Materials and Design 99 (2016) 201–210

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Numerical simulation of ballistic impact behavior of bio-inspired scale-like protection system

Peng Liu [a], Deju Zhu [a,*], Yiming Yao [b], Junwen Wang [a], Tinh Quoc Bui [c]

[a] College of Civil Engineering, Hunan University, Changsha 410082, PR China
[b] School of Sustainable Engineering and Built Environment, Arizona State University, Tempe, AZ 85287, United States
[c] Departement of Mechanical and Environmental Informatics, Tokyo Institute of Technology, 2-12-1-W8-22, Ookayama, Meguro-ku, Tokyo 152-8552, Japan

ARTICLE INFO

Article history:
Received 26 December 2015
Received in revised form 28 February 2016
Accepted 2 March 2016
Available online 11 March 2016

Keywords:
Fish scale
Bio-inspired composite scale
Scale-like protection system
Impact behavior
LS-DYNA

ABSTRACT

The teleost fish scales, such as Grass Carp and Cyprinoid, characterize hierarchical structure which usually consists of a hard bony outer layer and a soft inner cross-ply of collagen fibrils. Each scale overlaps with other neighboring scales, thus fish skin can effectively disperse external loadings with superior flexibility. Inspired by the two-layer structure and overlapping pattern of fish scales, bio-inspired composite scale, and scale-like protection system are designed in this study. Silicon carbide (SiC) ceramic and aluminum are selected as the outer and inner layers of the bio-inspired composite scale, respectively. In this study, the optimal thickness ratio of SiC/Al is chosen as 3:2 through numerical simulation on penetration test and residual velocity analysis of bio-inspired composite scale with LS-DYNA. Compared with pure SiC scales, the area density of bio-inspired composite scale can be reduced by 12.5% with the same ballistic performance at the impact velocity of 878 m/s. Further, a comparative simulation analysis among different overlapping ratios of scale-like protection systems, which consists of overlapped bio-inspired composite scales, is conducted and an optimal overlapping ratio of 0.40 is found. The present numerical study on scale-like protection system enables pathways to design a lightweight and flexible protective system.

1. Introduction

The design of lightweight materials with efficient energy-absorbing capability is challenging in engineering fields. However, biological materials such as bone, nacre, horn and animal scales, as well as biocomposites and bio-inspired structures present attractive advantages such as lightweight, high energy absorption capability and impact resistance [1–4]. The optimized structure and outstanding mechanical properties of such natural materials enable pathways to design novel high performance engineering materials. Fish scale, as an ultra-lightweight biological material, is characterized by its flexible and complex hierarchical structure which greatly improves the penetration resistance. In addition, its distinctive ordered arrangement of scales provides the outstanding flexibility of the fish [5]. Recent studies on fish scale, especially scale of teleost, which mainly consists of a hard outer bony layer supported by a softer well-organized collagen fibrils [6–9], reveal the remarkable penetration resistance of these structures. Zhu et al. [8] conducted puncture tests on striped bass scale using a sharp needle (tip radius = 25 μm). The results showed that the puncture resistance of striped bass scale with maximum penetration force of 3–3.5 N is higher than that of polycarbonate (about 3 N) and polystyrene (2 N). The overlapping scales connected by fish skin ensure the flexibility of fish, redistribute the penetration load and reduce the local stress, which result in superior puncture resistance [10,11].

To further study the protection mechanism of certain structure and to design biomimetic flexible protection system, a great amount of attention has been attracted on the mechanical interactions among overlapping scales, both in theoretical studies and numerical stimulations. Vernerey et al. [12,13] studied the flexibility of two-dimensional (2D) overlapping scales and provided a possible way to design flexible armor or electronic components. Researchers from Massachusetts Institute of Technology tried to mimic the overlapping pattern of Polypterussene gauss (*P. Sengalus*) scale using a multilateral 3D printer (OBJET Connex 500), and then investigated the mechanical properties of this biomimetic structure [14–17]. Their results indicated that overlapping scales distributed stress over a large volume of material compared to a continuous armor layer. On the other hand, the 4-layer structure of *P. Sengalus scale* demonstrated higher hardness than that of teleost fish scales.

Although the above-mentioned studies have obtained varying degree of success, questions still remain. For example, very few study on the impact behavior of individual fish scale has been reported [18]. Characterization and simulation of the impact behavior of overlapping scales will provide a critical pathway to design a scale-like flexible structure. On the other hand, Dutta et al. [19,20] investigated that an

* Corresponding author.
E-mail address: dzhu@hnu.edu.cn (D. Zhu).

http://dx.doi.org/10.1016/j.matdes.2016.03.040
0264-1275/

Table 1
The materials model of SiC [22].

ρ(kg/m^3)	G (GPa)	A	B	C	M	N
3163	127	0.96	0.35	0.0	1.0	0.65
Ref Strain Rate (EPS)	Tensile strength (GPa)	Normalized fracture strength	HEL (GPa)	HEL Pressure (GPa)	HEL Vol.Strain	HEL Strength (GPa)
1.0	0.37	0.8	14.567	5.9		13.0
D1	D2	K1(GPa)	K2	K3	Beta	PSFAIL
0.48	0.48	204.785	0	0	1.0	–

Table 2
The materials parameters of Steel 4340 and Al 6061-T6.

Materials	ρ (kg/m^3)	E (GPa)	ν	VP	A (GPa)	B (GPa)	N	C	PSFAIL
Al6061-T6 [33]	2700	69	0.33	0.0	324	114	0.42	0.002	–
Steel4310 [34]	7833.4	206.84	0.29	0.0	1.0767	5.7031	0.276266	0	0.5182

E: Elastic modulus; ν: Poisson's ratio; G: Shear modulus; ρ: Density

optimized overlapping length can improve the damage tolerance of nacre-like composite. Recent numerical studies [21–23] demonstrated the improved blast resistance of nacre-like plates compared to continuous plates with same thickness. Monteiro et.al [24] provides a novel ballistic ramie/epoxy composite armor and suggest that the 30% ramie fabric-reinforced epoxy produces a 10–20 small drop depth when subject to 7.62 mm bullet. These results also guide us to design a novel structure inspired by overlapping scales.

In the present work, numerical study on impact behavior of bio-inspired composite scale inspired by single teleost fish scale is performed using the LS-DYNA with certain bullet impact velocity. Optimization analysis is conducted and an optimal thickness ratio of materials is obtained. Subsequently, a novel flexible scale-like protection system inspired by teleost fish scales is proposed using a state-of-the-art composite design methodology. Numerical analysis as well as optimization for the proposed protection system is performed. Finally, the effects of overlapping ratio, different types of ceramics, layers of Kevlar, and bullet impact velocity are investigated based on the finite element models developed in this study.

2. Simulation of penetrate resistance of bio-inspired composite scale

2.1. Materials model

High performance ceramics, such as silicon carbide (SiC), boron carbide (B_4C) and aluminum oxide (Al_2O_3) [15], which are lightweight

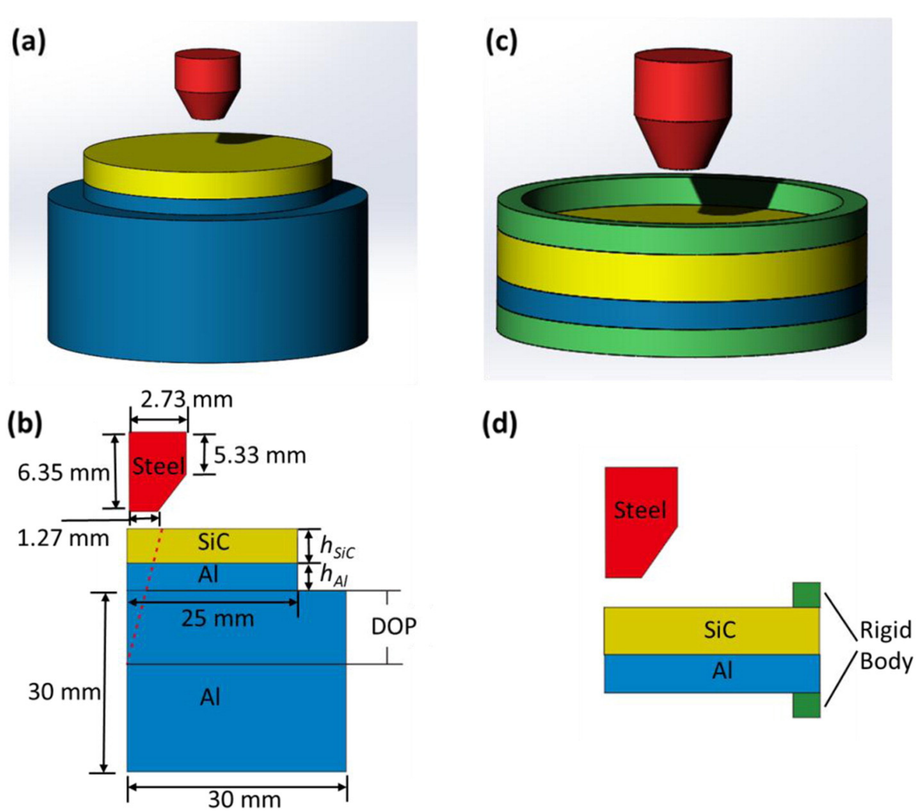

Fig. 1. FE models for (a) 3D; (b) 2D DOP; and (c) 3D; (d) 2D residual velocity.