

Comparative Analysis of the Static and Dynamic Mechanical Eggshell Behaviour of a Chicken Egg

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Abstract

A chicken egg is an already packaged food. An important quality aspect of the packaging material is the mechanical strength of the eggshell. A commonly used technique for the measurement of the shell strength is the quasi-static, non-destructive compression of an egg between two parallel steel plates. The slope of the force-deformation curve is a measure for the stiffness of the shell and for the eggshell strength. However this method is tedious and the required equipment is expensive. An alternative method has been developed based on the vibration behaviour of the egg after impact excitation. A dynamic stiffness parameter, k_{dyn} , is defined which is based on a mathematical mass-spring model of the dynamic behaviour of the egg. Moderate correlations are found between k_{stat} and k_{dyn} . A finite element model of the static and dynamic eggshell behaviour is developed in order to understand better the relationships between the two parameters. The influence of the different material and structural on the mechanical eggshell behaviour is analysed by performing a sensitivity analysis on each single parameter. These results are used to interpret the experimentally observed relationships.

1 Introduction

A chicken egg is an already packaged food. An important quality aspect of the packaging material is the mechanical integrity of the shell. The shell must be free of cracks and highly resistant to dynamic, impact loads and static compression during transport in trays. The eggshell strength is determined both by the genetic origin, the age of the laying hen, environmental factors as feed composition, diseases, climate conditions and management of the farmer [1]. Therefore breeders, nutritionists and egg producers are interested in fast and non-destructive measuring methods for monitoring eggshell strength characteristics.

Traditionally, the eggshell strength is evaluated in a non-destructive, quasi-static compression test [2]. The egg is placed horizontally between two parallel steel plates and a force of 5 N is exerted on the object. The force-deformation curve is registered and the slope of this curve is used for the assessment of a static stiffness parameter (k_{stat}). However this method is tedious and requires

expensive test equipment. The method can not be applied on egg grading machines for real-time assessment of shell strength.

Therefore alternative test methods have been investigated. Coucke [3] introduced a dynamic test method for eggshell stiffness assessment.

Based on an experimental modal analysis of a chicken egg, the dynamic behaviour was characterized. Several interesting spherical modes are detected in the frequency range 3-8 kHz. The mode shapes in this frequency range all show maximum deformation at the equator of the egg, while the sharp and blunt poles are immobile. The mode shape of the first, flexural spherical mode shows an oblate-prolate deformation at the equator (Figure 1). The damped natural frequency of this mode and the total egg mass are used to calculate the dynamic eggshell stiffness using a mass-spring model (1).

$$2 \cdot \pi \cdot RF = \sqrt{\frac{k_{dyn}}{mass}} \quad (1)$$

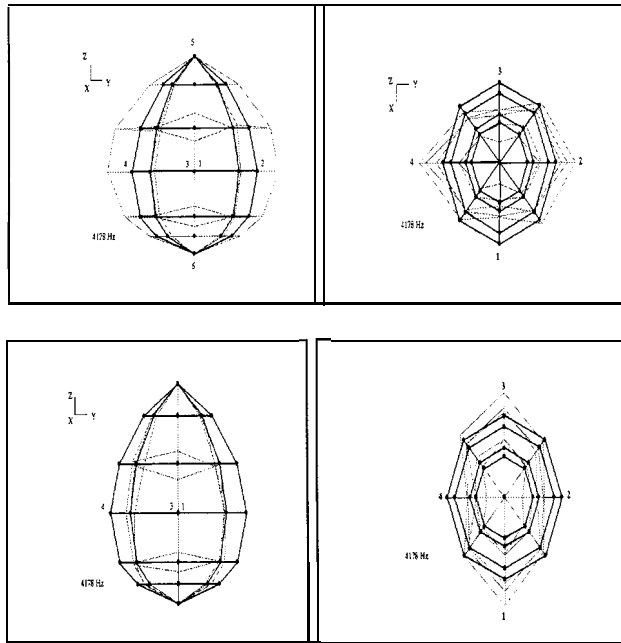


Figure 1 : Front view (left) and to view (right)of the mode shape of the first flexural, spherical modeat two different moments with a phase shift of 180”.

Experimentally observed correlations between k_{stat} and k_{dyn} ranges between 0.65-0.74 (Table 1). It is noticed that the eggshell thickness is highly correlated with k_{stat} while the k_{dyn} shows only moderate correlation with shell thickness. The egg shape expressed as a shape index(SI= width at the equator/length from pole to pole of the egg) has minor influence on the static stiffness while k_{dyn} is sensitive to the eggshell geometry. The statically measured stiffness is highly correlated with the shell thickness.

The goal of this study is the analysis of the influence of the different material and structural properties of the eggshell on k_{stat} and k_{dyn} . This static and dynamic analysis is done using the finite element method.

Table 1 : Ranges of experimentally observed correlations between several egg and eggshell parameters. Data originating from Coucke [3].

	mass	SI	RF	thick	k_{stat}	k_{dyn}
mass	1					
SI	.07 / .13	1				
RF	-.22 / -.56	.16 / .58	1			
thick	.04 / 0.45	-.04 / .14	.31 / .59	1		
k_{stat}	-.04 / .22	.08 / .31	.57 / .67	.81 / .91	1	
k_{dyn}	.02 / .29	.24 / .61	.77 / .87	.54 / .64	.65 / .74	1

2. Development of a finite element model of the eggshell

A chicken egg is a complex structure. The egg content contains an air-chamber and a viscous liquid. The shell thickness is not uniform. The shell consists of several layers with different material properties. Eggshell membranes are attached to the shell.

In the simulation studies a more simplified model is used. The eggshell is modeled as a one layer, shell structure. The thickness of the shell is assumed uniform over the whole eggshell surface. The egg content and shell membranes are not incorporated in the model.

The analysis was carried out using the Ansys version 5.0 (Ansys Inc., Houston, U.S.) finite element software. A g-nodes shell element type (type 93) is applied (Figure 2). It is assumed that the eggshell has linear elastic material properties.

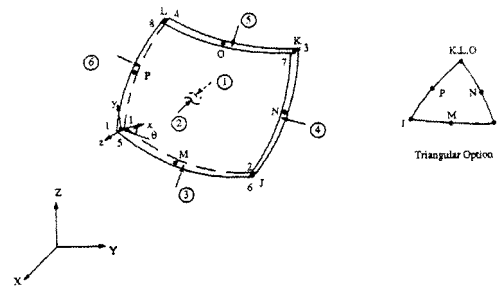


Figure 2 : Schematic view of the applied S-nodes shell element type 93 [4].

2.1 Structural properties

The structural properties of the eggshell are the size, shape and thickness of the shell. A reference shape is generated. The geometry generation is based on the elongation of sphere. A left and right scale factor (LSF and RSF) are defined for describing the degree of elongation. In order to create a sharp and blunt end, a LSF of 1.2 and a RSF of 1.4 is chosen a default values.

Eggshell thickness is assumed to be uniform over the shell surface. A default value of 0.36 mm is applied.

The default diameter of the egg at its equator is 4 cm.

2.2 Material properties

The material properties involved in the simulations are : the modulus of elasticity, Poisson ratio and the density of the shell material (only for dynamic simulations).

The default value of the E-modulus is 3.10^{10} N/m². This value corresponds with the average value in the simulations done by Bain [4]. The Poisson ratio is set at 0.3 and the density of the shell material for the default configuration is 2400 kg/m³.

No information about damping properties of the shell material is found in literature. This parameter is not incorporated in the simulation model. Hence, only natural frequencies and corresponding mode shapes are calculated.

2.3 Boundary conditions

In the static simulations the applied load and the location of the egg support are determined. The egg is laying down horizontally. The applied force of - 5 N is exerted vertically in a single point at the egg equator. The egg is supported in 5 nodes opposite to the loading point in the equator zone. These nodes are all fixed.

2.4 Mesh generation

Once the geometry of the eggshell is generated, a mesh generator procedure is used to divide the eggshell structure in a set of elements.

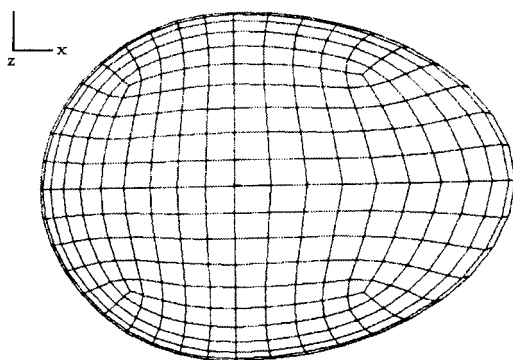


Figure 3 : Generated egg shell mesh using shell type elements

In case of the simulations of the static mechanical behaviour, a different mesh was used in order to

increase the mesh density near the contact area at the equator where high stresses are expected.

2.5 Solution and post-processing phase

The analysis was carried out using Ansys version 5.0 (Ansys Inc., Houston, U.S.) finite element software. The simulations are done on a IBM SP2 unix server.

The number of calculated modes in the dynamic simulations was restricted to 20. The resonant frequency (RF) of the first spherical mode was used in the sensitivity analysis. It was observed that RF's of higher modes are highly correlated with the RF of the first, spherical, flexural mode.

3. Results and discussion

3.1 Simulation results of the quasi-static compression

Maximum deformations are observed in the area of the load. The value of the deformation at the moading point corresponds with experimentally observed displacements under similar loads.

In the subsequent analysis each single geometrical and material property is varied within a reasonable range. The effect of these changes on the eggshell deformation is analysed.

3.1.1 Eggshell thickness

A 50 % reduction of the eggshell thickness results in a four times increase of the deformation or :

$$NDD \sim \frac{1}{T^2} \quad (2)$$

This observation has been confirmed by Ar et al. [5].

3.1.2 E-modulus

Doubling of the E-modulus results in a 50 % reduce of the eggshell deformation or :

$$NDD \sim \frac{1}{E} \quad (3)$$

Bain [4] observed a similar relationship between the E-modulus and the deformation of the shell under static loading conditions.

3.1.3 Egg shape

Traditionally the eggshape is described with the shape index (SI). In the simulation, a different description of the egg geometry is used in the finite element simulations. However, SI values can be calculated by varying the LSF and/or RSF. The width of the egg is 4 cm in all simulations.

It can be observed that a change in SI from 91 to 67 (27 %) results in an increase of the deformation of 31 % or:

$$NDD \sim \frac{1}{SI} \quad (4)$$

3.1.4 Poisson ratio

The Poisson ratio has only a minor influence on the deformation of the eggshell under static loading conditions.

3.2 Simulation results of the dynamic analysis

The values of the resonant frequencies of the simulations are much higher than the experimentally observed values. This is expected since only the eggshell was modeled and the egg content, which represents 85-90 % of the total egg mass, was not incorporated in the model.

The mode shapes and the sequence of appearance the of the calculated modes are very similar to the experimentally observed modes. Figure 4 represents a top view (left) and front view (right) of the mode shape of the first, flexural spherical mode.

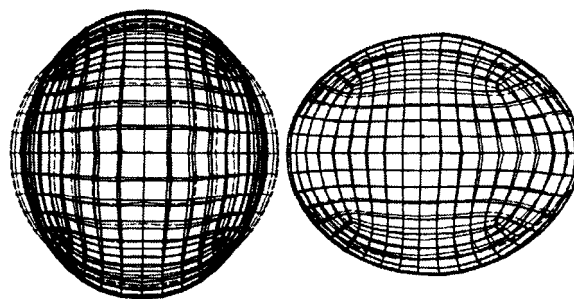


Figure 4

3.2.1 Eggshell thickness

The RF of the first spherical mode is almost not influenced by the shell thickness. This result can be explained by the opposite effects of the stiffness and the eggshell mass on the RF. A reduction in eggshell thickness reduces the mass and therefore the RF of the structure will increase. It also decreases the eggshell stiffness and this reduces the RF of the object.

However, for a fluid filled egg this reasoning can perhaps not be used. A reduction in shell stiffness will have an influence on the stiffness of the structure but the relatively small loss in eggshell mass will have less influence on the whole egg and thus on its RF.

A similar observation was described by Royles and El-Deeb [6]. They modeled the dynamic behaviour of an echinodome. This structure is an axial symmetric spherical object which shape is optimized to resist hydrostatic pressures under water.

3.2.2 E-modulus

A non-linear relationship is observed between the E-modulus and the RF of the first spherical mode. The mathematical relationship is described as :

$$RF \sim \sqrt{E} \quad (5)$$

3.2.3 Egg shape

An almost linear relationship is observed between the RF and the SI.

$$RF \sim SI \quad (6)$$

It should be noticed that the egg size (diameter at the equator ring) is not changed.

3.2.4 Poisson ratio

Changes in Poisson ratio have only minor influences on the RF.

3.2.5 Density of the shell material

An increase of the egg density results in a decrease of the RF. As all other parameters are not changed, an increase of the eggshell density will result in an increase of the total mass of the structure. In that way a relationship between RF and mass is determined by :

$$RF \sim \frac{1}{\sqrt{\text{density}}} \quad (7)$$

3.3 Comparaison between the experimental and simulated results

It is observed both in the numerical and experimental analysis that the eggshell thickness has a major influence on the eggshell deformation during quasi-static compression while the RF is not so strongly influenced by this parameter.

The influence of the egg shape is difficult to assess as different definitions have been applied both in the experimental data (SI) and in the numerical analysis (LSF and RSF). A combination of both the egg diameter and egg shape is included in the SI parameter, while the egg diameter is kept constant in the numerical analysis and only the shape of the egg is changed.

The mathematical relationship (1) which has been applied for the calculation of k_{dyn} is similar to the relationship between RF on the one side and density (7) and elasticity (5) on the other side.

4. Conclusions

The finite element method is a powerful method for modeling the static and dynamic mechanical

behaviour of an eggshell. The analysis given is incomplete because the egg content was not included. However some comparison between the simulation results and the experimentally observed relationships could be made.

Some deficiencies in the results between the numerical and experimental data can also come from the fact that the eggshell was modeled just as a shell element, neglecting the effect of the membranes at the inner side. Also the mechanical interaction between membranes and organic layer is not modeled. More experimental insight in this interaction would be of great value for modeling purposes. Similar observations hold for the properties of the albumen and the mechanical interaction between albumen and membranes or anorganic layer.

A major advantage of the dynamic method is the speed of the measurement. The total time of the signal response of an egg excited with an impact excitation is between 10 and 30 ms depending on the damping properties of the egg. This allows a fast and non-destructive eggshell strength evaluation which can be applied in real-time conditions of egg grading. In that case it is possible to position the eggs in a cardboard tray in an intelligent way.

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