Computers and Structures 122 (2013) 178–191

Contents lists available at SciVerse ScienceDirect

Computers and Structures

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

Multidisciplinary impact damage prognosis methodology for hybrid structural propulsion systems

Aaron Siddens, Javid Bayandor *

Crashworthiness for Aerospace Structures & Hybrids (CRASH) Lab, Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061-0238, USA

ARTICLE INFO

Article history:
Received 23 July 2012
Accepted 1 February 2013
Available online 17 April 2013

Keywords:
Hybrid structures
Progressive composite damage
Fluid-solid interaction
Bird strike
Crashworthiness
Propulsion

ABSTRACT

This work presents a detailed methodology for comprehensive crashworthiness analysis of hybrid or composite structures jet engine forward sections when subjected to soft impact. Effective strategies are developed within an explicit finite element framework for modeling a bird, intra-ply and inter-ply composite damage, and hybrid structural failure. These techniques are then combined to form a full multiphysics, multiscale crashworthiness analysis methodology. Hybrid fan blade fracture, leading edge de-bonding, composite casing delamination, and other progressive damage effects are captured. The methods developed thus far have the potential to accurately capture the full spectrum of forward section impact damage.

1. Introduction

Jet engines commonly ingest birds, hailstones, tire debris, and other foreign objects during flight. Even collisions with these relatively weak, soft objects can cause catastrophic engine damage. As of 2008, it was estimated that 262 fatalities have directly resulted from catastrophic bird strike on aircraft [1]. Over the past 18 years, the estimated cost to the civilian aviation industry due to bird strike-related damages was approximately $291.1 million [2].

During this time, aircraft engines have seen a shift from metals to laminated fiber-reinforced polymer (FRP) composite materials for many components. Compared to metals, composite materials offer lower weight-to-stiffness ratios, higher thermal stability, better vibration damping, and greater ease of manufacturing for parts with complex geometry, such as advanced swept fan blades. Metal subcomponents, including titanium leading and trailing edges, are incorporated into composite fan blades to counteract the poor impact resistance and brittle failure of the material. The resulting metal/composite part is called a hybrid structure.

Capturing bird strike damage on to engines incorporating hybrid metal-composite structures presents a complex multiphysics problem. The behavior of soft objects, such as birds, during impact with stiff structures is highly fluidic and is described using hydrodynamic theory, therefore presenting a fluid-solid interaction (FSI) problem.

In addition, modeling damage in fiber-reinforced composites is an inherently multiscale problem. Structural loads can induce fiber and matrix failure at the microscale and ply delamination at the mesoscale. In turn, these damage effects change the overall structural response and can initiate failure at the macroscale level. Numerical approaches for modeling composite impact damage are not well-established and require further development [3].

This paper presents the results of an ongoing study to develop a novel damage prediction methodology for capturing the full extent of soft impact damage to an engine forward section incorporating hybrid structures. A brief review of models for soft impact behavior and multiscale composite damage is presented, along with numerical simulation approaches in each of these areas.

A meshless particle approach is presented for modeling the fluidic bird. Particle behavior is governed by the Navier–Stokes (N–S) conservation equations. Parametric studies detail the influence of numerical factors and are used to develop a reliable bird model. Impact between a bird and a spinning hybrid fan assembly is simulated to demonstrate successful FSI.

A novel hybrid structure modeling approach is developed for the fan blades. Bonding of the metal leading edge and the composite portion is represented using an offset tied constraint with an embedded cohesive formulation. This fracture mechanics-based approach allows local weakening and failure of the bond to be captured. Concurrently, each part of the blades possesses individual ductile or composite failure criteria and captures impact-induced damage.

The cohesive formulation is again used for modeling inter-ply delamination damage in composite structures subject to surface

* Corresponding author. Address: Virginia Tech, 114S Randolph Hall, Blacksburg, VA 24060, USA. Tel.: +1 540 231 8492; fax: +1 540 231 9100.
E-mail address: bayandor@vt.edu (J. Bayandor).

0045-7949/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.compstruc.2013.02.001

impact. Each composite layer is explicitly represented and incorporates a material model that predicts fiber and/or matrix failure and the residual ply stiffness properties. Comparisons with experimental results from the literature demonstrate the method's efficacy. This approach is later applied for modeling a composite fan case.

These techniques are combined to form a multidisciplinary numerical modeling approach for full damage prediction in a jet engine with hybrid fan blades and a composite fan casing. Building upon a strategy developed by the authors for modeling soft impact on the fan stage [4], bird strike on a complete forward section is simulated, and the subsequent composite damage, hybrid component de-bonding, and delamination is wholly captured. The proposed methodology has the potential to accurately capture the full spectrum of damage to the forward section in order to assess the crashworthiness of advanced propulsion system designs.

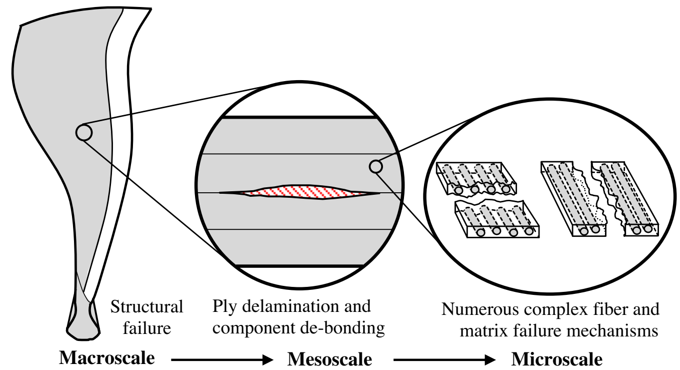

Fig. 1. Macroscale, mesoscale, and microscale damage in composites.

2. Fluidic behavior of soft impactors

Many materials behave like a fluid when impacted at high velocity [5]. Soft impact occurs when a relatively weak projectile, such as a bird, impacts a much stiffer, stronger target at high velocity. Stresses generated in the projectile far exceed its ultimate material strength, but stresses in the target are of the same order or below its maximum strength. An FSI problem arises as the projectile flows like a fluid over the solid structure.

Wilbeck used hydrodynamic theory describing the shock behavior of water columns to form a theory of soft impact [5–7]. These concepts, based on Rankine-Hugoniot relations for 1-D normal shockwaves, describe shockwave propagation and impact pressures on the structure.

The shockwave speed depends both on material properties and impact velocity. Wilbeck estimated the shockwave speed using the linear Hugoniot equation,

$$U_s = c_0 + kU_0, \tag{1}$$

where c_0 is the speed of sound in the undisturbed material, k is a material compressibility coefficient, and U_0 is the impact velocity. For moderate impact velocities, k is approximately equal to 2 for water and biological materials [8,9].

Using U_s, the shock, or Hugoniot, pressure is estimated as

$$P_H = \rho_0 U_s U_0, \tag{2}$$

where ρ_0 is the initial material density. After pressure release waves dissipate the shockwave, a steady fluid flow regime is established [7]. The dynamic pressure defined in Bernoulli's equation describes the pressure between the fluid and structure, expressed as

$$P_s = \frac{1}{2}\rho_0 U_0^2. \tag{3}$$

3. Multiscale damage in hybrid structures

Damage in composites is generally categorized into two main classes: (1) ply damage, and (2) inter-ply delamination. These effects occur simultaneously and interactively to influence the overall progression of damage in the composite structure. Within each ply, fiber diameters are in the micrometer range, and thus distinct fiber and matrix failure mechanisms can be observed at the microscale (Fig. 1). At the mesoscale, ply delamination is a distinct failure mechanism. Extensive ply damage and delamination can lead to failure at the structural level, or macroscale.

3.1. Ply damage modeling

Composite failure theories typically define in-plane ply strengths in terms of the longitudinal (along the fiber) and transverse (perpendicular to the fiber) directions [3,10–13]. Fiber properties dominate laminate behavior in the longitudinal direction, and fiber strength is usually considered the limiting factor for resisting damage due to longitudinally-oriented stresses, namely σ_{11} and σ_{12}. In the transverse direction, matrix strength is the limiting factor for damage due to transverse stresses, σ_{22} and σ_{12}.

Numerous studies have examined the wealth of available failure models in an effort to determine the most accurate, robust method. In an extensive investigation spanning a decade, Hinton et al. [10,11] conducted the World Wide Failure Exercise comparing 19 different theories for their ability to predict failure loads for 14 different biaxial loading cases. In the end, the most accurate models were only able to predict failure within ±50% of experimental results 75% of the time [3,12].

With these considerations, it was determined that assessing the most accurate composite failure model for the crashworthiness methodology was beyond the scope of this study. The goal of this work has been to develop a flexible modeling approach that can implement a wide variety of failure models.

3.2. Delamination/de-bonding modeling

Models for delamination often fall into two categories. The first group is theories that seek to represent delamination by estimating the post-damage reduced laminate stiffness and strength. Delamination models that use out-of-plane normal strength, S_{33}, and shear strengths, S_{13} and S_{23}, may be utilized.

The second group is approaches that aim to explicitly model the crack formation between plies resulting from delamination. Energy-based fracture mechanics models, such as the Virtual Crack Closure technique or cohesive formulations, are often used to predict the onset and progression of delamination. The cohesive approach has been studied in the work.

3.2.1. Cohesive formulation

Cohesive models are fracture mechanics-based methods that use the strain energy release rate during the formation of new fracture surfaces to predict delamination. The mode I release rate due to through-thickness tension, G_{IC}, the mode II release rate due to interlaminar shear, G_{IIC}, and the normal and shear strengths, T and S respectively, are critical properties that can be readily obtained from double cantilever beam and end load split tests [14].

A mixed-mode bilinear stress-displacement cohesive law was explored within the FE code (Fig. 2). The surface bond is represented as linear springs in the normal and tangential directions.

Bond softening occurs when separation and sliding between plies exceeds the softening strain, δ^0. Further loading decreases the stiffness and residual strength along a linear path. Upon reloading, the new path will be followed (Fig. 2). Once the failure strain,