SKIN-STRINGER DEBONDING AND DELAMINATION ANALYSIS IN COMPOSITE STIFFENED SHELLS

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ABSTRACT

In the present paper the skin-stringer delamination problem for composite stiffened shells is solved. The skin-stringer delamination is analyzed employing linear fracture mechanics approach. Energy release rates (ERR) are calculated by Modified Virtual Crack Closure Integral (MVCCI) method. The problem is solved not using the 3D solid finite elements, but employing the 2D shell elements. Employment of the 2D shell elements instead of 3D elements significantly reduces computational efforts in the case when whole composite stiffened structure is analyzed for post-buckling. Mode I, mode II and mixed mode I/II fracture properties are obtained for the fracture criterion of the carbon/epoxy composite laminate. The fracture criterion is used for prediction of debonding at the skin-stringer interface.

1 INTRODUCTION

Stiffened composite panels and shells are often used in different aircraft structural design. The deformations associated with post-buckling response can produce severe bending and shear loads at the skin-stringer interface. It can cause stiffener separation from the skin. Therefore, accurate computational methods are required to analyze and predict skin-stiffener debonding failures [1-3]. To analyze the skin-stringer debonding the fracture mechanics approach has been used based on 3D solid or shell finite element analysis results. A combined shell/3D modelling technique was developed in [4]. The 3D solid finite element model is used only in vicinity of the delamination front and the remainder of the structure is modelled using plate or shell elements. Such shell/3D technique can combine the computational efficiency of the shell finite element model with the accuracy of the full three-dimensional solution in the area of delamination.

The total number degrees of freedom can be reduced by the use of 2D plate or shell finite elements instead of 3D solid elements. Such approach was used in several papers [1-3]. It was shown that by using of shell or plate elements sufficient accuracy can be achieved in calculation of energy release rates. In the present paper for analysis of the skin-stringer debonding the 2D shell finite elements are employed.

For analysis of skin-stringer delamination the fracture criterion and fracture parameters for the mixed mode loading conditions should be obtained. There are different experimental methods and fracture criterions for the mixed mode loading conditions of composite laminates. Review on this subject was given in [5]. There also a compound version of the compact tension shear (CTS) specimen was proposed, which covers all in-plane mixed mode loading conditions starting from pure mode I through any mixed mode I/II ratio up to pure mode II loading. The CTS specimen is used also in the present paper to obtain fracture toughness of carbon/epoxy laminate at mixed mode I/II loading conditions. These fracture properties are used to model the skin-stringer separation problem.

2 FRACTURE CRITERION

Unidirectionally reinforced carbon/epoxy laminate is used for interlaminar fracture mixed mode I/II experiments. Material is assumed to be transversally isotropic (1 is a fiber direction, 2 and 3 are directions transverse to the fibres). The elastic properties of the material are as follows: elastic modulus in the fibre direction E_1 = 170 GPa, elastic modulus transverse to the fibres E_2 = 9.4 GPa, in-plane shear modulus G_{12} = G_{13} = 4 GPa, Poisson's ratio ν_{23} = 0.35, transverse shear modulus $G_{23}=E_2/2(1+\nu_{23})$ = 3.5 GPa and in-plane Poisson's ratio ν_{12} = 0.32. These elastic properties were used in the finite element analysis of the CTS specimen.

2.1 CTS specimen

The compound version of the CTS (compact tension shear) specimen (see Figure 1) was proposed in [5]. The CTS specimen was made by gluing the composite strip into the glassmat/epoxy-Aluminium blocks. The load P is applied to the specimen by the loading device under an arbitrary angle α with respect to the specimen. By this the mixed mode loading of the specimen can be achieved from pure mode I ($\alpha=0^0$) through mixed mode I/II loading ($0^0<\alpha<90^0$) up to pure mode II loading ($\alpha=90^0$). The forces acting on the holes of the CTS specimen are given in [5].

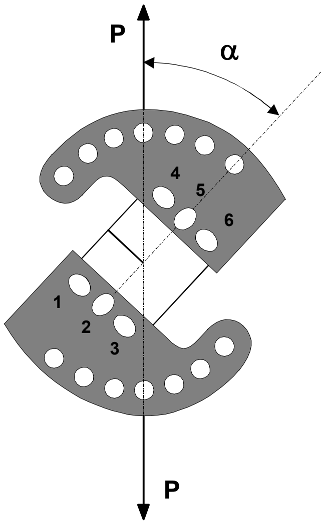

Figure 1: Loading of the CTS specimen.

The advantage of the compound version of the CTS specimen is that with the same test specimen all in-plane loading conditions can be generated, starting from pure mode I through all combinations of plane mixed mode I/II ratios and also including pure mode II. In the present paper experiments have been carried out for pure mode I ($\alpha=0^0$), pure mode II ($\alpha=90^0$) and for the mixed mode loading conditions with $\alpha=45^0$, 60^0, 75^0, 81^0, 84^0 and 87^0. The CTS specimens were tested on MTS testing machine. The specimens were loaded with a constant displacement rate 0.5 mm/min and the critical loads P_c at crack initiation were measured. At all 29 samples were tested under various mixed mode ratios.

The CTS specimen is analyzed by Modified Virtual Crack Closure Integral method employing 2D finite element solution. From the values of the separated energy release rates G_I and G_{II} calculated by FEM under given load, for example at P = 1000 N, easily can be obtained the experimental values of the critical energy release rates. In the experiment for each specimen the critical loads P_C at crack initiation were measured. Since the energy release rate is quadratic function of the applied external load $G = kP^2$ the critical energy release rates G_{IC}, G_{IIC} and also all mixed mode critical energy release rates can be easily calculated.

2.2 Parameters of fracture criterion

The fracture criterion under mixed mode loading conditions, in which exponents should be evaluated experimentally, was used in [6, 7]

$$\left(\frac{G_I}{G_{IC}}\right)^m + \left(\frac{G_{II}}{G_{IIC}}\right)^n = 1 \qquad (1)$$

It was reported in [7] that for graphite/thermoplastic materials the best-fit criterion was found with the exponents m=1 and n=3/2 in eqn (1).

In the present investigation the approximation of the results obtained by the CTS test are based on the criterion (1) using three variants: m=1, n=1, m=1, n=2 and m=2, n=2 for the exponents. The approximations have been performed by the method of least squares in the polar coordinates $G_I = \rho\cos\varphi, G_{II} = \rho\sin\varphi$. The cost function $f(\mathbf{x})$, which should be minimized, is squared differences between the experimental and numerical values calculated according to eqn (1)

$$f(\mathbf{x}) = \sum_{i=1}^{N}[\rho(\mathbf{x}) - \rho_i]^2 \qquad (2)$$

Here $\rho(\mathbf{x})$ is the criterion (1) in the polar coordinates, $\mathbf{x} = (G_{IC}, G_{IIC})$ contains the parameters of optimization, ρ_i are the experimental values of the critical energy release rates in the polar coordinates and N is the total number of the experimental points (in our case N = 29). The results of the minimization of the cost function (2) are presented in Table 1, where $f^* = f(\mathbf{x}^*)$ is value of the function $f(\mathbf{x})$ in the point of optimum $\mathbf{x}^*$. It is seen that a better approximation is obtained for the exponents m = 1 and n = 1 in criterion (1) because a lower value of the cost function indicates a better approximation.

Table 1: Parameters of the criterion (1) obtained by the method of least squares.

Criterion	G_{IC}, kJ/m^2	G_{IIC}, kJ/m^2	f^*
m=1; n=1	0.168	0.770	0.283
m=1; n=2	0.142	0.728	0.318
m=2; n=2	0.128	0.684	0.402

From the Table 1 it is seen that the best fit criterion is with the exponents m = 1; n = 1, i.e. for the linear criterion

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} = 1 \qquad (3)$$

In Figure 2 the experimental data and least squares approximation for the linear criterion is presented.

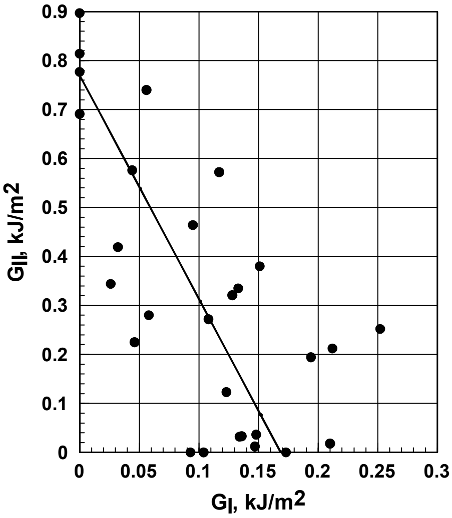

Figure 2: Approximation of mixed mode experimental data for eqn (3).

Despite the fact that there is large scatter of experimental data the criterion (3) can be used for calculation of crack propagation under mixed mode I/II loading conditions. In the case when at the crack front also mode III is presented for calculation of the crack propagation the same linear criterion can be used

$$\frac{G_I}{G_{IC}} + \frac{G_{II}}{G_{IIC}} + \frac{G_{III}}{G_{IIIC}} = 1 \tag{4}$$

For the present carbon/epoxy laminate can be assumed that mode II and mode III critical energy release rates are equal: $G_{IIC} = G_{IIIC}$. Thus, further for calculation of crack propagation the following fracture parameters are employed: $G_{IC} = 0.168$ kJ/m^2, $G_{IIC} = G_{IIIC} = 0.770$ kJ/m^2.

3 MODELING OF SKIN-STRINGER DELAMINATION

In the papers [2, 3] the skin-stringer separation analysis in composite stiffened panels was performed employing shell elements. Here the skin-stringer delamination is analysed for a more simple model – the flat plate with one stringer (see Figure 3). The initial delamination is modelled by Teflon insertion between the flange and skin of the panel. The stringer is constructed from the flange and web (blade). This is the so-called blade type stringer. Such model is chosen for experimental determination of fracture parameters at the skin-stringer interface.

A skin lay-up is symmetric quasi isotropic laminate $[0/90/45/-45]_S$ with eight single layers. The single layer thickness is t = 0.125 mm and the total thickness of skin is h = 1 mm. The symmetric lay-up of the web is as follows: $[(45/-45)_3/0_3]_S$. Thus, the web is formed by 18 layers with total thickness 2.25 mm, and web height is 20 mm. The flange lay-up is $[(45/-45)_3]$ and the width of the specimen is 60 mm.

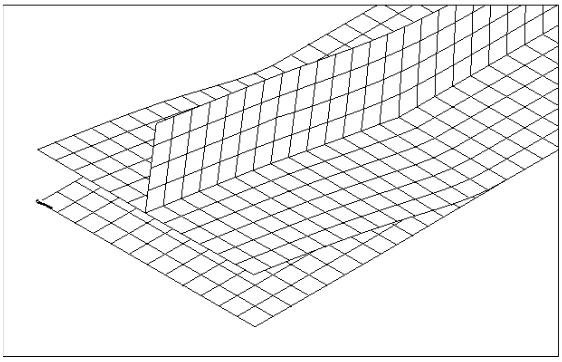

Figure 3: Finite element mesh of the skin-stringer deformed model.

The skin-stringer model is loaded in tension mode like a DCB specimen to generate similar as mode I loading conditions at the crack front. The finite element mesh of the skin-stringer deformed model loaded in tension mode is shown in Figure 3. The finite element modelling is performed employing software code ANSYS. The 8-noded shell elements (SHELL99) are employed. The modelling is such that the size of the elements ahead and behind the debonding front is the same and equal to Δa. Details of the model near the debonding front is shown in Figure 4.

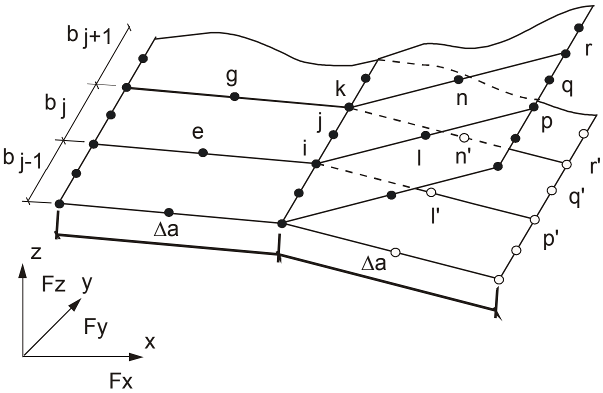

Figure 4: Model with 8-noded shell element near the debonding front.

In the present paper the so-called Technique-B is used [1], where formulae to calculate the separated energy release rates G_I, G_{II} and G_{III} are given.

The total energy release rate G_T can be calculated as sum of separated energy release rates

$$G_T = G_I + G_{II} + G_{III} \qquad (5)$$

This is the so-called local method for calculation of the total energy release rate since the separated energy release rates are calculated from the local stress and displacement field in the vicinity of the crack tip. The total energy release rate can also be calculated employing a discrete version of Irwin's formula

$$G_T = \frac{U(a-\Delta a) - U(a+\Delta a)}{2B\Delta a} \tag{6}$$

Here B is width of the skin-stringer model, $U(a-\Delta a)$ and $U(a+\Delta a)$ is total strain energy of structure at the crack length a - Δa and a + Δa, respectively.

Energy release rates for the skin-stringer model are calculated along the crack front and dominant is mode I. Comparison of the local and global methods is performed. The calculated energy release rate of the skin-stringer model for P = 40 N at crack length a = 70 mm is G_T = 0.163 N/mm^2. This value was obtained by the global method employing formula (6) with Δa = 5 mm. Also the separated energy release rates are calculated along the crack front. Maximum of mode I energy release rate is at the middle of crack. From separated energy release rates according eqn (5) the total energy release rates are calculated. A good agreement of the total energy release rates obtained by the local and global methods is observed.

CONCLUSIONS

The fracture parameters of the carbon/epoxy laminate for mixed mode criterion were obtained employing the compound version of the CTS specimen. It was shown that the best fit criterion is with linear terms. The skin-stringer debonding model was analyzed and total and separated energy release rates were obtained employing the shell finite elements. The strain energy release rate technique presented in this paper can be used in the prediction of skin-stringer separation of the composite stiffened shells in the post-buckling stage.

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