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Assessment of fatigue damage accumulation in natural material - Seashell

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ABSTRACT

Seashell has excellent mechanical property, which owes to its crossed lamella structure. Seashell is a type of natural composite material. In the viewpoint of material design, learning from nature is a best choice in nowadays. The fatigue damage accumulation in seashell is assessed in the present paper. As compared to the deformation behavior of simple tensile process for the original seashell specimen, the fatigued seashell specimen exhibits lower elasticity modulus, fracture strength and yielding flat free in its stress – strain curve; It is found that the relative decrease of the fracture energy density of the fatigued sample with respect to the fresh one coincides with the relative decrease of the elasticity modulus of these samples, it implies that the relative decrease of the fracture energy density could be taken as a proper damage variable to characterize the damage accumulation in the fatigue process of seashell.

KEYWORDS

Seashell;
Lamella structure;
Damage accumulation;
Elasticity modulus;
Fracture energy density.

INTRODUCTION

In the viewpoint of material design, it might be a best choice to learn from nature in nowadays, which makes material with excellent property. A typical natural composite is seashell, which possesses excellent mechanical strength and toughness[1-5]. It is found that the fracture toughness of seashell exceeds that of single crystals of the pure mineral by two to three orders of magnitude, though the content of the organic component is only a few percent inside the seashell. Numerous examples of strong and tough materials, such as bone and seashells, are fabricated from much weaker components, it is the natural world that makes these materials surprisingly strong and tough[6-9]. There are two discernible facets in biological composites (like bone and nacre), i.e., superior strength and light weightiness, it has caught substantial attention of the scientific community[10]. By the natural evolution over millions of years, biological composites have optimized their appropriate structures and properties. The typical examples are nacre and bone, which exhibit high stiffness, strength and especially, excellent toughness. The toughness of nacre is much higher than its inorganic (brittle minerals) and organic (ductile polymers) components, by even orders of magnitude. The brittle mineral tends to behave alternative structures and compositions. The seashell material is a typical crossed-lamellar composite, which composes of aragonite /or calcite with the orientation of the inorganic component being prismatic, nacre, or foliated. Large fracture strain of 5% has been observed in nacre, and high fracture strength of 450 MPa in compression tests[10]. A number of toughening mechanisms have been proposed as well[10].

Although the micro-structural characteristics and static loading behavior of the shell have been studied widely by many investigators, the damage accumulation in dynamic loading process is far from clear. In this paper, the comparison of deformation behavior of simple tensile sample of the fresh (original) seashell and the fatigued specimen is performed; the elasticity modulus, fracture energy density and fracture strength, etc. are taken as characteristic parameters to reflect the difference of the stress – strain behavior of the above two cases. As a result, it is found that the relative decrease of the fracture energy density could be taken as an appropriate damage variable to reveal the fatigue damage process in the dynamic process of the seashell.

FEATURE OF THE MACRO DEFORMATION BEHAVIOR OF SEASHELL

Preparation of the seashell specimen and test method

The China Qingdao fresh seashell is employed to manufacture the experimental samples, of which the size is 20mm×3.8mm×1.7mm. The small specimen is taken from the shell along the radial direction, as is shown in Figure 1. In order to remain the humidity of the seashell, the specimen is immersed into water immediately[4].

The clamps are fixed to the specimen with Expo resin, CMT 3204 test machine is employed to conduct the tensile test.

Characteristic parameters of the fresh seashell

Figure 2 shows the typical stress - strain curve of the fresh shell in uni-axial tensile loading process. It shows a three - stage curve in feature, i.e., an elastic stage, a yielding stage with a flat and a pseudo-elastic stage till fracture. Five specimens have been employed to conduct the tensile test. The average value of the fracture strength σ_f is 30.5MPa.

From the initial stress-strain relationship in Figure 2, it could get the elasticity modulus of the fresh shell, E_0=42.1GPa. Meanwhile, from the complete stress-strain curve in Figure 2, it could get the fracture energy density of the fresh shell (i.e., the integral of the stress – strain curve till fracture), w_0=1.156MPa.

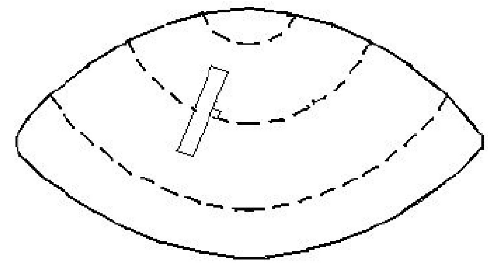

Figure 1 : Specimen along the radial direction

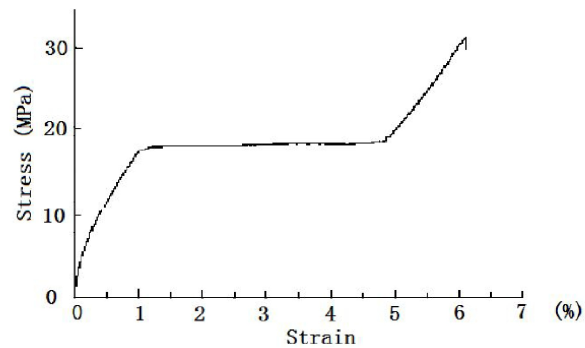

Figure 2 : Stress – strain curve of the fresh shell in uni-axial loading process

Degradation of characteristic parameters of the fatigued seashell

The micro-tester in Instron 5848 is employed to perform the fatigue test. The tension - tension fatigue is conducted at the loading ratio R = 0.1, the dynamic loading ranges from 13 to 130 N.

After the dynamic loading with the total cyclic number of 884467, a subsequent tensile loading is applied to the specimen till fracture, the stress – strain curve is shown in Figure 3. It can be seen from Figure 3 that the curve differs from that in Figure 2 obviously, the yielding flat disappears in the present case. The fracture strength of the fatigued specimen σ_f deceases to 27.8MPa.

From Figure 3, it could get the elasticity modulus and fracture energy density of the fatigued seashell, E_i =15.5GPa and w_i=0.408MPa, respectively.

The above results indicate a significant decrease of both elasticity modulus and fracture energy density of the fatigued seashell as compared to the fresh one, which implies a variation of the material in micro-scale.

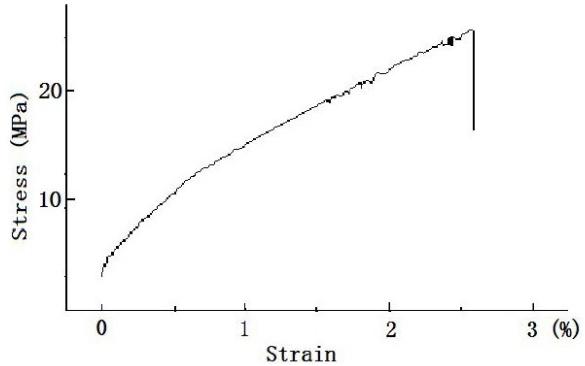

Figure 3 : Stress – strain curve of the fatigued shell in uniaxial loading process

FATIGUE DAMAGE IN THE DYNAMIC LOADING PROCESS

Early in 1958, L. M. Kachanov proposed the concept of integrity (or damage) to reflect the macro expression of the microscopic variation of material. Thereafter, the framework of damage mechanics is gradually formulated, till now damage mechanics is still in its developing stage. Both damage mechanics and fracture mechanics could describe the mechanical status of the whole servicing process of a machine or system from virginal state till failure and fracture.

In damage mechanics, a damage variable has been frequently introduced[11], which reflects the degradation of the material property parameters, such as elasticity modulus, yielding strength, creep duration, etc.

The decrease of elasticity modulus is quite often employed to reflect the damage status, and its relative decease is used as the damage variable[11], i.e.,

$$D = 1 - E_i / E_0 \quad (1)$$

in which D is the damage variable, E_0 and E_i express the original elasticity modulus and the instant elasticity modulus of the studied material or specimen.

Considering the tensile experimental results for the fresh and fatigued seashell specimens in the previous section, the value of the damage variable of the fatigued specimen is

$$D = 1 - E_i / E_0 = 1 - 15.5 / 42.1 = 0.632 \quad (2)$$

The numerical data of Eq. (2) indicates that the damage degree for the fatigued seashell is 0.632 in the viewpoint of elasticity modulus degradation, which suffered from the dynamic loading in the range of 13 to 130 N and the cyclic number of 884467.

Refers to[4], it is observed that the fracture surface for the fatigued specimen is different from that of the simple tensile one. The fiber pulling out is unapparent in the fracture surface of the fatigued specimen, and the fracture surface is smoother than that of the simple tensile loading ones. The brick breaking is more serious in the fracture surface of the fatigued specimen. Such serious brick breaking implies the damage accumulation by the fatigue loadings gradually during fatigue.

It also showed the voids formation process at the interface of the crossed lamella and organic glue from the in situ observation[4]. The organic glue formed a network in the material, which connects the bricks and lengthens the routines of the crack propagation; it results in a "zigzag" trace for the crack propagation generally, and thus increases the toughness of the material.

In addition, the de-bonding in bricks in the subsequent loading process was observed, such de-bonding phenomenon has not yet been observed in the simple tensile loading process[4].

In fact, during the dynamic loading process, both voids formation and micro - crack propagation exhausted energy and depredated the ability of material bearing extra loading and ductility, the more the energy exhausted the more the degradation.

Therefore, we could try to correlate the exhausted energy to the damage degree rationally.

From the last section, it shows that the fracture energy densities of the fresh seashell and the fatigued seashell are w_0=1.156MPa and w_i=0.408MPa, respectively. The difference (says, $w_0 - w_i$ = 0.748MPa) between these two fracture energy densities is due to the exhaust of the ductility, which implies the variation of material structure in micro-scale, as is seen in reference[4] and cited in the above paragraph.

Surprisingly, the relative difference of the fracture energy density of the fatigued specimen with respect to the fresh one is

$$(w_0 - w_i)/w_0 = (1.156 - 0.408) / 1.156 = 0.647, \quad (3)$$

which is close to the damage variable defined by the relative decrease of elasticity modulus.

Above numerical result implies that the relative decrease of fracture energy density could also be taken as a proper damage variable at least for the fatigued seashell, which reflects the degradation of seashell property and damage accumulation during fatigue process.

CONCLUDING REMARKS

From above analysis and discussion, it can be concluded,

1) Dynamic loading depredates micro structure and property of seashell, such as voids formation, brick breaking, elasticity modulus, fracture strength, fracture energy density, etc., which induces damage in seashell in the viewpoint of damage mechanics;
2) The fatigue damage accumulation could be assessed by the relative decrease of the fracture energy density and the relative variation of the elasticity modulus;
3) The features of the fatigue damage and fracture in seashell result from its lamella structures.

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