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Numerical investigation of the impact behaviour of bioinspired nacre-like aluminium composite plates

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ABSTRACT

Inspired by the hierarchical structure of nacre, an aluminium alloy (AA) 7075 based composite featuring layer waviness and cohesive interface is studied as a low weight impact resistant material. To investigate the mechanical response and the ballistic performance of this laminated structure, a numerical study of the proposed nacre-like composite plates made of 1.1-mm thick AA 7075 tablets bonded with toughened epoxy resin was performed using Abaqus/Explicit. Target thicknesses of 5.4-mm, 7.5-mm and 9.6-mm impacted by a rigid hemi-spherical projectile were simulated. The epoxy material was modelled using a user-defined interface cohesive element with compressive strength enhancement. A significant performance improvement was recorded for the 5.4-mm nacre-like plate (compared to the same thickness bulk plate), which was explained by the hierarchical structure facilitating both localised energy absorption (by deformation of the tablet) and more globalized energy absorption (by inter-layered delamination and friction). For a given projectile, however, the performance improvement of using the proposed composite decreased with increasing laminate thickness, which was attributed to the increased likelihood of ductile failure occurring prior to perforation in thicker bulk plates. For 5.4-mm thick plates impacted at high velocity, the nacre-like plate had a better ballistic performance than that of the plates made of continuous (flat and wavy) layers, which was attributed to the larger area of plastic deformation (observed in the nacre-like plate after impact) due to the tablets arrangement.

1. Introduction

The demand for energy-absorbing lightweight engineering structures for blast and impact applications in automotive, aeronautical and defence industry is growing at a fast pace [1]. This trend poses a challenge for innovative engineering design to address the competing constraints of light weight on one hand, and impact and shock mitigation on the other hand. In this context, structural biological materials such as wood, bone and abalone shells, are an excellent source for inspiration [2] considering that evolutionary developments have resulted in high-performance lightweight composites structures, made of relatively weak and mundane constituents [3–5]. These biological materials deform via several high energy-absorbing mechanisms resulting in the improvement of structural and mechanical properties such as stiffness, strength and toughness.

Nacre, commonly known as the mother-of-pearl, is a biological material that exhibits outstanding mechanical properties due to its hierarchical structure that spans several scales [6]. It is a brick-wall patterned composite made of aragonite tablets (a brittle mineral), surrounded by a soft organic biopolymer that “glues” them together [7]. Although nacre is made of 95% of aragonite, it exhibits a toughness of about 3000 times higher than that of aragonite [8]. This outstanding performance is attributed to the brick arrangement of the structure, the waviness of the tablets and the multiple interfaces between tablets [3,9–11].

The performance of nacre-like engineering composites at the macroscale (millimetre-size) has only been scarcely explored [8,10,12,13]; some recent investigations have shown their strong potential with respect to performance in sustaining impact and blast loading when compared to traditional laminated composite plates or bulk plates. A recent numerical work by Knipprath et al. [12] showed that the impact response of boron carbide ceramic can be improved by using a simplified nacre-like structural design that promotes crack delocalization. Tran et al. [14] also showed that nacre-like structural design can be used to improve the blast performance of glass fibre/thermoset resin composites.

The aim of this paper is to gain a better understanding of the mechanical behaviour of nacre-like aluminium composites under

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impact loading through a numerical parametric study of layered nacre-like plates made of 1.1-mm thick aluminium alloy (AA) 7075 tablets glued with toughened epoxy resin. The epoxy material was modelled using a user-defined cohesive element taking into account both the increase in strength and toughness when the debonding occurs under transverse interface compression, together with frictional effects after full debonding. Laminate thicknesses of 5.4-, 7.5- and 9.6-mm were modelled and the ballistic performance of bulk plates made of AA 7075 was compared with that of the equivalent (same thickness) nacre-like composites. For 5.4-mm thick plates impacted at high velocity, the ballistic performance of plates made of continuous (flat and wavy) layers was also studied. The problem description and validation of the numerical models are described in Section 2. Numerical results are presented and discussed in Section 3 followed by conclusions.

2. Problem description and finite element modelling

2.1. Problem description

To investigate the ballistic impact behaviour of nacre-like composite plates made of aluminium alloy with different thicknesses, the plates were impacted by a rigid 10-mm steel spherical projectile with a mass of 4.4 g and initial impact velocities in the range of 400–900 m/s. AA 7075-T651 was used for the target plates [15–17] (Table 1). A toughened epoxy adhesive Betamate 1044 was employed to model the interface between tablets and layers (Table 2). The parameters in Table 2 corresponding to the material properties of the epoxy resin used for the numerical model are identical to those required for standard cohesive elements (COH3D8) in Abaqus and were obtained from Wang et al. [18]. The two additional parameters in Table 2 used in the user-defined cohesive element, explained in Section 2.2.3, are the interface initial stiffness (in compression) K_s^f, which is taken to be two to three orders of magnitude less than the interface initial shear stiffness K_s (in this case is equal to *(2G₁/1000)*/interface thickness), as well as the coefficient of friction μ, which is assigned the rather common value of 0.2 [19].

The solid geometry of the 3D full model, inspired by the structure of nacre, consisted of a 100 mm × 100 mm plate made with aluminium alternate layers of 1.2-mm and 0.9-mm thick AA 7075 (Fig. 1). Targets of 5, 7 or 9 layers with total thicknesses of 5.4-, 7.5- or 9.6-mm, respectively, were simulated. Each layer, made of twenty-five 20 mm × 20 mm square tablets, was displaced with respect to its adjacent upper or/and lower neighbouring layer in such a way that individual tablets overlapped 1/4 of the surface area (Fig. 1). This overlapping is sufficiently close to the 1/3 of the surface overlap observed in the natural nacre material [9]. The waviness of the tablets was generated using a sinusoidal function with a wavelength of 20 mm and amplitude of 0.1 mm (Fig. 1). The solid geometry was generated using the computer-aided design software SolidWorks 2012 (Dassault Systemes, SolidWorks Corp., France) and then imported into Abaqus/Explicit (Version 6.11) [20] for pre- and post-processing.

Table 1
Material properties and Johnson–Cook model parameters for aluminium alloy.

Material properties	AA 7075-T651 [15–17]
Density ρ (kg/m^3)	2700
Young's modulus E (GPa)	70
Poisson's ratio ν	0.3
Inelastic heat fraction η	0.9
Specific heat C_p (J/kgK)	910
Strain hardening	
A (MPa)	520
B (MPa)	477
n	0.52
Strain rate hardening	
Reference strain rate $\dot{\varepsilon}_0$ (s^{-1})	5×10^{-4}
C	0.001
Temperature softening	
Reference temperature T_r (K)	293
Melting temperature T_m (K)	893
m	1
Damage parameters	
D_1	0.096
D_2	0.049
D_3	−3.465
D_4	0.016
D_5	1.099
u_{pl}^f (mm)	0.0009

Table 2
Material properties and UEL parameters for epoxy resin.

Material properties	Betamate 1044 [18]
Density ρ (kg/m^3)	1350
Elastic modulus in the normal direction E (GPa)	3.1
Elastic modulus in the transverse directions G_1, G_2 (GPa)	1.55
Maximum normal traction t_n (MPa)	85.5
Maximum shear traction t_s (MPa)	70
Critical energy-release rate mode I G_{Ic} (J/m^2)	1680
Critical energy-release rate mode II G_{IIc} (J/m^2)	3570
UEL parameters	
Mohr–Coulomb coefficient of friction μ	0.2
Compressive shear stiffness K_s^f (MPa/0.05 mm)	3.1

The mesh comprised of reduced-integration linear hexahedral elements (C3D8R) for the solid tablets and the rigid projectile, as well as user-defined elements (UEL, described in Section 2.2.3) for the cohesive interface between tablets and bondline. These interface elements are 0.05-mm thick and have coincident nodes with the adjacent solid elements. Although Abaqus/Explicit allows zero-thickness geometry in cohesive elements, it still requires a nominal thickness to calculate the initial elastic stiffness and density. This thickness can either be specified directly as an input to the constitutive model while the geometric model has zero-thickness interface elements, or used to geometrically model the cohesive elements as a finite-thickness layer. The latter approach was adopted in this investigation because it made the task of model generation significantly easier. The in-plane mesh was skewed to be finer towards the impact region (centre of the plate) with an average element size of 0.27 × 0.27 × 0.27 mm^3 as illustrated in Fig. 1. The target plates were fully clamped at all of the edge boundaries. The number of elements for each solid layer and cohesive interface layer were 135360 and 3240, respectively, and a mesh sensitivity analysis presented in Section 2.4 confirms that this level of refinement was sufficient to obtain a converged solution. The automatic time incrementation scheme available in Abaqus/Explicit was employed. This scheme ensures that a stable time increment, based on the time required to propagate a dilatational wave across the smallest element in the model, is used. The estimated time is conservative, which will give a smaller time increment than the true limit that is based upon the maximum frequency of the entire model. The simulation time for the 9.6-mm thick nacre-like plate, using a 16-CPU high performance computer with 42 gigabytes of RAM, was seven hours for an initial impact velocity of 400 m/s.

2.2. Material models

The Johnson–Cook material model [21] was used together with the Johnson–Cook fracture criterion [22] to simulate the constitu-