Damage evolution of sandwich composite structure using a progressive failure analysis methodology

X.L. Fan a, T.J. Wang a,*, Q. Sun b

aSV lab, School of Aerospace Engineering, Xi’an Jiao Tong University, Xi’an 710049, China
bSchool of Aeronautics, Northwestern Polytechnical University, Xi’an 710072, China

Abstract

Damage evolution in composite sandwich panels under quasi-static impact is investigated by using a progressive failure analysis methodology. Several failure criteria, e.g. Hashin’s and Besant’s criteria, are used for different failure mechanisms such as fiber breakage, matrix or core cracking, and interfacial delamination in the impacted face sheet. Material degradation is achieved through a set of degradation factors for different failure modes. Three dimensional honeycomb sandwich panels are analyzed by using commercial finite element code, ABAQUS, incorporating different failure criteria user-defined material model.

Keywords: Sandwich composites; Degradation; Progressive failure; Damage; Delamination

1. Introduction

The use of sandwich composite structures in aeronautics and astronautics engineering is increasing. The effects of low velocity impact of a foreign object on the facings is one of the major concerns in the use of sandwich composites as it often causes significant local stiffness reductions and stability performance of the structure [1–3]. Stiffness reduction of about 80% in tension and up to 60% under compression has been demonstrated on small coupons cut from impact damaged zone [4, 5]. Damage modes and mechanisms of such sandwich structures have characteristics substantially different from conventional laminated composite structures [6–8]. It is difficult to predict their integrality and overall performance, especially when structural degradation and damage propagation occur.

The structural responses of sandwich structures are generally determined empirically based upon component and full size test articles. However, this approach may not allow for adequate and timely design tradeoffs and can result in significant repetition work if problems materialize during full scale testing. The most effective way to obtain this quantification is through integrated computer codes that couple composite mechanics with structural analysis and progressive failure analysis models [9]. In recent years, the progression of damage in composite laminates has been

* Corresponding author. Tel.: +86-29-8849-4925; fax: +86-29-8849-2850.
E-mail address: fanxueling@mail.xjtu.edu.cn.
a focus of extensive research [9–13]. The simulation of progressive fracture has been verified to be in reasonable agreement with experimental data from tensile coupon test on graphite/epoxy laminates [12], damage progressive in carbon fibre reinforced plastic I–beams [13] and stiffened plate [9,11].

The purpose of this paper is to perform progressive failure analysis of sandwich composites subjected to quasi-static loading condition, in order to predict the damage initiation, growth, and propagation to fracture.

2. Progressive Failure Model

2.1. Failure initiation criteria

The catastrophic failure of sandwich composites is often due to the propagation or accumulation of local failures (or damage) as the load is increased. Initial failure can be predicted by applying an appropriate failure criterion or first ply failure theory. However, the subsequent failure prediction requires an understanding of failure modes and failure propagation. Sandwich composites may fail by fibre breakage, core or matrix cracking, or by delamination in the impacted face sheet.

In this paper, various failure criteria have been adopted to predict macroscopic failures based on the tensile, compressive, and shear strengths of the individual lamina. Hashin’s failure criteria [14] are used to predict the onset of face sheet damage in a complex stress state, e.g. fibre breakage and/or matrix cracking. Assuming that fibres are aligned with the first material principal direction, $1$–direction, thus making the material transversely isotropic about $1$–direction, the Hashin’s criteria read as follows:

\[
\left( \frac{\sigma_{11}}{X_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 \geq 1 \quad \text{if} \quad \sigma_{11} > 0
\]  

(1)

\[
\left( \frac{\sigma_{11}}{X_c} \right)^2 \geq 1 \quad \text{if} \quad \sigma_{11} < 0
\]  

(2)

\[
\left( \frac{\sigma_{22} + \sigma_{33}}{Y_t} \right)^2 + \left( \frac{\tau_{12}}{S_{12}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 + \frac{1}{S_{23}^2} \left( \tau_{23}^2 - \sigma_{22} \sigma_{33} \right) \geq 1 \quad \text{if} \quad \sigma_{22} + \sigma_{33} > 0
\]  

(3)

\[
\left( \frac{\sigma_{22} + \sigma_{33}}{2S_{12}} \right)^2 + \left( \frac{\sigma_{22} + \sigma_{33}}{Y_c} \right)^2 \left[ 1 - \frac{Y_c}{2S_{23}} \right] + \left( \frac{\tau_{12}}{S_{12}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 + \frac{1}{S_{23}^2} \left( \tau_{23}^2 - \sigma_{22} \sigma_{33} \right) \geq 1 \quad \text{if} \quad \sigma_{22} + \sigma_{33} < 0
\]  

(4)

\[
\left( \frac{\sigma_{33}}{Z_t} \right)^2 + \left( \frac{\tau_{23}}{S_{23}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 = 1 \quad \text{if} \quad \sigma_{33} > 0
\]  

(5)

\[
\left( \frac{\tau_{23}}{S_{23}} \right)^2 + \left( \frac{\tau_{13}}{S_{13}} \right)^2 = 1 \quad \text{if} \quad \sigma_{33} < 0
\]  

(6)

where $X_t$ and $X_c$ are the tensile and compressive ply strengths in the fibre direction, i.e. $1$–direction, $Y_t$ and $Y_c$ are the tensile and compressive ply strengths in the direction perpendicular to the fibres, or $2$–direction, and $S_{12}$ and $S_{23}$ are...
the shear strengths on the 1–2 plane (in–plane of ply) and on 2–3 plane (out–of–plane of ply), $\sigma$ and $\tau$ with various subscript are stress components, respectively. Failure will initiated when any of Hashin’s failure conditions is violated.

Besant’s failure criterion [15] is used to predict the failure behaviour of honeycomb, which is usually loaded under combined shear and compression.

$$\left( \frac{\sigma_{33}}{\sigma_{cu}} \right)^n + \left( \frac{\tau_{13}}{\tau_{lu}} \right)^n + \left( \frac{\tau_{23}}{\tau_{lu}} \right)^n = 1 \quad (7)$$

where $\sigma_{cu}, \tau_{lu}$ and $\tau_{lu}$ are the corresponding yield stresses.

2.2. Material degradation strategy

Various material degradation models have been proposed and demonstrated for laminated composite structures [10]. A common strategy for degrading the material properties in damaged laminate composites is the ply discount method. In this strategy, ply discounting involves degrading the mechanical properties of the materials directly, and then updating the local material stiffness coefficients using the degraded mechanical properties. For the various criteria, the material degradation rules follow the heuristics strategy. Upon a given loading, the stress level at each integration point is calculated and compared with appropriate failure criteria. Once a failure is detected in a particular mode, say when the first failure flag is nonzero, then the mechanical properties associated with the failure mode are degraded until the material properties reach a specified minimum value and then are held constant at the minimum value to avoid convergence problem. Therefore, these elements on the damaged area do not contribute to the stiffness or the strength of the sandwich structures.

Material degradation is also dependent on the failure mode. Therefore, independent degradation factors should be specified according to failure modes. In this paper, the face sheets and honeycomb exhibit quite different stress–strain response, as indicated in Fig. 1. Different material degradation model for the honeycomb core and face sheets are presented in Table 1 and Table 2. The material properties can be slowly degraded if a failure occurs.

![Fig. 1. Typical stress–strain curves for (a) fiberglass face sheets; (b) NOMEX honeycomb core](image)

| Table 1. Degradation strategy for honeycomb core |
|-----------------------------------------------|
|                | $\sigma_{i, plat} / \sigma_{ult}$ | Degraded modulus         |
| Compressive    | $\lambda_{A1}$                    | $\lambda_{A4} E_{33}$     |
| Out–of–plane shear (1–3 plane) | $\lambda_{A2}$ | $\lambda_{A5} G_{13}$     |
| Out–of–plane shear (2–3 plane) | $\lambda_{A3}$ | $\lambda_{A6} G_{23}$     |
Table 2. Degradation strategy for face sheets

| Strategy                  | $E_{11}$ | $E_{22}$ | $E_{33}$ | $G_{12}$ | $G_{13}$ | $G_{23}$ | $V_{12}$ | $V_{13}$ | $V_{23}$ |
|---------------------------|----------|----------|----------|----------|----------|----------|----------|----------|----------|
| Tensile fiber failure     | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ | $\lambda_f$ |
| Compressive fiber failure | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ | $\lambda_{cf}$ |
| Tensile matrix failure    | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ | $\lambda_{tm}$ |
| Compressive matrix failure| $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ | $\lambda_{cm}$ |
| Delamination              | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ | $\lambda_d$ |

3. Experiments

Quasi–static tests were carried out on 30 specimens using MTS–810, as shown in Fig. 2. Each specimen was measured 150 mm in length, 100 mm in width, with a core thickness of 20 mm and a thickness of 0.375 mm for top and bottom face sheets. The specimens were impacted at energy level of 6.67J by a spherical steel projectile of 16 mm in diameter. All tests were performed at room temperature. The layup configurations of investigated sandwich composite structures were [(45/0/–45)/CORE]s. The face sheets and NOMEX honeycomb core were made of MXB7701/7781 and HRH10–1/8–3.0, respectively. For the damage pattern visualization a C–scan non-destructive inspection ultrasonic technology was used with 5 MHz scan frequency and 30mm/s scan speed.

4. Finite Element Model

Finite element analysis was performed using the ABAQUS and UMAT code to analyze the quasi–static impact behaviour of the sandwich panels. Only a quarter of the panel was modelled due to the symmetry of the problem (Fig. 3). The face sheets and the honeycomb core were modelled with SC8R 8–node shell elements and three dimensional C3D8R 8–node solid elements, respectively. The projectile was modelled with three dimensional 4–node tetrahedral elements. The impact damage was included in the model by modelling a compliant section in the front face sheet. The damage area was situated at the geometric canter of the front face sheet and determined by comparing with the experimental results. Boundary conditions were imposed on opposite ends of the finite element models to simulate the experimental situation.

Fig. 2. Experimental apparatus with specimen
For the damaged face sheets, the numerical researches reported here use a degradation factor of 0.05 for $\lambda_{tf}$, 0.15 for $\lambda_{cf}$, 0.4 for $\lambda_{cm}$, 10$^{-3}$ for $\lambda_f$ and $\lambda_m$, and 10$^{-5}$ for $\lambda_d$. The stress values of the damaged NOMEX honeycomb core elements are not zero but maintain at a constant stress state (stage BC in Fig. 1 b). Therefore, it is not enough to effectively simulate the failure behaviour of core only by stiffness degradation. In this paper, 2.3MPa is adopted as the constant damaged stress state on for NOMEX honeycomb core. Buckling and shear are two major failure modes for honeycomb core studied here. Therefore, the stiffness coefficients in Table 1 are chosen to discounted with 0.3 for $\lambda_{h1}$, $\lambda_{h4}$, $\lambda_{h5}$, and $\lambda_{h6}$, while zero for $\lambda_{h2}$ and $\lambda_{h3}$. For others coefficients a degradation factor of 0.5 as a default value was used.

5. Model Validation

The numerical results were compared with the experimental tests to validate the progressive failure model. The variables selected to validate the numerical model were the maximum contact force and the evaluated damage area. Fig. 4 shows experimental and numerical contact force history as the projectile advance. In the FEA simulation, the maximum contact force was 577N whereas the experiment data was 562N. Numerical results were very close to the experimental data so that the model can be effectively adopted to predict the maximum contact force.

Damage areas are qualitative indications of damage, as shown in Fig. 5, showing delaminations, matrix cracks and fibre fracture, etc. The minimum circle (diameter $D$) that encloses the damage area was chosen to represent the calculated damage area. The damage areas from the C–scan and the numerical results for different compression distances are compared in Fig. 6. As a whole, the numerical results agreed reasonably with the experiment data (with a maximum error of 6.11%). Therefore, this parameter also enabled validation of the numerical model.
6. Conclusion

An efficient progressive failure analysis method for sandwich composites has been implemented into the commercial finite element software ABAQUS through the use of a user subroutine UMAT. The validation of the presented model was demonstrated by analysis of a sandwich composites subjected to quasi-static loads. The calculated maximum contact force and damage areas agree well with experimental data.

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