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Biomechanical Properties of Hen's Eggshell: Experimental Study and Numerical Modeling

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Abstract**—**In this article, biomechanical aspects of hen's eggshell as a natural ceramic structure are studied. The images, taken by a scanning electron microscope (SEM), are used to investigate the microscopic aspects of the egg. It is observed that eggshell has a three-layered microstructure with different morphological and structural characteristics. Studies on the eggshell membrane (ESM) as a prosperous tissue suggest that it is placed to prevent the penetration of microorganisms into the egg. Finally, numerical models of the egg are presented to study the stress distribution and its deformation under different loading conditions. The effects of two different types of loading (hydrostatic and point loadings) on two different shell models (with constant and variable thicknesses) are investigated in detail.

Keywords**—**Eggshell, biomechanical properties, Scanning electron microscope, Numerical Modeling.

I. Introduction

NATURE has always astonished scientists and engineers by its engineering structures. Many samples of innovations in engineering science are due to inspiration from the nature. As time passes and technology develops, this inspiration finds new aspects too. Today, we can find many researches on the microscopic characteristics of the natural structures to study their different micromechanical properties.

In recent years, biological ceramics such as bone, tooth, etc. have attracted many attentions because of their desirable mechanical properties. As we know, birds' eggs which are made of calcium carbonate (in form of calcite) have remarkable mechanical characteristics too [1].

Studies on the eggshells can be classified into three major categories. The first are those that focused on physical and chemical properties. Tung et al. [2] measured the hardness of the hen's eggshell in different layers. Cusack et al. [3] showed that distribution of calcium in the shell is homogeneous, while magnesium and phosphorus have variable distributions.

In the second one, there are studies that considered the eggshells as an alternative source of calcium carbonate in industrial processes, because they are mainly composed of calcium carbonate (about 95%). One of these researches suggests that the eggshell can be recycled and used as filler for polypropylene composites [4].

Finally, there are investigations that studied the geometry of the eggs. One of the advantages of this geometry is its low ratio of surface area to volume in comparison with other common geometries. This feature reduces heat conduction and helps to save thermal energy [5]. Also, in an egg-shaped structure the mixing efficiency is higher than other common shapes [6].

In this article we try to study the influence of the microstructure of hen's egg on its biomechanical properties. Detailed microscopic images are provided from different parts of the shell. The specific functions of each layer are thoroughly explained. The obtained data are used to develop finite element (FE) models of the egg. The mechanical behavior of the models under different loads is investigated. The results of this paper may be useful in the design and manufacture of new engineering structures inspired from nature.

II. Materials and Methods

A. Scanning Electron Microscopy

An electron microscope device (Philips XL30) is used to take images of the eggshell and ESM. For this reason, some hen's eggs were provided. After breaking the eggs, their contents were completely emptied. Six samples were cut in suitable size. They were kept in the room temperature for 24 hours to be dried. Finally, they were coated with an 8nm thin layer of gold and placed under the microscope.

B. Numerical Modeling

1. Geometry

Two dimensional (2D) cross-section images were provided to obtain the correct profile of the hen's egg. The images were inserted into Matlab and the coordinates of all points were determined using an image processing technique. ANSYS 12 software was employed to develop FE models of the egg. As we will see, the results from the microscopy study indicate that the thickness of the shell in various points of an eggshell varies between 0.35 to 0.5mm. Hence, in order to study the effects of thickness on the mechanical properties of the egg, two different models were developed. The first one is a model with a constant thickness of 0.425mm. The other model has a thickness same as a real egg and variable between the obtained

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values.

2. Loading and Boundary Conditions

The eggshell is considered to be under following loading conditions:

1. External point load,
2. Internal hydrostatic pressure.

Also, the shell is assumed to be clamped at its end.

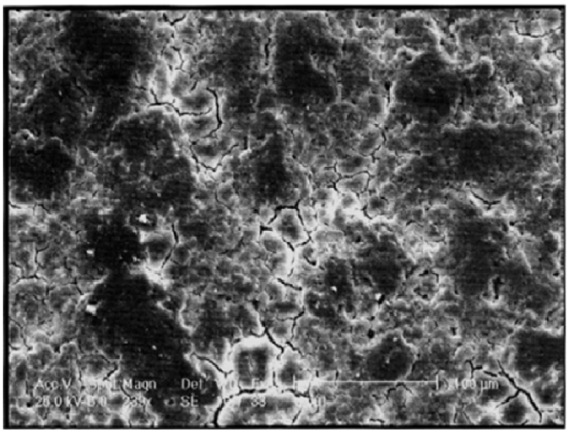

Fig. 1 An SEM image of the cuticle
The cracks on this layer are necessary for passage of air

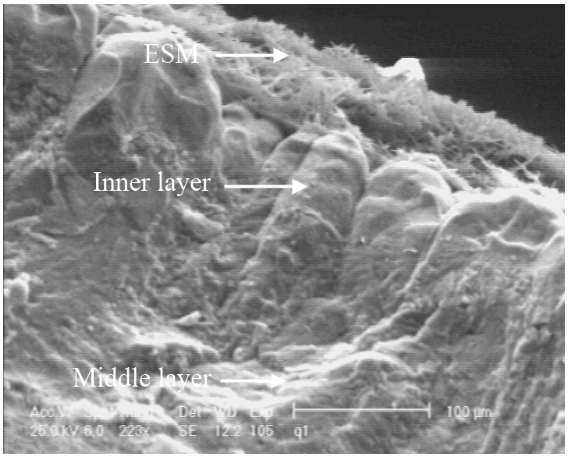

Fig. 2 An SEM image which shows regular structure of calcium carbonate in the shell

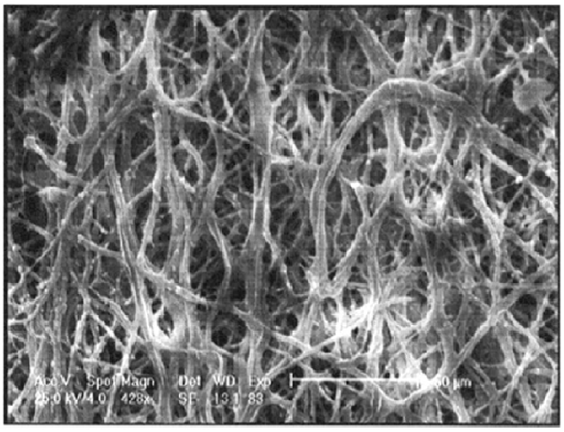

Fig. 3 SEM picture from the shell membrane, the figure shows collagen type protein fibers which make a semi-permeable membrane

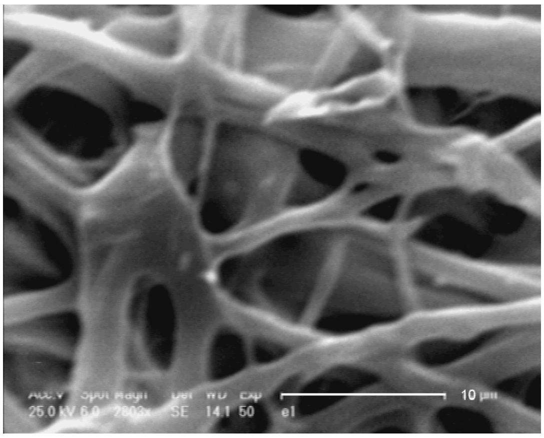

Fig. 4 A closer view of the ESM

3. Material Characteristics

Approximately 95 percent of eggshell is composed of calcium carbonate. Therefore, the Young's modulus and Poisson's ratio are taken to be equal to 72.35GPa and 0.3, respectively [7]. The density of the albumen and yolk inside the egg are 950 and 1035Kg.m^{-3}, respectively [6].

III. Results and Discussion

A. Microstructure

Eggshell is usually made of ceramic materials which form a three-layered microstructure. The external layer, which is called cuticle, is actually an organic layer with a thickness of 10µm (Fig. 1). Most of the pigments are in this layer. Fig. 1 shows numerous cracks which are necessary for passage of the air. Middle and inner layers are mainly composed of calcium carbonate. The inner layer has a thickness of about 70µm is composed of calcareous cone-shaped columns that penetrate into the membrane (Fig. 2). Indeed, these columns firmly connect the shell to the membrane.

The most inner layer of the egg is the ESM, which is located between eggshell and the egg albumen. This layer has 70µm thickness and it is in direct contact with albumen. This layer is made of organic protein fibers that are placed parallel to the surface of the shell and almost form a semi-permeable membrane (Fig. 3). It is believed that the structure actually operates as a barrier for micro-organisms. In fact, the membrane is an organized and complex network of stable and insoluble protein fibers. A closer view is shown in Fig. 4.

B. Mechanical Behavior

As it is mentioned before, in order to study the effects of thickness on the mechanical properties of the eggshell, two models with different thicknesses are presented. The first one is a model with a constant thickness equal to the average value and the second one is a model with variable thickness as same as the real sample.

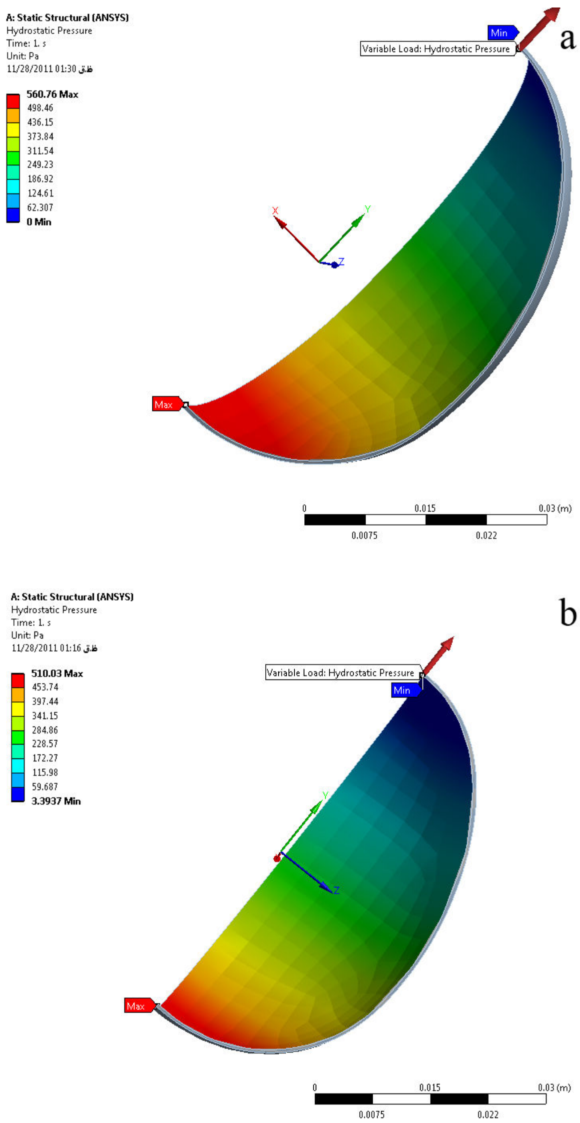

Fig. 5 Models of the hen's egg under hydrostatic pressure (a) With constant thickness (b) with variable thickness. The models have different deformation patterns

Fig. 5 illustrates the elastic deformations of the models. The deformation patterns are completely different. In the first model, the maximum deformation occurs at the center of the structure, but in the second one it appears at the top part. Moreover, the value of the maximum deformation at the first model is approximately 2.5 times higher than the second one.

The models are also used to stimulate the elastic deformations under point external loading. Fig. 6 shows the elastic deformations in the models. It can be found that the model with variable thickness experiences lower deformation under the same load. Therefore, it can be concluded that the variable thickness can increase the load bearing ability of the whole structure.

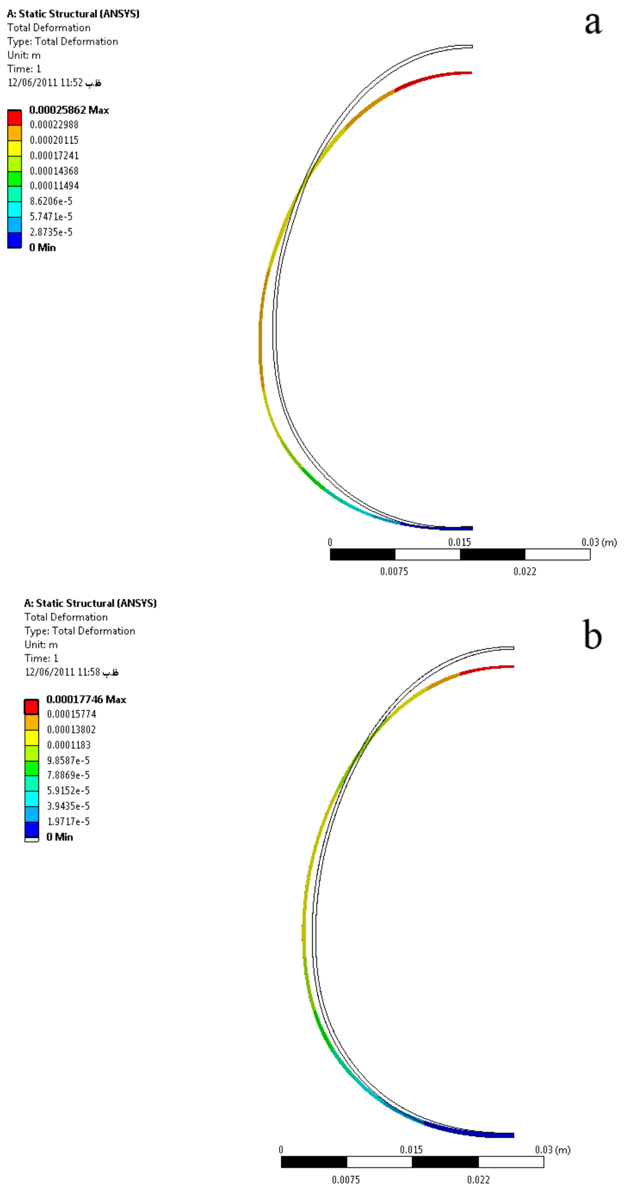

Fig. 6 Models of the hen's egg under point loading (a) With constant thickness (b) with variable thickness

IV. Conclusion

SEM showed that the hen's eggshell is made of three main layers. Each layer has a different thickness and microstructural features. The inside of the shell has been covered by a fibrous membrane which called ESM. The layers together provide a complex composite structure with desirable mechanical properties which protect hen's embryo during its development period.

Results from the Numerical modeling indicated that the structure of the shell, as a natural ceramic, despite its very small thickness, reveals high strength. The obtained data also showed that the variable thickness of the shell remarkably reduces the produced stress which is followed by a reduction in the elastic deformation. The result of this paper may be use in the design and manufacture of egg-shaped structures.

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