Composite Structures 113 (2014) 476–491

Contents lists available at ScienceDirect

Composite Structures

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

Numerical prediction of compression after impact behavior of woven composite laminates

P.A.A.E. Mendes *, M.V. Donadon

Instituto Tecnológico de Aeronáutica, CTA-ITA-IEA, São José dos Campos, SP 12228-900, Brazil

ARTICLE INFO

Article history:
Available online 5 April 2014

Keywords:
CAI
Damage model
CFRP
Finite elements

ABSTRACT

This work investigates the numerical prediction of compression after impact strength in woven composite laminates. Intralaminar and interlaminar damage prediction were evaluated using proposed damage models implemented as user defined material in ABAQUS Explicit multipurpose FE code. The numerical models were developed using the finite elements method with two different modeling approaches named Single Shell Model (SSM) and Split Shell Model (SpSM). The Single Shell Model (SSM) used only shell elements to model the laminates and the delamination effects were neglected. The delamination effects were included in the Split Shell Model (SpSM) by using a delamination contact-logic. An experimental programme was carried out to validate the proposed damage modeling approaches. The proposed damage models and the modeling approaches have proven to be capable of reproducing experimental results with good accuracy for the impact tests and CAI tests.

1. Introduction

The aerospace industry is focused on increasing the efficiency and reliability of the aircrafts, reducing operational costs. Optimized and reliable lighter structures are desired to the design of new aircrafts. To achieve these objectives materials such Carbon Fiber Reinforced Plastics (CFRP) has advantageous structural and manufacturing properties that can supply those needs. Moreover high performance composite materials utilization and importance have grown over the years for the construction of aircraft primary structures.

Composite structures have a high strength-to-weight and stiffness-to-weight ratio, good fatigue and corrosive properties and fewer parts counts. However, composites structures do have drawbacks which include poorer performance at high temperatures, reduced failure strain at low temperature, poor through-the-thickness properties and poor performance to transverse impact load. CFRPs are inherently brittle and vulnerable to impact damage.

In low velocity impact the contact duration is sufficiently long enough for entire structure to respond and impact energy is absorbed elastically and/or eventually in damage creation. The resulting damage mechanism due to impact loading can be divided into four distinct categories: delamination, matrix cracking, fiber breakage and total perforation. For high velocity impact the damage is almost exclusively perforation and delamination of surrounding area [1–3]. Despite the non-apparent effects of low velocity impact seemingly appears less severe than the ballistic impact effects, it can affect the performance of the composite structural component for subsequent loading conditions, as compression load.

Based on that, ensuring the structural integrity of aircraft components in the presence of low velocity impact damage is main concern of composite materials utilization. Predict these complex effects in the design phase through analytical and numerical models can increase the reliability of composite structures, decreasing the related design costs.

Compression After Impact (CAI) is the test methodology developed to evaluate the residual strength properties of multidirectional plates which have been previously subjected to indentation caused by an impact of weight drop, prior to the compressive loading. Industry standards were created to regulate the compression after impact test [4–6]. Experimental evidences have shown that the CAI strength of a composite laminate depends on the impact energy level, lay-up, thickness and environmental conditions [7].

Considerable efforts have been dedicated in the development of numerical and analytical models that can predict the CAI strength and the complex interactions between the failure modes occurring during the impact and CAI tests.

The impact induced damage in composites is a complex event to model. Abrate [8] and Olsson [9] proposed solutions that are

* Corresponding author. Tel.: +55 11995054899; fax: +55 011995054899..
E-mail address: pmendes@ita.br (P.A.A.E. Mendes).

http://dx.doi.org/10.1016/j.compstruct.2014.03.051
0263-8223/

restricted to simple impact cases where a target is relatively small and complicating factors such as transverse shear deformation and rotary inertia do not play any significant role. Also neither the impactor nor plate geometry were described and contact is assumed to be localized at a single point of the structure. These strategies are very limited and generalized numerical models are required.

The finite element method has become the most popular numerical method for impact modeling. The explicit formulation available in commercial codes, such as ABAQUS/Explicit, has advanced contact logics to deal with a wide range of contact problems, and a wide range of element formulation. Since the materials models plays a crucial rule for the damage prediction, the implementation of constitutive damage models within user defined subroutines is another desirable characteristic for this application.

In recent years, Continuum Damage Mechanics (CDM) has been investigated by many researchers [1,10–20] and its application and impact damage modeling has shown very efficient [1]. The advantage of CDM approach is that can be easily combined with a stress and/or strain failure criteria for predicting damage initiation and fracture mechanics approach for the failure progression by coupling the internal damage variables with the fracture energy.

In addition to the development of models to predict the impact induced damage in composite laminates, as an isolated event, there some researchers that used the developed models to predict the post impact behavior [21,22], but few studies in literature focus on both impact and CAI modeling.

Soutis and Curtis [23] studied several CFRP specimens and proposed a fracture toughness model to predict the CAI residual strength. The work showed the several types of impact-induced failures like delamination, fiber failure and splitting, and the evolution of delamination in the presence of compressive loads. The fracture toughness model predicts the CAI strength accurately for impacted coupons with certain failure characteristics.

Yan, et al. [24] investigated the CAI behavior of woven glass fiber-reinforced vinyl ester (glass/VE) panels using an eigendeformation-based reduced order computational homogenization (EHM) model to predicted the ply failure and compare the results with test results. The initial impact-induced damage was inferred from experimental observations using a conical representation of damaged area. The authors concluded that the delamination propagation of damaged coupons is critical to sublaminate buckling and leads to final shear failure.

Mendes et al. [25] evaluated the CAI of CFRP coupons using a single shell finite element model combined with an energy based damage model. The energy based damage model was implemented as an user defined material in ABAQUS explicit commercial package. For comparison and validation purposes the Hashin failure model available in ABAQUS was also used. The numerical results were compared against test results published in open literature. The energy based damage model showed better correlation in terms of impact peak force, impact duration, displacement versus time history, absorbed energy and CAI strength compared to the Hashin failure model available in ABAQUS. The numerical predictions obtained using both damage models showed that the CAI strength did not decrease for the higher impact energy coupons, since the shells elements formulation do not handle out-of-plane stress and strain that rules the delamination behavior.

Rivallant et al. [26], presented a numerical simulation study of impact damage, permanent indentation and CAI in CFRP laminates. For both impact tests and CAI test, a model for the formation of damage developing during low-velocity/low-energy was used. The different impact and CAI elementary damages, like matrix cracking, fiber failure and interface delamination were taken into account. Impact tests, using energy range from 1.6 to 29.5 J, and CAI tests on $100 \times 150 \times 4.16\,\text{mm}^3$ quasi-static lay-ups were performed. The numerical results showed good correlation with the test results for the impact loading and CAI results. Gonzalez et al. [27], simulated the performance of monolithic flat and rectangular composites plates to impact and compression after impact sequence using a constitutive material models formulated in the context of continuum damage mechanics implemented as a user-defined model routine in ABAQUS software. The simulations confirmed that FE models, based on suitable constitutive models are a powerful tool for the design of damage resistant and damage tolerant structures manufactured with composites materials and subjected to impact loading.

Based on this scenario, this paper presents a novel finite element model to predict the CAI strength of woven fabric laminates. For this work, a plane stress energy based constitutive damage model was used. The constitutive model combines continuum damage mechanics and fracture mechanics approaches within a unified way by using a smeared cracking formulation. The damage model formulation allows the failure prediction either in tension or compression in both warp and weft directions, and an additional damage variable is also included into the formulation to account for in-plane shear failure at ply level. Delamination effects are also incorporated into the proposed modeling methodology by using a newly developed mixed-mode delamination contact-logic.

2. Damage models

2.1. Intralaminar damage modeling

The damage model used in this work to model damage at ply level was developed by Donadon and co-authors and several references are available in open literature [1,15,20,28]. The smeared cracking formulation is used to model progressive failure. It relates the specific or volumetric energy, which is defined by the area underneath the stress–strain curve, with the strain energy release rate of the material. The method assumes a strain softening constitutive law for modeling the gradual stiffness reduction due to the micro-cracking process within the cohesive or process zone of the material. In order to avoid pathological problem associated with strain localization and mesh dependence during softening, the softening portion of a stress–strain curve is adjusted according to the element topology and cracking direction for each failure mode using an advanced objectivity algorithm [1].

2.1.1. Failure criteria

Eq. (1) is the general form for all failure criteria used to detect damage initiation for all in-plane failure modes [28],

$$F_{ij}^{k}(\sigma_{ij}) = \frac{\sigma_{ij}}{S_{ij}^{k}} - 1 \geqslant 0 \tag{1}$$

where k refers to the associated failure modes ($k = t$ for failure in tension, $k = c$ for failure in compression and $k = s$ for failure in shear). The subscripts ij indicate the failure direction ($i = j = 1$ for warp direction, $i = j = 2$ for weft direction and $i \neq j$ for shear direction). S_{ij}^{k} is the strength in ij direction for k failure mode and σ_{ij} is the acting stress on each layer of the materiaĺs local coordinate system.

2.1.2. Damage evolution laws

Once the failure criteria are met, the damage commences and grows according the damage evolution laws taken from Ref. [28] and defined as follows.

2.1.2.1. Damage evolution laws for failure in the warp and weft directions. Eq. (2) is the general expression for damage evolution laws in the warp and weft directions [28],

$$d_{ii}(\lambda_{i,1}, \lambda_{i,2}) = \lambda_{i,1} + \lambda_{i,2} - \lambda_{i,1}\lambda_{i,2} \tag{2}$$