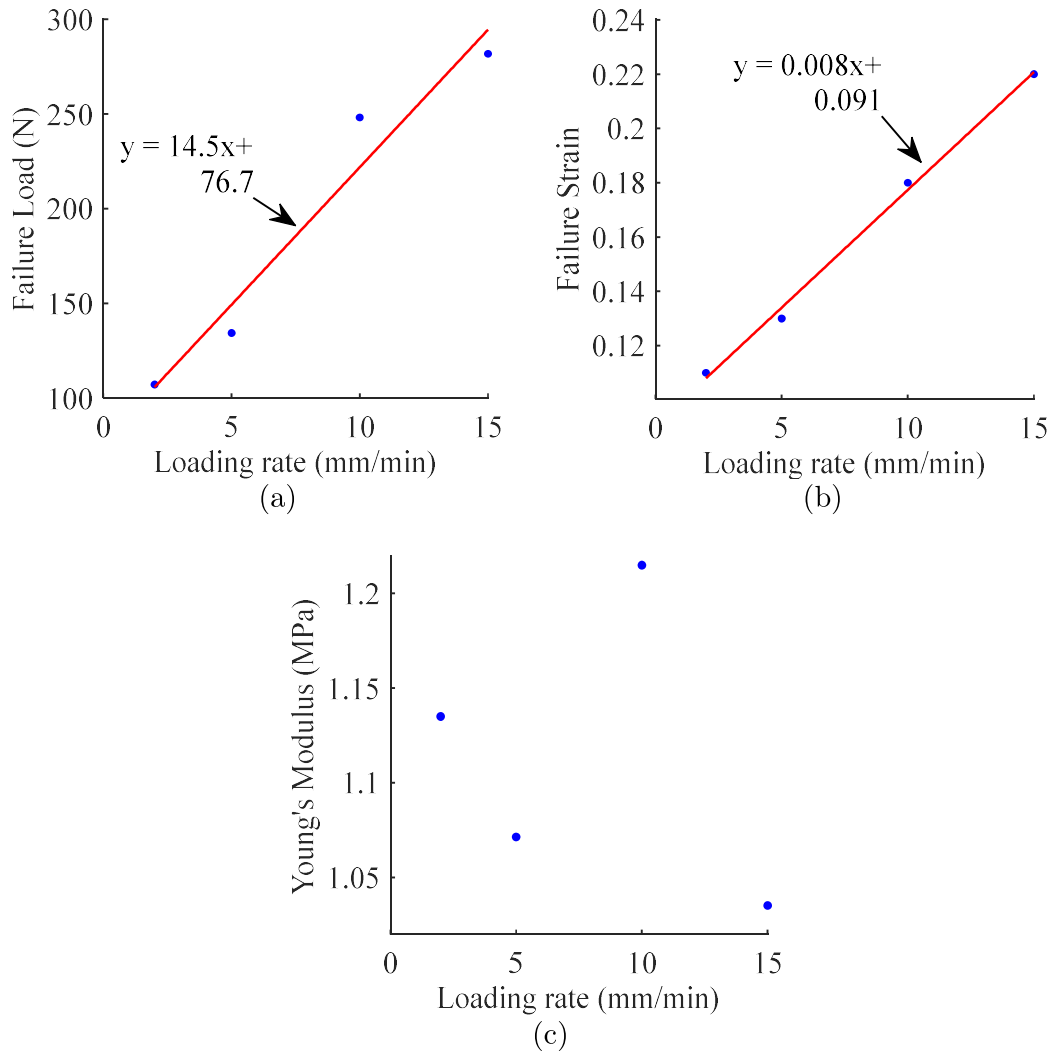


Figure 5.5: Loading rate dependency (a)for failure load (b) for failure strain (c) for Young's modulus

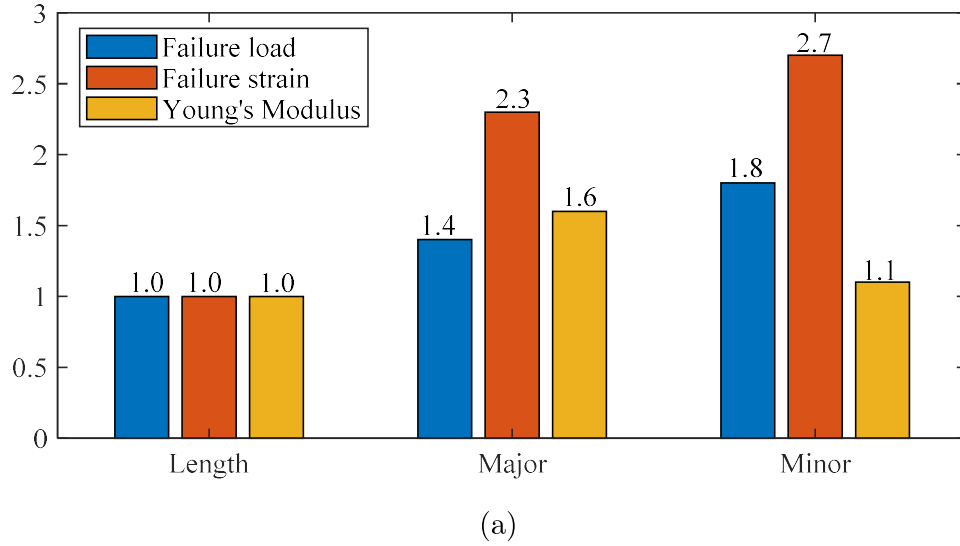


Figure 5.6: Loading direction dependency

It is proposed in Section 5.2 that the seed provides most of the stiffness of the fruit. Therefore, the Young's modulus' dependence can be explained by the anisotropy of the seed. It may be that the seed is stiffest along the major diameter. Carrying out quasi-static compression tests along the major axes of the seed would verify this. Another factor to be considered is the arrangement of multiple seeds within the fruit as their interaction may differ along each direction thereby affecting the stiffness. This dependency on loading direction suggests that the fruit may have a preferred orientation for impact.

5.1.5 Effect of Spikiness

An interesting parameter that was investigated in terms of its effect on the mechanical properties is the spikiness. Figure 5.7 illustrates the relationship between each mechanical property to the spikiness. Although a linear correlation between failure load and Young's modulus with spikiness was observed, there is no correlation between failure strain and spikiness. This is unexpected as a higher spikiness corresponds to longer spikes, so some distance is travelled before actual compression of the fruit occurs. Therefore, for a given failure load, a higher spikiness should yield a higher failure strain. Therefore, the results are inconsistent and the effect of spikes cannot be inferred. However, the stiffness of the spikes was not considered during the

classification. Furthermore, the number of samples differed for each level of spikiness e.g. there was only one fruit with a spikiness of 0, but there were 19 fruits with a spikiness of 2. Therefore, to draw a conclusion, a large number of samples at each level of spikiness must be tested.

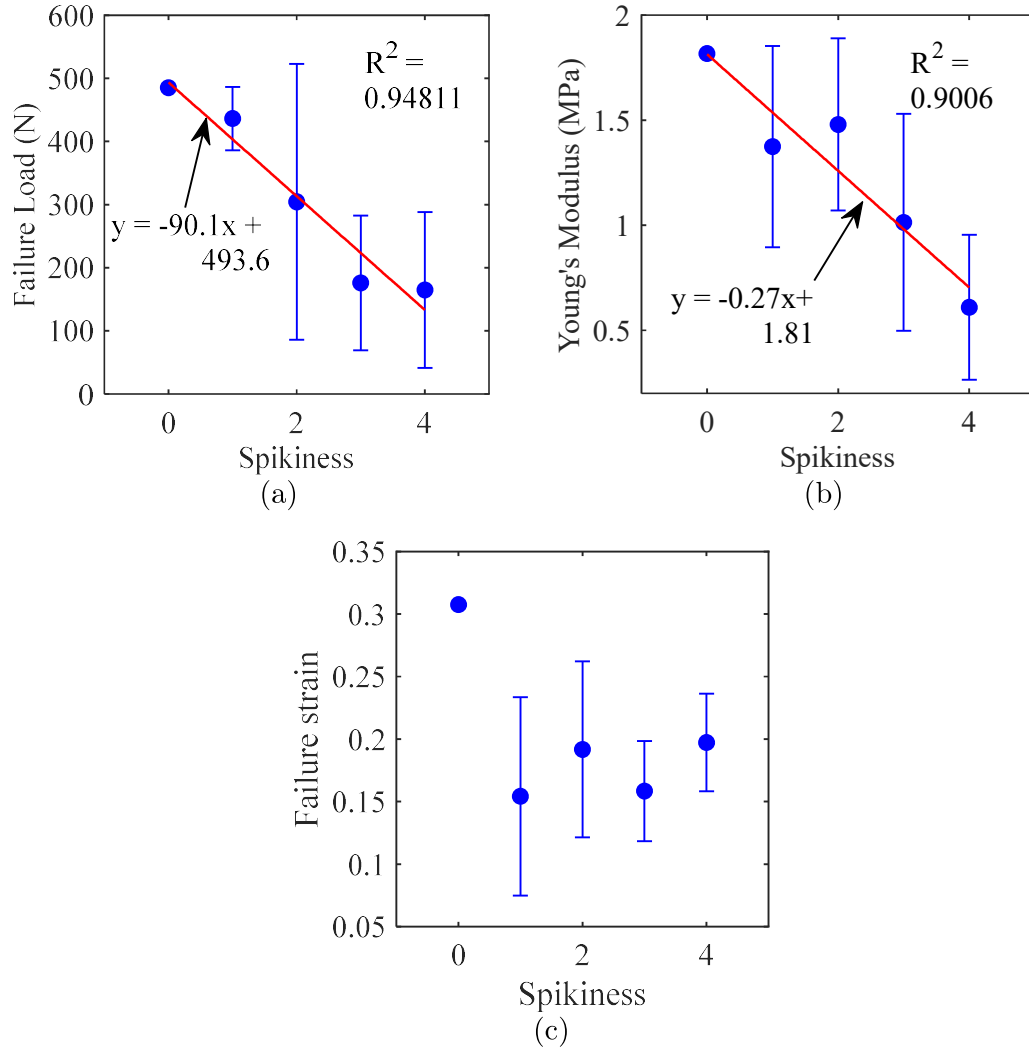


Figure 5.7: Spike effect (a)Failure load dependency (b)Young's Modulus Dependency (c) Failure strain dependency

5.2 Mechanical Behaviour of the Conker Seed (NC)

5.2.1 Deformation Behaviour

The compression curves for all seeds tested are illustrated in Figure 5.8(a). They are linear, suggesting the seed behaves similarly to a linearly elastic strut in compression. The failure load and failure strain were estimated at 506.8 ± 91.6 N and 0.225 ± 0.043 , respectively. Because of this linear behaviour, the stress-strain curve can easily be derived using equations 5.1 and 5.2.

$$\sigma = \frac{4F}{\pi D_n d_n} \quad (5.1)$$

$$\varepsilon = \frac{\delta}{L_n} \quad (5.2)$$

Where F is the applied load, D_n , d_n , L_n are the major diameter, the minor diameter and length of the seed respectively and δ is the deflection.

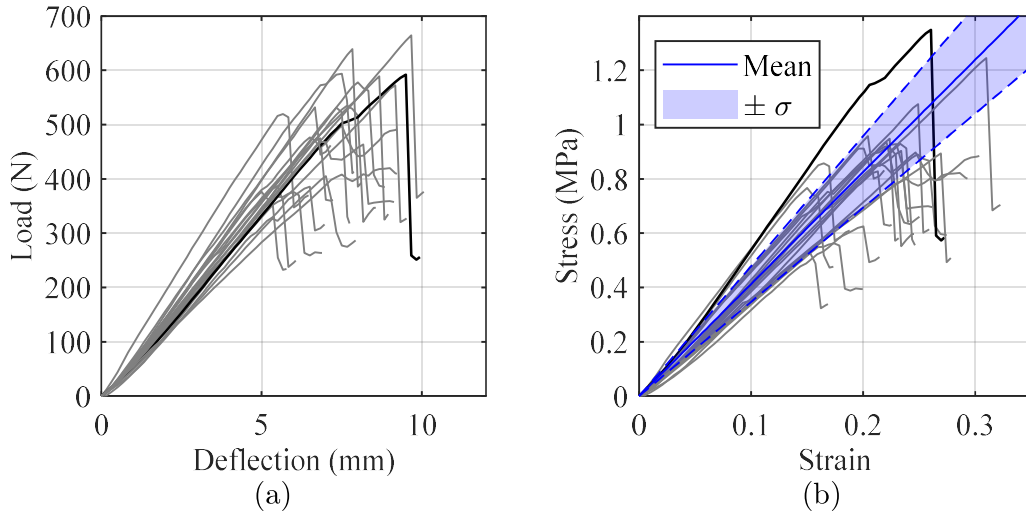


Figure 5.8: Seed compression (a) Load -deflection curve (c) Stress strain curve with dispersion of Young's modulus

Using Hooke's law, the Young's modulus is calculated as the slope of the stress-strain curve and the value came to 4.12 ± 0.66 MPa. The stress-strain curves from the experimental data as well as the calculated mean and dispersion of the Young's modulus are illustrated in Figure 5.8(b).

5.3 Mechanical Behaviour of Conker Shell

5.3.1 Deformation Behaviour

A typical load-deflection curve for the shell is illustrated in Figure 5.9(a). It consists of two regimes: (i)the flattening regime and (ii)the loading regime. This is due to the experimental set-up used where each shell sample had an initial arched shape. The flattening regime corresponds to the flattening of this arch and extended till a deflection of 10 mm to 20 mm corresponding to the initial height of the specimen. Because of this, there was no rigorous way to distinguish the expected linear elastic region from the flattening regime. It could equally be that the stiffness is so low and the elastic region is so short that this regime is indistinguishable. The loading regime was estimated as where the curve has an increasing slope. As the area of contact could not be calculated, it was estimated using the mass of the specimen and the surface area of the fruit from which it was extracted from following Equation 5.3.

$$A = \frac{M_s}{M_w} \times \pi D_w^2 \quad (5.3)$$

Where M_s is the mass of the shell, M_w is the mass of the fruit, D_w is the geometric mean diameter of the fruit.

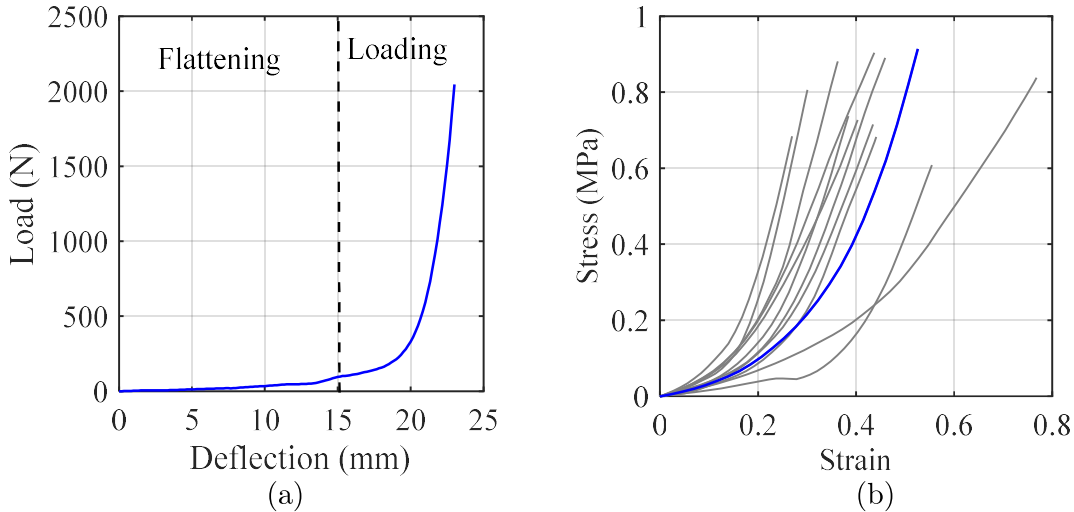


Figure 5.9 (a)Typical load deflection curve (b)Stress-strain curves)

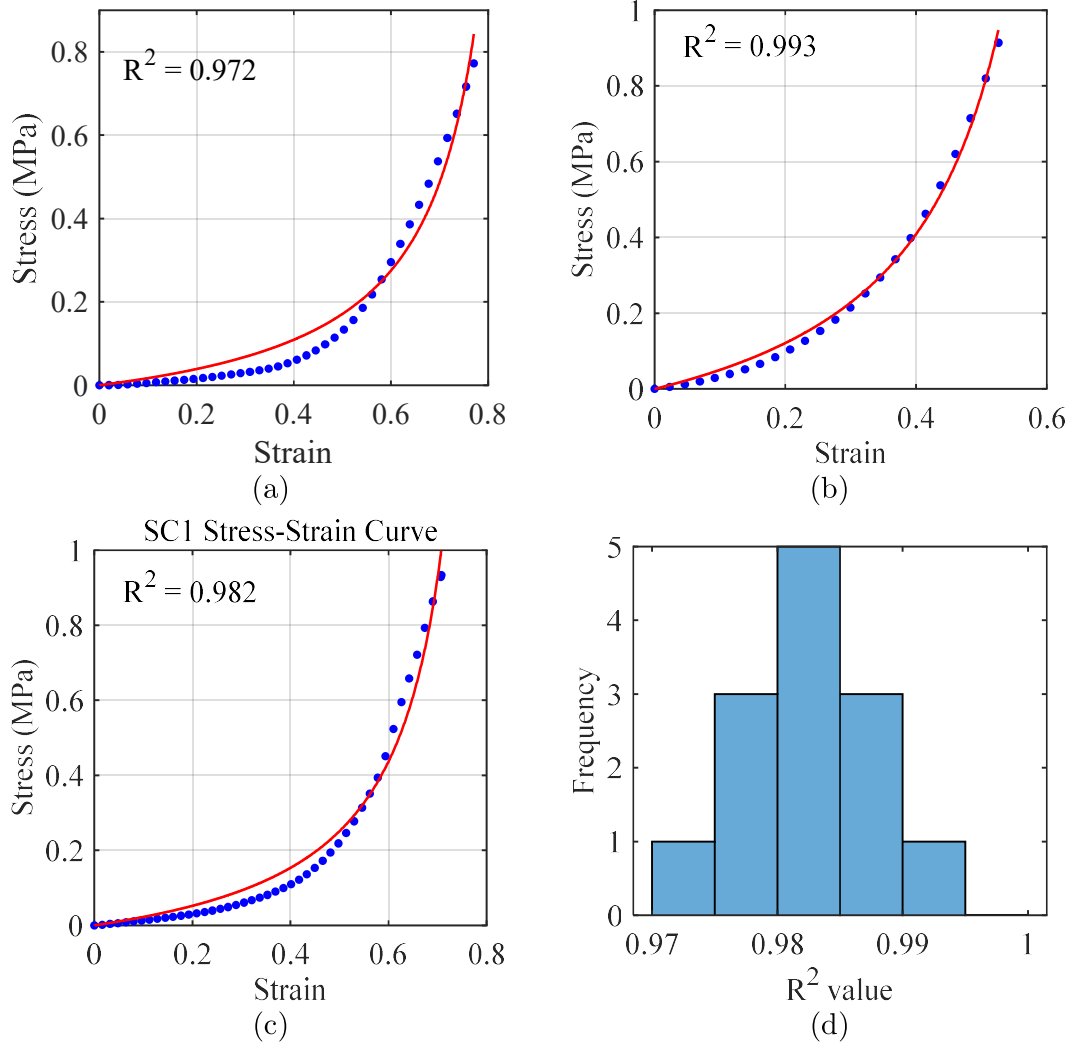


Figure 5.10: Fit of SC1data to Foam Post Collapse Model (a)Worst fit (b) Best fit (c) Average fit (d)Distribution of r-squared value

The stress-strain curves for all the data are illustrated in Figure 5.9(b). The data was fit to Equation 1.2, ignoring the first term of the right-hand side which is the contribution from elastic behaviour. A summary of the results of the fit is presented in Figure 5.10. It shows the data is in excellent agreement with the model with an average r-squared value of 0.982 and the minimum being 0.972. This suggests that the shell behaves similarly to a closed-cell foam despite it looking like an open cell foam in Figure 1.2 (c). Its properties are summarised in Table 5.1. The relative density was extracted as one of the parameters of the fit and substituted into Equation 1.1 to calculate the densification strain.

Table 5.1: Parameters describing the cellular structure of the conker shell

Parameter	Mean	Standard Deviation
Densification strain	0.54	0.19
Relative density	0.33	0.14

5.3.2 Shell Stiffness

Unfortunately, the Young's Modulus of the shell cannot be directly estimated from the test data. However, taking the fruit as a composite system and estimating its spherical geometry into a slab as in Figure 5.11, the Young's modulus of the shell can be estimated from that of the fruit and seed. This is done by using the rule of mixtures used to estimate the average properties of a composite given in Equation 5.4. Applying this equation, the average Young's Modulus of the shell was estimated as 0.5 MPa which seems reasonable as the Young's Modulus of the Pomelo peel is the same order of magnitude between 0.2– 0.3 MPa [30]. But this is about half that of the fruit and considerably less than the stiffness of the seed. This suggests that most of the stiffness of the fruit is contributed by the seed and the shell may just provide a load path to the seed as well as energy absorption by plastic deformation.

$$E_{fruit} = \frac{E_{seed}E_{shell}}{E_{seed}V_{shell} + E_{shell}(1 - V_{shell})} \quad (5.4)$$

Where V_{shell} is the average volume fraction of the shell calculated as 0.65.

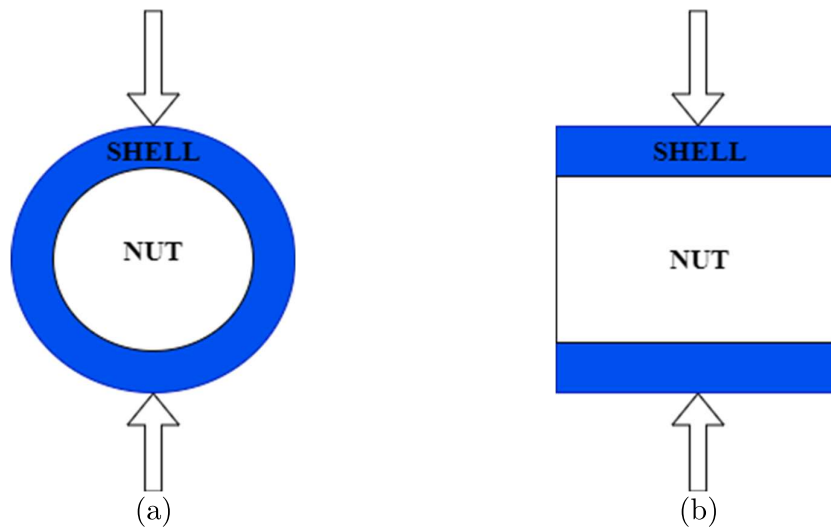


Figure 5.11: Approximation of Fruit composite system (a)spherical model (b)slab model

5.3.3 Comparison with EPS

A typical design constraint for a helmet is to maximise energy absorption for a given liner thickness for a threshold peak force. This is achieved by maximising the plateau stress and densification strain,[11]. Therefore, a comparison of these properties for the shell and EPS-15 (density of 15 kg/m^3) found in [9] is outlined in table 5.2. It should be noted that the plastic collapse stress of the shell was estimated by assuming the linear elastic region only extends to a 5% strain. The plastic collapse stress is simply the product of this strain and the Young's modulus estimated in the previous section. K is a measure of the energy absorbed during compression and is simply the product of the densification strain and plastic collapse stress.

Table 5.2: Comparison of Shell and EPS

Material	Shell	EPS-15
Plastic collapse stress (KPa)	25	95
Densification strain	0.54	0.95
K (KPa)	13.5	90.25

The shell has a lower plastic collapse stress due to its much lower Young's modulus. The lower densification strain may be due to the trapped water in the cell walls, which are less compressible than the air in EPS. On compression, this trapped fluid exerts further pressure on the collapsing cell walls leading to a steep stress rise at a lower densification strain. The energy absorbed by the EPS is more than six times the energy absorbed by the shell. This suggests that the shell may not outperform existing load mitigating structures. However, this analysis does not consider the difference in relative densities, the relative size of the samples, strain rate and the difference in entrapped fluids of both solids.

5.4 Concluding Remarks

5.4.1 Key Findings

This section aimed at understanding the quasi-static behaviour of the fruit, seed and shell of a conker. To describe the mechanical behaviour, the Hertzian contact model (Equation 1.4.) was applied for the fruit, the closed-cell foam post-collapse model given

by Gibson and Ashby (Equation 1.2) was applied for the shell and the Hookean model for an elastic solid was applied for the seed. In each case, the Young's modulus could be estimated from the model except for the shell which employed the composite's Rule of Mixtures to estimate it from the Young's modulus of the fruit and the seed. The energy absorption capacity of the shell was also compared with that of the EPS foam that is usually employed in bicycle helmets.

The fruit was found to behave similarly to an elastic spherical solid with a Young's modulus of 1.11 ± 0.56 MPa. Its mechanical properties are independent of mass and geometry, although it was found that smaller fruits are more likely to be stronger than larger fruits. However, the effect of moisture was not considered. Additionally, its strength linearly increases with loading rate suggesting that the fruit is stronger under dynamic load. It also exhibited a loading direction dependency suggesting that there is a favourable orientation for impact which may be due to anisotropy of the seed. The effect of spikiness could not be determined.

The seed was found to behave similarly to a linearly elastic strut in compression with a Young's modulus of 4.12 ± 0.66 MPa. On the other hand, the shell was found to behave similarly to a closed-cell foam with a relative density of 0.331 ± 0.14 and Young's modulus of about 0.5 MPa. This large difference in Young's modulus suggests that the seed is the primary load-bearing component of the fruit. A qualitative comparison of the performance of the shell with that EPS demonstrates that EPS greatly outperforms the shell ignoring size effects and structural differences.

5.4.2 Future Work

Further directions for future work would involve accurately estimating contact areas and stresses, investigating the effect of moisture content as well as anisotropy of the seed.

Due to the geometry of the samples, directly deriving a stress-strain plot from the compression data poses a challenge. To more accurately do this, a tactile sensor and measurement system can be employed as in [31]. This can either directly measure and

record the stress acting at a given compressive displacement or record the area of contact, which can be used to calculate the stress. The varying area of contact is accounted for in this way, giving a stress-strain curve that Young's modulus can be directly estimated from.

The effect of moisture content on the mechanical properties can be investigated. Moisture can be measured by oven-drying samples and then measuring the loss in mass. However, this destroys the sample and can only be carried out after testing, but some of the moisture could be lost during testing. Another method is the use of an electronic moisture meter which works on the principle that the resistance of the sample is affected by the moisture content. This is a non-destructive means of measuring moisture and is preferred [32].

As the seed plays a key role in providing strength and stiffness to the system, the dependency of its mechanical behaviour on loading direction can also be explored to explain that of the whole system.

6 Dynamic Mechanical Behaviour

Free-fall drop tests were carried out on uncracked fruit to determine the energy absorption capability of the shell as well as to determine dynamic mechanical properties. 14% of the fruits tested failed by partial cracking while 9% of them failed by total rupture. However, moisture content may have played a role in these results as it was closer to the end of the conker season when the fruits had less moisture that the failure occurred more often. On average, the impact energy was about 1.1 J and the energy absorbed was about 82% of this on average. The evolution of acceleration during impact was fit to a Gaussian pulse is illustrated in Figure 6.1(a). There is initially close to zero acceleration measured before impact. At the start of impact, the acceleration rises rapidly until it reaches a value of about 200 m/s² on average. This is when maximum deflection occurs. Following this, the acceleration decreases rapidly. This gives a single pulse indicating a single impact as expected.

According to N.J. Mills [15], one of the constraints on the design of helmets is that the deflection must not exceed the thickness of the foam liner. This principle was considered in the analysis and the distribution of deflection during impact was compared with the distribution of the shell thickness. As shown in Figure 6.1(b), the deflection is almost always greater than the thickness, by about 8 mm on average. This is considered as the corresponding deflection of the seed. Using the Young's modulus value derived in Section 5.2.1, the force acting on the seed at maximum deflection was estimated at about 500 N (applying Hooke's law) which is comparable to the failure load under quasi-static loading. Thus, a high load is transmitted to the seed. This suggests that the shell only provides cushioning to protect the surface but does not dissipate considerable energy. However, it could be that rather than taking the conventional route of having a shell for protection, it seems like the seed is designed to have high strength and stiffness to withstand most of the load on its own. The shell can also provide protection from the environment and animals.

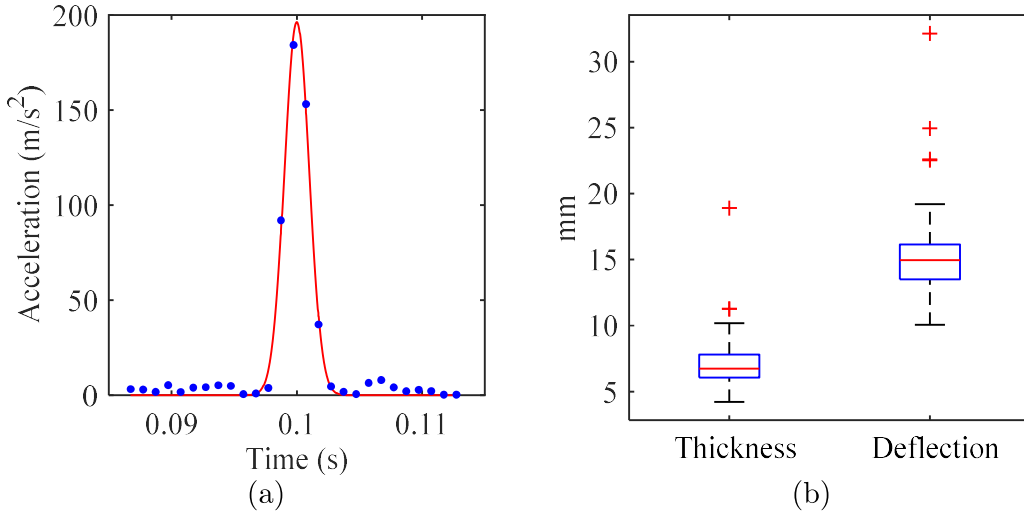


Figure 6.1: Drop test results (a)Typical acceleration plot (b)Comparison of shell thickness and maximum deflection

6.1.1 Dynamic Stiffness Estimation

To derive the stiffness under dynamic loading, the Hertzian model for impact specifies a relationship between the maximum deflection and the impact velocity as in Equation

1.5. The data was found to have a good agreement with the model, as illustrated in Figure 6.2(a) and using average measured values for mass and geometric radius, the Young's modulus was estimated as 7.6 MPa which is about seven times the corresponding value under quasi-static loading. This higher stiffness despite the independence of the Young's modulus under quasi-static loading rate suggests that the fruit is more suitable for dynamic loading conditions. However, the data also have a good agreement to a linear fit (Figure 6.2(b)) so there is some uncertainty. This can be remedied by gathering data for impact velocities greater than 9m/s to ascertain the relationship.

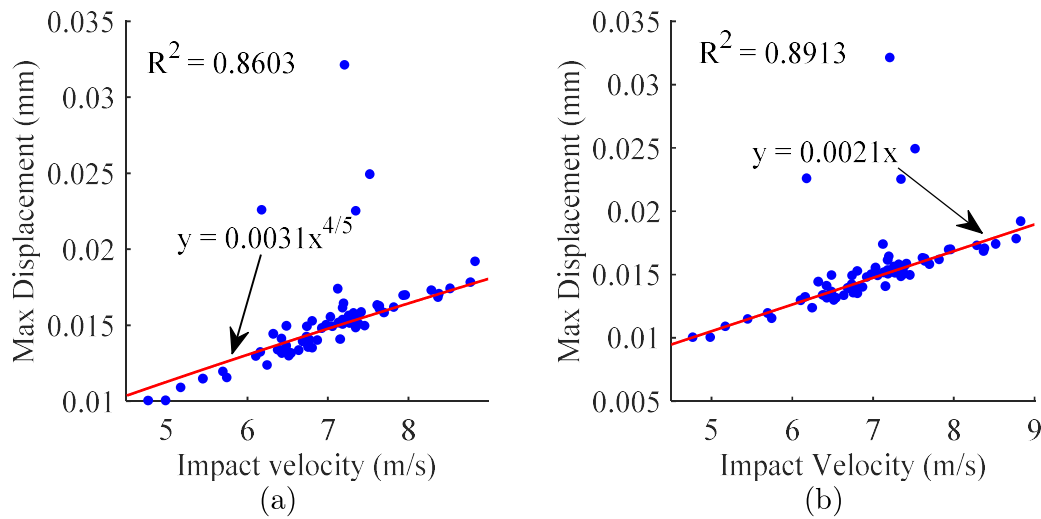


Figure 6.2: Fit of drop test data (a)Hertzian model (b)Linear fit

6.2 Concluding Remarks

This section outlined the results of drop tests carried out at measured impact velocities ranging from 4 m/s to 9 m/s as well as employed the Hertzian impact model (Equation 1.5) to estimate the dynamic Young's modulus. The effectiveness of the shell at these impact velocities was determined by comparing the maximum impact during deflection to the shell thickness.

The Young's modulus was estimated to be 7.6 MPa which is about seven times greater than its quasi-static equivalent. This suggests the fruit is more suited to withstand

loads under dynamic loading as expected. The shell proved ineffective at these impact velocities as an estimated peak load of 500N was transmitted to the seed during impact, which is similar to the seed's failure load under quasi-static conditions.

Directions for future research would include considering moisture content, accurately measuring contact pressure and area as well as varying impact energies by use of varying drop heights of dropped weights to determine the range of operation of the shell. The orientation of impact could also be changed to investigate loading direction dependency.

7 Conclusions

This report provides a detailed analysis of the components of the conker fruit under both quasi-static and dynamic loading as well as microstructure characterisation of the shell. This research primarily aims to provide new insights into the design of better load mitigating structures by contributing an additional biological model as inspiration.

7.1 Contributions

This experimental work is based on a comprehensive laboratory testing programme that includes a series of quasi-static compression tests on the fruit, shell and seed as well as dynamic drop tests. The key contributions are summarised below.

- 1) **Physical properties characterisation** – The physical properties were estimated to follow a normal distribution as expected of a natural phenomenon with a mean mass of 48.4 g and geometric mean diameter of 45.9 mm.
- 2) **Microstructure investigation** – The shell consists of 4 layers: the inner membrane, the middle layer, outer layer and the spiky green skin. Each layer consisted of a fluid-filled cellular solid.
- 3) **Mechanical behaviour under quasi-static loading** – The results of the analysis of the fruit, the seed and the shell are summarised in Table 7.1 stating the models used to describe the behaviour. The difference in stiffness suggests that the seed is

the main load-bearing member of the fruit. The seed can withstand high loads without failure, which undermines the need for large energy absorption in the shell.

Table 7.1: Summary of Mechanical Behaviour under Quasi-static loading

Specimen	Mechanical Model	Behaviour	Result
Fruit	Hertzian contact model (Eq. 1.4)	Elastic spherical solid	$E = 1.11\text{MPa}$
Seed	Hooke's Law	Linearly Elastic strut	$E = 4.12\text{MPa}$
Shell	Post-collapse behaviour of closed-cell foams (Eq. 1.2)	Foam	$E = 0.5\text{MPa}$

- **Physical properties dependency of fruit** – There exists no correlation between strength and stiffness with mass and geometry of the fruit. However, it was concluded that smaller fruits are more likely to have higher strength than larger fruits. Further testing is required to infer the effect of spikiness.
 - **Loading rate dependency of fruit** – Unlike the stiffness, the strength of the fruit linearly increases with loading rate suggesting that under dynamic loading, the fruit has higher strength.
 - **Loading direction dependency** – The fruit's strength and stiffness depend on the direction of loading which suggests that there is a favourable orientation for impact.
- 4) **Comparison of the shell with EPS** – EPS considerably outperformed the shell in terms of energy absorption due to its much larger plastic collapse stress and densification strain.
- 5) **Mechanical behaviour under dynamic loading** – According to the Hertzian impact model, the stiffness was significantly higher than that under quasi-static conditions. Also, at the experimented impact velocities, the peak load transmitted to the seed was substantial.

7.2 Implications for Biomimetic Design

From the findings of this research, no evidence that the conker shell can inspire better load mitigating structures was found. The proposed mechanism for protecting the seed

from impact is the high strength and highly elastic behaviour of the seed which allows it to withstand high loads and bounce back after reflection. However, the loading direction dependency means that it can be a potential strategy for the design of structures with a favoured configuration for loading such as a phone protective case.

7.3 Suggestions for Future Experimental Work

- **Sample Preservation** – One of the primary limitations of the experimental work presented is the narrow testing window that spans about two months at the peak of conker season close to the end of summer. Therefore, a long-term testing schedule cannot be employed. Further research can be carried out into investigating preservation methods that cause little degradation to the mechanical and physical properties of the samples. Such methods may include freezing, cryopreservation, freeze-drying and freezing with irradiation.
- **Further Applications** – The conker fruit can be investigated as a biological model for a phone protective case as a load mitigating structure with favoured orientation for impact as well as an orientation which leads to the most damage.

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9 Appendix

9.1 Risk Assessment Retrospective

The major risks in the project were associated with the summer internship. The hazards identified for the experimental work carried out were an adverse reaction to the conker fruit and its components, flying debris and dropped objects when carrying out the drop test, high forces and flying debris associated with using the Instron machine and lone working in the Biolab. When control measures involving the use of adequate PPE, careful use and proper training were employed. The residual risks of these hazards were low. However, very limited laboratory testing mostly involving the handling of the fruit was carried out. Therefore, exposure to hazards associated with the drop tower and Instron machine did not occur.

9.2 COVID-19 Disruption

This project was entirely computer-based therefore there was no need to reroute the project. The only further experiment that could not be carried out was microscopy of the frozen conker shells. Also, I was unable to get a scale for the image in Figure 4.1(e) due to closure of the department. Following closure of the university, I returned to my home country, Nigeria. Unfortunately, regular power cuts are experienced which affected work due to lack of access to a computer. I was also severely ill for a 2-week period and required an extension of the final report deadline. Unsteady internet connection also affected consultation with supervisor with a few meetings where communication was an issue.