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An efficient approach for damage quantification in quasi-isotropic composite laminates under low speed impact

Fardin Esrail, Christos Kassapoglou *

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

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ABSTRACT

An efficient method to determine the type, size, and location of damage in impacted quasi-isotropic composite laminates is presented. The method uses the peak force during impact obtained from energy balance, a Hertzian contact formulation and energy minimization to determine the complete state of stress in the laminate. Comparisons of the analytical predictions to limiting cases of infinite thickness plates or to detailed finite element models for finite thickness plates shows the predicted stresses to be in excellent agreement with other methods. The stresses are then modified to account for the creation of damage and used in out-of-plane and in-plane failure criteria to predict delamination sizes, matrix failure and fiber failure. The predicted damage states are then compared to published test results for two different materials, eight different stacking sequences, and a range of impact energies from 5 to 50 J. Very good agreement of the predicted damage sizes with the experimentally measured values is observed for a wide range of energy levels but, for two laminates, the discrepancies are significant. Possible improvements of the method are discussed briefly. This method is very promising and can be used in preliminary design allowing extensive trade studies and, eventually, layup optimization. It can also form the beginning of an efficient methodology to predict compression after impact strength of quasi-isotropic laminates.
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1. Introduction

Since the late 1970s, impact damage has been known to be one of the critical design conditions for composite structures. Even at low impact energies, corresponding, for example, to small tool drops, significant damage is created below the impacted surface with little or no evidence of damage on the surface. This damage, in the form of matrix cracks, delaminations, and fiber breakage, reduces the compression (and shear) strengths of the laminate by as much as 60% for some materials and laminates with Barely Visible Impact Damage (BVID). There has been, therefore, a need for understanding the mechanisms of damage creation and how the resulting damage affects residual strength.

The problem of impact damage in composites is challenging for two reasons: first, the physical phenomena taking place during damage creation and the way this damage affects residual strength, are quite complex. Second, accurate modeling of the mechanisms involved can be very complex and computationally expensive. Over the years, many approaches have been proposed to model the impact event from the pioneering efforts by Sun and Chattopadhyay [1], and Dobyns [2] to the more elaborate approaches by Cairns and Lagacé [3], Abrate [4], Olsson [5–7] or to numerical, finite-element-based, solutions by Luo et al. [8] or Ghelli and Minak [9]. These are a few of the more representative approaches which, among others, deal with the emphasis of the present work, which is the damage resistance. Damage resistance, first defined by Cairns and Lagacé [10] refers to the amount of damage a structure sustains for a given threat scenario. The present work focuses on the damage created during the impact event. In addition to the investigations just mentioned, other researchers also focused on the damage resistance aspect of the impact problem [11–18]. The approaches range from numerical solutions to the governing equations (static or dynamic) to the use of modal superposition, and, finally, even less involved approaches based on test results and semi-empirical methods. The discussion here does not aim to cover all the work done in the area of damage resistance but to highlight the main directions. Excellent overviews of most of the work done in the area of impact damage can be found in review papers [19,20].

One of the most revealing descriptions of the extent of the problem of impact damage in composites was given by Dost et al. [21]. In this work, Dost, Ilcewicz and Avery, obtained extensive experimental data on impact of composite laminates. Some of their results are shown in Fig. 1. What is particularly important in this case is the range of compression after impact strengths for a given

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

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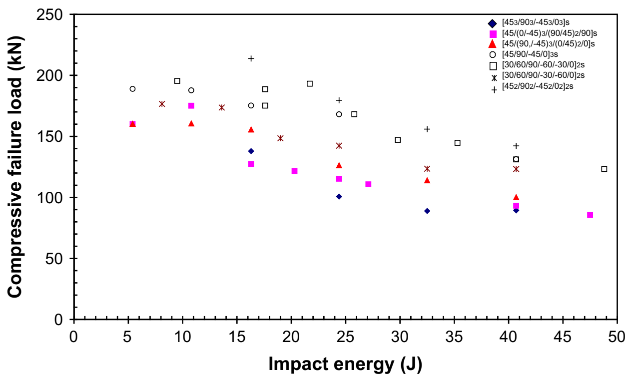

Fig. 1. Compression after impact failure loads from Dost et al. [21].

energy level. These laminates are all made with the same material and the same process. Six of them have the exact same thickness, and, all of them, have the exact same in-plane stiffness in every direction. They are quasi-isotropic. Yet, as can be seen in Fig. 1, the differences in compression after impact between same thickness laminates can be as high as a factor of 1.7.

In order to understand and predict this kind of behavior, it is important that the type, location, and extent of damage created during impact is understood. In what follows, an analysis model is presented to predict the three-dimensional state of stress in a quasi-isotropic laminate during low speed impact damage. These stresses are then modified to account for damage created and are used in a failure criterion to predict damage in the laminate.

2. Stress model

The focus here is on low speed impact which can be modeled as a quasi-static event. This is the low energy high mass situation [22] where the impact event, at least up to the point when the highest contact force is reached is long enough for the boundary reflections to have died out and the response of the plate is dominated by static response characteristics.

With this assumption, an energy balance can be used to determine the peak force during impact. It is assumed that the peak force is reached when all the impactor energy has been momentarily transferred to the impacted laminate. For now, energy absorbed in damage creation is not included in the energy balance. This will be discussed at some length later when the model to predict the size of damage is presented. In addition, other than internal energy in the plate due to bending and indentation, all other forms of energy storage or absorption (e.g. plate vibrations) will be neglected. Thus:

$$E_k = U_b + W_{ind} \tag{1}$$

where E_k is the kinetic energy of the impactor, and U_b and W_{ind} are the energy stored in bending and work done indenting the laminate respectively.

The bending energy, assuming linear relationship between applied force and out-of-plane deflection of the impacted plate, has the form:

$$U_b = \frac{Fw_{\max}}{2} \tag{2}$$

where F is the peak force during impact which for this calculation is assumed to be a point force. This is a valid assumption as long as the contact area during impact is very small compared to the plate dimensions.

The peak deflection $w_{\max}$ when F is applied is determined by assuming

$$w = \sum_{m=1}^{M}\sum_{n=1}^{N} A_{mn} \sin\frac{m\pi x}{a} \sin\frac{n\pi y}{b} \tag{3}$$

where a and b are the plate dimensions (see also Fig. 2). The unknown coefficients A_{mn} are obtained by minimizing the total energy:

$$\begin{aligned}\Pi = \frac{1}{2}\int_0^a\int_0^b \Bigg\{ & D_{11}\left(\frac{\partial^2 w}{\partial x^2}\right)^2 + 2D_{12}\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial y^2} + 4D_{16}\frac{\partial^2 w}{\partial x^2}\frac{\partial^2 w}{\partial x \partial y} \\ & + D_{22}\left(\frac{\partial^2 w}{\partial y^2}\right)^2 + 4D_{26}\frac{\partial^2 w}{\partial y^2}\frac{\partial^2 w}{\partial x \partial y} + 4D_{66}\left(\frac{\partial^2 w}{\partial x \partial y}\right)^2 \Bigg\} dxdy \\ & - Fw(x = a/2, y = b/2) \end{aligned} \tag{4}$$

It should be noted that Eq. (3) assumes that the plate is simply supported. The case of a clamped plate was also solved and showed that in some cases the difference in $w_{\max}$ for the same applied F can be as much as 40%.

Note that it is also assumed that the laminate is symmetric and balanced but the bending-twisting coupling terms D_{16} and D_{26} can be non-zero as is shown in Eq. (4). It is important to note that when D_{16} and D_{26} are significant, (greater than 15% of the next lowest term in the D matrix of the laminate), they have an important effect on the results and should not be ignored. In addition, using a series as in Eq. (3) can have very slow or even erratic convergence [23].

Using Eq. (3) to substitute in Eq. (4) and minimizing with respect to A_{mn} results in a linear system of equations ($M = N = 30$ was used here resulting in a system of 900 equations). Using the A_{mn} obtained by solving this system allows determination of $w_{\max}$ by evaluating Eq. (3) at the center of the plate. As a result, the relationship between peak force F and $w_{\max}$ can now be written as:

$$F = k_p w_{\max} \tag{5}$$

where the stiffness k_p of the plate behaves as a spring constant and is a function of the A_{mn}. Note that to avoid convergence issues with this method, a finite element model was also created and run to obtain the slope of Eq. (5). In the special case for which D_{16} and D_{26} are negligible, the governing equation for w can be solved exactly using infinite series and k_p can be shown to be [24]:

$$k_p = \left[\sum\sum \frac{\frac{4}{ab}\sin^2\frac{m\pi}{2}\sin^2\frac{n\pi}{2}}{D_{11}\left(\frac{m\pi}{a}\right)^4 + 2(D_{12} + 2D_{66})\frac{m^2n^2\pi^4}{a^2b^2} + D_{22}\left(\frac{n\pi}{b}\right)^4}\right]^{-1} \tag{6}$$

with D_{11}, D_{12}, D_{22}, and D_{66} bending stiffnesses of the composite laminate. With k_p determined, the bending energy U_b can be determined using Eq. (2).

The indentation work W_{ind} is determined from the relation:

$$W_{ind} = \int_0^{\delta_{\max}} F(\delta)(d\delta) \tag{7}$$

where δ is the indentation when the applied force is $F(\delta)$ and $\delta_{\max}$ is the maximum indentation reached when the peak force F is reached.

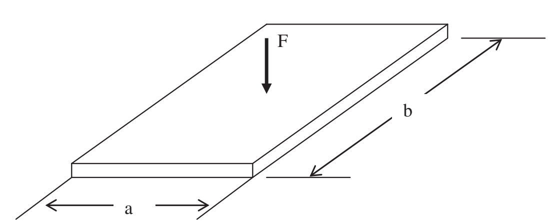

Fig. 2. Composite plate under point load at its center.

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