IMPACT OF PLY DROPS

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SUMMARY: This paper covers impact testing of ply drop features, using non-crimp fabric composite material. It has been found that, whilst the energy to initiate damage may vary, the threshold force for damage initiation is constant. An impact damage growth parameter has been proposed to assess the extent of impact damage growth. It has been shown that the impact performance of ply drop specimens is more critical than the equivalent flat laminate. The emphasis of this study is to establish a basic understanding of the underlying failure mechanisms associated with the impact response of ply drop features and the implications for structural design. Experimental results were formulated into simple rules for design purposes. Some limited, quasi-static, finite element analysis was undertaken, and the results were compared to experimental observations.

KEYWORDS: impact, ply drops, threshold force, threshold energy, test rig, finite element analysis.

INTRODUCTION

Ply drops often occur in composite structures to tailor the laminate thickness to loading requirements. Such ply drops constitute stress concentration features, especially so with the non-crimp fabric material used in this investigation. Impact damage resistance is a key element in composite structural design. Impact tests are often undertaken on flat laminates to assess the impact damage resistance of a given material lay-up. In this study, the impact performance of ply drop features is investigated and the results are compared to the equivalent flat laminate [1]. The objective is to show how sensitive a ply drop feature is to impact, and understand the underlying failure mechanisms. A series of experimental tests were undertaken, and the results examined in detail. Experimental results were compared with a simple two-dimensional finite element analysis prediction.

EXPERIMENTAL

The material of the ply drop specimen is T300/914C carbon fibre/epoxy resin non-crimp fabric with nominal fibre volume fraction of 0.55. Semi-pregged fabric is manufactured using the resin film infusion process. Nominal cured +45° or –45° ply thickness is 0.23mm, whilst nominal cured 0° ply thickness is 0.4mm. The material is arranged in (-45/+45/0) and (0/+45/-45) stitched ply stacks, with a (0/+45/-45) ply stack drop-off as shown in Fig. 1. A (0/+45/-45) ply stack is referred to as '*A*' blanket, whilst a (-45/+45/0) ply stack is designated as '*B*' blanket. Each blanket is stitched together using polyester yarn. The advantage with this procedure is an efficient laying-up technique, thus reducing the manufacturing cost. In this case, the ply drop specimen is 8 to 7 blanket drop.

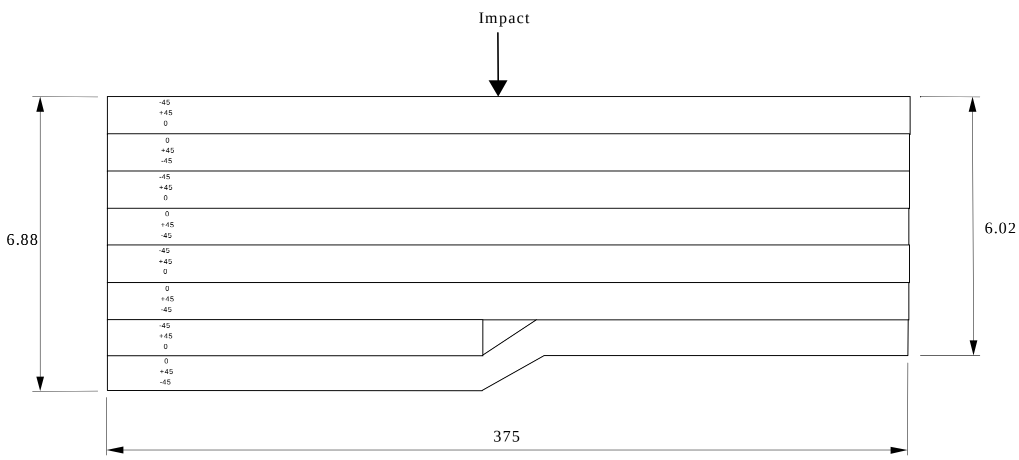

Fig. 1: Cross-section of the ply drop specimen, showing the lay-up and location of impact. Dimensions are given in mm (not to scale).

Lay-up of the thick section of the laminate is $[(-45/+45/0/0/+45/-45)_2]_s$ and that of the thin section of the laminate is $[-45/+45/0/(-45/+45/0/0/+45/-45/-45/+45/0)_s]$. This gives a ply drop step of 0.86mm. Nominal thickness of the thick section of the ply drop is 6.88mm, whilst that of the thin section is 6.02mm. The specimen size is 375 x 250mm with the ply drop at the centre of the specimen as shown in Fig. 1. Metallic shims are used to support the specimen, around the 'thin' section edges, in the impact rig. The impact test rig provided light point-clamping force on the specimen at four points, as shown in Fig. 2. A minimum clamping force was used, that was sufficient to retain the specimen in the rig during impact. Impact testing was undertaken using a 'Rosand' instrumented impact test machine, with a 16mm diameter steel impact head.

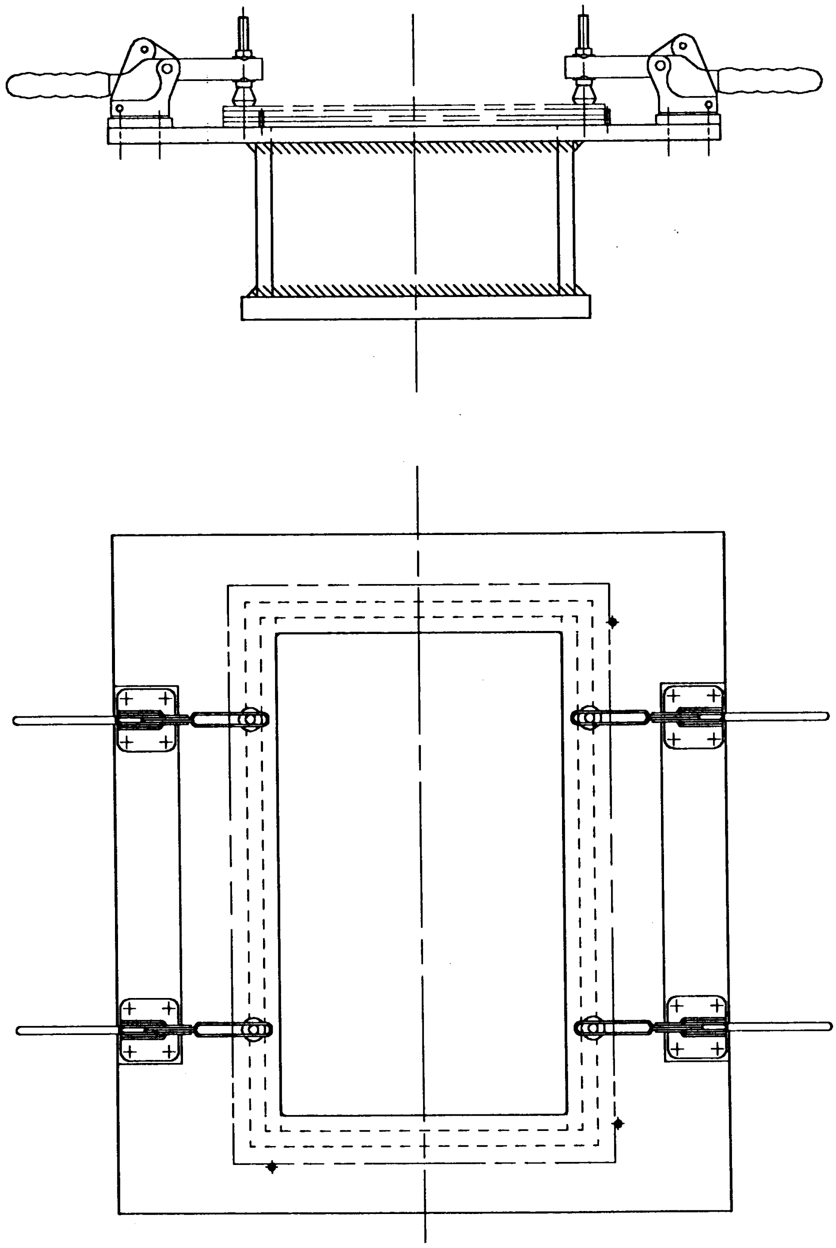

Fig. 2: The impact test rig, with the specimen shown in dashed lines. Three dowel pins locate the specimen in the rig, with light load point clamping at four positions.

A series of impact energies were applied, ranging from 14.3J to 52.8J. Test results are presented in Table 1. Force versus time, and force versus displacement plots of a typical impact event at 52.8J (specimen No. 0727-03) are given in Figs. 3(a) and (b) respectively. Force versus impact energy, absorbed energy versus impact energy, and damage area from C-scan versus impact energy plots, for all ply drop tests, are shown in Figs. 4 to 6 respectively.

Table 1: Ply drop impact test results.

Specimen No.	*Impact energy, E_4 (J)*	*Absorbed energy, E_5 (J)*	*Damage area from C-scan, A_0 (cm^2)*	*Energy transferred to the specimen at threshold force, E_1 (J)*	*Threshold force, P_1 (kN)*
0727-01	42.2	25.3	8.1	17.9	6.8
0727-02	25.3	14.3	4.9	15.6	6.4
0727-03	52.8	37.5	9.9	14.4	6.2
0727-04	31.8	18.0	5.3	18.7	6.9
0727-A1	41.5	26.2	9.1	19.0	6.4
0727-A2	14.3	6.3	Initiation	13.8	5.8
0727-A3	20.2	11.8	4.2	17.7	6.7
0727-A4	20.1	11.2	3.5	14.8	6.1
0728-A1	40.7	22.9	9.1	13.7	6.2
0728-A2	52.7	34.8	12.6	14.6	6.3
0728-A3	52.7	36.0	14.4	13.8	5.9
0578-04	24.1	13.6	5.6	14.6	6.0
Average	-	-	-	15.7	6.3

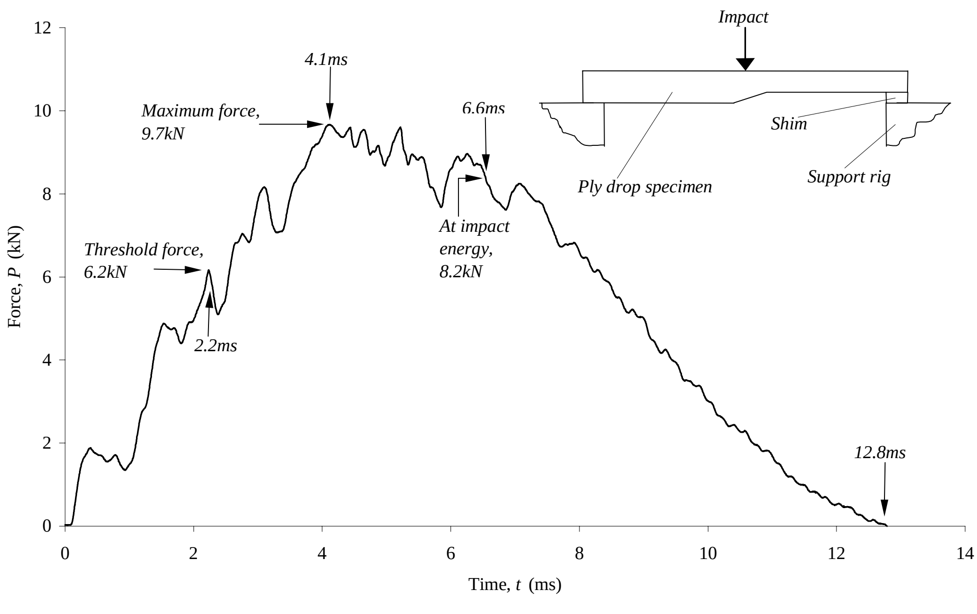

Fig. 3(a): Force versus time plot for ply drop specimen No. 0727-03. The impact energy is 52.8J.

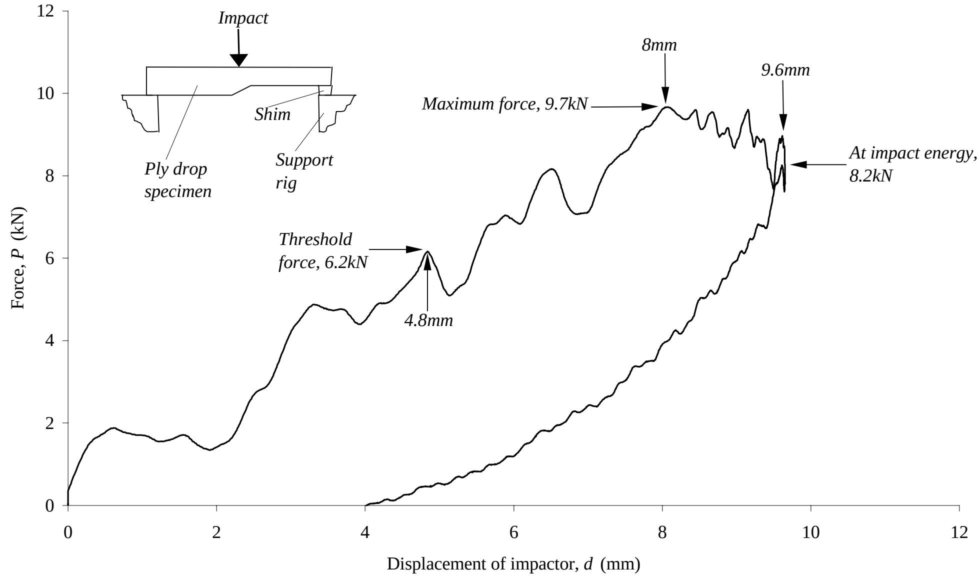

Fig. 3(b): Force versus displacement of impactor plot for ply drop specimen No. 0727-03. The impact energy is 52.8J.

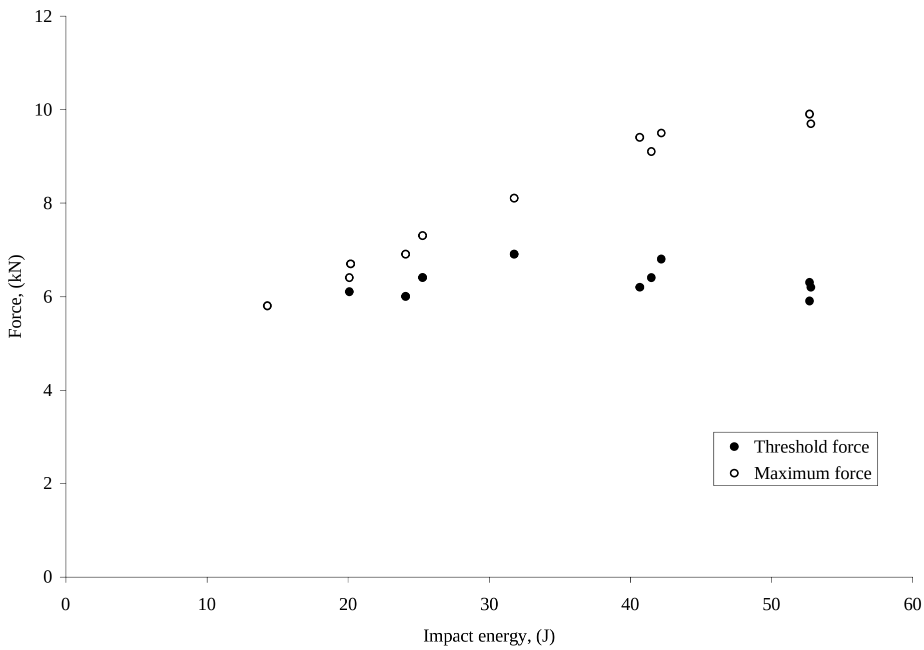

Fig. 4. Force versus impact energy plot for all ply drop test specimens.

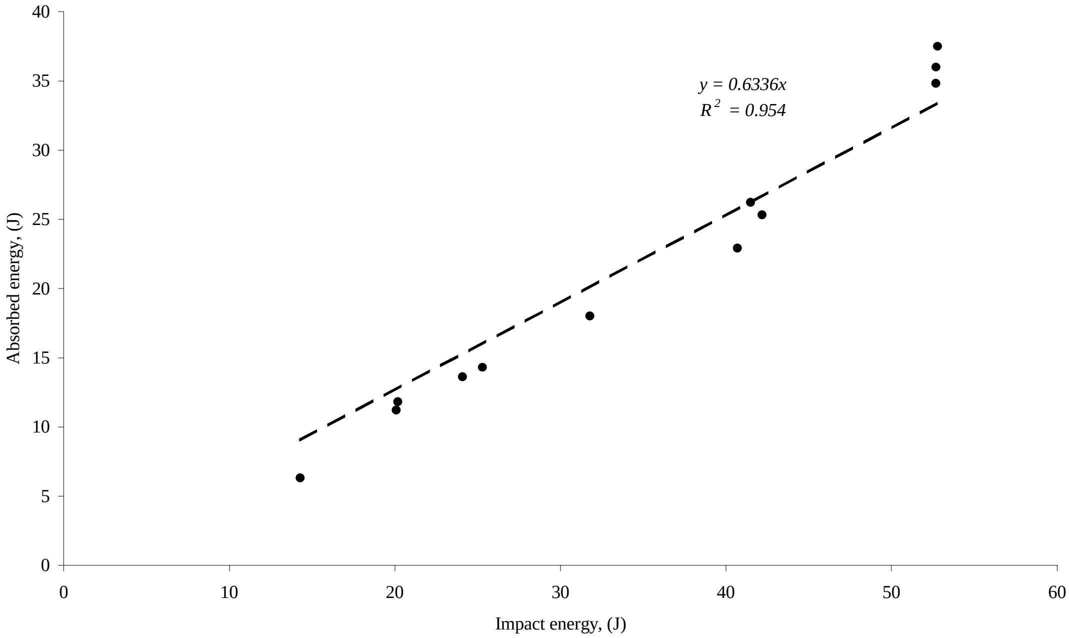

Fig. 5: Absorbed energy versus impact energy plot for all ply drop test specimens

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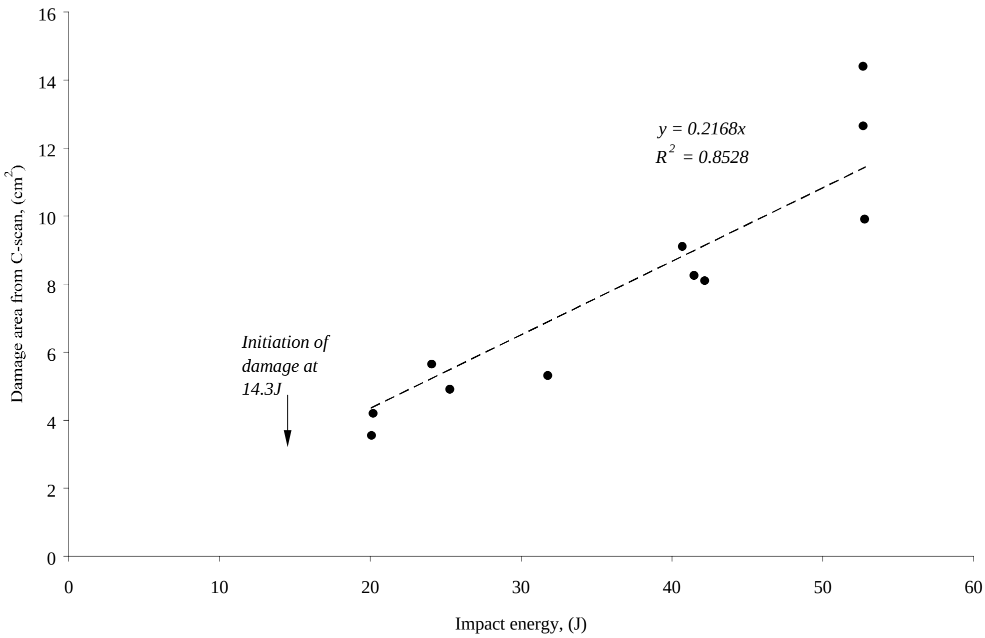

Fig. 6: Damage area from C-scan versus impact energy plot for all ply drop test specimens.

FINITE ELEMENT ANALYSIS

A simple two-dimensional finite element analysis was undertaken to model quasi-static loading of a ply drop feature as depicted in Fig. 7. Quasi-static loading is justified in this case because of the low strain rate involved with low velocity impact. Li [2] undertook quasi-static loading and obtained similar threshold force values to

Ball [1] using low velocity impact. The Abaqus [3] finite element system was used. The model used 906 4-noded bilinear plane stress quadrilateral, reduced integration with hourglass control elements (CPS4R). This resulted in 1839 degrees of freedom. The impactor's head was semi-circular of 16mm diameter, and was modelled as a rigid surface of infinite stiffness. Benefits of rigid surface modelling are: (a) more accurate representation of a curved surface than with faceted deformable mesh, (b) improved contact between the impactor's head and the ply drop, and hence earlier convergence of the solution, and (c) ease of creation of the model.

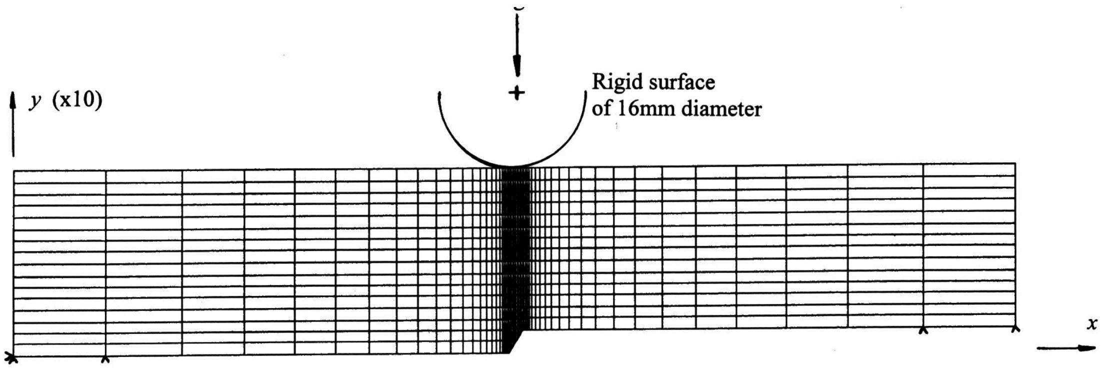

Fig. 7: Two-dimensional finite element model of the impact specimen and the impactor's head. The boundary conditions are shown as small arows.

The 'master and slave' contact formulation was used, with a geometrically nonlinear analysis. No friction was assumed between the impactor's head and the ply drop specimen. The 'small sliding' option between the master (impactor's head) and the slave (ply drop specimen) was employed. Displacement loading was applied by forcing a downward displacement of 8mm at the reference node of the rigid surface. This represents the deflection at peak force of 9.7kN for specimen No. 0727-03, as presented in Figs. 3(a) and (b). The equivalent impact energy at peak force is 38.3J.

The specimen is supported in the impact rig over a 33.25mm wide strip around the periphery. This is modelled by fixing the vertical displacement at the nearest nodes as depicted in Fig. 7. One node is fixed against horizontal displacement to avoid horizontal translation of the ply drop model. Material properties used in the analysis are given in Table 2. Note that the ±45° plies are combined together, as there is no difference between the +45° and –45° plies with this type of two-dimensional modelling. A contour plot of the axial strain along the 0° fibre direction (x-axis) at the ply drop region is given in Fig. 8.

Table 2: Mechanical properties of the composite material and resin matrix used for the two-dimensional finite element analysis.
(a) T300/914C composite material.

Mechanical property	*0° ply*	*±45° plies*
Longitudinal elastic modulus, E_{11} (MPa)	135200	17263
Through-thickness elastic modulus, E_{33} (MPa)	9000	9000
Poisson's ratio, ν_{13}	0.3	0.097
Shear modulus, G_{13} (MPa)	4875	3875

1 = along the 0° fibre direction; 3 = through-thickness direction *(b) 914 resin matrix.*

Mechanical property	*Value*
Elastic modulus, *E* (MPa)	3900
Poisson's ratio, ν	0.41

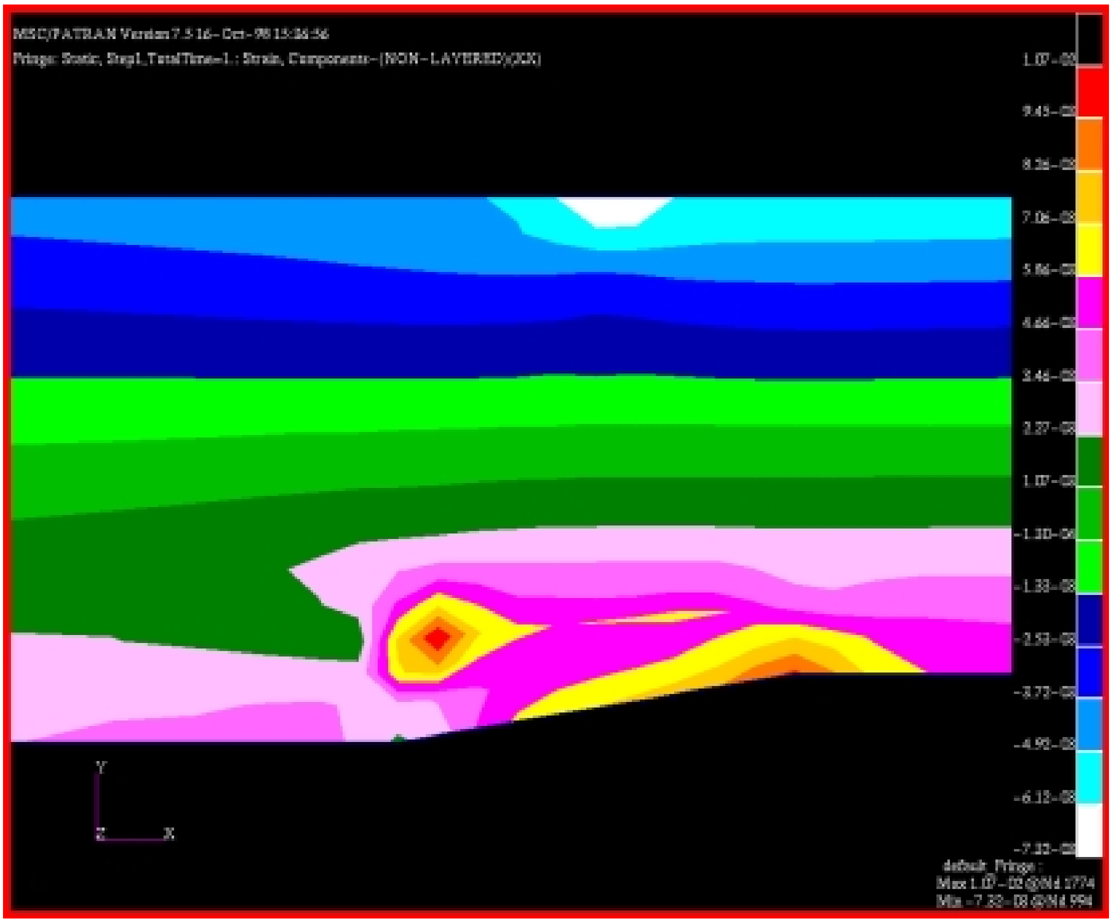

Fig. 8: Contours of axial strain along the x-axis, ε_{xx}, due to 8mm downward displacement (Ref. Specimen No. 0727-03). The peak tensile strain at the resin rich pocket region (red contour) is 9450$\mu\varepsilon$, whilst the peak compressive strain (white contour) is -7320$\mu\varepsilon$.

DISCUSSION

Figs. 3(a) and (b) show the force versus time, and force versus displacement plots for specimen No. 0727-03 at an impact energy of 52.8J. Three critical positions are indicated on the curves, viz. the threshold force for damage initiation at 6.2kN, the maximum force imposed on the specimen at 9.7kN, and the force at the impact energy of 8.2kN. The drops in force prior to the 6.2kN threshold force are thought to be micro-damage un-detectable by C-scan. Such micro-damage is likely to be associated with the resin rich pocket in the ply drop. This has been demonstrated numerically, as will be seen in the finite element analysis results. The drop in force at the threshold position is associated with the minimum detectable damage by C-scan. This is approximately 4mm^2 area, as seen from specimen No. 0727-A2 at 14.3J impact energy and 5.8kN threshold force. There is a slight reduction of the gradient of the force versus displacement curve after the initial occurrence of the threshold damage. Notice that further damage occurs between the threshold force and the maximum force, as indicated by the drops in the force versus time and displacement curves.

Fig. 7 shows a two-dimensional finite element model of a ply drop specimen with a rigid surface impactor for quasi-static load introduction by displacement loading. The displacement loading in this case is 8mm, corresponding to the maximum force value of 9.7kN for specimen No. 0727-3. Fig. 8 shows contours of axial strain along the *x*-axis, ε_{xx}. It can be seen that the peak tensile strain is 9450με at the resin rich pocket, whilst the peak compressive strain is -7320με at the impactor head. This tensile strain exceeds the tensile strain at failure of 7700με indicating resin fracture.

Fig. 4 presents the threshold force, P_1 (kN), and the maximum force, P_3 (kN), versus the impact energy, E_4 (J). It can be seen that whilst the maximum force increases with increasing impact energy, the threshold force for impact damage initiation is almost constant. The average threshold force for damage initiation is 6.3kN, corresponding to an average threshold energy of 15.7J, and 4.9mm average displacement of the impactor (d_1). The threshold force for ply drops is 26% lower than that for eight non-crimp blanket laminates value of 8.59kN as given by Ball [1]. Li [2] obtained similar threshold force values for quasi-static loading. It should be noted that the asymmetric side of the ply drop is seven blankets thick, and that the threshold force value would be lower than that for the eight blankets symmetric section. However, it is expected that the threshold force for a seven-blanket laminate would be higher than that for an eight to seven blanket drop-off. This is attributed to the stress concentration effect at the ply drop, triggering premature fracture. The predicted threshold force for a seven blanket laminate is 6.71kN. This has been obtained using the formula given in Ref. [1], viz.

$$P_1 = 0.36\, t^{1.63} \tag{1}$$

where P_1 = threshold force for damage initiation (kN), and t = thickness of laminate (mm). This gives a 6.5% difference to a ply drop. At the position of the ply drop, an average thickness is used to reflect a transition region. Thus, for a thickness of 6.45mm, the predicted threshold force is 7.51kN, giving a 19% difference to a ply drop.

Fig. 5 is a plot of the absorbed energy, E_5 (J), versus the impact energy, E_4 (J), for all ply drop test specimens. The gradient of the straight line fit through the origin is 0.6336, i.e. the absorbed energy is about 63% the impact energy. The regression analysis parameter R^2 is indicated on the plot. The damage area from the C-scan, or the projected damage area, A_0 (cm^2), is plotted against the impact energy, E_4 (J), as shown in Fig. 6. A straight line passing through the origin is fitted through the data points to give a gradient of 0.2168cm^2/J. The inverse of this gradient is 4.6J/cm^2 (or 0.046J/mm^2). Thus, an Energy Damage Growth Parameter (*EDGP*) is defined, i.e. *EDGP* = 0.046J/mm^2. This value is specimen specific. In order to generalise this to any structure, the absorbed energy is used by using the factor of 0.63. Thus, the *EDGP* based on the absorbed energy is 0.03J/mm^2. This is an important parameter indicating the area of damage growth as the energy is increased past the threshold value. The average threshold energy is 15.7J from Table 1. The initiation energy value shown in Fig. 6 (14.3J) corresponds to the minimum impact energy applied during this series of tests, where C-scan indicated minimal damage. In this case, it is suggested that 15.7J be used as a threshold energy value due to its average nature. The equivalent absorbed energies may be deduced by using the factor above.

CONCLUSIONS

Impact damage usually initiates at the resin rich pocket of the ply drop, and is always biased towards the thin section of the ply drop feature. The energy absorbed by the laminate in an impact event is about 63% of the impact energy. This is due to energy losses due to friction, flexure and other mechanisms. An Energy Damage Growth Parameter (*EDGP*) has been proposed, which, in this case, is 0.03J/mm^2. This is the absorbed energy required to grow an impact damage by a unit-projected area, past the threshold energy value for the material. The threshold energy corresponds to the threshold force at which damage initiates. The *EDGP* is a useful parameter for design to assess the extent of an impact damage growth.

The test results show that the threshold force for impact damage initiation is constant at 6.3kN (corresponding to 15.7J threshold energy) for any impact energy. In other words, whilst the threshold energy for damage initiation may vary, the threshold force for damage initiation is constant. This defines a force parameter that may be used to assess an impact damage threat. The threshold force for a ply drop specimen is 19% lower than that for a flat laminate due to the stress concentration feature inherent with ply drops. This makes the ply drop impact test more critical than the equivalent flat laminate impact test for the assessment of damage resistance.

REFERENCES

1. Ball, J., 'Impact Damage in Thick CFRP Laminate Material', BAe Tech. Report MC/RPT/DC/0000/1564, Issue 1, 1996.

2. Li, D.S., 'Transverse (Out-of-Plane) Stiffness of Composite Laminates', BAe Tech. Report MC/RPT/DC/0000/3631, Issue A, 1998.

3. Abaqus (version 5.6), Hibbitt, Karlsson and Sorensen Inc., Providence, R.I., U.S.A.