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New Trends for Understanding Stability of Biological Materials from Engineering Prospective

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1. Introduction

Economic loss due to egg shell breakage is an important problem in intensive egg production systems (Oosterwoud, 1987). Eggs are subjected to mechanical impacts at the moment of lay, during collection, in the sorting equipment and during transport in trays. Bain (1991) reported that 6% to 8% of all eggs laid are broken during handling from the production unit to the consumer, and in monetary terms this gives rise to losses of at least $600 million on a world wide basis. The value of egg production was $3.389 billion in 1992, compared to $ 3.209 billion in 1987 (Madison and Perez, 1994). Therefore, egg shell breakage continues to be a costly problem for the egg industry. In addition, people are at high risk when eating eggs which might be contaminated after being damaged, i.e., with cracks or checks (Amer, 1998; Bain, 1990).

Egg shell breakage depends both on the strength of the egg shell and magnitude of the mechanical load applied. Variables associated with shell strength are biological in nature (Hamilton, 1982). They involve the material and structural properties of the different layers which comprise the egg shell. The material properties depend on the type and the association between the mineral and organic components of the shell. The structural properties depend on egg shell thickness, size and shape of the egg and the distribution of shell over the egg surface.

In most of the methods used for measuring egg shell strength these basic physical properties are not quantified separately because of their complexity. Indeed, the shell curvature and its brittle nature make it difficult to measure the material properties of the shell by classical means (Amer Eissa & Gamea, 2003; Bain, 1990). Therefore, more practical techniques have to be developed. Such methods, however, describe the behaviour in terms of a superposition of several material and structural properties of the egg. One such commonly used method is the non-destructive, quasi static compression test. In this test the elastic stiffness properties of the whole egg shell structure are measured. An egg is placed horizontally between 2 flat parallel steel plates and then compressed at a constant compression speed until a predefined

non-destructive load is applied. The slope of the force-deformation curve is an indicator of the mechanical stiffness of the shell. This mechanical stiffness depends on the thickness of the egg shell, the curvature of the egg shell, the diameter of the egg and the Young's modulus of the material in each layer of the shell (Amer, 1998; Bain, 1990).

A more precise method of measuring the impact strength of an egg is to record the force on the shell throughout the impact. Using this technique, Voisey and Hunt (1967 a,b) developed an instrument to measure the impact force required to fracture an egg. With this instrument the egg is supported in an adjustable plastic (nylon) cradle directly below a suspended aluminium rod 1900 mm in length, this cradle is adjusted, using a dial gauge, so that the upper surface of the egg is at a constant distance (5.0 mm) from the end of the aluminium rod for all measurements. The rod is suspended by an upper spherical end that fits into a socket connected to a vacuum pump. By opening a solenoid valve the vacuum is released and the rod falls freely until it strikes the egg. The impact of the rod on the egg is measured by a piezoelectric transducer attached to the lower end of the rod; the rod and transducer weigh 695 g. The transducer can be calibrated in either force or acceleration units. The electrical output of the transducer during the impact is recorded by a peak-shock meter and the maximum value displayed by a 4-digit voltmeter. The impact strength of about 150 eggs can be measured per hour with this instrument. Force-time plots can also be obtained using an oscilographa and camera to record the graph for each egg. It is very important that shock waves generated within the rod during the impact with an egg do not affect the measurement. This effect may be overcome by changing the length of the rod or the material from which it is made (Voisey and Hunt, 1968).

During handling of eggs, several impacts may be imparted to the egg shells, if not limited, will cause considerable damage. Several researchers have investigated the effects of impacts on agricultural products. Zapp et al., (1990) investigated the impact on apples by simulating an apple with an 'instrumented sphere'. Jindal and Mohsenin (1976) analysed a pendulum impacting device with which apples and corn kernels were tested. Finney and Massie (1975) also investigated a pendulum impacting device for testing the response of fruits to impacts. Other authors who have investigated impact devices for agricultural products include Amin (1995), Tennes et al., (1988), Siyami et al., (1986), Hughes et al., (1985), Simpson and Rehkugler (1972) and Bilanski (1964).

In the case of a chicken egg, the interpretation of the impact response of an egg is even more complex than for apples. An egg consists of several types of material: a shell, an air-chamber, egg white and yolk. The egg shell structure itself contains several distinct layers that are penetrated by pores. Within 1 layer, the material properties are not homogeneous. The material properties of the egg content are also variable. Nevertheless, it is worthwhile to asses the experimental relationships between the dynamic impact, mechanical properties of an egg and commonly measured physical egg and egg shell variables.

The values of the material property of eggshell were reported over 25 years ago. These values might be obsolete due to significant changes in chickens' species, feed and management practices. Therefore, it is necessary to measure the key material properties of present day shell eggs.

The aim of this chapter is to describe the different approaches used to evaluate mechanical properties and damage to the chicken eggshell. Furthermore we   describe a pendulum which is portable and which will impact eggshell under a wide range of velocities and energies.

2. Finite element methods applications in biological materials

Finite element approach for simulating the dynamic mechanical behaviour of a chicken egg Perianu, et al., (2010) noticed that A numerical investigation of the structural acoustic behaviour of a chicken egg was carried out. A three-dimensional finite element (FE) model was developed to simulate both the dynamic behaviour of the eggshell and the fluid loading of the inside fluid. The aim was to analyse the effects of variations in certain geometrical and material parameters of the egg on the structural acoustic frequency response functions. It was found that geometrical modifications (eggshell thickness, size of the egg) had a considerable influence on the fluid structure coupled natural frequencies. In general, variations of material characteristics did not have much influence on dynamic behaviour. However, the Young's modulus of the eggshell strongly affected the natural frequencies of the coupled system. The results obtained were used to interpret experimentally observed relationships. Nowadays, consumers are primarily concerned with the quality and safety of the food. In the case of the consumption of eggs, shell integrity is one of the main issues. During the last decade, several methods were developed for rapid assessment of shell integrity and strength (De Ketelaere, et al., 2004). Eggshell strength is regulated by a certain number of variables such as genetic origin, the age of the laying hen, environmental factors such as feed composition, diseases, climatic conditions and management by the farmer (Solomon, 1991).

Classically, eggshell strength this evaluated by means of a nondestructive, quasi-static compression test (Voisey & Hunt, 1974). The egg is placed horizontally between two parallel steel plates and a compression load is exerted on the object. Force and displacement are recorded throughout the test and used to calculate the static stiffness (k_{stat}), being defined as the slope of the force e displacement curve. However, this method is time-consuming and requires expensive test equipment. Hence, it cannot be used as an industrial tool for real-time assessment of shell strength. As an alternative to traditional techniques, Coucke, et al., (1994) introduced a dynamic test method for eggshell stiffness assessment. The dynamic behaviour of a chicken egg was characterised using an experimental modal analysis. Several spherical modes were identified in the frequency range between 3 and 8 kHz. The mode shapes in this frequency range all showed maximum deformation at the equator of the egg, whilst the sharp and blunt poles were immobile. The mode shape of the first, flexural spherical mode (S20) produced an oblate-prolate deformation at the equator. The damped natural frequency of this mode and the total egg mass were used to calculate the dynamic eggshell stiffness (k_{dyn}). Modeling the egg as a mass-spring system, the dynamic stiffness k_{dyn} is given as: $k_{dyn} = cte.\ m.\ RF^2$, with m the mass of the egg, cte a constant (set to 1) and RF the resonant frequency of the first spherical mode (S20). Later, Coucke, et al., (1999) and De Ketelaere, et al., (2000) described a laboratory scale device for the measurement of the dynamic stiffness of the eggshell based on the identification of the mode shapes, the corresponding resonant frequencies and damping ratios of these modes using the interpretation of the vibration response of an egg excited at its equator with a nondestructive impact. This technique can also be used to detect cracks in the eggshell. The relationships between some of the physical and mechanical egg and eggshell quality parameters and the dynamic, mechanical properties of a chicken egg have been evaluated in many studies. However, little information is available about the contribution of the basic material and geometrical properties to the results of the dynamic tests. No full explanation could be found for the different effects of egg size and eggshell thickness on the mechanical

behaviour. Coucke (1998) utilised simple structural models to simulate the dynamic mechanical behaviour of the egg using the finite element (FE) method. The analysis was incomplete since the egg content, i.e. the interior fluid, was not incorporated in the model. Since the content effect was neglected, the analysis results showed several deficiencies when comparing numerical and experimental data. In spite of some important observations achieved using the above-mentioned structural models, there is still a gap between models including only the eggshell and highly detailed structural acoustic models incorporating both eggshell and fluid content In the light of the above, the object of this paper is to set up a realistic model for an egg structural acoustic analysis, that is useful to assess, and can be visualised and compared with the structural acoustic behaviour of the egg for different material and geometrical properties. Using this parametric model, the influence of gradual changes in different parameters of the egg on structural acoustic frequency response functions is investigated. It was expected that the approach and the obtained results would be of interest to specialists working on acoustic-based egg grading machines. It was also expected that this approach could allow an improved interpretation of the experimentally observed correlations between egg and eggshell parameters.

The avian egg is a biological structure of high complexity. It contains an air chamber and a viscous liquid surrounded by two membranes and an external covering called the eggshell. The base numerical model used in this study represents a simplified replica of a chicken egg, a fluid filled shell, yielding a coupled structural acoustic problem. Here, the eggshell is modeled as a single layer shell structure of uniform thickness. The acoustic content includes the air chamber and water, the major component of albumen (w90%) and yolk (w50%). The shell membranes are not incorporated in the model. Vibrating structures induce acoustic pressure waves in a connected fluid and, vice versa, acoustic pressure waves act as external loads yielding structural vibrations. This fully coupled structural acoustic problem description is a thoroughly investigated field of research (Fahy, 1985). The numerical approach used in this paper for the representation of the coupling effects between fluid and structure is based on a FE representation of the structure as well as the interior fluids (Zienkiewicz, et al., 2005). The main advantage of such a method is that it is possible to represent in one model cavities with different types of fluid, e.g. water and air (Stavrinidis, et al., 2001). In the following section, the formulation of the coupled structural acoustic problem using the finite element method (FEM) is described.

2.1 Description of the base model

The base model represents a simplified replica of a chicken egg. The egg-shaped geometry was approximated by a half ellipsoid fused to a half-sphere. The overall dimensions of the egg model are 4.6, 5.8 and 4.6 cm, respectively in X (longitudinal), Y (vertical) and Z (lateral) direction. Eggshell thickness is assumed to be uniform over the shell surface. A default value of 0.38mm was applied. The material parameters of the eggshell are as follows: Young's modulus, $E = 3 \times 10^{10}\,Nm^{-2}$, Poisson's ratio $\upsilon = 0.307$ and the mass density $\rho = 2400$ kgm^{-3} (Coucke, 1998). The egg content was represented by an air chamber and a water domain. The height of the air chamber for the default configuration is 4 mm. The acoustic parameters of the air are: speed of sound 343 ms^{-1} and the mass density 1.25 kgm^{-3}. The default values for the acoustic parameters of water are: speed of sound 1500 ms^{-1} and the mass density 997 kgm^{-3}. The FE meshes (see Fig. 1) for both structural and acoustic domain were generated using MSC. Patran (MSC Software, Santa Ana, CA, USA). All uncoupled structural results were obtained with the MSC. Nastran software, while the acoustic and

coupled vibro-acoustic results are obtained with the LMS. Sysnoise software (LMS International, Leuven Belgium). Using mesh morphing techniques, the base meshes were modified for the various analyses (see below). Therefore all models comprised exactly the same number of nodes and elements. For the structural part of the analysis, bilinear four-noded quadrilateral and three-noded triangular shell elements (6 degrees of freedom per node) were used, whereas for the acoustic part linear eight-noded hexahedral and six-noded wedge elements (1 degree of freedom per node) were employed. The applied element size was consistent with the rule of thumb that states that at least six linear elements should be used per wavelength to assure sufficient prediction accuracy. The maximum frequency of interest was selected as 5000 Hz yielding an element size of 0.0025 m, which results in 4920 acoustic and 1050 structural elements.

The structural acoustic model involved in the simulations was a free boundary condition model excited by a unit normal point force exerted at the egg equator (Fig. 1).

Perianu et al., (2010) studied that, the first 50 structural modes were calculated as a first step. The eigenfrequencies of these uncoupled structural modes are in general higher than the experimentally observed values. This could be expected since only the eggshell is modeled and the egg content, which represents 85-90% of the total egg mass, is not yet incorporated in the structural model. However, for a fluid filled egg, the eigenfrequencies of the coupled modes were close to the experimental results. The mode shapes and the sequence of appearance of the calculated modes were very similar to the experimentally observed modes (see Coucke, 1998). Fig. 2 represents a top view (left) and a front view (right) of the mode shape of the first, flexural spherical mode. The first flexural mode has an eigenfrequency of 4190 Hz; this is called the oblate-prolate mode. As can be seen in Fig. 2, all deformation is concentrated towards the equator zone of the egg. An elliptic shape can be recognised at the equator ring. The magnitude of the deformation decreases gradually towards the poles of the egg. In the subsequent analysis each single geometrical and material property was varied within a reasonable range. The effect of these changes on the eigenfrequency of the first flexural mode (S20) was evaluated.
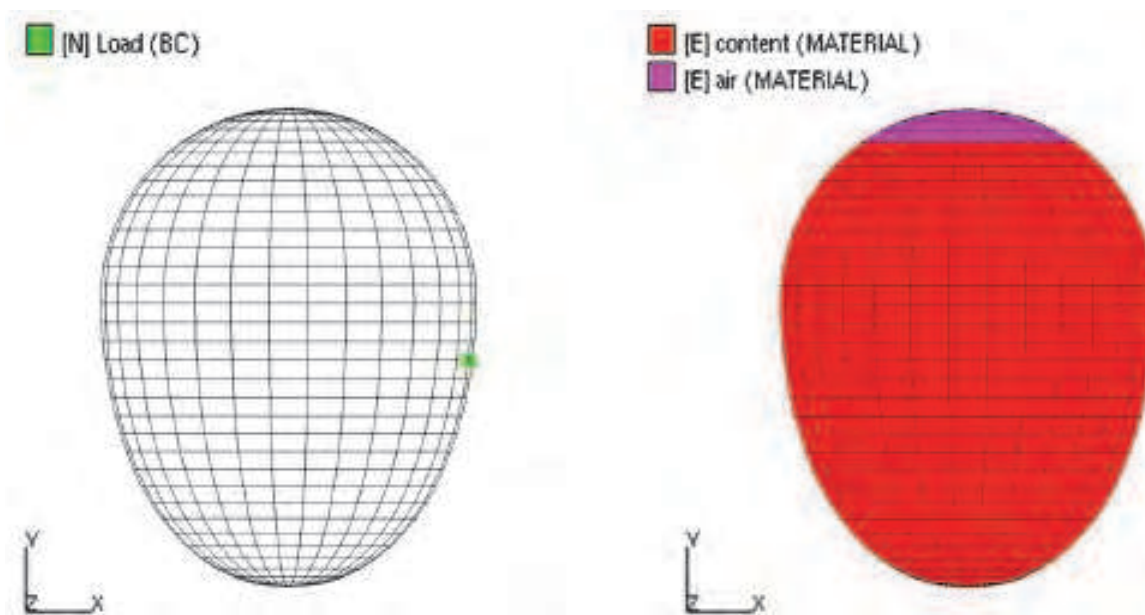

Fig. 1. FE mesh of the eggshell (left) and of its acoustic content (right).
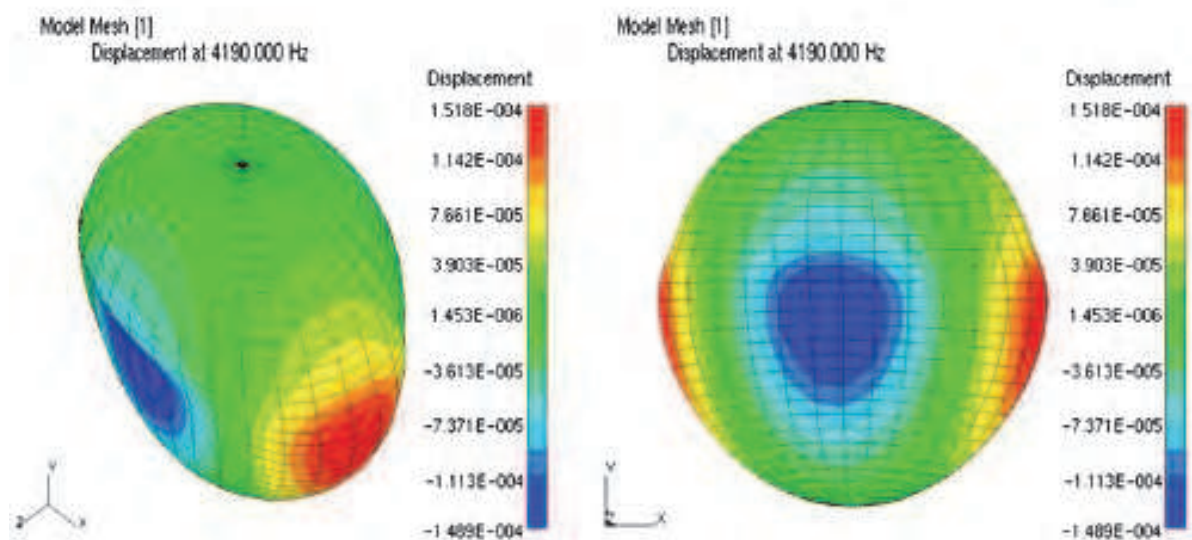
Fig. 2. Top and front view of the mode shape of S20 mode.

3. Operational modal analysis

Amer Eissa and Gomaa (2007) showed that the presence of cracks in eggshells is a common problem in high speed commercial egg grading machines. Non-destructive physical quality assessment of foods is mainly based on vibration analysis with resonant frequency and damping of the vibration being the main parameters. The focus of this research was to investigate the capability of the operational modal analysis as a non-destructive tool to characterise and to quantify the fracture behaviour of eggshells. This was achieved by studying the response of modal testing to the variation in strength as the main factor affecting fracture. Two different methods were applied: 1- traditional modal analysis using transfer function between actuator and sensor and 2- operational modal analysis using transmittance function between pairs of sensors in which input excitation is provided through a piezoelectric force transducer bonded to the centre of the cup used for egg installation in order to extract the corresponding modal parameters and damping ratio. The test for strength was performed on 200 eggs deriving from two genotypes of hens that were correlated to modal parameters and the behaviour of the fracture. Damping loss factor enabled to distinguish the strength for two types of eggs. Natural frequency showed a greater response to egg type and strength increased as frequency response function (FRF) increased for the two types of eggs (R= 0.979 & 0.984). These methods allow for an evaluation of the suitability of modal testing predicting fracture using an empirical formula. The damage index based on changes in transmittance function is very sensitive to a change in crack length. Structural information obtained from the biomaterial at different length scales is important in relation to the functional properties of the structure. This knowledge and the principles behind the formation of biomaterials could be used in an attempt to develop new systems of bioengineering.

Cracking of eggshells is a common problem in commercial egg production resulting in downgrading of eggs and substantial economic losses. Also cracked eggs are more vulnerable to Salmonella and other bacterial infections leading to health hazards. Therefore, detection and removal of cracked eggs continues to be very important for quality assurance in the egg industry. Candling is a reliable and most often used technique for egg quality

assessment. However, egg candling is an immensely difficult task and requires a combination of great skill, practice and concentration by the human operators, especially when linking it with high speed grading machines. As a result, attempts have been made to replace the human operators with the so-called machine vision systems to detect cracks and other defects on the egg surface (Elster & Goodrum, 1991; Goodrum & Elster, 1992; Patel et al., 1994). It has been shown that several problems associated with misclassified images may affect the overall accuracy of such systems considerably (Garcia-Alegre et al., 2001). Recently it has been reported that acoustic impulses resulting from a soft mechanical impact could be used for online inspection of eggshell cracks non-destructively in real time (Cho et al., 2000; De Ketelaere et al., 2000). Cho et al. (2000) developed classification criteria for detecting surface cracks in egg shells based on the frequency spectrum of acoustic impulses using multiple regression and multivariate discriminate analysis. The errors associated with incorrect identification of cracked and intact eggs were found at 4 and 6%, respectively. In another approach, De Ketelaere et al. (2000) used Pearson correlation coefficients between the frequency spectra of acoustic responses to classify eggs. They showed an accuracy of about 90% for cracked egg detection with a false reject of less than 0.5%. Finally, Bain et al., (2006) and Mertens et al. (2006) showed that dynamic stiffness provides a good estimation of eggshell strength in relation to the likelihood of breakage in practice. Artificial neural networks (ANNs) have been widely applied to classification problems in many fields. Several successful implementations of ANN classifiers reveal their capability to extract trends and patterns from large data sets (Das & Evans, 1992; Chen et al., 1998; Ghazanfari et al., 1996; Jindal & Chauhan, 2001). They offer significant advantages when dealing with noisy or obscure patterns from statistical pattern classifiers (Jindal and Chauhan, 2001). Due to higher speeds in commercial egg grading machines (which grade up to 120,000 eggs/h), an automated quality sorting device is of interest to assure a consistent egg quality. One of the main physical quality parameters for the consumption of eggs is the absence of eggshell cracks. Very recent research shows that it is possible to detect cracks in eggshells on-line using vibration analysis (De Ketelaere et al. 1997; De Ketelaere et al. 2000; Coucke, 1998; Moshou et al., 1997). For this purpose, the egg is hit four times around its equator and the similarity (correlation) between the four measurements is used as a sorting criterion. In this way, up to 90% of the cracks can be removed while the number of false rejects (the percentage of intact eggs that are classified as broken) remains well below 0.5% (De Ketelaere et al., 2000). Because of the complexity of the eggs' structure and transport conditions, no clear guideline and methodology for the experimental analysis of the dynamic egg characteristics has emerged, especially damping on line. Egg shell strength provides a proper estimation of eggshell life. To avoid sudden or unexpected fractures of eggshells, non-destructive tests and modal parameters are investigated and correlated to strength. Two methods for estimating modal damping to verify the accuracy of the estimated modal damping ratio were investigated by Brincker et al. (2002).

Our research focuses on the question of whether it is possible to use vibration measurements to assess eggshell strength online as another potential quality parameter towards an integrated on-line egg quality assessment. Different techniques can be found for eggshell strength determination in the literature. In general, these can be split up into direct and indirect methods (Hamilton, 1982). Indirect methods measure a parameter that is related to the eggshell strength. The correlation between the different methods is moderate, and the method of choice often depends on the application, although most methods are destructive. Measuring eggshell thickness is one of the most frequent used indirect methods to get an

indication of eggshell strength. Using a micrometer, it is possible to determine the thickness up to 0.02 mm. Another indirect measure for the strength of the egg is provided by the calculation of the eggshell percentage. Abdallah et al. (1993) showed that 80% of the breakage percentage of a batch of consumption eggs can be explained by this percentage. A third widely used indirect method makes use of the quasi-static compression of the eggs between two parallel plates. By measuring the force deformation curve, it is possible to determine the static stiffness of the egg. In the present study, this method is used as a reference.

Various direct methods are described in the literature. The most widely used is the compression fraction force measured during quasi-static compression (Voisey & Hunt, 1967 a,b; Abdallah et al., 1993). Other methods include puncture tests and impact tests. All direct methods are destructive. From the literature it appears that their behaviour has been simulated as a mass–spring system from which the stiffness of the product is the factor describing its quality. The stiffness of the product is hence a function of both the mass of the object and its resonant frequency given by Coucke (1998) with the dynamic stiffness, the mass of the egg and the resonant frequency. This is clearly an invariable model, linking only one vibration parameter (the dynamic stiffness) with a reference quality parameter. The dynamic stiffness of the eggshell is used to estimate the static stiffness. This invariable model is not applicable as such for eggshell strength assessment because of the moderate correlation between the kdyn and kstat (Coucke et al., 1999). The current study focuses on the expansion of the invariable model to obtain more accurate estimates of the eggshell strength. Additional and improved information will be provided by:

1. A very accurate estimation of the resonant frequency (note that this is quadratically related to the dynamic stiffness and hence plays a crucial role).
2. Expanding the model by incorporating the damping of the vibration, which was ignored in all research found in the literature; including the mode shape, and provision of an empirical formula to correlate between modal parameters (natural frequency, damping ratio and magnitude of frequency response function) and strength. Therefore, the objective of this study was to develop a method for detecting eggshell cracks based on transmittance function of frequency response of eggs on line.

2.1 Methods of damage detection

Various methods of detecting damage have been proposed. One of the approaches that have received considerable attention in the technical literature is vibration–based damage detection. The fundamental idea behind vibration-based damage detection techniques is that changes in the physical properties will alter a system's modal properties such as natural frequencies, modal shapes and damping. The discussion herein focuses on feature selection for damage detection (Doebling et al., 1998) summarizing many features that have been proposed for vibration-based damage detection.

Comprehensive literature reviews of subject structural health monitoring can be found (Doebling et al., 1996; Farrar & Doebling, 1997; Zou et al., 2000; Amer Eissa and Gomaa, 2009). Todd et al. (2001) used chaotic input signature and a state-space method for damage detection. A novel feature called the local attractor variance ratio was developed using chaos theory. They showed how a properly tuned chaotic excitation could be used to robustly detect structural changes. Techniques based on neural networks require a model to train the system to detect damage (Wang & Huang, 2000). Zubaydi et al. (2002) investigated the damage detection of composite ship hulls using neural networks. They developed a

finite element model for a stiffened plate to stimulate dynamic response of the structure with and without damage. Very small damage in composite materials, such as cracks, was successfully found using wavelet analysis (Yan & Yam, 2002). Ganguli (2001) used a fuzzy logic system to locate damage on helicopter rotor blades. Salawu (1997) presented a review of various investigations on the effects of structural damage on natural frequencies. Many damage location methods use the change in resonant frequencies because frequency measurements can quickly be conducted and are often reliable. However, changes in ambient condition can cause a significant frequency change in composite materials, and findings suggest that detection of damage using frequency measurements might be unreliable when the damage is located at regions of low stress. Kuo & Jayasuriya (2002) used transfer functions to determine the extent of joint loosening in automobile vehicle frames with high mileage. The method was successful but did neither give specifics of the frequency range investigated nor about the used type of FRFs .

The successful transmittance function testing for wind turbine blade damage analysis was presented by (Ghoshal et al. (2000) and Schulz et al. (1999). Caccese et al. (2004) used three different monitoring techniques at low frequency modal analysis and for high frequency transfer functions between the actuator and sensors. These experiments demonstrated that the transmittance function is very sensitive to changed bolt load. To confirm the characteristics of the transmittance function technique, this paper focuses on the detection of fractures in eggshells.

2.2 Operational modal analysis using transmittance function

Transmittance testing procedures are similar to the procedures using the transfer function (Richardson & Potter, 1974; Caccese et al., 2004). For the transmittance test the response frequency domains of the two sensors are compared with each other. In contrast to this test, the response of the sensor is compared to the excitation signals. Thus, for transmittance testing sensor A was connected to input channel A and sensor B was connected to reference channel B. The transmittance function between two response points, a and b is given by:

$$T_{ab}(f) = \frac{G_{ab}(f)}{G_{bb}(f)}$$

where
G_{bb}: is an auto spectral density function.
G_{ab}: cross spectral density function, one side auto spectral density function and cross-spectral can be computed from real data:

$$G_{ab}(f) = \frac{2}{(n_d \Delta T)} \sum_{i=1}^{n_d} A(f,T)B^*(f,T).....(f > 0)$$

The spectral densities are a function of frequency that can be averaged across (n_d), where n_d: is a distinct sub-record of duration ΔT , * : Complex conjugate.

The cross-spectral density function is the Fourier transformation of the cross correlation function. It represents the frequency domain, and characterization of similarity of the magnitude and phase of two signals, therefore it can accurately detect damage over small distances on the structure. Furthermore, measured transmittance data include complete information on the dynamic behaviour of the test structure, in terms of vibration modes and

damping, at many frequency points. So it is much easier to display ODS's from a set of ODS
FRF and observe mode shapes at resonance frequencies. The magnitude of the scale factor is
calculated by Vold et al. (2000):

$$Scale\ factor(i) = \frac{\sum_{i=1}^{No.of.Meas.sets} ARM(i)}{No.of.Meas.setXARM(i)}$$

where ARM (i) =Average value of the reference response APs for measurements set (i). This
scale factor corrects each of ODS FRF magnitude according to the average level of all
reference response signals and the average value can be calculated for any desired range of
frequency samples (Mohanty & Rixen, 2004). Modal analysis is used to analyze the effect of
aging on the dynamic properties of an egg. The egg is made up of several types of materials
such as shell, yolk and egg white and these material properties are non homogeneous.

Amer Eissa and Gomaa (2007) found that, the response of the eggshell sensed by a light
piezoelectric accelerometer, weight (2.2 gm), mounting surface flatness, charge sensitivity
(0.318) pc / ms-2, voltage sensitivity (0.415) mv/ms-2 which was bonded to the opposite
direction of impact hammer using a wax for free suspension that represent the inherent
properties of egg. Without regard to the external constraint condition at frequency (0 - 1.6
KHz), both signals from impact hammer and accelerometer were supplied to FFT analyzer
as in Fig. (3 a, b), and estimation FRF with a narrow band of 800 Hz, centered around the
fundamental frequency a sample of FRF and coherence function are in Fig. (4) Because of
complexity of eggs structure and transporting condition there is no clear guide line and
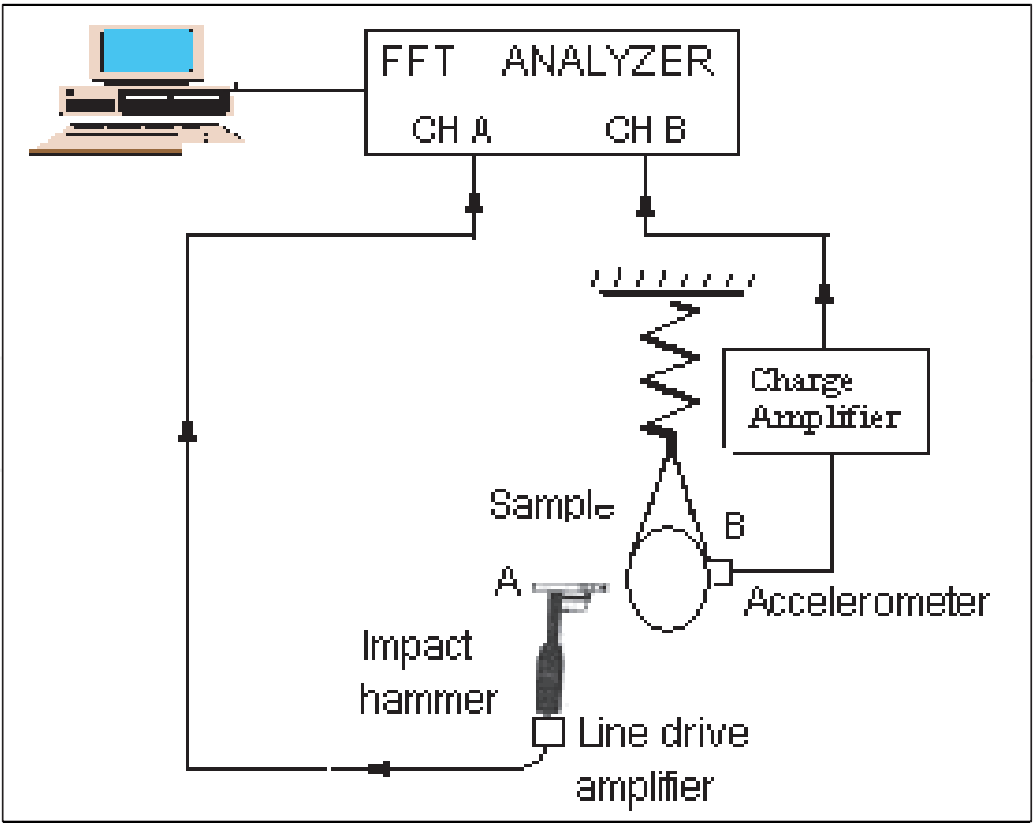

Fig. 3. (a) Schematic layout of the system used for (TMA) modal analysis.

Fig. 3. (b) Free suspension for modal analysis.

methodology for experimental analysis to be emerged. As mentioned this work focused on two different methods for vibration measurements traditional Modal Analysis (TMA) and transmittance function (T.F). In order to verify the accuracy of the estimated modal damping, the same set of data were presented using operating moving average ODS Brian Schwarz et al (2000). Fixed installation using cup and transmittance function were obtained experimentally, as in Fig. (5 a, b) [The support of the egg is chosen in such a way that they coincide with the nodal points of the first elliptic]. The system excitation was using exciter control through generator with variable force but did not measure. For transmittance testing sensor A was connected to input channel A and sensor B was connected to reference channel B of FFT analyzer (Amer Eissa and Gomaa, 2007).

Fig. 4. A sample of FRF and coherence function.

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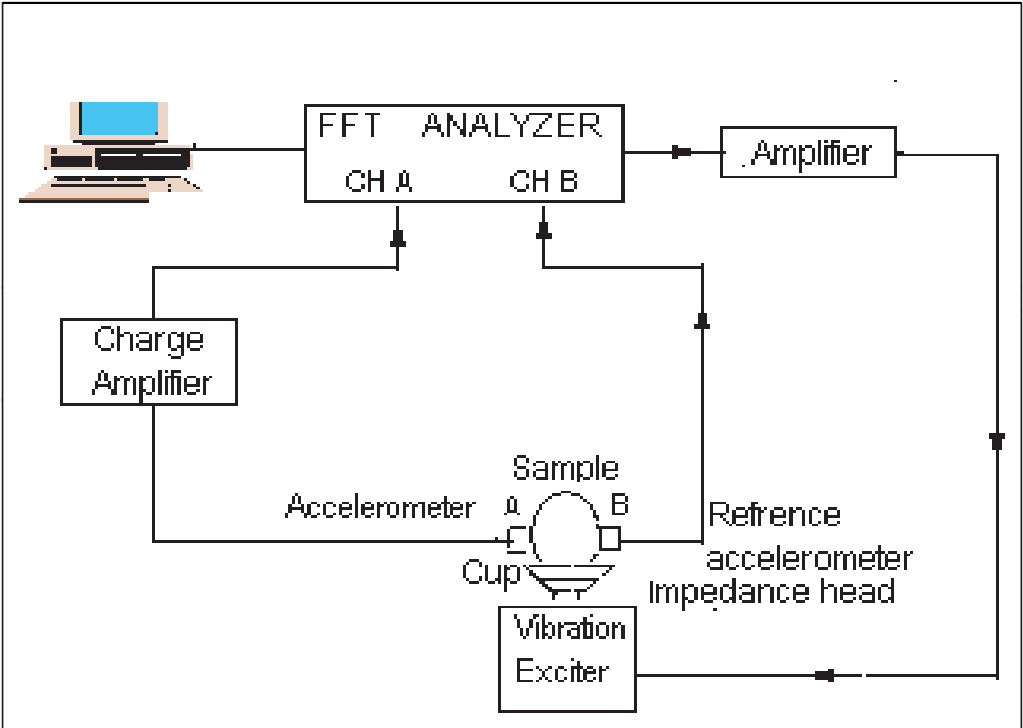– From Analysis and Modeling to Technology Applications

Fig. 5. (a) Schematic layout of the system used for operation modal analysis.

Fig. 5. (b) Fixed installation using a cup for operation modal analysis.

4. Pendulum for impact characterization

Amer Eissa (2005) suggested that, a mechanical breakage egg is cumulative and can occur each time when eggs are handled. It is a major problem in Egypt, Europe and world leads to

direct losses in intensive egg production systems and increased labours costs during grading, sorting and processing. Eggs are subjected to mechanical impacts at the moment of lay, during collection, in the sorting equipment and during transport in trays.

A chicken egg is an already packaged food. An important quality aspect of the packaging material is the mechanical strength of the egg shell. A commonly used technique for the measurement of the shell strength is the quasi-static, non-destructive compression of an egg. The slope of the force-deformation curve is a measure for the stiffness of the shell and for the egg shell strength. However this method is tedious and the required equipment is expensive. An alternative method has been developed based on the impact behaviour of the egg. A portable pendulum for measuring the extent of dynamic shell breakage in eggs. It can be used to measure energy absorbed during impact. Measurements are made using an angular displacement transducer and interpreted by means of logic circuits. A coefficient of restitution parameter is defined which is based of the dynamic behaviour of the egg. Both impact velocity and rebound velocity showed promise as an indicator for evaluating the coefficient of restitution of egg shell during impact.

The new impact test method is a promising alternative for evaluating mechanical egg shell properties because it's destructive and non-destructive nature.

Economic loss due to egg shell breakage is an important problem in intensive egg production systems (Oosterwoud, 1987). Eggs are subjected to mechanical impacts at the moment of lay, during collection, in the sorting equipment and during transport in trays. Bain (1991) reported that 6% to 8% of all eggs laid are broken during handling from the production unit to the consumer, and in monetary terms this gives rise to losses of at least $600 million on a world wide basis. The value of egg production was $3.389 billion in 1992, compared to $ 3.209 billion in 1987 (Madison and Perez, 1994). Therefore, egg shell breakage continues to be a costly problem for the egg industry. In addition, people are at high risk when eating eggs which might be contaminated after being damaged, i.e., with cracks or checks (Amer, 1998; Bain, 1990).

Egg shell breakage depends both on the strength of the egg shell and magnitude of the mechanical load applied. Variables associated with shell strength are biological in nature (Hamilton, 1982). They involve the material and structural properties of the different layers which comprise the egg shell. The material properties depend on the type and the association between the mineral and organic components of the shell. The structural properties depend on egg shell thickness, size and shape of the egg and the distribution of shell over the egg surface.

In most of the methods used for measuring egg shell strength these basic physical properties are not quantified separately because of their complexity. Indeed, the shell curvature and its brittle nature make it difficult to measure the material properties of the shell by classical means (Amer Eissa & Gamea, 2003; Bain, 1990). Therefore, more practical techniques have to be developed. Such methods, however, describe the behaviour in terms of a superposition of several material and structural properties of the egg. One such commonly used method is the non-destructive, quasi static compression test. In this test the elastic stiffness properties of the whole egg shell structure are measured. An egg is placed horizontally between 2 flat parallel steel plates and then compressed at a constant compression speed until a predefined non-destructive load is applied. The slope of the force-deformation curve is an indicator of the mechanical stiffness of the shell. This mechanical stiffness depends on the thickness of the egg shell, the curvature of the egg shell, the diameter of the egg and the Young's modulus of the material in each layer of the shell (Amer, 1998; Bain, 1990).

A more precise method of measuring the impact strength of an egg is to record the force on the shell throughout the impact. Using this technique, Voisey and Hunt (1967 a,b) developed an instrument to measure the impact force required to fracture an egg. With this instrument the egg is supported in an adjustable plastic (nylon) cradle directly below a suspended aluminium rod 1900 mm in length, this cradle is adjusted, using a dial gauge, so that the upper surface of the egg is at a constant distance (5.0 mm) from the end of the aluminium rod for all measurements. The rod is suspended by an upper spherical end that fits into a socket connected to a vacuum pump. By opening a solenoid valve the vacuum is released and the rod falls freely until it strikes the egg. The impact of the rod on the egg is measured by a piezoelectric transducer attached to the lower end of the rod; the rod and transducer weigh 695 g. The transducer can be calibrated in either force or acceleration units. The electrical output of the transducer during the impact is recorded by a peak-shock meter and the maximum value displayed by a 4-digit voltmeter. The impact strength of about 150 eggs can be measured per hour with this instrument. Force-time plots can also be obtained using an oscilographa and camera to record the graph for each egg. It is very important that shock waves generated within the rod during the impact with an egg do not affect the measurement. This effect may be overcome by changing the length of the rod or the material from which it is made (Voisey and Hunt, 1968).

During handling of eggs, several impacts may be imparted to the egg shells, if not limited, will cause considerable damage. Several researchers have investigated the effects of impacts on agricultural products. Zapp et al., (1990) investigated the impact on apples by simulating an apple with an 'instrumented sphere'. Jindal and Mohsenin (1976) analysed a pendulum impacting device with which apples and corn kernels were tested. Finney and Massie (1975) also investigated a pendulum impacting device for testing the response of fruits to impacts. Other authors who have investigated impact devices for agricultural products include Amin (1995), Tennes et al., (1988), Siyami et al., (1986), Hughes et al., (1985), Simpson and Rehkugler (1972) and Bilanski (1964).

In the case of a chicken egg, the interpretation of the impact response of an egg is even more complex than for apples. An egg consists of several types of material: a shell, an air-chamber, egg white and yolk. The egg shell structure itself contains several distinct layers that are penetrated by pores. Within 1 layer, the material properties are not homogeneous. The material properties of the egg content are also variable. Nevertheless, it is worthwhile to asses the experimental relationships between the dynamic impact, mechanical properties of an egg and commonly measured physical egg and egg shell variables.

The values of the material property of eggshell were reported over 25 years ago. These values might be obsolete due to significant changes in chickens' species, feed and management practices. Therefore, it is necessary to measure the key material properties of present day shell eggs.

The objective of this work has been to develop apparatus able to evaluate shell dynamic strength, stiffness and relate their measurements with the egg shell quality purposes. This paper describes a pendulum which is portable and which will impact eggshell under a wide range of velocities and energies.

4.1 Construction of the pendulum

A pendulum impactor Figure (6) was used to apply the preselected amount of energy to the eggshell during impact. The portable folding pendulum a dynamic shell egg tester. It consists of two main parts: (1) a pendulum with an angular displacement transducer and

arm release mechanism, length of the pendulum arm is 40 cm (2) a box containing the battery powered electronics, including control and display units, connected by cable to the angular displacement transducer. An angular displacement transducer attached to one end of the spindle is used to determine the rebound angle of the arm after impact for absorbed energy calculation. A simple pendulum, consisting of a steel ball cylindrical and spherical specimen on a lightweight (6.83 and 5.4 5 g, respectively), was used as the basic dropping apparatus as shown in Figure (6). This provided a simple system for negligible frictional losses during the drop. The main body and the platform of the pendulum are constructed from metal and its arm oscillates along a pivot supported by bearing. The duration of sample impact by the indentor and the time taken for the indentor to return to the point of initial contact with the egg are shown on individual displays. Signal from the angle meter first goes to a synchronic converter and then to a structural dynamic analyser. Impact parameters such as rebound angle can be monitored and recorded. These data are displayed by a single digital read out and selector switch. The height of the pendulum arm can be adjusted by moving the release catch mechanism on the metal plate (calibrated in cm drop height of the indentor). The various drop weights of the indentor are interchangeable and can be screwed to the end of the pendulum arm.

4.2 Dynamic tests

They differed in size, shape and mechanical properties from those tested in the fall under static loading will affect the impact characteristics to that from drop height, one of these two parameters must be known or estimated. By mathematical dependency, the known or estimated parameter can be derived from one of the following: impact velocity, rebound velocity, velocity ratio (coefficient of restitution), drop height and rebound height. The impact loads were expressed in terms of total energy, energy absorbed, total momentum and momentum absorbed. For user convenience, maximum and minimum values for each of these parameters are displayed for each impact. Once any one of the above parameter is estimated Amer Eissa, (2004). These properties may all be displayed simultaneously. These were defined by.

E_{imp} = W h_{drop} = total energy or energy of impact, (N.m=J.106= µ J)

E_{abs} = W (hdrop-hreb) = energy absorbed by the egg, (N.m=J.106= µ J)

M = (W / 9.81) V1 = total momentum, (N.s.106=µN. s)

M_{abs}= (W / 9.81) (V1-V2) = momentum absorbed, (N.s.106=µN. s)

E_{reb} = Eimp (h_{reb} / h_{drop}) = energy of rebound of the pendulum arm, (J)

Where: V1 = (19.62 hdrop / 100)1/2 = impact velocity, m/s

V2 = (19.62 h_{reb} /100)1/2 = rebound velocity, m/s

W = Weight of the ball or rigid object (indentor), kg

h_{drop} = The height of drop, m = L (1- cos θ)

h_{reb} = The height of rebound, m = L (1- cos α)

L = The height of arm (0.40 m)

θ = The angle of drop, in degrees

α = The angle of rebound, in degrees.

The coefficient of restitution (e) which describes the rebound characteristics was calculated from.

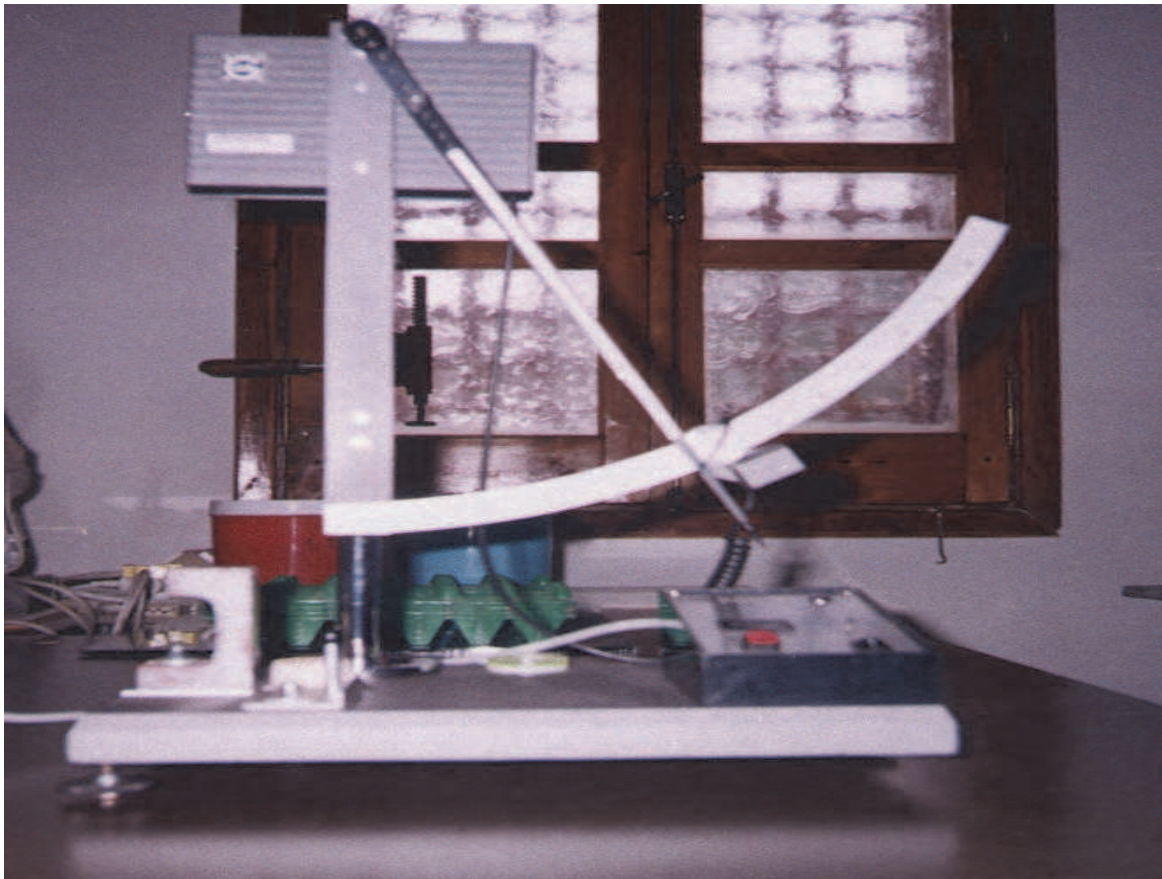$$e = \left(h_{reb} / h_{drop} \right) 1 / 2 = V2 \; / \; V1$$

Fig. 6. The portable pendulum instrument.

This coefficient is usually defined as the ratio of final to initial relative velocity components of the striking bodies in the direction normal to the contact surfaces.

Mechanical breakage during collection of egg operations can affect both the egg and egg shell quality. The slope of the force deformation curve is a measure for the static stiffness (k_{stat}) of the egg, as:

$$F = k_{stat}\delta$$

where: F = force on the egg shell

k_{stat} = static stiffness

δ = deformation of the egg shell.

4.3 Strength under impact loading

Hen's eggshell strength under impact loading Šarka Nedomova (2009) found that An experimental method for evaluation of an eggshell's mechanical characteristics under impact loading is discussed. Proposed experimental set up enables recording of time history of the force at the contact area between the rod and eggshell, as well as the vibration response of the tested egg. By the gradual increasing of the rod impact velocity, a rupture force of the eggshell was determined. The value of this force depends on the position of the rod impact. This dependence is more significant than that of static loading of the eggs. The preliminary results also show the non-negligible dependence of rupture force on the loading rate. An introductory numerical simulation of the given test was also performed. The LS

DYNA finite element code was used. Numerical results exhibit reasonable agreement with experimental results.

For the egg industry and its consumers, an intact shell is the first and most important egg quality criterion. Since egg handling became more and more mechanized, eggshell quality became the topic of extensive research, probably because the balance between eggshell strength and the handling load applied to the shell became less favorable for the eggshell. The shell must be free of cracks and highly resistant to dynamic impact loads and static compression. Eggs are exposed to mechanical impacts at the moment of lay, during collection, in the sorting equipment, and during transport in trays. Static compression is the most critical consequence of the egg's packing. There are many methods for the study of the eggshell strength. Total shell strength is influenced by material and structural strength. In most of the methods used for measuring eggshell strength these basic physical properties are not quantified separately because of their complexity. Indeed, the shell curvature and its brittle nature make it difficult to measure the material properties of the shell by classical means (Bain, 1992). This is probably the main reason why eggshell strength is determined by the entire egg. For example, static stiffness (Ks; Voisey and Hunt, 1967) and dynamic stiffness (Kd; Coucke et al., 1998) are a measure for total shell strength. To determine Ks, an egg is compressed between parallel plates and, therefore, it is a measure for the interaction between structure and material characteristics. To determine Kd, the egg is excited by a small impact, and the vibration behavior is registered. Subsequently, from the resonant frequency and the mass of the egg, the Kd is calculated. These methods are non-destructive. To study the egg's resistance to impact, many other methods have been developed – see e.g. Tyler and Geake (1963), Voisey and Hunt (1968). These methods use balls or rods, which are dropped on the eggshell. The height of the fall, the size of ball, or a number of blows are used to estimate shell strength. The aim of the given paper is to further develop these experimental methods of dynamic strength evaluation. The loading has been performed by the impact of the free falling rods. The record of the force at the point of rod–eggshell contact enables evaluation of the rupture force at a definite impact velocity. The obtained results have been compared with results of the static compression of the eggs in order to find some evidence of the loading rate influence.

The values of the eggshell strength in terms of the rupture force are affected by many factors (egg specific gravity, egg mass, egg volume, egg surface area, egg thickness, shell weight, shape, and shell percentage). In order to avoid the simultaneous influence of these factors, the numerical simulation of these experiments should be performed. This procedure has been successfully used in Macleod et al. (2006) for the description of static loading. In the given paper this analysis has been performed for the dynamic loading.

4.3.1 Static loading

The test device (TIRATEST 27025, Germany) used for performing the measurements has three main components: a stationary and a moving platform, and a data acquisition system. Compression force was measured by the data acquisition system. The egg sample was placed on a block of polyurethane foam positioned on the stationary plate. The egg has been loaded by the moving rod (6 mm in diameter) at a speed of 20 mm/min. Two compression axes (X and Z) for the egg were used in order to determine the rupture force and deformation. The X-axis was the loading axis through the length dimension, and the Z-axis was the transverse axis containing the width dimension. Along the X-axis, two other orientations were considered. The eggs were loaded at the sharp end and at the blunt end

see Fig. 7. For each orientation, 30 eggs were tested. The geometry of the eggshell was described using the shape index, SI. The average value of the shape index has been 76.18 ± 2.35 (%). In Fig. 9, the example of experimental record of the force vs. rod displacement is shown. One can see that the shape of this curve is different from those obtained at the eggs compression between two plates see Altuntas and Saekerog lu (2008).

4.3.2 Dynamic loading

The experimental set-up is shown in Fig. 8 and consists of three major components; the egg support, the loading device, and the response- measuring device (laser vibrometers POLITEC CLV 2000, USA). (1) The egg support used is a cube of soft polyurethane foam. The stiffness of this foam is significantly lower than the eggshell stiffness; therefore, there is very little influence of this foam on the dynamic behavior of the egg. (2) A bar of the circular cross-section with strain gauges (semi conducting, 3 mm in length) is used as a loading device. The bar is made from aluminum alloy. It is 200 mm long with a diameter of 6 mm. The bar is allowed to fall freely from a pre selected height. The instrumentation of the bar by the strain gauges enables to record time history of the force at the area of bar–eggshell contact. (3) The response of the egg to the impact loading, described above, was measured using the laser vibrometer. This device enables one to obtain the time history of the eggshell surface displacement. The eggs were impacted on the sharp end, on the blunt end, and on the equator. For each loading orientation, 20 eggs were used. The height of the bar fall was increased up to a value at which

the eggshell damage was observed. The displacement was recorded on the equator of the egg. The displacement was measured in the normal direction to the eggshell surface. Measuring the conductance of eggshells using the acoustic resonance technique and optical transmission spectra Bamelis, et al., (2008) found that , during the incubation of an avian egg, water vapour, oxygen and carbon dioxide are exchanged through the porous shell of the incubated egg. Due to the high variability of the eggshell conductance (G), large variation in exchange rates are present and hence a significant number of eggs are incubated in suboptimal conditions for humidity and partial pressures of carbon dioxide. Because there is no reliable technique to measure G in a non-destructive and fast way, the direct adaptation of the ambient conditions during incubation in relation to the G of the incubated eggs is not yet possible and this has repercussions on both the hatchability and chick quality. In the subject, two non-destructive and fast techniques, the Acoustic Resonance Technique (ART) and the measurement of light transmission through the egg, are used to estimate G. It was found that the dynamic stiffness of the egg ($k$dyn) and the optical transmission at 611nm are the parameters with the highest predictive power when estimating G. Although this model is highly significant ($P < 0.0001$), the R-value for the best model is only moderate ($R = 0.67$).

This indicates that there are still other parameters involved in the eggshell conductance that are not measurable by the ART and transmission of light. However, with the presented combination of non-destructive techniques, different classes of eggs based on their shell conductance could be created and incubated separately. During the incubation of chicken eggs, water vapour, oxygen and carbon dioxide are exchanged through the porous eggshell. Theoretically, the exchange rate of each gas is determined by the difference in the vapour pressure of each gas between the inside and the outside of the egg and the eggshell conductance for each gas (GH2O, GO2 or GCO2) (Paganelli, 1980; Tullett, 1981). Since GH2O, GO2 and GCO2 are closely related (Rahn, 1981), GH2O is often used as a general
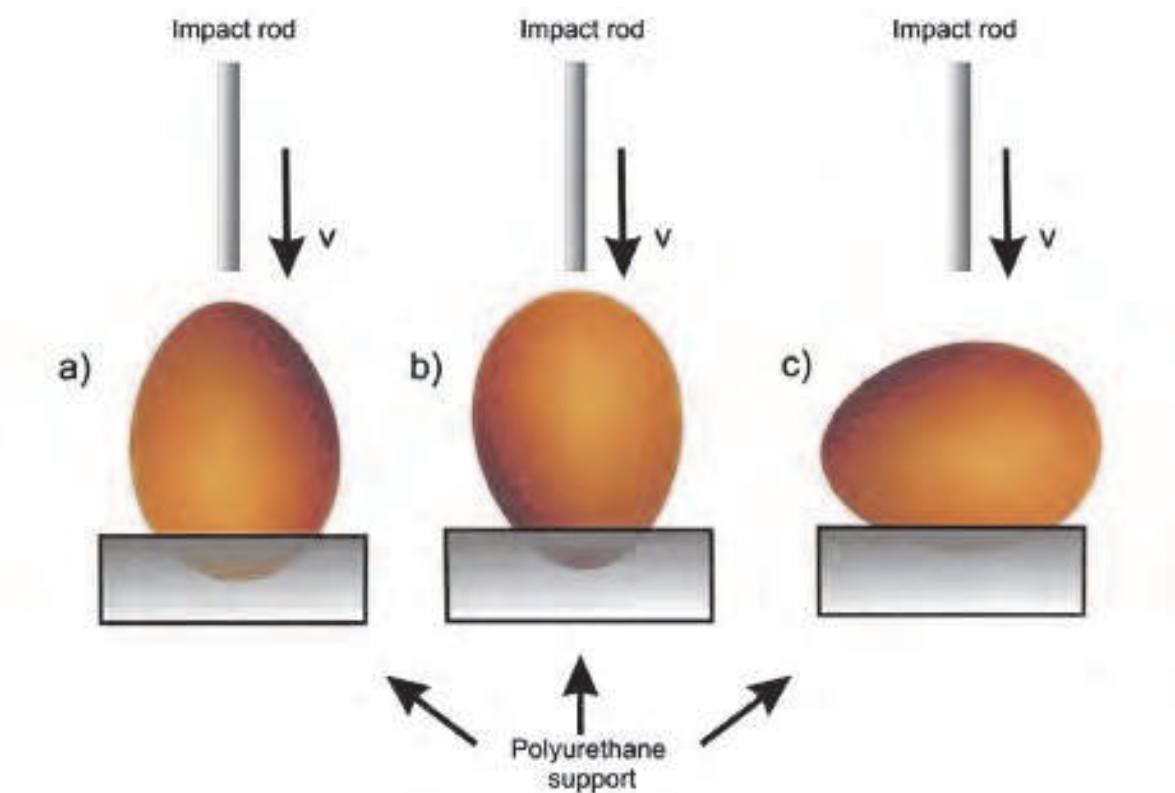
Fig. 7. Schematic of impact loading; (a) along X-axis (sharp end), (b) along X-axis (blunt end), (c) along Z-axis (equator).
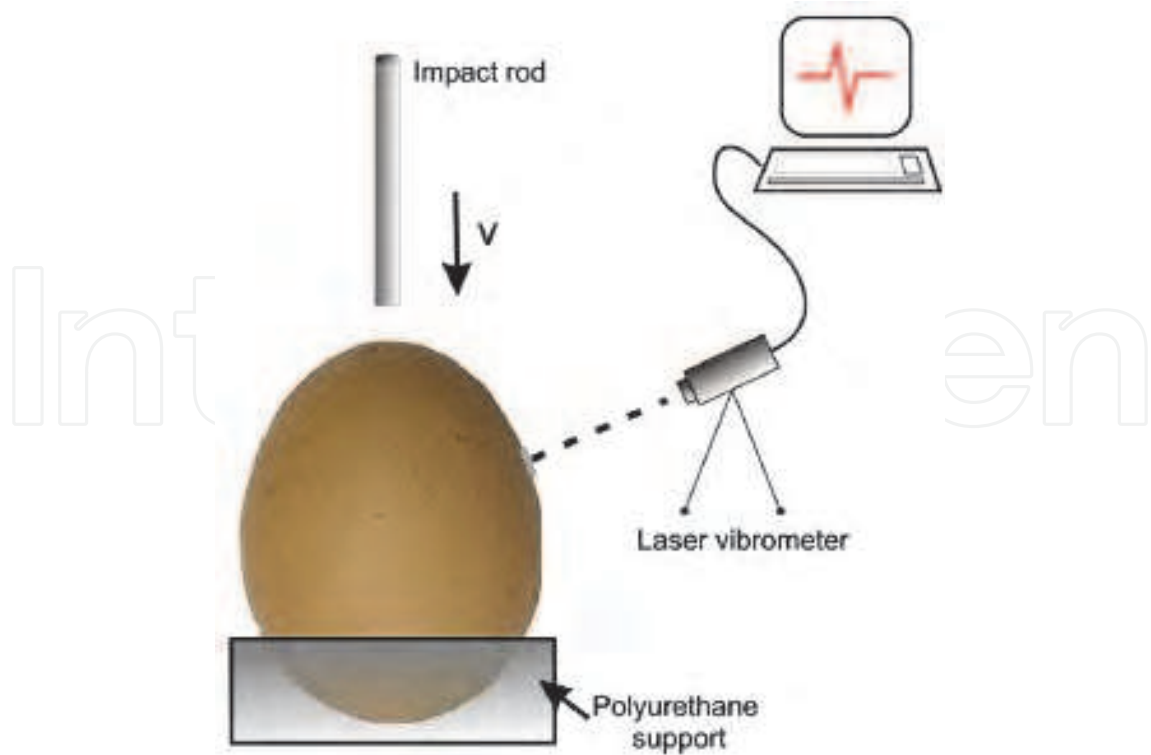

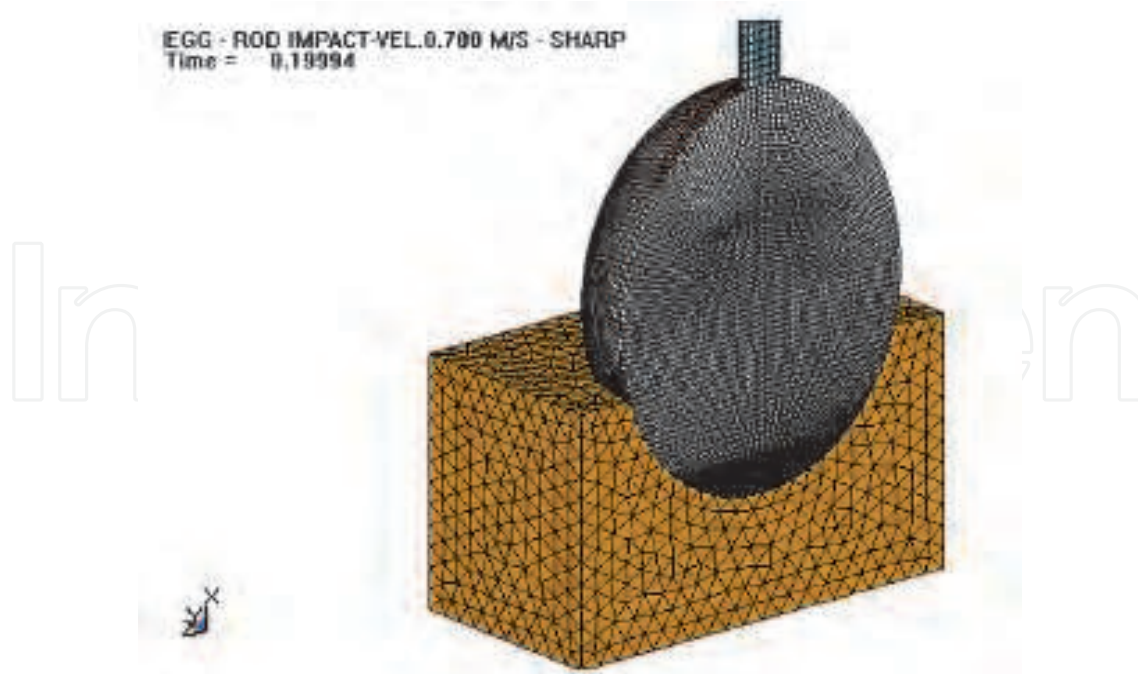Fig. 8. Experimental set-up – dynamic loading.

Fig. 9. Numerical model of the experimental set-up.

measure for the eggshell conductance and noted as *G*. The ambient environment of eggs during artificial incubation is usually kept constant and therefore the eggshell conductance and the inside partial gas pressure in the egg are the major players in the exchange process of water vapour, oxygen and carbon dioxide.

The air in the air chamber and between the fibres of the shell membranes is totally saturated with water vapour, making the exchange rate of water vapour through the eggshell towards the outside only dependent on *G* for fixed incubator humidity. Since the respiration quotient of the developing chick inside is about 0.772, the mass of the exchanged CO_2 equals the mass of the O_2 taken up (Tullett, 1981). Thus, the measurement of the mass loss of the egg during the incubation is a suitable estimator for the water loss and hence for *G*. The developing embryo produces more CO_2 and requires more O_2 towards the end of the 21-day incubation period. This change causes the gradient of the partial pressure of CO_2 and O_2 over the eggshell to increase, and as a consequence, the diffusion rate of those two gases will increase during the ongoing incubation. At a certain moment, the difference in partial pressures over the eggshell for both gases cannot increase more for physiologic reasons, and hence, a maximal diffusion rate of CO_2 and O_2 is reached. The period in which a maximal exchange rate is established is called the plateau phase (Rahn et al., 1979). During the plateau phase, the amount of O_2 that can reach the embryo and the amount of CO_2 that can leave from the embryo are limited by *G*. A high variability is reported on *G* by French and Tullett (1991), even in eggs from chickens of the same line and age. Therefore the duration and the level of the plateau phase are variable and hence the physiology of the developing embryo will be affected in different ways concerning the conductance of the eggshell (Ar and Rahn, 1980; Tazawa, 1980).

Until now, there has been no suitable technique to measure or closely estimate *G* besides the measurement of mass loss over a fixed period (mostly 4 days) in a controlled humidity environment with at least two different measurements of the mass of the egg. Online measurements of weigh losses of egg trays in modern incubators are valuable for adapting

the mass losses of the mean of all setted eggs, not for differentiating eggs based on *G* before the incubation starts. If there should be a single measurement technique that is not destructive and fast before the incubation starts, then it could become possible to adapt the environmental factors in the incubator (humidity, CO2 andO2 partial pressures). This adjustment could make the conditions for different classes of eggs more adapted to their physiological needs, and hence, an increased hatchability may be expected. In the research presented here, two non-destructive and fast measurement techniques were tested for their ability to estimate *G*. The first technique, the Acoustic Resonance Technique (ART) is used to estimate the dynamic stiffness of the eggshell (k_{dyn}) from the resonant frequency of the S20 vibrational mode after an excitation of the egg (Coucke et al., 1999). During this S20 vibrational mode, the equator of the shell describes an elliptic, spherical deformation with two nodal lines passing over the poles of the egg. Since k_{dyn} is correlated with the eggshell thickness, in the same manner as *G*, k_{dyn} might be an estimator for *G*. Moreover, the ART technology is fast and non-destructive (Coucke, 1998). In the second technique, the light transmission (200–900 nm) through the egg was measured. Since it was assumed that light may travel more easily through a more porous medium, the transmitted spectrum of visible light through the egg may include some information about the porosity of the eggshell. Also this type of measurement is non-destructive and fast (Williams and Norris, 1987).

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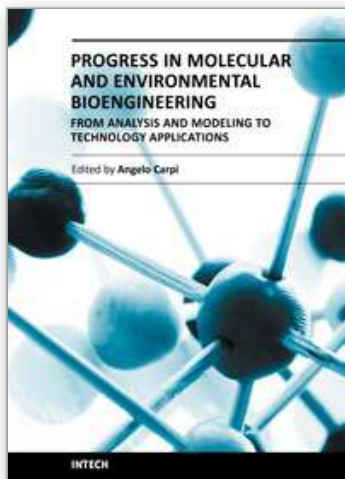Ar, A. and H. Rahn. (1980). Water in the avian egg: Overall budget of incubation. Am. Zool. 20:373–384.

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