Modeling anisotropic fracture in a metal-fiber reinforced composite system

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Abstract. Hybrid structures consisting of metal and composites can be applied to specific requirements of different applications. The computational modeling of composites is quite complex compared to homogeneous and isotropic materials like metals because of the heterogeneity introduced due to the presence of different phases such as matrix, fiber and matrix-fiber interface, and anisotropy due to the fiber alignment. The crack propagation in a composite material depends on a combination of various damage modes, namely, fiber pull-out, matrix cracking, delamination. The strength and stiffness of the composite depend on the mechanical and fracture properties of the individual phases, and the fiber inclination. The metal-composite interface is modeled using the cohesive zone approach. A nonlocal diffused approach is proposed to model the anisotropic failure in composites reinforced with unidirectional and woven fibers and the interaction of the crack with the interface. Parametric studies are conducted to understand the role of fiber orientation and interface fracture properties of the system. The proposed model is illustrated through numerical examples to understand various failure mechanisms in a metal-composite system.

1. Introduction
Hybrid structures are multi material structures formed by stacking different materials for a specified purpose. Hybrid metal composite structures consist of alternative layers of metal and fiber reinforced composites (FRC). These structures have the advantages of both metals and composites, namely, good strength, light weight, ductility, fatigue resistance and can be designed according to the need. The motivation for developing these structures is to improve the mechanical properties and produce low weight materials, especially in marine, aerospace industries (see [1] and [2]). The role of the metal is to protect from environmental degradation, provide higher impact resistance and strength to the structure and composite structure can resist the fatigue failure due to its high strength to weight and high stiffness to weight ratios (see [3] and [4]). Studies are conducted to analyze the mechanical properties by conducting experimental tests and to understand the optimisation of these hybrid structures (see [5], [6], [7] and [8]). There exists an interface between the two materials as shown in Fig.1 and the strength and failure mechanism in these structures mostly depend on the interface and its fracture properties. Based on the relative value of fracture toughness of the interface to that of the bulk, interfaces are classified as stiff and soft interfaces [9]. The interfaces are present between the metal and FRC (metal-composite interface) and also among the constituents of the composites (matrix-fiber interface). The properties at the macroscopic level are mostly affected by metal-composite interface.
The failure modes of composite can be broadly classified as (a) Intralaminar (matrix/fiber failure) (b) Interlaminar (delamination) (c) Translaminar (failure across different lamina). Several numerical methods have been developed to understand the complex fracture phenomena in composites such as continuum damage models [10], XFEM [11], cohesive zone models (see [12] and [13]), peridynamics [14], gradient damage models [15]. Smeared crack models like phase field method (PFM) have been widely applied in solving complex problems involving crack initiation, crack branching and multiple cracking phenomena [16]. It considers the regularization of the crack which is represented by a decaying exponential function. PFM have been adopted to model the brittle fracture (see [17] and [18]), ductile fracture [19], dynamic fracture [20] and cohesive fracture [21]. This approach has been applied to model anisotropic materials such as composites by considering anisotropic surface energy and structural tensors (see [22] and [23]). The intralaminar and translaminar fracture in the composites have been modeled using PFM [24]. It has also been applied to nanocomposites [25], composites with varied stiffness [26] and hyper elastic materials [27]. The interfaces can be modeled using a cohesive zone approach from the works of Dugdale [28] and Barenblatt [29]. The PFM together with the cohesive zone model have been developed to understand the interaction between crack and interface in brittle materials [30], microstructures [31] and to analyze the crack penetration-deflection events at the interface [32].

In the present study, both the crack and interface are regularized according to the phase field approach. Anisotropic crack surface density functional is introduced to model FRC. The metal-composite interface is modeled using an exponential cohesive zone law where the traction components (normal and tangential) depends on the displacement jump in both normal and tangential directions. The displacement jump is evaluated as a difference between the displacements across the interface based on the geometry of the element considered. A structural tensor depending on the orientation of fiber families is introduced to consider the direction dependent fracture. The main aim of the paper is to understand (a) the interaction of the crack with the metal-composite interface (b) the crack propagation in composites reinforced with one and two fiber families (c) the influence of the anisotropy parameters which indicates the extent of anisotropy considered on the mechanical behavior and crack propagation.

2. Methodology
A solid body $\Omega$ consisting of metal $\Omega_1$ and fiber reinforced composite $\Omega_2$ having two fiber families oriented at angles $\theta$ and $\bar{\theta}$ respectively is considered as shown in Fig. 2(a). The solid body consists of sharp crack $\Gamma$ and the metal-composite interface is represented by $\Gamma_1$. 

**Fig.1:** Fiber Metal laminates (FML) with composite reinforced with fiber families.
The body forces and the surface traction are neglected for the analysis. The free energy functional can be written as

\[
E = \int_{\Omega} \Psi^e (\epsilon) \, d\Omega + \int_{\Gamma} G_c \, d\Gamma + \int_{\Gamma_I} \Psi^I ([u], \kappa) \, d\Gamma_I
\]  

(1)

The sharp crack and interface are diffused to \( \Gamma_\phi \) and \( \Gamma_\alpha \) as shown in Fig. 2(b). The regularized crack can be written as (refer [33])

\[
\Gamma_\phi = \int_{\Omega} \gamma (\phi, \nabla \phi) \, d\Omega, \quad \gamma (\phi, \nabla \phi) = \frac{1}{2l_\phi} \phi^2 + \frac{l_{\phi}}{2} (\nabla \phi \cdot \mathbf{A} \nabla \phi)
\]  

(2)

The structural tensor \( \mathbf{A} \) can be written in terms of fiber orientation tensors \( \mathbf{f} \) and \( \bar{\mathbf{f}} \), anisotropy parameters \( \beta \) and \( \bar{\beta} \) as [33]

\[
\mathbf{A} = \mathbf{I} + \beta \mathbf{f} \otimes \mathbf{f} + \bar{\beta} \bar{\mathbf{f}} \otimes \bar{\mathbf{f}}, \quad \mathbf{f} = [\cos \theta, \sin \theta, 0]^T, \quad \bar{\mathbf{f}} = [\cos \bar{\theta}, \sin \bar{\theta}, 0]^T
\]  

(3)
Both the crack phase field $\phi$ and interface phase field $\alpha$ are approximated as a decaying exponential function represented in Fig.2(c). The displacement jump $[u]$ in Eq.(1) is approximated as $d(x)$ which has both normal and tangential components $d_n$ and $d_t$ respectively. The traction vector components corresponding to the interface can be obtained from the coupled exponential cohesive zone law (refer [34]) as

$$
t_n = \frac{\partial \Psi}{\partial d_n}, \quad t_t = \frac{\partial \Psi}{\partial d_t}
$$

(4)

3. Numerical problem

Consider a $0.5\, \text{mm} \times 1\, \text{mm}$ specimen consisting of aluminium(metal) and fiber reinforced composite. The geometry and boundary conditions are depicted in Fig.3.

![Fig.3: Geometry and boundary conditions of hybrid composite structure](image)

The main aim of the study is to understand the effect of (a) fiber orientation (b) anisotropy parameter and (c) interface properties, on the mechanical response and crack propagation of the hybrid system. For this purpose, three cases are considered namely, CaseA: Unidirection fibers oriented at $30^\circ$ with $\beta = 20$, CaseB: Unidirection fibers oriented at $-30^\circ$ with $\beta = 20$, CaseC: fiber families oriented at angles $30^\circ$ and $-30^\circ$ with $\beta = 10$ and $\bar{\beta} = 30$ and CaseD: fiber families oriented at angles $30^\circ$ and $-30^\circ$ with $\beta = 30$ and $\bar{\beta} = 10$. As a first study, in all the four cases, the interface is considered to be perfect (no displacement jump across the interface) and for the second study, the relative value of the fracture toughness of the interface is taken less which can be considered to be a soft interface. The material properties for the aluminium are taken as $E_m = 70\, \text{GPa}$, poisson’s ratio, $\nu = 0.33$ and fracture toughness $G_{mc}^c = 9.98\, \text{MPa mm}$. For the woven fiber reinforced composite, the lamé’s constants are taken as $\lambda = 5.2\, \text{GPa}$, $\mu = 4.04\, \text{GPa}$, $\mu_f = 64.6\, \text{GPa}$, critical energy release rate attributed to fibers $G_{aniso}^c = 80\, \text{MPa mm}$, critical energy release rate attributed to matrix $G_{iso}^{\text{iso}} = 5.5\, \text{MPa mm}$ [33]. The fracture toughness of the interface is taken as $G_{Ic}^I = 0.01 G_{aniso}^c$ for the soft interface. Length scales are taken as $0.01\, \text{mm}$. Four noded bilinear elements are considered for the analysis.
Fig. 4: Evolution of the crack phase field for (i) perfect metal-composite interface (a) CaseA, (b) CaseB, (c) CaseC and (d) CaseD (ii) soft metal-composite interface (e) CaseA, (f) CaseB and (g) CaseC.

Fig. 5: Load displacement curves for CaseA, CaseB, CaseC, CaseD for (a) perfect interface and (b) soft interface.

The crack propagation for unidirectional FRC (CaseA and CaseB) and woven FRC (CaseC
and CaseD) for perfect interface and the crack propagation for CaseA, CaseB and CaseC for soft interface is shown in Fig.4. The load displacement curves for all the four cases for perfect interface and soft interface are plotted in Fig.5(a) and Fig.5(b) respectively.

4. Results and conclusions

From Fig.4(a)-(g), it is evident that the crack propagates at 0° in the metal phase and then penetrates into the composite in Fig.4(a)-(d), and deflects along the interface and then penetrates into composite in Fig.4(e)-(g). The crack propagates along the fiber direction in unidirectional FRC ((a) and (b)) while in woven FRC, the crack propagation is along the fiber family which has higher anisotropy parameter $\bar{\beta}$ in (c) and $\beta$ in (d). The spread of the crack along the interface is less in woven FRC compared to unidirectional FRC ((e)-(g)). From Fig.5, it is clear that for the perfect interface, unidirectional FRC has higher strength and for soft interface, woven FRC has higher strength. It can also be observed that the load displacement plots for CaseA and CaseB, CaseC and CaseD are same. The failure loads for a soft interface are very less when compared to perfect metal-composite interface.

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