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An efficient approach to determine compression after impact strength of quasi-isotropic composite laminates

Fardin Esrail, Christos Kassapoglou *

Chair of Aerospace Structures and Computational Mechanics, Delft University of Technology, Netherlands

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ABSTRACT

An approach to obtain accurate estimates of the compression after impact strength of quasi-isotropic composite laminates is presented. The method makes use of the damage size and type calculations obtained previously, and models the damaged region as an area of concentric ellipses each with different stiffness and strength properties. A Rayleigh–Ritz approach is used to calculate the stresses in each of the inclusions representing the damage. Failure is predicted as material failure when local stresses exceed the load carrying capability of the elliptical inclusion in question. Once a portion of the damaged region fails, its load is redistributed to adjacent elliptical inclusions or sub-laminates. A progressive failure analysis follows until the entire laminate fails. This process requires an accurate prediction of the undamaged failure stress. Comparison with test results shows the analytical predictions to be in good agreement for the majority of cases.

1. Introduction

Accurate determination of the residual strength of composite laminates after impact continues to be a challenge. It is of great interest because, in a composite aircraft, it must be demonstrated that structure with damage corresponding to the threshold of detectability does not fail below ultimate load [1].

Over the years, many different approaches have been proposed for predicting Compression After Impact (CAI) strength of composite laminates. Cairns [2] developed the basics of a maximum strain-based method to predict material failure. He combined that with a buckling analysis of the sub-laminates created during impact to deal with compression-loaded laminates. Abrate [3,4], Olsson [5,6] and Huang et al. [7] developed a variety of methods ranging from analytical or semi-analytical approaches to detailed finite element models that adjust the properties locally to account for local failure.

Accurately accounting for the state and extent of damage and incorporating this damage in the constitutive relationships is necessary for the development of a model that can deal with different laminates and impact energies. To this end, several models have been developed for the determination of the stiffness properties in the damaged region ranging from relatively simple models with discounted properties [2] to elaborate models using damage mechanics and inverse methods that use the local deflections to back-calculate the corresponding stiffnesses [8–11].

Despite these difficulties, such methods [6,12] have been found to be useful in giving insight on laminate behavior, allowing relative comparison of candidate designs, and, even, being reasonably accurate for certain classes of laminates and/or impact ranges.

During the preliminary design effort of a composite program, there is a need to evaluate a large number of candidate layups in order to find the one that meets all load requirements including compression after impact. This has to be done at a large number of locations and requires the use of an accurate model for predicting compression after impact. The more accurate models available today are computationally expensive as they make use of cohesive elements and/or require detailed time-consuming progressive damage calculations. They cannot effectively be used to perform optimization or simple tradeoffs. As a result, designers resort to a combination of expensive and lengthy test programs and the use of stacking sequences with which they have had good experiences in the past, thus limiting the design space and missing out on weight saving opportunities. An approximate but reasonably accurate method to predict compression after impact strength would be very useful in this context.

With this in mind, an approximate method was proposed by Esrail and Kassapoglou [13] to determine the type and extent of damage in quasi-isotropic laminates under low speed impact. The method first determines the three-dimensional stress state under the impact site using an energy minimization. Its predictions

* Corresponding author. Tel.: +31 15 2781382.
E-mail address: c.kassapoglou@tudelft.nl (C. Kassapoglou).

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were compared to finite element results and exact solutions for semi-infinite plates and were found to be in good to excellent agreement. This linear solution is then modified by truncating the interlaminar stresses so they do not exceed their respective ultimate strength values making sure force equilibrium is maintained. As a result, for a given through-the-thickness location and radial orientation from the center of impact, the region (in terms of radial distance from the center of impact) over which stresses exceed their corresponding allowables can be calculated indicating local failure. Depending on the type of failure, in-plane or out-of-plane, the extent of matrix cracks, fiber breakage, and delaminations can be estimated. Maps of the complete through the thickness damage can be obtained. The predictions of the type and extent of damage were compared to test results from [14] and, with minor exceptions, were found to be in good agreement.

The damage state predicted by the approach in [13] is used here as the starting point for predicting CAI strength. As in [13], the test results obtained by Dost et al. [14] are used to compare to analytical predictions. The reason is that these results, shown in Fig. 1, challenge the ability of the analysis model. They are generated on the same material, on laminates with the same thickness and in-plane stiffness (they are all quasi-isotropic). The CAI strength however, varies by as much as a factor of 1.7. These tests indicate that different stacking sequences, even if all are quasi-isotropic and with the same thickness, can have significant differences in their CAI strength. They, therefore, can serve as a good benchmark for any analytical method attempting to predict CAI strength of composite laminates. They reduce the number of variables that can affect CAI strength yet the CAI strength varies significantly across these laminates. If a method works well for the laminates in Fig. 1 it can be used or extended to more complex situations.

2. Analysis model – stress determination

As already alluded to, the damaged region is modeled as a series of concentric ellipses as shown in Fig. 2. Each ellipse has its own stiffness and strength properties. The number of ellipses to be used is a function of the damage state. The boundary of the outer-most ellipse is defined as the outer edge, or envelope, of the delaminations created during impact.

This idea has its roots in modeling the damaged region as an elastic inclusion. This was done first by Cairns [2] and Kassapoglou [12]. Here this idea is extended to using an inclusion with multiple zones having different stiffness and thus better capturing the variation of properties in the damaged region.

It is crucial to include enough elliptical inclusions and determine the stiffness of each so that the damage state is clearly reflected. In each ply, the damage present at each location is

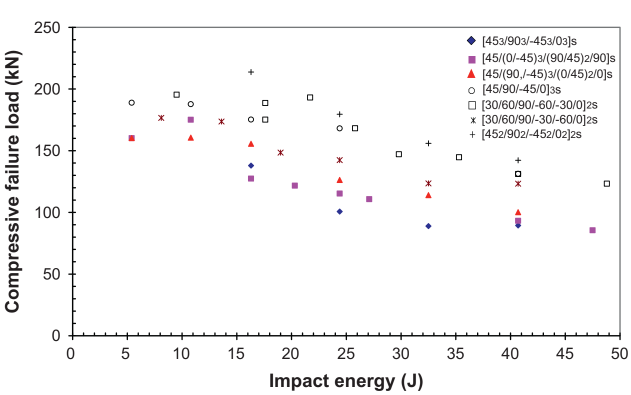

Fig. 1. Compression after impact failure loads from Dost et al. [14].

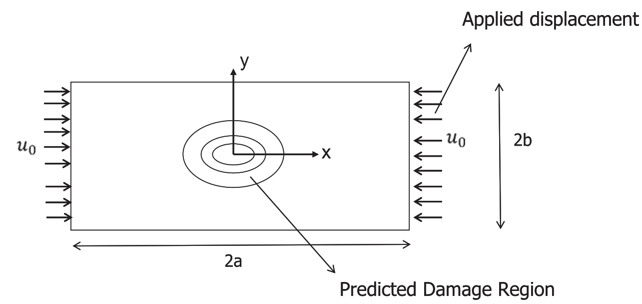

Fig. 2. Laminate with impact damage modeled as ellipses with different material properties.

translated to a set of reduced stiffness properties. Special care is taken to differentiate between fiber breakage, matrix cracks, and delaminations. The local stiffness is determined by using appropriate combinations of springs in parallel and in series maintaining strain and load compatibility respectively. Combining the reduced stiffnesses through the thickness at each radial location gives an estimate of the stiffness of the damage laminate at that location. An elliptical inclusion is then postulated to contain portions of the damaged laminate with nearly the same stiffness. It should be noted, that, for increased accuracy, more elliptical inclusions can be used. These being quasi-isotropic laminates, the assumption of nearly circular damage regions is in good agreement with experimental results. For general laminates, this assumption of elliptical inclusions would have to be revisited.

The present model will not give a detailed understanding of the damage mechanisms and their effect on residual strength. It will, however, serve as a screening tool to evaluate effectively a large number of designs before focusing on the few that will be analyzed with more accurate but computationally intensive models.

The origin of the coordinate system is located at the center of the inner-most ellipse. The length and width of the laminate are 2a and 2b respectively with loading applied parallel to the x direction. A uniform displacement u_o is applied (see Fig. 2).

Each ellipse is assumed to be orthotropic with in-plane properties described by its own A matrix. The displacements in the entire laminate are assumed to be:

$$u = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} P_{mn} \sin\frac{m\pi x}{a} \cos\frac{n\pi y}{2b} + u_o \frac{x}{a} \tag{1}$$

$$v = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} H_{mn} \cos\frac{m\pi x}{a} \sin\frac{n\pi y}{2b} - \frac{\nu_{xyeq} u_o y}{a} \tag{2}$$

with P_{mn} and H_{mn} unknown constants.

Eqs. (1) and (2) reproduce the boundary and symmetry conditions that $u = u_o$ at $x = a$, $u = 0$ at $x = 0$ and $v = 0$ at $y = 0$. In addition,

$$\frac{\partial u}{\partial y} = 0, \ x = 0 \tag{3}$$

$$\frac{\partial v}{\partial x} = 0, \ y = 0 \tag{4}$$

Of interest is the last term in Eq. (2) which includes an "area-weighted" Poisson's ratio ν_{xyeq} for the entire laminate:

$$\nu_{xyeq} = \frac{\sum_{i=1}^{q} (\nu_{xy})_i (Area)_i}{4ab} \tag{5}$$

where the summation is taken over all regions into which the ellipses divide the original laminate and the subscript i refers to the ith region which has its own Poisson's ratio and area.