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An Experimental and Analytical Study of Delamination of Unidirectional Specimens with Cut Central Plies

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ABSTRACT: The effect of various factors on delamination has been studied using unidirectional glass fibre and carbon fibre-epoxy specimens with cut central plies. It is concluded that the fracture energy is not a material constant. Among the various factors which affect the fracture energy, the specimen thickness and the through thickness normal stress are the two most significant ones. A simple model is proposed to take account of these two factors. The new model gives excellent correlation with experimental results and is able to account for the effect of through thickness compressive stresses in mode II fracture, which is ignored in conventional fracture mechanics calculations.

1. INTRODUCTION

DELAMINATION IS A major cause of failure in composite structures and so accurate prediction of its occurrence is of considerable importance. Free edges of laminates [1–4] and ply drops [5] are two areas which are particularly prone to delamination. Both of these give rise to potentially singular stress fields. A fracture mechanics approach is therefore often adopted to predict failure, usually based on strain energy release rate analysis [1–3,5,6]. This approach requires a knowledge of the fracture energy, G_c. However, there is considerable evidence

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to indicate that the fracture energy, especially the delamination propagation fracture energy, is not a material constant. It is well known that the magnitude of the fracture energy depends on the mode ratios and this problem is usually overcome by using an interaction equation. However, it has been reported that even when the mode ratio remains the same, the fracture energy is not necessarily a constant. For example, the specimen thickness has been found to have a great effect on the fracture energy [4,7–13].

The problem of whether or not the fracture energy is a material constant has been investigated on both glass fibre-epoxy and carbon fibre-epoxy using unidirectional specimens with the central plies cut across the complete width. This is a very simple specimen which allows the effect of the stress concentration at a terminating ply to be investigated without the additional complication of free edge effects. Both test and analysis for this type of specimen are very easy and therefore it has been strongly recommended by Prinz and co-workers [7,14–15] as a candidate specimen for measuring the mode II fracture energy. A comprehensive experimental and analytical study has been made at Bristol University on unidirectional glass fibre-epoxy and carbon fibre-epoxy laminates with cut central plies. Glass fibre-epoxy has the advantage that the delamination can be detected visually. Carbon fibre-epoxy is used to investigate the effect of a different material on delamination behaviour. Some of the results have already been reported [8–13], but since then many new tests have been carried out. The purpose of this paper is to present the new results and provide a summary for this type of problem. Detailed stress and strain energy release rate analyses are carried out in order to understand the delamination mechanisms. Various factors which affect the fracture energy are investigated quantitatively. It is found that the specimen thickness and the through thickness normal stress are the two main factors. A new model is proposed which assumes that the fracture energy is a function of the specimen thickness and the average through thickness normal stress. In addition to its ability to take account of the through thickness normal compressive stress around the crack tips which is often found in practice but totally ignored in the conventional fracture mechanics approach, the new model is also able to handle the mixed mode problem.

2. EXPERIMENTS

2.1 Test Procedure

Two types of cut ply specimens of two types of composite material were investigated. The two materials are glass fibre-epoxy (E-glass/913) and carbon fibre-epoxy (XAS/913). The unidirectional prepreg was supplied by Ciba Geigy. The panels were laid up with the central plies cut perpendicular to the fibre direction across the full width of the panels. Each of the central plies was cut with a sharp knife, and then laid up either with or without a gap between the two ends. For the cut ply specimens without a gap, the two ends were butted together in their original positions. This specimen is shown schematically in Figure 1. For

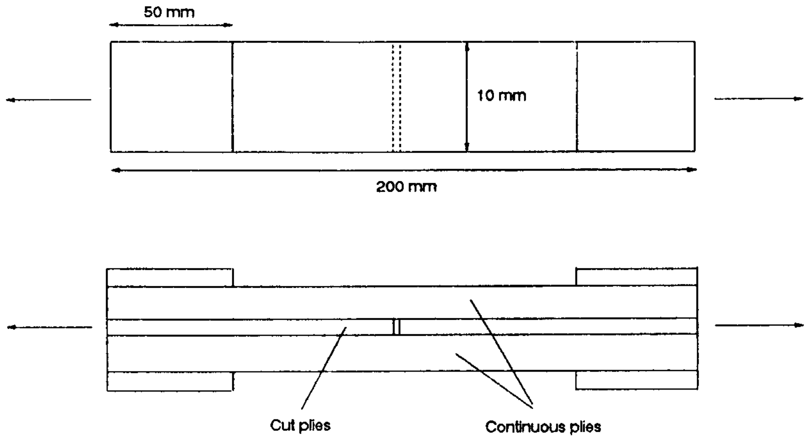

Figure 1. *Schematic representation of cut ply specimen.*

the cut ply specimens with a gap, a thin steel strip was placed between the ends of the cut plies in order to maintain the surface plies straight over the gap. The strip was 0.25 mm thick, equivalent to two plies, and 2 mm wide. It was polished and the edges rounded and then coated with release agent. Panels were cured according to the manufacturer's specification. After curing, the strip was gripped and carefully pulled out, leaving a gap between the ends of the cut plies.

For the tension tests, specimens 200 × 10 mm were cut out with a diamond wheel such that the cut plies were in the centre of the gauge length. Soft aluminium tabs 50 mm long and 1.6 mm thick were bonded to the ends of all the specimens except for the thickest ones, where it was found to be unnecessary. For the compression tests, specimens 90 × 10 mm were cut out. The compression specimens were prepared with glass fibre composite end tabs 40 mm long and about 2 mm thick and tested in the rig developed at Imperial College [16]. Various parameters such as the specimen thickness, the ratio of cut plies to continuous plies, and the loading mode (tension or compression) were studied. For the cut ply specimens without a gap, six types of glass fibre-epoxy (1 cut/4 continuous, 2 cut/8 continuous, 4 cut/16 continuous, 8 cut/32 continuous, 1 cut/8 continuous, 2 cut/8 continuous) and two types of carbon fibre-epoxy (1 cut/4 continuous, 2 cut/8 continuous) were made and tested in tension. For the cut ply specimens with a gap, one type (2 cut/8 continuous) of both glass fibre-epoxy and carbon fibre-epoxy was made and these specimens were tested in both tension and compression. Tests were carried out in an Instron servo-hydraulic testing machine. Displacement control at a rate of 0.5 mm/min was used for the tension tests and 0.25 mm/min for the compression tests. The glass-epoxy specimens were lit from the back, and this enabled the onset and spread of delamination to be seen quite clearly by eye. A chart recorder or computer based data logger was used to plot the load-crosshead deflection response.

2.2 Test Results

For the cut ply specimens without a gap, there is generally a thin matrix layer between the ends of the cut plies. In tension this matrix layer fractured at a relatively low load. This could be seen by a darkening of the line across the specimen. As the load was increased, at a certain point the line started to become fuzzy, indicating the onset of delamination. Delamination occurred above and below the cut plies on both sides of the cut. Initially there was up to a couple of millimetres of very slow propagation during which the load was increasing. The delamination then spread more quickly to the tabs at both ends of the specimen. This corresponded to a significant load drop on the load-deflection graph. The load at which this occurred was recorded as the propagation load. For the cut ply specimens with a gap, the failure process was basically the same except that the matrix was already effectively fractured. Behaviour was similar in compression although delamination tended to be more unstable. The average delamination propagation stresses are shown in Table 1. Stresses have been calculated from the measured width and nominal thickness based on a ply thickness of 0.127 mm and the total number of continuous plies. The experimental results are found to be very consistent for all types of cut ply specimen. The coefficients of variation in tension are around 2% and the coefficients of variation in compression are less than 5%.

2.3 Discussion

Effect of manufacturing variability: The effect of small differences in the way the specimens were made has been investigated by making two different panels which have nominally identical ply configuration (2 cut/8 continuous unidirectional glass fibre-epoxy without a gap). The difference between the average delamination propagation stresses for the specimens cut from the two panels is only 1.5% [11]. This difference is of the same order as the test scatter. Therefore, the variability due to fabrication is negligible. The result in Table 1 for this type of specimen is the average of these two panels.

Effect of specimen width: For the thickest specimens (8 cut/32 continuous unidirectional glass fibre-epoxy without a gap), 10 mm and 20 mm wide specimens were tested. The difference between the average delamination propagation stresses due to width is 1.3% [11]. This difference is similar to the test scatter. Therefore, it is concluded that the width has no effect on the delamination stresses of unidirectional laminates. The result in Table 1 for this type of specimen is the average of these two widths.

Effect of test rate: For the case of 2 cut/8 continuous ply specimens without a gap, two specimens were tested at a displacement rate of 5 mm/min instead of 0.5 mm/min. These specimens showed about 8% increase in the delamination initiation stress (968 MPa compared with 895 MPa). Slow loading is therefore the worst case from a design point of view. Since these two results are for initiation rather than propagation, they are not included in Table 1.

Matrix fracture stresses: The edges of three specimens were examined under a travelling microscope during the tests and the point at which the matrix fractured

Table 1. ***Comparison of predictions with experiments, constant fracture energy (G_c = 1.0 N/mm, glass fibre-epoxy, G_c = 0.82 N/mm, carbon fibre-epoxy).***

No. Cut Plies	No. Cont. Plies	Gap	Tension or Compression	Delamination Stress (MPa)		Difference (%)	G_c^{ex} (N/mm) Equation (2)
				Measured	Predicted		
Glass Fibre-Epoxy							
1	4	No	T	1219	1315	7.9	0.86
2	8	No	T	966	930	−3.7	1.08
4	16	No	T	768	657	−14.4	1.37
8	32	No	T	563	465	−17.4	1.47
1	8	No	T	1298	1247	−3.9	1.08
2	18	No	T	1047	876	−16.3	1.43
2	8	Yes	T	1021	930	−8.9	1.21
2	8	Yes	C	685	930	35.8	0.54
Carbon Fibre-Epoxy							
1	4	No	T	1925	2111	9.7	0.68
2	8	No	T	1493	1493	0.0	0.82
2	8	Yes	T	1607	1493	−7.1	0.95
2	8	Yes	C	932	1493	60.2	0.32

between the cut plies was determined. For two specimens with 4 cut/16 continuous plies, the stresses were 466 and 526 MPa whilst for one specimen with 2 cut/18 continuous plies the stress was 458 MPa. These are relatively low stresses, between 40% and 70% of the delamination stresses. For other cases of cut ply specimens without a gap, the matrix fracture stresses have not been measured but from the similar failure mechanisms observed, it is thought that the matrix also fractured before delamination initiation.

Initiation and propagation stress: The initiation stresses were estimated based on visual observation of delamination. The propagation stresses given in Table 1 are based on the load at the first major delamination which was easily identified from a drop in load. Therefore, the initiation stress is more subjective than the propagation stress. Both initiation and propagation stresses have been reported elsewhere [8, 11]. The initiation stress is generally between 87% and 97% of the propagation stress. In this paper, the propagation stress is regarded as the delamination stress.

Effect of specimen thickness: The results for the four sets of scaled specimens show a significant decrease in strength with increasing thickness. The delamination stress decreases by 54% for an increase in thickness of a factor of 8.

Effect of the ratio of cut plies to continuous plies: Comparing the case of 4 cut/16 continuous plies with the case of 2 cut/18 continuous plies in which the thicknesses of the specimens are the same, the propagation stress for the specimen with 4 cut plies is 27% lower. Therefore this ratio has a significant effect on the delamination stress. However, by comparing the case of 1 cut/4 continuous plies with the case of 1 cut/8 continuous plies, and the case of 2 cut/8 continuous plies with the case of 2 cut/18 continuous plies, it is found that the strength is more closely related to the number of cut plies than to the number of continuous plies.

Tension and compression loading: Comparing the tension and compression results for the cut ply specimens with a gap, it is found that the delamination stress in compression is much lower than that in tension. For the glass fibre-epoxy the reduction is 33%, whilst for the carbon fibre specimens it is 42%.

Cut ply specimen with and without a gap: Comparing the two cases of cut ply specimens with and without a gap loaded in tension, it is found that the specimens with a gap are stronger than those with no gap. The increase in strength due to the gap is 6% for glass fibre-epoxy and 8% for carbon fibre-epoxy. Although the actual increase is not very high, compared with the general test scatter, the increase is statistically significant.

3. ANALYSIS

3.1 Analysis Description

The purpose of the analysis is to understand the delamination failure mechanisms observed in this type of specimen and explain the various effects on delamination. Both stress and strain energy release rate analyses are carried out in ABAQUS [17]. The geometry of the cut ply specimen is shown in Figure 1. A

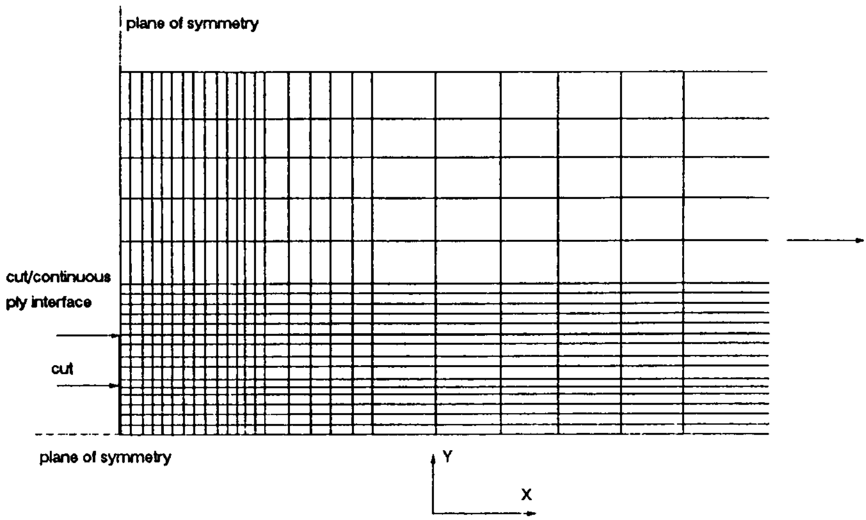

Figure 2. Finite element mesh in region of cut (not to scale).

two dimensional analysis of a slice through the thickness is carried out. Due to symmetry, only a quarter of the specimen needs to be modelled. Eight-noded rectangular plane stress elements with reduced integration (CPS8R element type in ABAQUS) are used. A typical finite element model is shown in Figure 2. For the cut ply case with no gap, the matrix between the ends of the cut plies is assumed to be already fractured, i.e., the effect of the cut is modelled as a sharp crack. For the case with a gap, elements are removed to leave a sharp cornered rectangular hole in the mesh. The composite is assumed to be linear elastic with material properties shown in Table 2. A uniformly distributed load is applied at the far field and the value is chosen so that the average net section stress in the continuous plies is 1000 MPa.

The effect of mesh size on stress distribution has been investigated. Due to the singularity at the tip of the cut plies, a very fine mesh is found to be necessary in this region in order to obtain a smooth stress distribution. In this paper, a mesh

Table 2. Material properties.

	Glass Fibre-Epoxy (E-glass/913)	Carbon Fibre-Epoxy (XAS/913)
E_{11} (GPa)	43.9	138.0
E_{22} (GPa)	15.4	9.65
ν_{12}	0.3	0.26
G_{12} (GPa)	4.34	5.0

size as small as 0.005 mm long by 0.01 mm thick at the tip of the cut plies is used for the stress analysis and 0.1 × 0.02 mm at the tip of the crack for the strain energy release rate analysis.

3.2 Analysis Results

Stress distributions: Two cases have been studied in tension. The first case models the cut ply specimen without a gap. The second case models the cut ply specimen with a gap of 2 mm. The stress distributions along the interface between the cut plies and continuous plies are shown in Figures 3 to 5 for the case of 2 cut/8 continuous plies. The shapes of the stress distributions for the two types of specimen are very similar. The through thickness normal stress is initially tensile but the length over which this tensile stress occurs is so small, of the same order as a fibre diameter, that the possible effect of this tensile stress is ignored. It can be seen that the through thickness normal compressive stress is higher in the cut ply specimen with a gap than in that without a gap.

Strain energy release rate: Delamination is often predicted using the strain energy release rate criterion. This is because for a body with cracks, the stresses are singular at the crack tips. Stress based failure criteria are difficult to apply in this situation.

The strain energy release rate is calculated for the cut ply specimens with and without a gap. In tension, it has been shown that the interlaminar normal stress is compressive near the crack tip and therefore this is a pure mode II problem. This is modelled by using duplicate nodes along the interface. Before delamination all the duplicate nodes are connected by multipoint constraint equations. Then the constraints in the longitudinal direction are released for each pair of nodes while the constraints in the through thickness direction are still kept in

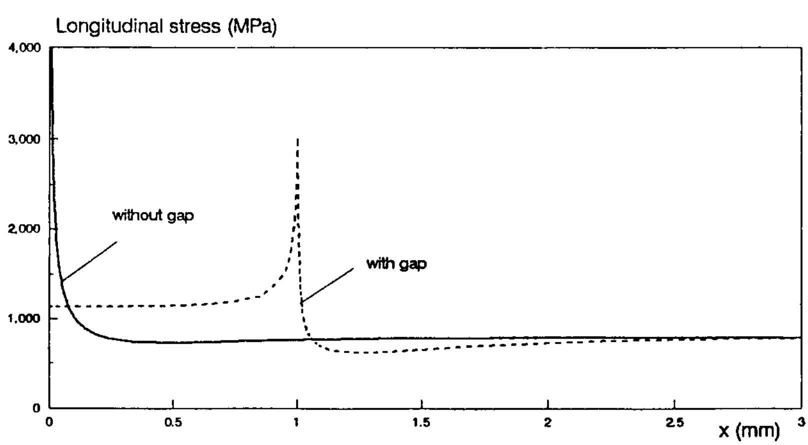

Figure 3. *Longitudinal stress distribution along the interface between cut and continuous plies, glass/epoxy 2 cut/8 continuous ply specimens, 1000 MPa net section stress.*

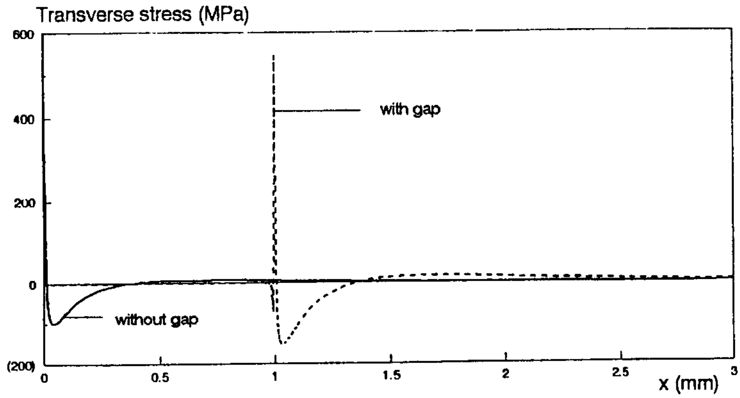

Figure 4. *Through thickness stress distribution along the interface between cut and continuous plies, glass/epoxy 2 cut/8 continuous ply specimens, 1000 MPa net section stress.*

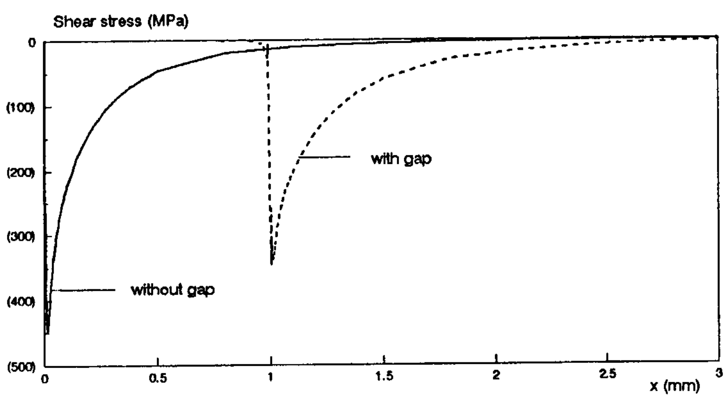

Figure 5. *Shear stress distribution along the interface between cut and continuous plies, glass/epoxy 2 cut/8 continuous ply specimens, 1000 MPa net section stress.*

order to prevent overlapping. The strain energy release rate is calculated by the energy method [6], i.e.,

$$G = \Delta U/\Delta A \tag{1}$$

where ΔU is the strain energy difference and ΔA is the area of the crack increment. In compression, the interlaminar normal stresses are tensile and therefore it is a mixed mode problem. The release of the constraints in both directions will represent the propagation of delamination. Both the virtual crack closure technique [1,2] and the energy method are used to calculate the strain energy release rate. The energy method can only calculate the total strain energy release rate while the virtual crack closure technique can also compute the components.

Figure 6 shows the results of the strain energy release rate analysis. For the cut ply specimens without a gap, only the strain energy release rate in tension is calculated because these specimens were only tested in tension. The total strain energy release rate initially increases to a peak value and then decreases to a constant value.

For the cut ply specimens with a gap, the strain energy release rates in both tension and compression are given. It can be seen that in compression, initially the mode I component makes up about 20% of the total and increases slowly up to about 28% as delamination propagates to a length of about 3 mm. Therefore, the mode II component also dominates in this type of specimen. In contrast to the cut ply specimens without a gap, the initial total strain energy release rate is lower than the constant value. As delamination propagates, it approaches the same constant value.

Comparisons were made between using the initial strain energy release rate and the constant strain energy release rate to predict delamination [8]. It was

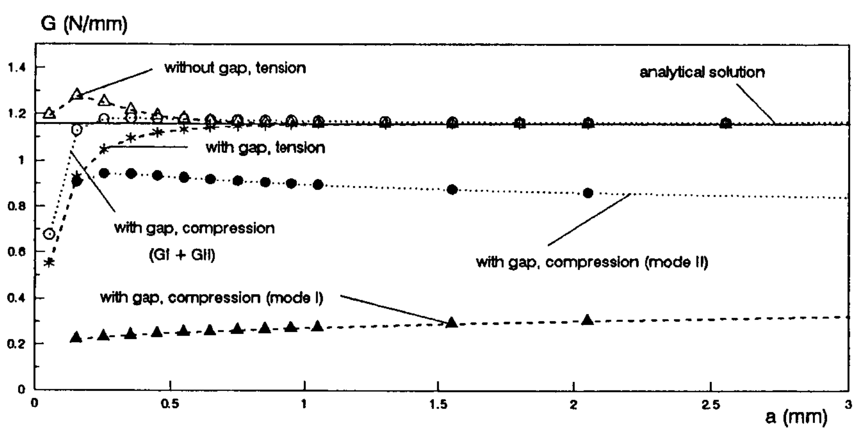

Figure 6. *Strain energy release rate for delamination along the interface between cut and continuous plies, glass/epoxy 2 cut/8 continuous ply specimens, 1000 MPa net section stress.*

found that using the constant value gives better results than the initial value. Using the constant value after some propagation has also been found to be good for edge delamination [2,3]. Therefore, from now on, attention is paid to calculating the constant value. A closed form solution exists for laminates with cut central plies [11]. For unidirectional laminates, the formula is as follows:

$$G = \frac{\sigma_{net}^2 \, (h-t)\, t}{4\, E_{11} h} \tag{2}$$

where E_{11} is the longitudinal modulus, h is the total specimen thickness, t is the thickness of the cut plies, σ_{net} is the average net section stress.

The comparison between finite element analysis and Equation (2) is also shown in Figure 6. It can be seen that the methods agree very well except for the very initial part, as expected. In the following, Equation (2) will be used to predict the delamination stress.

4. CORRELATION STUDY

4.1 Constant Fracture Energy Assumption

In order to predict the delamination stress, the fracture energy must be known. For glass fibre-epoxy, this value has been measured experimentally using the 2 cut/8 continuous ply specimens by the area method. The measured value is 1.0 N/mm [8]. This value is very close to the value of 1.08 N/mm given by Equation (2) by substituting the delamination propagation stress. This also confirms the validity of using Equation (2) to calculate the strain energy release rate. For carbon fibre-epoxy, the 2 cut/8 continuous case was chosen to calculate the fracture energy and the result using Equation (2) is $G_c = 0.82$ N/mm.

Assuming the fracture energy is a material constant, which is a basic assumption of fracture mechanics, then by using Equation (2), we can predict the delamination stress for every case tested. The predicted stresses are compared with the experimental delamination stresses in Table 1. It can be seen that the predictions in most cases are reasonable, within 20%. However, in compression, it is found that the predictions are very unconservative. For the tension results, by examining the differences closely, a trend can be found that as the specimen becomes thicker, the prediction tends to be more and more conservative while for the thinnest specimen, the prediction is unconservative. This indicates that the fracture energy is not a material constant. In order to examine this, the delamination stress is substituted into Equation (2) to calculate the fracture energy G_c^{ex}. From the four cases in which the ratio of cut plies to continuous plies are the same, it is found that the total specimen thickness has a great effect on the fracture energy. From the stress analysis, it is known that the most important difference between the three cases of 2 cut/8 continuous ply specimens is in the through thickness normal stress. So it can be postulated that the through thickness normal stress also has a great effect on the fracture energy.

4.2 Effect of Through Thickness Stress on Fracture Energy

To investigate this, it is assumed that the fracture energy is a function of through thickness normal stress. There are many ways to represent the through thickness normal stress. One of the common ways is to choose an average stress over some distance. It has been shown that for specimens in tension, the through thickness stress is compressive near the end of the discontinuous plies, and then becomes tensile (Figure 4). In order to avoid the subjective choice of the distance, the average through thickness normal stress over the whole area of compressive stress is taken. Similarly for specimens in compression, the through thickness normal stress is averaged over the whole length subject to tensile normal stress. The fracture energy can also be assumed to be a function of the specimen thickness. If we further assume that the effects of the through thickness normal stress and the specimen thickness are independent, then the function can be expressed in the following format:

$$G_c = F(h,\sigma_2) = f(h)g(\sigma_2) \tag{3}$$

The effects of specimen thickness and the through thickness normal stress can be investigated separately. The effect of the through thickness normal stress is shown in Figure 7 in which the specimen thickness is fixed at 1.27 mm (10 plies). For both carbon fibre-epoxy and glass fibre-epoxy, the fracture energy is a linear function of the average through thickness normal stress. Whilst the reduction of fracture energy with through thickness tensile stress could be expected due to the effect of the mode I component, the increase under through thickness compression cannot be explained by the conventional mixed mode approach.

Based on this result, equation (3) can be further assumed to be

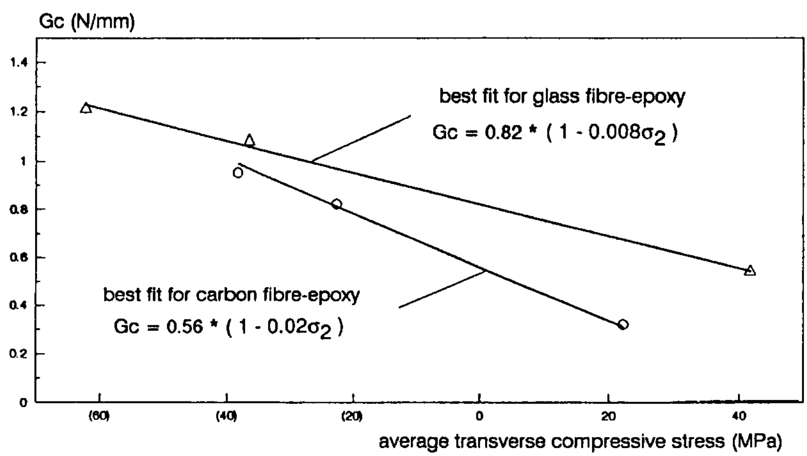

Figure 7. Effect of through thickness stress on fracture energy, 2 cut/8 continuous ply specimens.

$$G_c = f(h)(1 - \beta\sigma_2) \quad (4)$$

Using the least squares method, the values can be obtained $\beta = 0.008$ for glass fibre-epoxy and $\beta = 0.02$ for carbon fibre-epoxy.

4.3 Effect of Specimen Thickness on Fracture Energy

The effect of specimen thickness has been investigated for glass fibre-epoxy through the four sets of scaled cut ply specimens in which the ratio of cut plies to continuous plies is kept the same. For these specimens, the average through thickness normal stresses will be the same under unit applied stress. The result from the finite element analysis for the case of 2 cut/8 continuous plies without a gap is $\sigma_2^{\circ} = -37.72 \times 10^{-3}$. However, since the failure stresses are different for the different cases, the actual average through thickness normal stresses at failure will be different for the different cases. This can be calculated by the following relation:

$$\sigma_2 = \sigma_2^0 \sigma_{ex} \quad (5)$$

where σ_{ex} represents the experimentally determined failure stress or expected specimen delamination stress. Therefore, the effect of through thickness normal stress can be corrected for by the following formula for glass fibre-epoxy:

$$G_c' = \frac{G_c}{(1 + 0.008 \times 37.72 \times 10^{-3}\ \sigma_{ex})} = f(h) \quad (6)$$

The above equation represents the pure thickness effect on the fracture energy. The result is shown in Figure 8. From this figure, it can be seen clearly that the

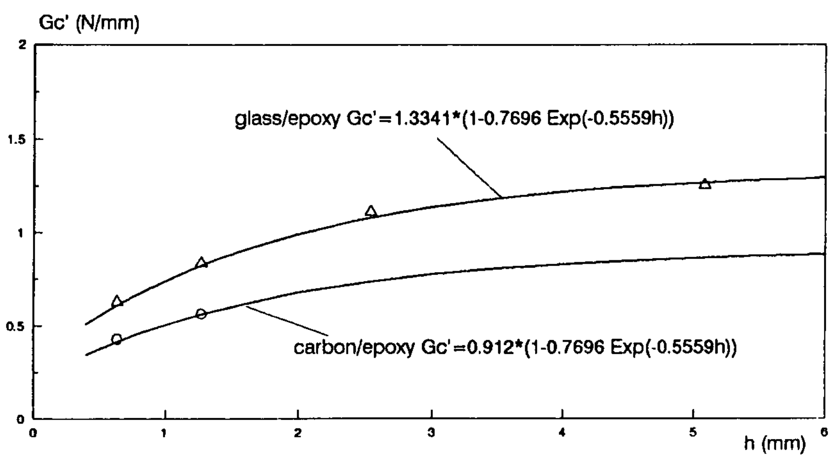

Figure 8. Effect of specimen thickness on fracture energy.

fracture energy is not a linear function of the specimen thickness. When the specimen thickness is smaller, the effect is bigger. As the specimen becomes thicker and thicker, the fracture energy looks as if it may approach an asymptotic value. Based on this observation, $f(h)$ can be assumed to have the following format:

$$f(h) = (1 - Be^{-\alpha h}) \qquad (7)$$

The least squares method is used to determine these equation coefficients based on the four sets of scaled specimen results. The determined values are $A = 1.3341, B = 0.796, \alpha = 0.5559$. Therefore, the fracture energy for glass fibre-epoxy can be expressed as

$$G_c = 1.3341 * (1 - 0.7696e^{-0.5559h})(1 - 0.008\sigma_2) \qquad (8)$$

For carbon fibre-epoxy, only two thicknesses (1 cut/4 continuous and 2 cut/8 continuous) were tested which is not adequate to determine the three equation coefficients. Based on the similar ratio of the delamination stress between 1 cut/4 continuous and 2 cut/8 continuous which is 1.26 for glass fibre-epoxy and 1.29 for carbon fibre-epoxy, it is assumed that both B and α are the same for glass fibre-epoxy and carbon fibre-epoxy. Thus, only one parameter A is left to be determined. The least squares method is used based on the experimental results of one case of 1 cut/4 continuous plies and three cases of 2 cut/8 continuous plies, and the result is $A = 0.912$. Therefore, the fracture energy for carbon fibre-epoxy can be expressed as:

$$G_c = 0.912 * (1 - 0.7696e^{-0.5559h})(1 - 0.02\sigma_2) \qquad (9)$$

4.4 Correlation with Experiments and Discussion

Using Equations (8) and (9) to calculate the fracture energy and then using Equation (2), we can predict the delamination stress. The predictions are compared with the experiments in Table 3 for carbon fibre-epoxy and Table 4 for glass fibre-epoxy. It can be seen that extremely good correlation is found between predictions and experiments.

The through thickness normal stress σ_2 is required for the predictions. This has been calculated by finite element analysis based on the experimental values of delamination stress. The values used are shown in Tables 3 and 4. Strictly speaking, for a prediction without reference to the experimental results σ_2 should be taken as a function of the delamination stress as in Equation (5) before substitution into Equation (8) or (9). This would yield a quadratic equation for the delamination stress. However, since the predicted and measured delamination stresses are very close, using this procedure would have negligible effect on the results.

The excellent correlation seen for the cases of 1 cut/8 continuous and 2 cut/18 continuous plies for glass fibre-epoxy further confirms the usefulness of the correction using Equation (8) because these two cases were not used in determining

Table 3. Comparison of predictions with experiments for carbon fibre-epoxy, variable fracture energy.

No. cut plies		1	2	2	2
No. continuous plies		4	8	8	8
Gap		No	No	Yes	Yes
Tension or Compression		T	T	T	C
Thickness h (mm)		0.635	1.27	1.27	1.27
Normal stress σ_2 (MPa)		−29.1	−22.6	−38.3	22.2
Fracture	Measured	0.682	0.821	0.951	0.320
Energy	Predicted	0.663	0.821	0.998	0.315
(N/mm)	Diff. (%)	−2.8	0.0	4.9	−1.6
Delamination	Measured	1925	1493	1607	932
Stress	Predicted	1898	1493	1646	925
(MPa)	Diff. (%)	−1.4	0.0	2.4	−0.7

the equation coefficients. The model proposed here is also found to be able to predict the delamination stress of tapered laminates with dropped plies [19].

A possible explanation for why the through thickness normal stress affects the fracture energy is as follows. It is well known that the yield stress of epoxy is affected by hydrostatic stresses [18]. The presence of compression increases the yield stress, and so might be expected to increase the energy absorbed due to plasticity, which is believed to be the major contribution to the fracture energy [12]. This would cause the fracture energy to increase with the magnitude of through thickness compressive stresses, as suggested by the experimental results. Similarly the epoxy yield stress decreases under hydrostatic tension, leading to lower fracture energy under combined shear and through thickness tension. Friction may also have some effect on the apparent fracture energy when the through thickness normal stress is compressive.

The effect of specimen thickness on fracture energy could be due to the size of the plastic zone. If the size of the zone increases with specimen thickness, then the fracture energy will also increase.

5. SUMMARY AND CONCLUSIONS

A comprehensive experimental and analytical study has been made to investigate the delamination failure of unidirectional laminates with cut central plies. From this investigation, the following conclusions can be drawn:

1. The specimens delaminated at the interface between the cut plies and the continuous plies. For specimens without a gap, a small resin region exists between the ends of the cut plies. This resin fractured much earlier than delamination initiation.
2. In applying the strain energy release rate criterion, predictions based on the

Table 4. Comparison of predictions with experiments for glass fibre-epoxy, variable fracture energy.

No. cut plies		1	2	2	2	4	8	1	2
No. continuous plies		4	8	8	8	16	32	8	18
Gap		No	No	Yes	Yes	No	No	No	No
Tension or Compression		T	T	T	C	T	T	T	T
Thickness *h* (mm)		0.635	1.27	1.27	1.27	2.54	5.08	1.14	2.54
Normal stress σ_2 (MPa)		−46.0	−36.4	−62.2	41.7	−29.0	−21.2	−56.7	−43.0
Fracture	Measured	0.860	1.080	1.210	0.543	1.370	1.470	1.080	1.430
Energy	Predicted	0.838	1.068	1.239	0.551	1.335	1.489	1.149	1.457
(N/mm)	Diff. (%)	−2.6	−1.1	2.4	1.5	−2.5	1.3	6.4	1.9
Delamination	Measured	1219	966	1021	685	768	563	1298	1047
Stress	Predicted	1203	961	1033	690	758	567	1339	1057
(MPa)	Diff. (%)	−1.3	−0.5	1.2	0.7	−1.3	0.7	3.2	1.0

assumption of constant fracture energy are reasonable for tension, but do not agree very well with the experimental results for compression loading.

3. Possible factors which might affect the fracture energy have been investigated and it is found that the specimen thickness and the through thickness normal stress are the two most important factors.
4. If the fracture energy is assmued to be a function of the specimen thickness and the average through thickness normal stress, extremely good correlation with experimental results is obtained for both tension and compression loading.
5. A major advantage of this correction on fracture energy is that it is able to take account of the effect of both tensile and compressive through thickness normal stresses. The effect of through thickness compressive stresses is normally ignored in fracture mechanics calculations, and so the proposed method offers a significant improvement. However, the method is also advantageous for cases where through thickness stresses are tensile since it avoids the need to calculate mode ratios in the more usual mixed mode approach.

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