ID-1284

EFFECT OF THICKNESS ON IMPACT OF PLY DROPS

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SUMMARY: The effect of laminate thickness on impact performance of ply drops is investigated in this paper. An empirical framework for impact behaviour of ply drops is proposed. 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 study. Impact damage resistance is a key element in composite structural design. Impact tests are often undertaken on flat laminates to assess impact damage resistance of a given material lay-up. In this study, the impact performance of ply drop features is undertaken, using two laminate thicknesses.

KEYWORDS: impact, ply drops, threshold force, thickness effects

INTRODUCTION

The presence of a ply drop feature in a laminate causes a stress concentration effect. Impact on a ply drop feature can cause premature damage as compared to flat laminates. Previous investigations on impact of ply drops have shown that, for a given laminate thickness and lay-up, the energy to initiate damage may vary depending on the local stiffness of the structure, i.e. boundary conditions, while the threshold force for damage initiation is constant [1 and 2]. Other complementary studies have addressed impact of flat laminates, including the effect of thickness [3-8]. In this paper, the influence of ply drop laminate thickness on impact performance is considered. An empirical impact behaviour model is discussed, highlighting the process of initiation of micro-damage, onset of delamination/macro-damage, and growth of damage.

EXPERIMENTAL

The ply drop specimens were manufactured from T300/914C semi-pregged non-crimp fabric material, using the resin infusion method. The non-crimped fabric material consisted of 0.86mm thick (-45/+45/0) or (0/+45/-45) stitched, using polyester yarn, ply stacks. This technique of manufacturing offers reduced manufacturing cost. The specimen size was 375 x 250mm with the ply drop at the centre of the specimen. Metallic shims were used to support the specimen, around the thin section's edges, in the impact rig. Impact testing was undertaken using a 'Rosand' instrumented impact test machine, with a 16mm diameter steel impact head.

For 'thin' ply drops, the lay-up of the thick section of 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. The nominal thickness of the thick section of the ply

drop is 6.88mm, whilst that of the thin section is 6.02mm. Thin ply drop impact test results are presented in Table 1(a). Kairouz and Ball [1 and 2] reported on the impact performance of thin (6.88 to 6.02mm) ply drops. The work covered an evaluation of experimental results, and two-dimensional quasi-static finite element analysis. Further work has been carried, since then, on assessing damage caused by impact in order to understand the underlying failure mechanisms. Sectioning of impacted specimens and examination of the cross-section using an optical microscope were undertaken to understand the failure process. Typical force versus displacement curve is presented in Figure 1(a).

For 'thick' ply drops, the lay-up of the thick section of laminate is $[(-45/+45/0/0/+45/-45)_4]_s$ and that of the thin section of the laminate is $[-45/+45/0/(-45/+45/0/0/+45/-45)_7]$. Thick ply-drops were manufactured, for the same lay-up, with various symmetric and unsymmetric stacking sequences, causing in certain cases, an out-of-plane deformation of a maximum value of 1.2mm, with some specimens. Impact test results are given in Table 1(b), with a typical force versus displacement curve presented in Figure 1(b). The force versus displacement curve shows negative displacement at zero force, which may be related to the curvature of the specimen. It should be noted that, with thick ply drops, there was difficulty in reading some of the impact parameters from the impact traces.

EMPIRICAL IMPACT BEHAVIOUR MODEL

A simple empirical impact behaviour model for ply drops is proposed, which has the main features of a flat laminate model as described by Ball *et al*. [7], but includes additional terms to reflect the performance of ply drops. This model applies to thin and thick ply drops, as presented in Figure 2. A framework for impact damage process of ply-drops is given in Figure 3. Figure 4 shows force versus impact energy plot for thin and thick ply drops.

Initiation of micro-damage

Initiation force

A unique characteristic of ply-drops is the *initial* force drop (P_{s1}); in this case being at 10.9kN for specimen 0952/1, as shown in Figure 1(b). The average value of P_{s1} for the 12 thick specimens tested was 8.7kN, corresponding to an average energy of 4.3J (E_{s1}) and 0.7mm average displacement (d_{s1}). This initial damage is thought to be related to the resin rich pocket fracture, and micro-damage at the ply drop feature due to the stress concentration effect. Residual *curing stresses* at the resin rich pocket contribute to premature failure in this region. The damage caused here may not be detectable by C-scan, but may be a collection of micro-damage sites. A stress-based failure criterion is often considered in this case, e.g. maximum shear stress, as depicted in Figure 3. The force then drops (P_{s2} = 8.7kN for specimen 0952/1) as the specimen compliance has

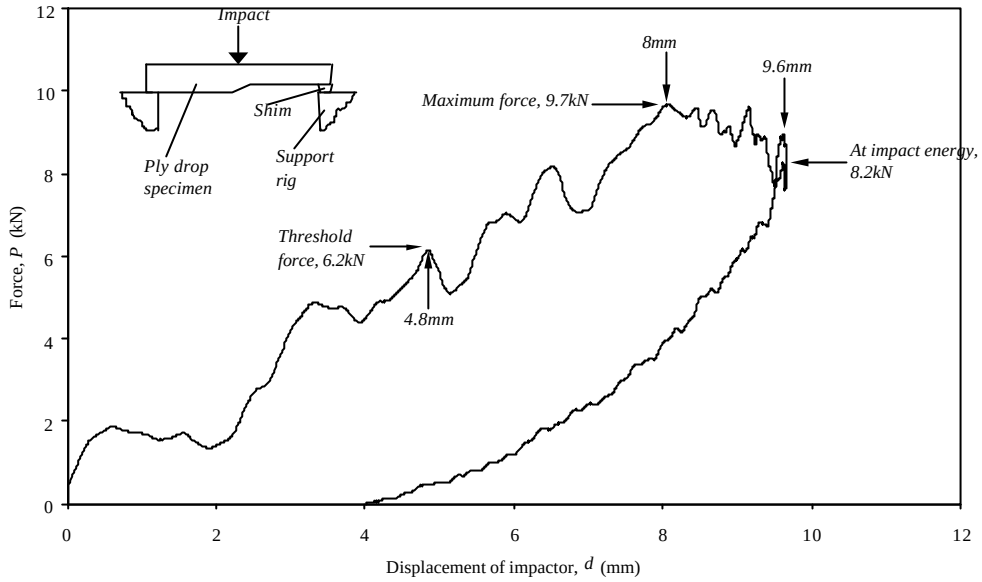
Table 1. Impact test results at impact energy (or maximum displacement), shown as position *i* on the generalised force versus displacement curve presented in Figure 2.

(*a*) Thin ply drops: 6.88 to 6.02mm.

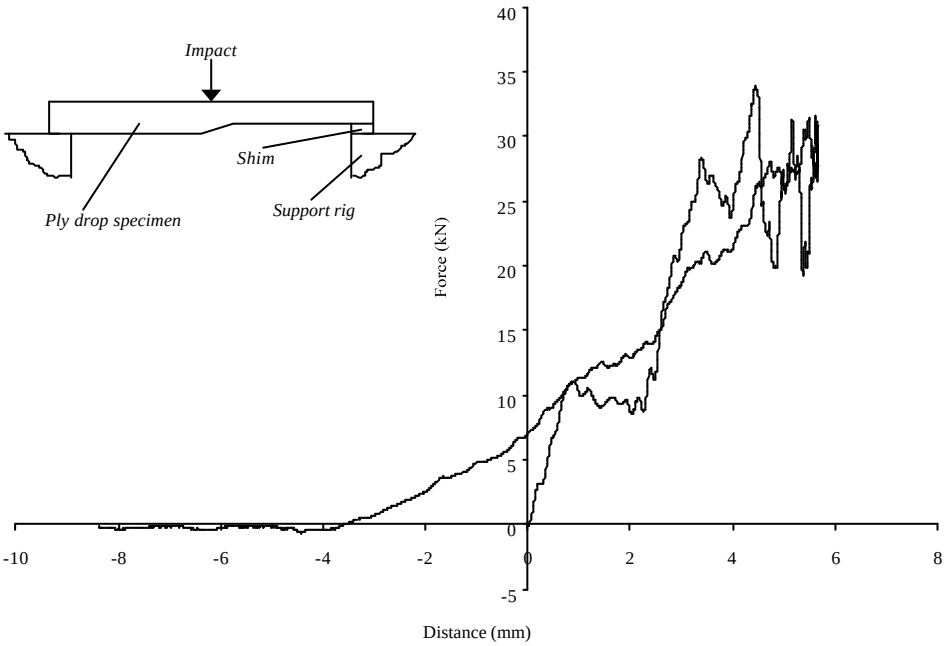
Specimen No.	*Impact energy,* E_0 (= E_3) (J)	*Force at the impact energy,* P_i (kN)	*Maximum displacement,* d_3 (mm	*Time at impact energy,* t_i (ms)
0727-01	42.2	8.6	8.4	6.5
0727-02	25.3	7.2	6.5	6.7
0727-03	52.8	8.2	9.6	6.6
0727-04	31.8	7.7	7.1	6.4
0727-A1	41.5	8.6	8.5	6.7
0727-A2	14.3	5.6	4.9	6.3
0727-A3	20.2	6.0	5.8	6.6
0727-A4	20.1	6.3	5.9	6.7
0728-A1	40.7	9.0	8.3	6.4
0728-A2	52.7	8.8	9.6	6.6
0728-A3	52.7	8.3	9.5	6.7
0578-04	24.1	6.3	6.6	6.9

(*b*) Thick ply drops: 13.76 to 12.9mm.

Specimen No.	*Impact energy,* E_0 (= E_3) (J)	*Force at the impact energy,* P_i (kN)	*Maximum displacement,* d_3 (mm)	*Time at impact energy,* t_i (ms)
0952/1	98	30.7	5.6	5.6
0952/3	73	25.1	4.3	4.3
0952/4	23.8	19.8	2.9	-
0952/5	39	25.5	3.1	3.1
0952/6	34.9	24.6	3.0	3.1
0952/7	61.4	19.1	4.0	-
0952/8	126	32.9	6.2	6.2
0953/1	40	24.7	3.2	3.2
0953/2	71	23.9	4.6	4.7
0953/3	126	30.2	6.9	6.8
0953/5	126	31.9	6.8	-
0953/7	72	24.4	4.3	4.3



(*a*) Thin ply drop, 6.88 to 6.02mm, specimen No. 0723-03 at 52.8J impact energy.



(*b*) Thick ply drop, 13.76 to 12.9mm, specimen No. 0952/1 at 98J impact energy.

Fig. 1. Force versus displacement of impactor.

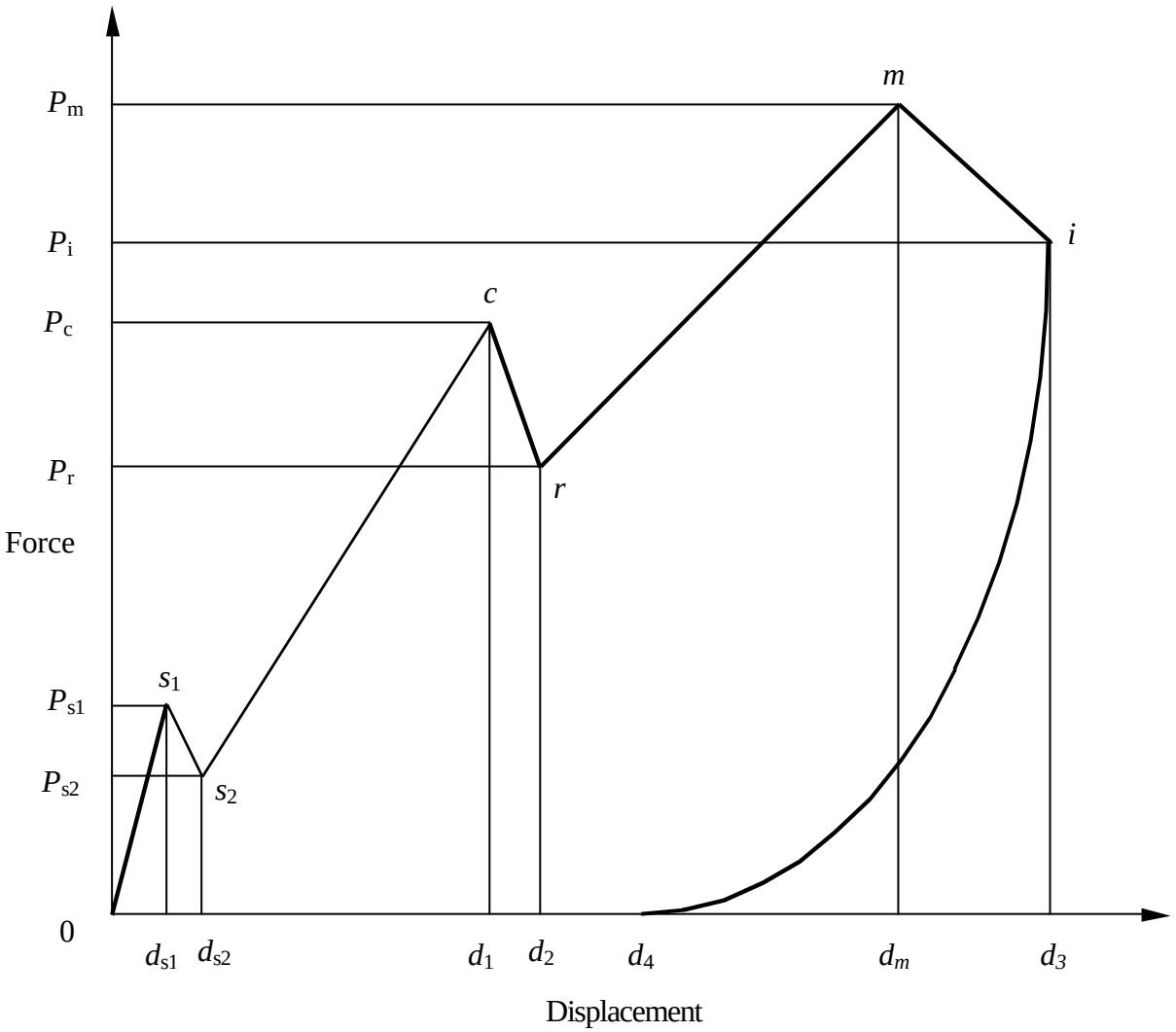


Fig. 2. Generalised force versus displacement curve for thin and thick ply drops.

P_{s1}	Initiation force at position s_1 (start of damage process)
P_{s2}	Initiation force at position s_2 (start of damage process)
P_c	Threshold (or critical) force
P_r	Residual force
P_m	Maximum force
P_i	Force at impact energy (or force at maximum displacement)
d_{s1}	Displacement at initiation force at position s_1
d_{s2}	Displacement at initiation force at position s_2
d_1	Displacement at threshold force
d_2	Displacement at residual force
d_3	Displacement at impact energy (or maximum displacement)
d_4	Displacement at zero force
d_m	Displacement at maximum force
$E_0 = 0,s_1,s_2,c,r,m,i,d_3,0$	Impact energy of $0.5mv^2$
$E_1 = 0,s_1,s_2,c,d_1,0$	Threshold energy (or energy at threshold force)
$E_2 = 0,s_1,s_2,c,r,d_2,0$	Residual energy, or energy at residual force
$E_3 = 0,s_1,s_2,c,r,m,i,d_3,0$	Impact energy, or energy at maximum displacement (kinetic energy of $0.5mv^2$)
$E_4 = 0,s_1,s_2,c,r,m,i,d_4,0$	Absorbed energy
$E_5 = 0,s_1,s_2,c,r,0$	Initiation energy
$E_6 = 0,r,m,i,d_4,0 = E_4 - E_2$	(Absorbed energy – residual energy)
$E_{s1} = 0,s_1,d_{s1},0$	Energy at the start of the damage process, position s1
$E_{s2} = 0,s_1,s_2,d_{s2},0$	Energy at the start of the damage process, position s2
$E_m = 0,s_1,s_2,c,r,m,d_m,0$	Energy at maximum force
$E_r = i,d_3,d_4,i$	Return energy of impactor, or (impact energy – absorbed energy)
m	Mass of impactor
v	Velocity of impactor

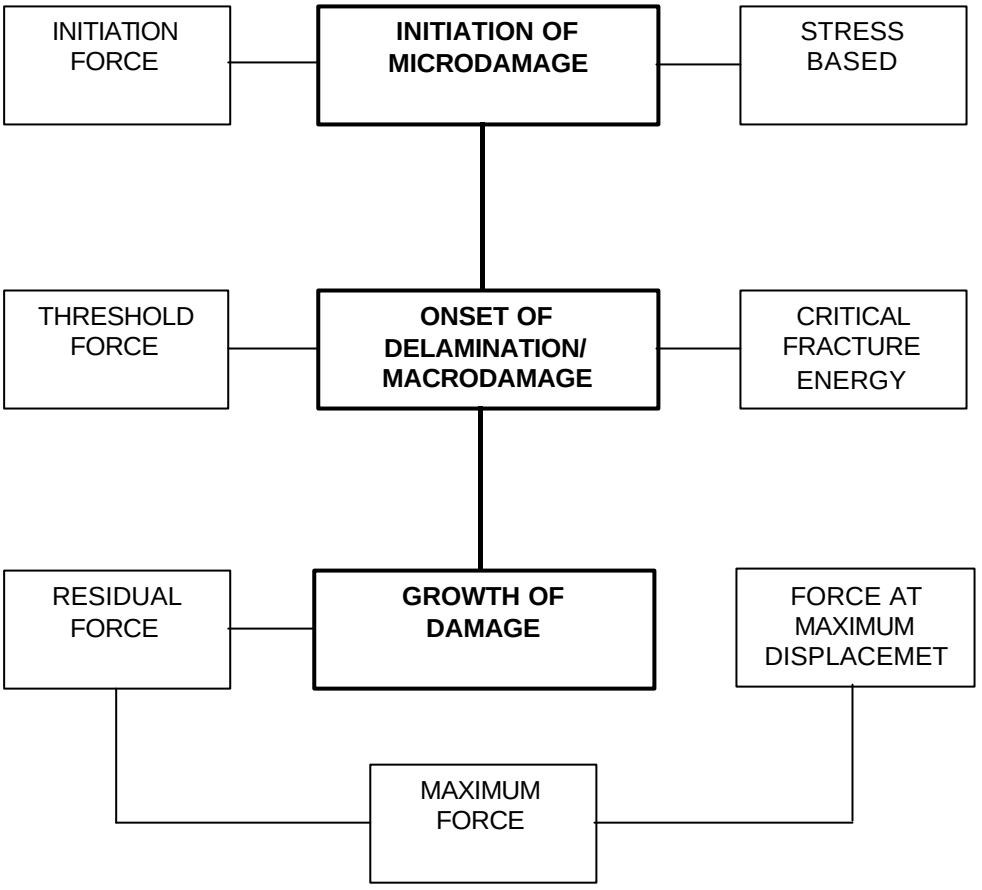
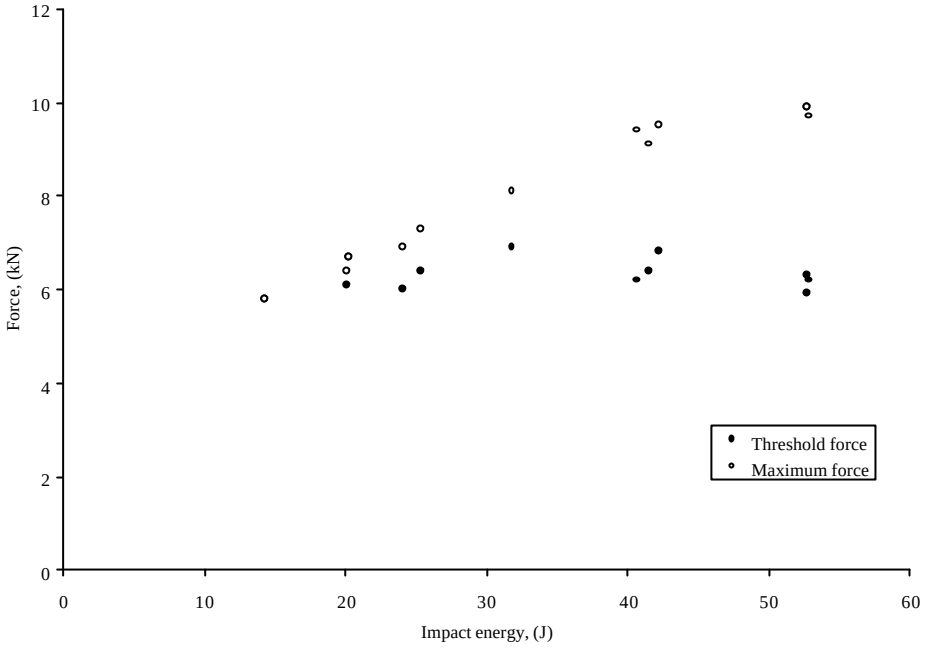
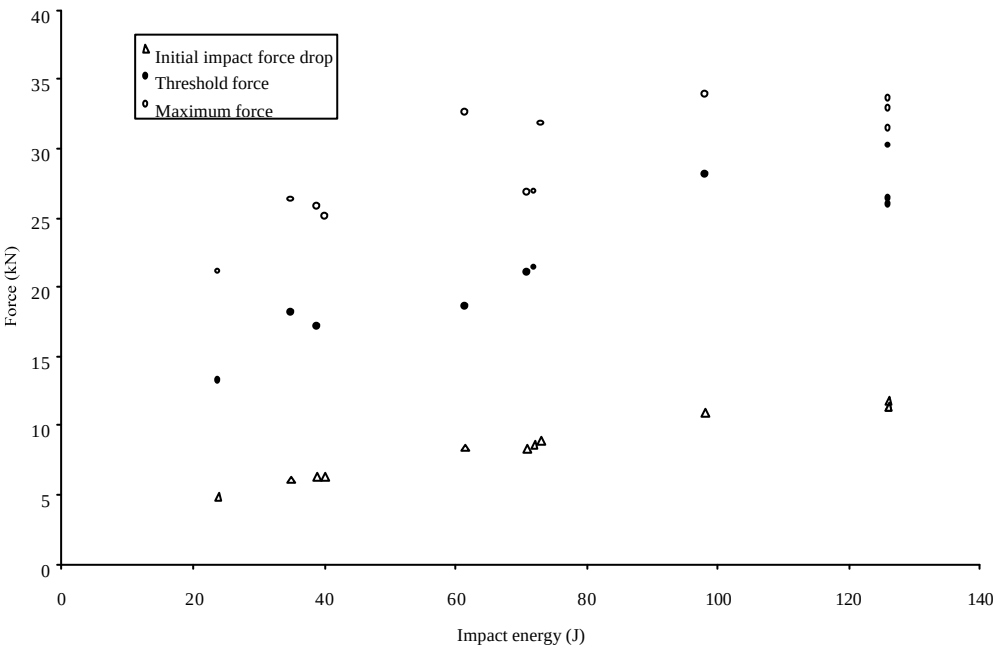


Fig. 3. Framework for impact damage process of ply drops.



(*a*) Thin ply drops: 6.88 to 6.02mm.



(*b*) Thick ply drops: 13.76 to 12.9mm.

Fig. 4. Force (initial: P_{s1}, threshold: P_c and maximum: P_m) versus impact energy (E_0) plot for all ply drop test specimens.

slightly increased due to formation of micro-damage. In this case, the drop of the force value is 2.2kN. The average value of P_{s2} is 7.5kN, corresponding to an average energy of 7.9J (E_{s2}) and average displacement of 1.2mm (d_{s2}). The following ratios may be calculated for thick ply drops using average values: P_{s1}/P_{s2} = 8.7/7.7 = 1.1; d_{s1}/d_{s2} = 0.7/1.6 =0.44; E_{s1}/E_{s2} = 4.3/7.9 =0.54. Note that multiplying the force and displacement ratios gives as estimate of the energy ratio: $E_{s1}/E_{s2} = P_{s1}/P_{s2}\, x\, d_{s1}/d_{s2}$ = 1.1 x 0.44 = 0.48

Similar performance is observed for a thin ply drop as depicted in Figure 1(a) (P_{s1} = 1.8kN for specimen 0727/3) – see also Ball *et al.* [7]. The average value of P_{s1} for thin ply drops is 1.42kN, corresponding to an average energy of 0.75J (E_{s1}) and 0.54mm average displacement (d_{s1}). The average value of P_{s2} is 1.0kN, corresponding to average values of 1.9J (E_{s2}) and 1.6mm (d_{s2}). Thin ply drop ratios are as follows:
P_{s1}/P_{s2} = 1.8/1.0 = 1.8; d_{s1}/d_{s2} = 0.54/1.6 = 0.34; E_{s1}/E_{s2} = 0.75/1.9 = 0.39

Thick to thin ply drop ratios are as follows: $P_{s1\ thick}/P_{s1\ thin}$ = 8.7/1.8 = 4.8;
$d_{s1\ thick}/d_{s1\ thin}$ = 0.7/0.54 = 1.3; $E_{s1\ thick}/E_{s1\ thin}$ = 4.3/0.75 = 5.7 and
$P_{s2\ thick}/P_{s2\ thin}$ = 7.5/1.0 = 7.5; $d_{s2\ thick}/d_{s2\ thin}$ = 1.2/1.6 = 0.75;
$E_{s2\ thick}/E_{s2\ thin}$ = 7.9/1.9 = 4.2

Onset of delamination/macro-damage

Threshold force

After this initial damage, the force builds up in the specimen to a so-called *threshold* or *critical* (P_c) value of 28.1kN for thick ply drop specimen 0952/1- see Figure 1(b). This is the force to initiate damage in the specimen, which is detectable by C-scan. This is a key parameter in the impact process, and has been found to be independent of the boundary conditions for a given thickness. Thus, whilst the energy at the threshold force may vary with the boundary conditions of the specimen or structure, the threshold force can be assumed constant. This is a useful parameter as a design guideline for impact threats. However, it is difficult to quantify the impact force, and the impact energy for that matter, for an impacted structure in service, so its usefulness is limited in this regard. The threshold force causing the onset of delamination and macro-damage, as shown in Figure 3, is often predicted using a failure criterion involving critical fracture toughness in mode II (shear), as shown by Ball [6].

There is a fair scatter of the threshold force values for thick ply drops, with an average value of 21.6kN, due to variation of stacking sequence. There is also large scatter in the energy and displacement corresponding to the threshold force. The average energy at threshold force (E_1) is 31.1J, whilst the average displacement at threshold force (d_1) is 2.6mm.

Thin ply drops showed more consistency in threshold force values, as given by Kairouz and Ball [2] and Ball *et al.* [7], with an average value of 6.3kN (P_c). The corresponding average energy is 15.7J (E_1), and 4.9mm average displacement (d_1).

Thick to thin ply drop threshold force, energy and displacement ratios are as follows:
$P_{c\ thick}/P_{c\ thin}$ = 21.6/6.3 = 3.4; $d_{1\ thick}/d_{1\ thin}$ = 2.6/4.9 = 0.53;
$E_{1\ thick}/E_{1\ thin}$ = 31.1/15.7 = 2.0. It is interesting to note that the threshold energy for thick ply drops is twice the energy for thin ply drops, corresponding to a factor of 2 on thickness.

Growth of damage

Residual force

The *residual* force, after the formation of damage due to the threshold force, is P_r. For specimen 0952/1, as an example, the residual force is 23.7kN, i.e. a drop of 4.4kN from the threshold force value. Again, this residual force value is seen to be constant with variation of impact energy, and independent of boundary conditions for a given thickness, as reported by Ball [3] for flat laminates. The average value of P_r for thick laminates is 15.7kN, corresponding to an average energy (E_2) of 43.1J and 3.2mm displacement (d_2). For thick ply drops, the ratios of threshold to residual values are: $P_c/P_r = 21.6/15.7 = 1.4$;
$d_1/d_2 = 2.6/3.2 = 0.81$; $E_1/E_2 = 31.1/43.1 = 0.72$

For thin ply drops, the average value of P_r is 5.5kN, corresponding to E_2 of 17.8J and d_2 of 5.4mm as presented by Ball *et al.* [7], giving the following ratios: $P_c/P_r = 6.3/5.5 = 1.1$;
$d_1/d_2 = 4.9/5.4 = 0.91$; $E_1/E_2 = 15.7/17.8 = 0.88$

The ratios of thick to thin ply drops are: $P_{r\,thick}/P_{r\,thin} = 15.7/5.5 = 2.8$;
$d_{2\,thick}/d_{2\,thin} = 3.2/5.4 = 0.59$; $E_{2\,thick}/E_{2\,thin} = 43.1/17.8 = 2.4$

Maximum force

A peak force (P_m) is then achieved during the impact event, as shown in Figure 1(b), of 33.9kN for specimen 0952/1 at 98J impact energy, as an example. The corresponding energy at maximum force (E_m) is 68.2J, and the displacement of impactor at maximum force (d_m) is 4.4mm.

Force at maximum displacement

After the maximum force is reached, damage will grow in the laminate - provided enough energy is available - to reach a maximum displacement (d_3) value (or force at impact energy) as depicted in Figure 2. For specimen No. 0952/1, the force at impact energy (P_i) was 30.7kN, i.e. a drop of 3.2kN from the maximum force. An alternative method of determining the impact energy, E_3, is to integrate the force versus displacement curve to obtain the impact energy at maximum displacement. This is performed by the software (Microsoft Excel or Rosand post-impact analysis code) and can be obtained by establishing the time at maximum displacement from the force versus displacement curve, and then reading the energy at the same time from the energy versus time plot. An alternative approach is to simply read the energy value at maximum displacement from an energy versus displacement plot.

CONCLUSIONS

A simple empirical model describing the performance of ply drops upon impact loading is given. Ply drops are more sensitive to impact than flat laminates, exhibiting some damage initiation prior to the threshold force value. This initiated damage may not be detectable by C-scan, and is thought to be due to resin cracking in the resin rich pocket at the ply drop feature site. It is thought that this initial damage is not critical to the laminate's performance.

For thin ply drops, key parameters of the impact process are the apparent constant values of the threshold and residual forces. The threshold value may be used for design against impact threats. The thick ply drops exhibited more scatter in the test results, due to variation of

stacking sequence. A distinction is made between the position of maximum force and position of maximum displacement (or impact energy). Some ply drop thickness effect ratios are given, but the work needs to be extended to include a range of ply drop thickness' to establish trends for design. There is also a need to examine different specimen sizes to confirm zero effect from specimen boundary conditions.

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