PREDICTION OF COMPRESSION-AFTER-IMPACT (CAI) STRENGTH OF CFRP LAMINATED COMPOSITES

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Abstract

In order to predict CAI strength of IM7/8552 composite laminate ($[45/-45/0/90]_{3s}$), the Soutis-Fleck model, that mathematically replaces microbuckling/kinking of the 0°-plies with a through-thickness line crack, was used. The model requires a damage area, reduced properties in the damage site and in-plane stress distribution near the damage site. The damage site was modelled as an equivalent hole and a soft inclusion. For the in-plane stress distribution near an open hole or a soft inclusion, a complex variable method was used. The damage area and reduced properties in the damage site predicted from the damage model developed using a simple non-linear approximation method (Rayleigh-Ritz method) in the current study were applied to the Soutis-Fleck model. From the comparison of the theoretical predictions and experimental measurements for CAI strength, it was found that when fibre breakage occurs at certain plies, the equivalent hole model was more suitable for the prediction. The difference between the theoretical and experimental strength results was less than 10%. However the soft inclusion model over-predicted the residual strength by between 37% and 40%.

1 Introduction

The application of carbon fibre reinforced composites in primary aircraft structures requires the consideration of damage tolerance during the design phase. Impact loading is known to cause extensive internal delaminations, matrix cracking and fibre breakage in composite structures. Since composites, in general, are not damage tolerant, impact damage can significantly degrade the compressive strength of a composite laminate. Therefore the compression-after-impact (CAI) behaviour of laminates is a major concern in the design of primary composite structures. Considerable attention has recently been drawn to problems relating to the prediction of CAI strength with most of the research using fracture and numerical procedures[1-7].

A model to predict compressive strength after low velocity impact strength taking into account all these factors such as delamination, matrix cracking and fibre breakage would be complex and take considerable time to develop. It has been recognised that the problem could be simplified by making some assumptions about the nature of the impact damage. This approach would then make the writing of a modelling tool that predicts compression after impact strength with less effort.

In the present study, to predict CAI strength of IM7/8552 composite laminate ($[45/-45/0/90]_{3s}$), the Soutis-Fleck model[8] was used. Impact damage area was simulated with an open hole and a soft inclusion, as proposed by Soutis[1] and Qi[4]. The model requires a damage area, damage area properties and the in-plane stress distribution at the edge of the damage site. The damage area and damage area properties predicted from the developed model[A9] by authors were applied to the model. A complex variable method[10] was used to determine the stress distribution near the impact-induced damage such as an open hole or a soft inclusion. Failure strength predictions are compared to experimental results.

2 Analytical Model

The procedure for calculating the failure stress is as follows: the exact stress distribution near an open hole[10] and a soft inclusion[11] in the laminate is first determined using the complex variable mapping method. A soft inclusion is modelled as a hole filled with a perfect-fit core made of a dissimilar material.

The failure stress is then determined using the Soutis-Fleck fracture mechanics model, which was specially developed for predicting the compression failure of open-hole laminates. It could be also used to tackle the case of orthotropic laminates containing a soft inclusion. A brief review of the impact damage model for predicting damage area and its degraded properties and the Soutis-Fleck model appears in the following sections.

2.1 Impact Damage Model[9]

The impact damage model is based on the concept that the low velocity impact response is similar to the deformation due to a static concentrated lateral load[12] and that when a plate is subjected to such a lateral loading, the expressions for the deflection of both isotropic and composite plates have the same form[13]. The damage of composite plates, therefore, induced by low velocity impact can be studied by treating the plate response to the impact as static global bending[7]. In the model, by neglecting the inertia forces of the plate, the problem could be reduced to a static equivalent one and by considering degraded stiffness in the plate with increasing loads, idealized damage accumulation was introduced using Rayleigh-Ritz method applied to the principle of virtual displacement ($\overline{w}$). In addition, energy could be correlated to force and deformation by considering the load-deflection relationship and assuming that the maximum strains occur at the maximum deflection when all impact kinetic energy has been absorbed by the structural strain and damage.

In order to predict damage area, the maximum failure strain criterion is adopted. For simplicity, it is assumed that ply damage occurs if any radial strain value (ε_r) along the radius r exceeds its ultimate mean strain between tensile strain value (ε_{11}^T) and compressive strain value (ε_{11}^C). It is also assumed that the ply damage has a circular shape of radius r due to the axisymmetric out-of-plane displacement field. The maximum strain criterion is formulated below:

$$\frac{\varepsilon_r}{\varepsilon_{11}^{T/C}} \geq 1 \qquad (1)$$

where ε_r denotes radial strain at each ply and $\varepsilon_{11}^{T/C}$ is the ultimate mean strain between unidirectional tensile and compressive failure strain.

In the non-linear case, the kth ply radial strain equation is expressed as the combination of membrane stretching radial strain and bending radial strain, i.e.,

$$\varepsilon_r^k = \varepsilon_{Sr} + \varepsilon_{Br} = \frac{1}{2}\left(\frac{dw}{dr}\right)^2 + Z_k\left(\frac{d^2w}{dr^2}\right) \qquad (2)$$

where ε_{Sr} is the membrane stretching radial strain and ε_{Br} is the bending radial stain. Z_k is a distance of the bottom surface of the kth ply measured from the middle plane of the plate.

2.2 Soutis-Fleck Model[8]

The Soutis-Fleck model considers a multi-directional composite laminate which contains a central circular hole and is subjected to uniaxial compression. Such a laminate fails by growth of a microbuckle from the hole edge perpendicular to the loading direction. Fibre/matrix debonding and matrix yielding promote the microbuckling mechanism (See Fig. 1).

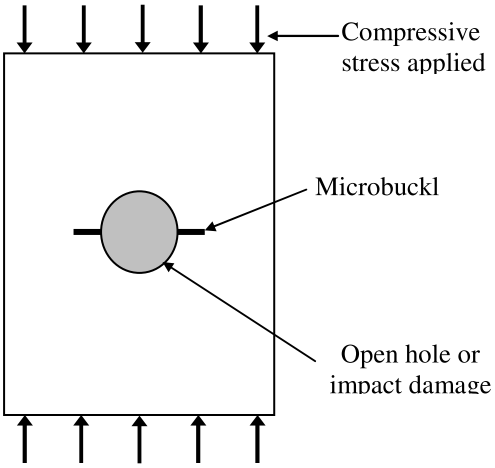


Fig. 1 Microbuckling growth from the edge of the hole or impact damage site

The initiation and propagation of this type of failure has been modelled using the stress distribution at the edge of the hole and linear elastic fracture mechanics concepts, assuming that the respective plate is sufficiently thin for plane-stress conditions to apply. Soutis and Fleck mathematically replaced the buckled zone by a line-crack with no traction on the crack surfaces. This through-thickness crack initiates at the hole boundary and propagates in a transverse direction to the loading. The respective model assumes that microbuckling initially grows first in a stable manner under increasing load and then in an unstable manner whereupon the specimen fails. The model uses the stress distribution at the edge of the hole to predict stable microbuckle growth and fracture mechanics to predict unstable crack growth.

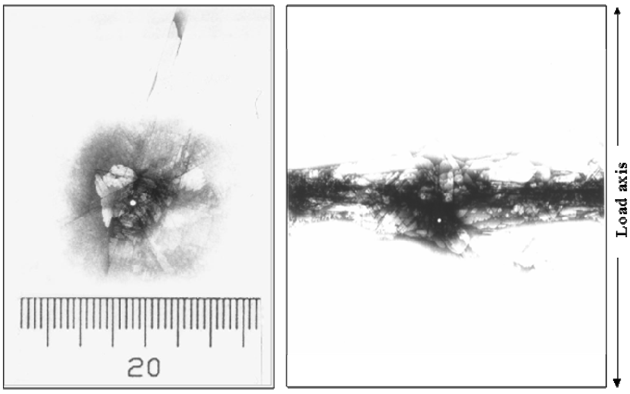
3 CAI Strength Tests

Post-impact tests were performed to determine CAI strengths for a range of impact levels which induce fibre damage. A side-supported fixture developed by the Boeing Company for compression residual strength tests was used in the current study. The fixture does not need any special instruments and is easy to use.

Fig. 2 Boeing fixture for CAI strength test

During an in-plane compression test, specimens are supported in the fixture (see Fig. 2). The vertical sides of the specimen are restrained by antibuckling rails with knife edge supports. The specimen fits into slots in the bottom of the main fixture and in the loading plate which sits on the top of the assembly. The specimen dimensions used in this study are 110mm x 100mm x 3mm in length x width x thickness with the stacking sequence (IM7/8552 – $[45/-45/0/90]_{3s}$).

Examination of the failed specimens removed from the test fixture confirmed that the local delaminations extended completely across the specimen width but extended only a short distance in the axial direction with a kink shear band through the laminate thickness (see Figure 3 (b)). This pattern of damage growth is similar to that observed in specimens with open holes under uniaxial compression[1,3,8]. Figure 3 (a) and (b) show a typical impacted specimen before and after CAI strength test taken by X-ray radiography. Specimen failure after CAI strength test shows fibre kink band shear through its thickness.



(a) X-ray before CAI test (b) X-ray after CAI test

Fig. 3 Impacted CAI specimen (a) before and (b) after CAI strength test showing compression failure with a kink-band shear ($[45/-45/0/90]_{3s}$ – IM7/8552)

4 Results and Discussion

In order to predict the residual strength of an impact-damaged specimens, the area of impact damage was modelled as an equivalent hole and a soft inclusion. The damage width based on the fibre breakage length predicted from the new model[9] is applied to the Soutis-Fleck model[8]. For the soft inclusion properties, the degraded stiffness values estimated from the model are also used. The degraded force-deflection curve predicted with damage accumulation process is converted into force-energy. Table 1 presents observed energies converted from the degraded force-deflection, peak force, predicted fibre damage width, degraded stiffness for a soft inclusion model and impact test results.

Table 1 Details for the CAI strength prediction and measurement results for a composite laminate (IM7/8552-$[45/-45/0/90]_{3s}$)

Impact damage model results			
Impact energy (J)	7.8	10.3	13.5
Peak force (kN)	7	8	9
Fibre damage width* (mm)	12	12	12
Degraded stiffness** (GPa)($E_{x'}/E_{y'}/G_{xy'}/\nu_{xy'}$)	40/43/ 15/ 0.3	39/39/ 15/ 0.3	36/36/ 11/ 0.25
FE results			
Nonlinear static analysis			
Impact energy (J)	13.8	17.0	20.4
Peak force (kN)	9	10	11
Fibre damage width* (mm)	16	24	24
Nonlinear dynamic analysis			
Impact energy (J)	5	10	17
Peak force (kN)	6.2	9.9	11
Fibre damage width* (mm)	10	26	28
Impact test results			
Impact energy (J)	17.8	18.2	18.7
Peak force (kN)	9.7	10.1	10.3
Damage Diameter*** (mm)	13	17	18

(*: Fibre damage width is considered as the diameter of an equivalent hole in the model. **: Degraded stiffness is used for a soft inclusion to predict CAI strength. ***: Damage diameter is measured from X-ray radiograph.)

The predicted residual strengths from an equivalent hole and a soft inclusion model are compared with data measured from CAI test of a 3mm thick composite laminate (IM7/8552 – $[45/-45/0/90]_{3s}$) (see Fig. 4 and Table 2). The predicted strength ratio, which is defined as the ratio of the compressive strength of the damaged laminate to that of the measured undamaged laminate (685 MPa), are plotted against various impact energy as shown in the figure.

Comparison between predictions from the open hole model and experimental data shows good agreement, see Table 2. Soutis *et. al.*[1-3] have also performed this strategy, which considers impact damage site as an equivalent hole to predict the CAI strength of different composite systems and lay-ups. They used damage width measured from X-ray radiographs for the prediction. The theoretical predictions are in a good agreement with the experimental measurements, less than 10% difference. However the soft inclusion model in the present study significantly over-predicts the residual strength by between 37% and 40% (see Fig. 4 and Table 2) suggesting that the stiffness properties of the soft inclusion should be further reduced.

Table 2 Details for the CAI strength prediction and measurement results for a composite laminate (IM7/8552-$[45/-45/0/90]_{3s}$)

CAI strength predictions (MPa)				
Impact damage model results				
Impact energy (J)		7.8	10.3	13.5
Open hole model	CAI strength	306	306	306
Soft inclusion model	CAI strength	571	544	525
FE results				
Nonlinear static analysis				
Impact energy (J)		13.8	17.0	20.4
Open hole model	CAI strength	228	260	260
Nonlinear dynamic analysis				
Impact energy (J)		5	10	17
Open hole model	CAI strength	316	254	248
CAI strength measurements (MPa)				
Impact energy (J)		17.8	18.2	18.7
CAI strength		280	243	242

When fibre breakage occurs due to impact, it is more reasonable for the impact damage region to be modelled with an equivalent open hole. This follows a comparison of the equivalent open hole model and the soft inclusion model. In fact when fibre breakage occurs, severe internal damages such as delamination, matrix cracking and fibre splitting are yielded in the laminate. The properties within the fibre breakage area are closer to 0% of undamaged plate, i.e. an open hole.

In the case of the soft inclusion model, it can be inferred that the predicted degraded moduli are significantly over-estimated when compared to experimental data measured in the damage area with fibre breakage. As explained about the compressive failure behaviour[3], 0° fibre micrbuckling is the critical damage mechanism that causes final failure. This depends very much on a matrix stiffness and initial fibre waviness. The matrix under the damage site could not support the fibres and microbuckling will initiate at a very low applied load. Compressive elastic modulus at the damage site, therefore, is not as high as the predicted one even though plies containing undamaged fibres but serious matrix cracks, fibre splitting and delamination in the laminate exist. The soft inclusion model with reduced stiffness predicted using the present fibre damage model might not be valid for prediction of the CAI strength.

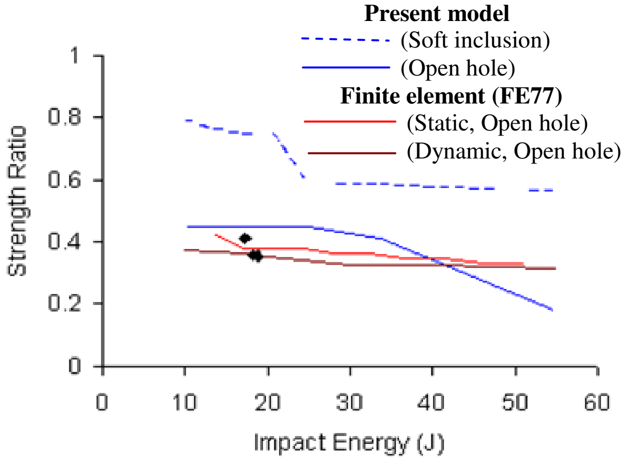


Fig. 4 Residual compressive strength of IM7/8552 ([45/-45/0/90]$_{3s}$) laminates with impact energy

Also, if delaminations occur only in few interfaces through the thickness without any visible damage, namely, no fibre breakage, then the equivalent hole model is less appropriate and a modified or alternative fracture theory may be needed.

5 Concluding Remarks

The present investigation focused on the prediction of CAI strength of IM7/8552 composite laminates ([45/-45/0/90]$_{3s}$) using the Soutis-Fleck model[8], that mathematically replaces microbuckling/kinking of the 0°-plies with a through-thickness line crack. The model requires a damage area, reduced properties in the damage site and in-plane stress distribution near the damage site. The damage site was modelled as an equivalent hole and a soft inclusion. For the in-plane stress distribution near an open hole or a soft inclusion, a complex variable method was used. The damage area and reduced properties in the damage site predicted from the damage model developed using a simple non-linear approximation method (Rayleigh-Ritz method)[9] were applied to the Soutis-Fleck fracture model[8]. The impact damage model was based on the concept that the low velocity impact response is similar to the deformation due to a static concentrated load and that when a plate is subjected to a transverse lateral loading, the expressions for the deflection of both isotropic and composite plates have the same form.

From the comparison of the theoretical predictions and experimental measurements for CAI strength, it was found that when fibre breakage occurs at certain plies, the equivalent hole model was more suitable for the prediction. The difference between the theoretical and experimental strength results was less than 10%. However the soft inclusion model over-predicted the residual strength by between 37% and 40%. This may be caused by the reduced properties in the damage site over-predicted from the damage model. In practice the compressive elastic modulus in the damage site will be much lower than the predicted one due to the fact that the damage such as matrix cracks, fibre splitting and delamination is not nearly able to support fibres to prevent the 0°-plies microbuckling or kinking. The extent of property reduction in the impact damage site could be identified from the experimental results carried out by researchers[4]. The results show that the damage properties are reduced exponentially but of course this depends very much on the actual impact energy.

With the limited experimental data, it could be concluded that when fibre breakage occurs, the impact damage site for the CAI prediction should be modelled with an equivalent hole rather than a soft inclusion. Further work is required to predict more accurately the reduced stiffness properties of the impact region as a function of impact energy and lay-up configuration.

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