Mechanical Evaluations of Structure and Material Composition of Eggshell

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Mechanical Evaluations of Structural and Material Composition of Eggshell*

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An eggshell is cracked easily by an inside load, but has strong resistance to an outside load. In this study, the structural and material composition of an eggshell (from a hen's egg) is analyzed by microscopic observation, static and dynamic penetration tests and FEM. The results obtained are as follows. (1) From microscopic observation, the eggshell is found to have a laminated structure of many material compositions. (2) The outer eggshell membrane acts as a strong adhesive agent between the inner eggshell membrane and the eggshell. (3) A cone-type punch and striker makes an initial crack easily, but subsequently large penetration energies are required. (4) The penetration energy required from outside of an eggshell is larger than from inside because it includes the energies required to break the membrane and peel it off the eggshell.

Key Words: Biomechanics, Biomaterials, Eggshell, Composite Material, Laminated Construction, Material Testing, Finite Element Method

1. Introduction

An eggshell has various reasons and utilities for its existence. From the point of strength, it needs strong resistance from the foreign enemies during the hatching period. On the other hand, when the hatching is accomplished, the eggshell must be fractured easily by load applied from within by the hatching embryo. This means the eggshell is stronger for external loads, but weaker for internal loads. In analogy, such functions are also desirable for an automobile windshield. In general, the front glass (windshield) needs strong resistance from high speed missile. On the other hand, it must be fractured easily by internal load because in case of a traffic accident the drivers head impacts heavily on the front glass. Usually the front glass is constructed of two glass plates of the same thickness and a thin middle layer of polyvinyl butyral[1]. It does not behave anisotropically in the inside and outside directions.

Analysis of the structural and material composition of eggshell is very useful in development of new automobile front glass with above mentioned anisotropy.

In this paper, a hen's egg is selected as an analytical model, because of its cheap availability in abundance[2]. The structural and material composition of the eggshell is analyzed experimentally by microscopic observation and several mechanical testings. The results are evaluated with regard to strength.

2. Structural and Material Composition of Eggshell

2.1 Structural composition of an eggshell

Figure 1 and Table 1 show the shape of an eggshell, the cross section and the several sizes. From these, it is recognized that a eggshell is constructed of cuticle, the eggshell and two membranes[3]. The cuticle is very thin layer at 0.01 - 0.05 mm thickness and

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Table 1 Shapes of eggshell and membrane

L(mm)	58.80 ~ 61.95
D(mm)	45.05 ~ 47.25
R_1(mm)	12 ~ 15
R_2(mm)	15 ~ 17
	Eggshell / Membrane
Thickness(mm)	0.355 / 0.077

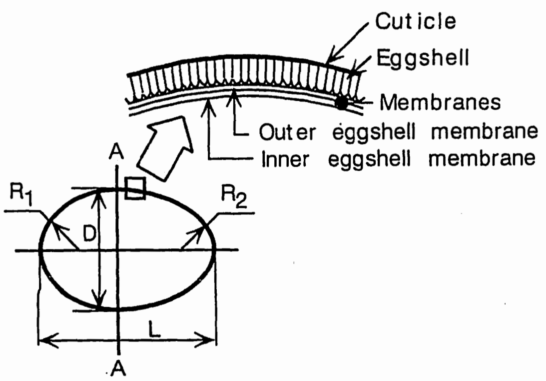


Fig. 1 Cross section of eggshell

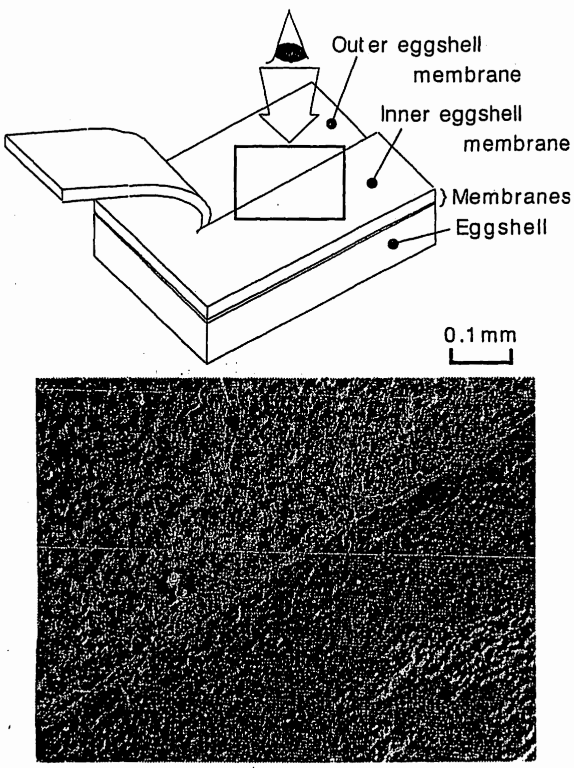


Fig. 2 Surfaces of inner and outer eggshell membranes

its function is to protect the egg from the micro-organisms. The eggshell is almost made of the carbonic calcium crystals and the construction is similar to an arch type structure of brick. The outer surface is smooth, but the inner surface is rough. From this, it is estimated that a crack initiates easily at the inner

Table 2 Material properties of eggshell and membrane

	Eggshell	Membrane
Young's modulus(MPa)	7760	4.38
Tensile strength(MPa)	1.99	2.23
Peel strength(N/25mm)		0.327(4)
Buckling pressure(MPa)	3.53	

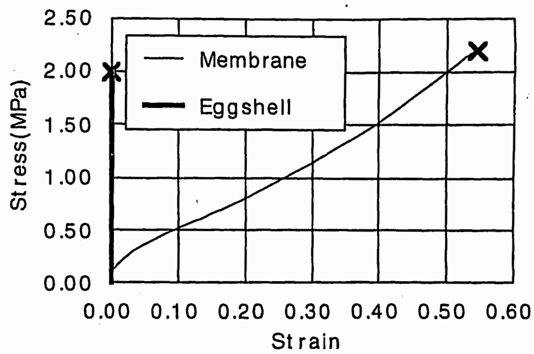


Fig. 3 Stress-strain diagram of eggshell and membrane

surface. The eggshell membrane is composed of two inner and outer membranes. Fig. 2 shows a scanning electro microscopic observation of eggshell membrane. From the figure, it is recognized that the outer eggshell membrane is thinner than the inner membrane and the fiber composition is rough. We can consider that the function of outer eggshell membrane is to adhere strongly between the inner membrane and the rough outer surface of the eggshell.

2. 2 Material properties

Table 2 and Fig. 3 show the material properties of eggshell and its membrane. These data are very difficult to obtain because the testing specimens were limited as very small or thin one. Therefore, we had to consider many ideas for the material testing method. For example, the Young's modulus of eggshell is estimated using the mixed law on the tensile test data of an epoxy resin specimen mixed by pieces of broken eggshell. From the experimental results, it is obvious that the eggshell is a typically brittle material and on the contrary its membrane is a super-ductile material. But those tensile strengths are almost equal. It is considered that the high buckling pressure as shown in Table 2 results from these unique material properties.

3. Static Penetration Test and Its Considerations

3. 1 Testing method

To evaluate the strength of an eggshell, static penetration test was planned and performed, using the testing method as shown in Fig. 4. The penetration test is done from the inside and outside directions of

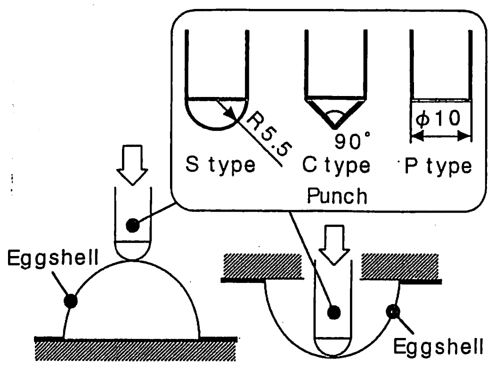


Fig. 4 Static penetration test and three types of punch

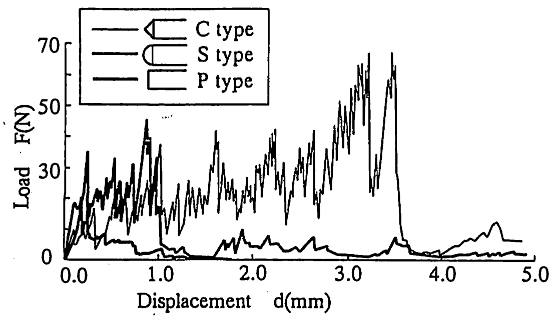


Fig. 5 Static displacement-load diagram

the eggshell. The indentor (punching object) is a stainless steel cylinder of 10 mm in diameter and the head shapes selected are in the three types as shown in Fig. 4. They are spherical type (S type), cone type (C type) and flat plane type (P type). Especially, the cone type is simulating the shapes as a beak of bird or a fang of snake, and various other examples drawn from the nature.

The eggshell specimen is made by cutting a boiled egg on A-A line in Fig. 1. The data obtained are crack initiation loads F_{cr}, maximum fracture loads F_{max} and static penetration energies U_s. These data are obtained from the testing load-displacement diagrams as shown in Fig. 5. For example, U_s is obtained from the area of the load-displacement diagram.

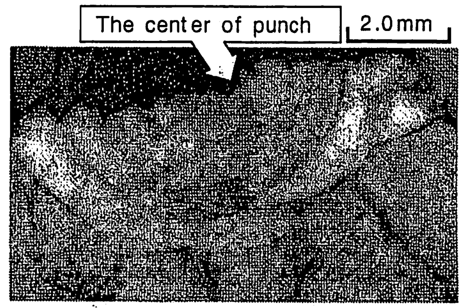
3.2 Testing results and its considerations

Figure 5 shows the load-displacement diagram on the external load test. Here it is obvious that eggshell is easily fractured by the C type indentor, but the fracture is limited at the local area in the neighborhood of indentor and the global fracture needs a corresponding bigger load. On the other hand, the eggshell is not easily fractured by the P type indentor. But when an initial crack occurs, the crack propagates easily all over the surface. Figures 6(a) and (b) show the fracture patterns by the C and P type indentors respectively.

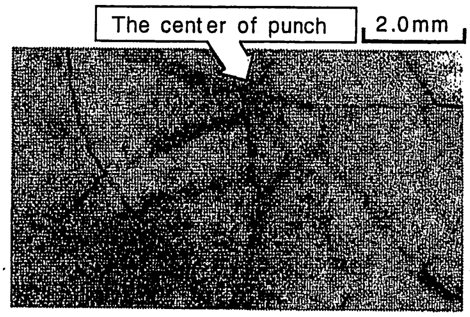
Figure 7 shows the values of F_{max} for several testing conditions. In this figure, the notation shows the mean value in black point and the variation in length of the testing data. From the results, it is obvious that F_{max} for the internal load condition are almost zero, but the values for the external condition are considerable. Especially F_{max} for the C type indentor is bigger than ones of S and P type indentors. The reason for this can be concluded as that the load condition of eggshell changes from bending to compression as shown in Fig. 8 after the initial fracture by the C type test.

Figure 9 shows the static penetration energy U_s for several testing conditions such as the internal and external load conditions for the given eggshell specimen with or without the membrane. In this figure, it is recognized that U_s for the external load condition is bigger than the one for the internal load condition and the values for the C type indentor is bigger than ones for the S and P type indentors.

Here the experimental result, claiming the fact that F_{max} and U_s for the C type indentor are extremely big, is very interesting because the C type indentor is similar to the beak of bird or the fang of snake. That



(a) By C type punch



(b) By P type punch

Fig. 6 Shape of fracture after static penetration

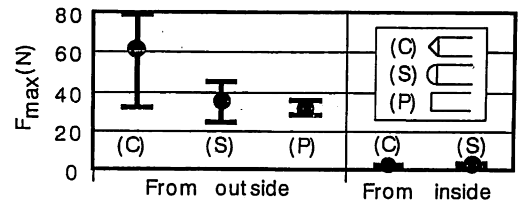


Fig. 7 Maximum static load to penetrate

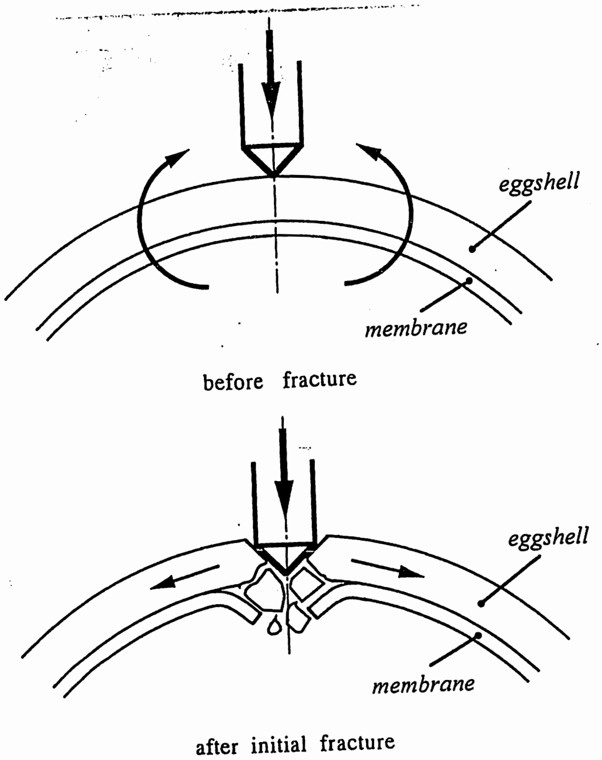


Fig. 8 Fracture behavior of eggshell by C type indentor

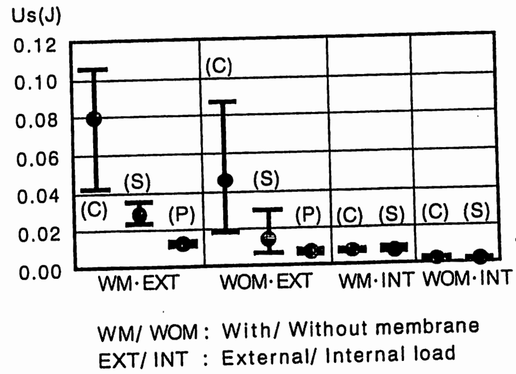


Fig. 9 Static penetration energy U_s (J)

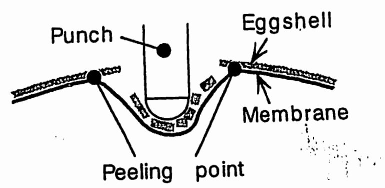


Fig. 10 Peeling mechanism of membrane

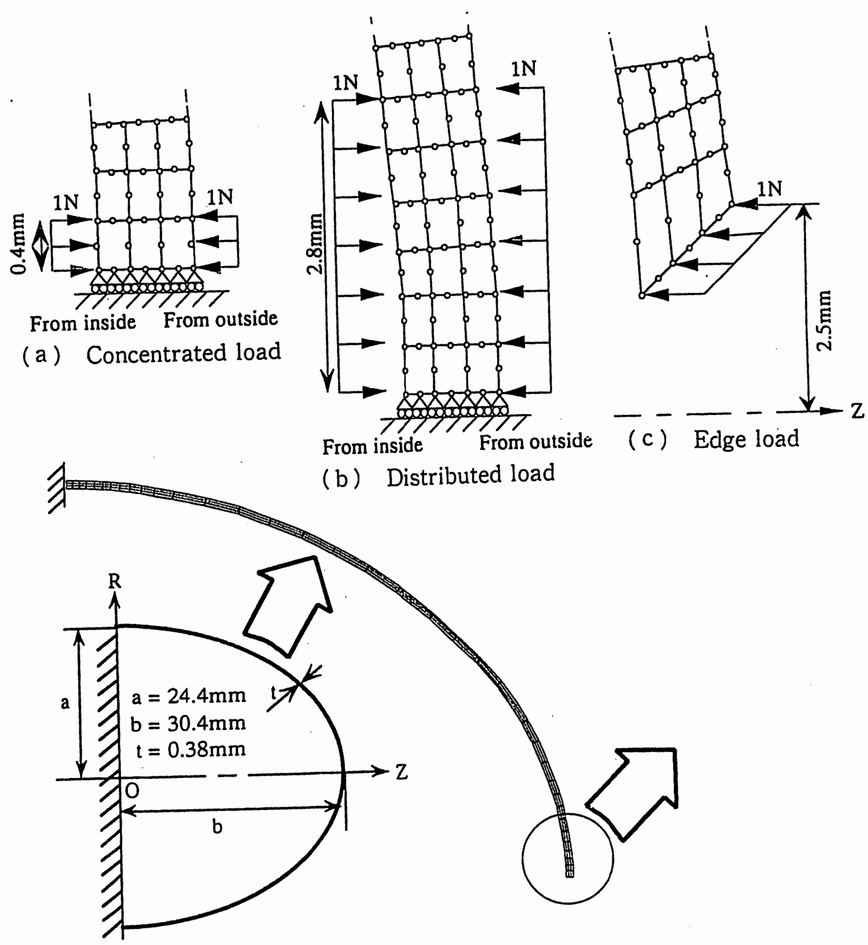


Fig. 11 Loading and supporting conditions for FEM analysis

is, the eggshell is strong on the attacks of the foreign enemies as bird and other animals.

On the mechanisms of the strength, it is considered that shape of eggshell is arch type and the crystal growing direction is radial as shown in Fig. 1. Furthermore, on the reasons that U_s for the external load condition are bigger than ones for the internal load condition, the effect of eggshell membrane is very important. That is, as Fig. 10 shows, the mechanism such as U_s is not only spent for the fracture of eggshell but also the peeling between eggshell and membrane.

3. 3 FEM analysis and its considerations

To enhance the understanding of the fracture mechanism on the static penetration tests, FEM analysis was performed. Figure 11 shows the analytical and finite element idealization using axi-symmetrical isoparametric element. The model is an eggshell without membrane and constructed of 111 elements and 414 nodes. On the load condition, Fig. 11 (a) corresponds to the C type indentor as a nearly concentrated load condition. Figure 11 (b) corresponds to the P and S type indentors as a distributed load condition. Figure 11 (c) corresponds to the load condition of C type indentor after an initial fracture, that is the edge load condition. From these models, we can estimate an elastic fracture force F_{cr} and the corresponding elastic energy W_{cr} of the eggshell. The results are shown in Fig. 12. F_{cr} and W_{cr} for the external load condition are bigger than ones for the internal load condition. From the result for the edge load condition, it is recognized that the eggshell after an initial fracture is very strong. These results almost coincide with the previously presented experimental results.

4. Dynamic Penetration Test and Its Considerations

4. 1 Testing method

Considering many enemies in a natural setting, the dynamic strength of an egg is more important than the static strength. To evaluate the dynamic strength, the dynamic penetration test was designed and performed using the testing method as shown in Fig. 13. Dynamic penetration fracture of the eggshell is done by dropping the above indentors or the "striker" from 1.58 m high. A penetration energy U_D is determined by measuring the striker speeds before and after the penetration fracture. The penetration area S is also obtained by analyzing the fractured area of the specimen. The specimens are the same with the ones for static test, that is one with or without membrane. Furthermore, the testing condition for the internal or external load condition is also same with the static test.

4. 2 Testing results and its considerations

Figure 14 shows U_D for several test conditions. From the results, it is obvious that U_D for the eggshell

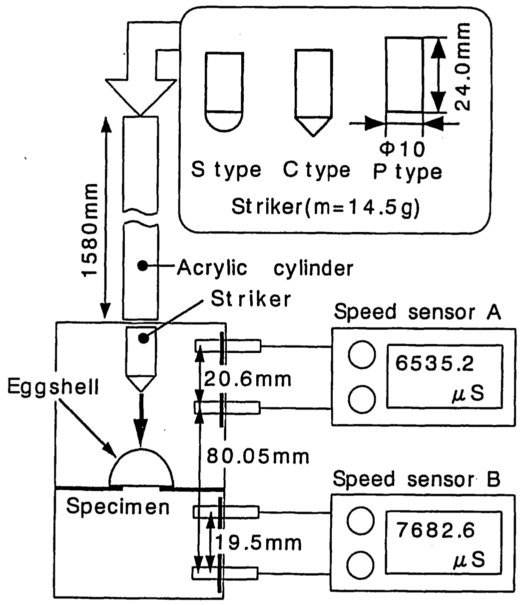


Fig. 13 Measurement set-up of dynamic penetration test

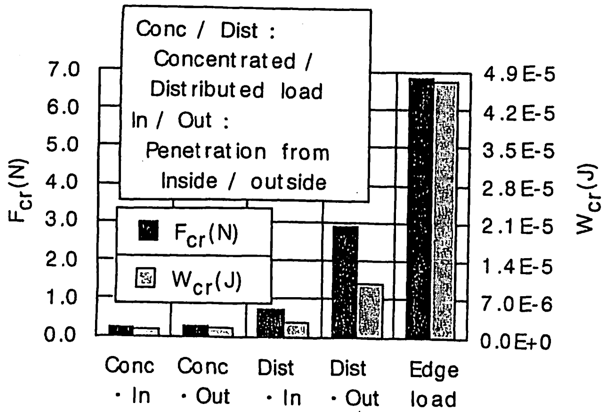


Fig. 12 Results of FEM analysis

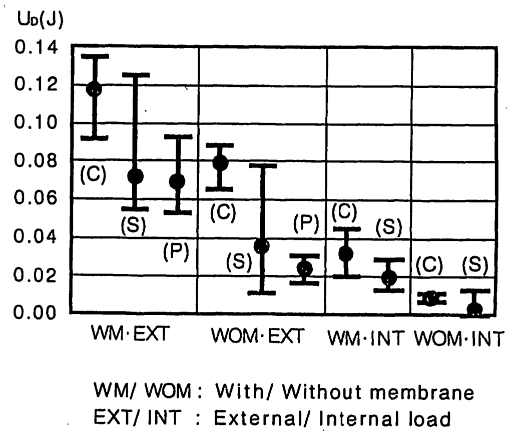


Fig. 14 Dynamic penetration energy U_D (J)

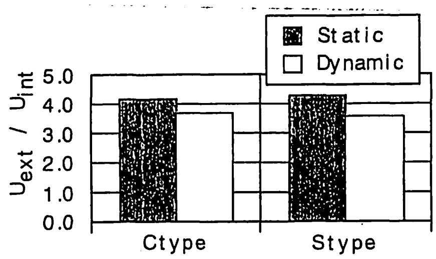


Fig. 15 Ratio of penetration energies U_{ext} and U_{int} (with membrane)

with membrane by external load is largest and the value for the eggshell without membrane by external load is next lower value. Notice the effect of striker, U_D for the C type striker is largest in the data on all the strikers. These tendencies are similar to the static test results.

On the penetration area S, the values for the specimen without membrane under the external load condition are from 500 to 700 mm^2 and 2 or 3 times of ones for the specimen with membrane. This means that the membrane has very important function to maintain the shape.

Figure 15 shows the ratio U_{ext}/U_{int} of U_D for the external load condition to one for the internal load condition. The static and dynamic values are almost equal from 3.5 to 4.2. From the result, it is obvious that an anisotropy of eggshell in the direction of thickness is very extreme in the point of penetration energy and the anisotropy results from the existence of a membrane.

5. Conclusions

In this paper, the structural and material compositions of an eggshell are analyzed experimentally by microscopic observation and several mechanical impact and incidence testings. The results are evaluated in the point of strength, and the following facts are conclusively obtained:

(1) From microscopic observation, the eggshell is found to have a laminated structure of many material compositions.

(2) The outer eggshell membrane acts as a strong adhesive between the inner eggshell membrane and the eggshell.

(3) A cone-type punch and striker makes an initial crack easily, but large penetration energies are required.

(4) The penetration energy required from outside of an eggshell is larger than from the inside and consists of the energies required to break the membrane and peel it off the eggshell.

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