IMPACT DAMAGE TOLERANCE ASSESSMENT IN POLYMER COMPOSITES : A NEW APPROACH

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Abstract : The impact behaviour of polymer composites is a complex phenomena affected by material parameters, instrument parameters, testing conditions and process variations. As it has not been possible to quantify the impact behaviour based solely on impact studies, post-impact tests such as compression-after-impact or tension-after-impact have been used to study the degradation in strength properties and quantify impact damage. Since these post impact tests are very expensive and rigorous, this work, gives a simpler approach route for evaluation of impact damage tolerance of advanced composites by the use of repeated drop tests.

Low velocity (1.2~2.4 m/s, incident energy range being 3.5J – 15J) impact tests have been carried out on three variants of glass and one variant of carbon epoxy composites using an instrumented impact test machine (DYNATUP 8250). The composites were subjected to repeated impacts until failure for a fixed energy level. Number of drops to failure (N_f) data were obtained for each of the pre-determined incident energies (E_{in}) in the above range. E_{in} Vs N_f plot for each composite was obtained and a relationship between them was evolved and verified. Further, from the E_{in} Vs N_f plots, a critical incident energy parameter termed E_c was obtained. This critical energy value turns out to be the threshold value, below which the composite takes infinite drops to fail, and above which, it fails after very few drops. E_c , therefore, can be used as an important input in the design of impact damage tolerant composites by composite designers. This E_c forms yet another criteria for damage tolerance assessment in advanced composites, apart from the very expensive/ sophisticated Compression-After-Impact tests, hitherto being considered.

1. INTRODUCTION

The concept of advanced composites today, has reached a crucial phase, wherein their proven abilities has slowly transformed the application range from secondary (Non-load bearing) structures to primary (load bearing) structures in the aerospace industry. With increasing research and solutions on different aspects being addressed and accounted for, the confidence level as regards its performance and reliability aspects has improved a lot. In spite of these advancements, there are still some important issues that are not fully understood and are being looked into by researchers. One such important issue of concern, and that, which is drawing research focus today in the area of polymer composites is the quantification of its impact damage tolerance.

Damage tolerance by its very basic definition, is the ability of the material to perform given a specified amount of damage [1]. This aspect becomes important in load bearing structures of aircrafts for damage sustenance that occurs during flight. The fundamental requirement for understanding damage tolerance in a material is the ability to predict its mode of failure which has been well understood in metals. This, in the case of composites is not fully understood and therefore, unlike metals, is not possible to relatively evaluate due to their inherent complexity [2]. In reality, it has been found that a structure without appropriate damage tolerant design provisions may fail due to internal damage without any externally visible signs of damage[3], which, in a sense has become an impeding factor for composites to be extensively used. Of all the varied inputs and effects governing damage tolerance of polymer composites, material response to impact behaviour is a vital ingredient. The complexity of structures, testing aspects, impact scenarios, target and specimen variables has made the understanding of impact behaviour a very trickish issue. Impact, on its own, does not give a quantifiable end-point. This would become important if the structure has to be designed for impact damage tolerance. Hitherto, a via-media approach has been adopted, wherein, post impact tests such as compression after impact, tension after impact have been carried out and the resulting strength degradation quantified and used by designers. This, although is beneficial in understanding the effects of impact, it is not self contained and the specimens have to be tailor-made to suit these post impact tests resulting in large deviations from real- life scenarios. Moreover, in some situations such as large panels and actual structures, it may not always be possible to carry out these rigorous and costly tests. In this context, a review paper on low velocity impact by Richardson and Wisheart [4] includes a very useful generalised response of post-impact test on composites.

In view of the above, this work, adopts a novel approach for the understanding and evaluation of impact behaviour of composites solely based on impact response during repeated drop tests. Repeated drop tests have been used earlier by researchers in different contexts. Some of these that can be cited here are studies on severity of impact (Single versus repeated drops) by Wyrick and Adams[5], repeated impact response of ductile and brittle composites by Rotem[6], material response of specimens subjected to repeated impacts at varied energy levels by Found and Howard[7], Effects of fibre volume fraction and incident energy on damage by Bijoysri Khan et.al., [8] and damage growth studies on specimens subjected to repeated impact by Rachid et.al.,[9]. Differing from the above citations, this work, uses repeated drop tests solely for effective quantification of impact damage without resorting to the post-impact tests such as compression, tension-after-impact. Also, results of these research studies bring out a well quantifiable damage tolerance criteria in composites in terms of a critical energy parameter that is of great value to composite designers.

2. The concept of Repeated Drop Tests

Contrary to single drops, repeated drops comprises of impacting a specimen a number of times until failure(total perforation) with a pre-defined incident energy (termed E_{in}). For any given E_{in} the number of drops taken by the material for perforation is termed as N_f. For a given specimen, a range of E_{in} and N_f values can thus be obtained. This technique of impact testing can be carried out even on custom made machines without data acquisition sophistication, as failure is determined quantitatively. The most practical scenario simulative of repeated drop tests is the frequent undercarriage debris hits that takes place during each take-off or landing of aircrafts.

3. Experimental work

Composite laminates were prepared from twill woven Glass and carbon fabric reinforcements using epoxy resin as matrix material by Resin Transfer Moulding Process. Three classes of resin systems viz., Room temperature cure termed RT cure (LY 556, HY 951), 120°c cure (L 552, K 552) and 180°C cure (C14,K68,K112) with their defined post-cure schedules (provided by the manufacturer)were used as matrix material for laminate preparation. Pre-qualification tests to check for Resin transfer effectiveness, Resin cure completion, composite characteristics (W_f, thickness), Iinter-layer bonding checks (ILSS) were carried out on these specimens. Repeated impact testing were carried out using an instrumented impact test facility from M/s Instron. The test facility is equipped with 930-I Data Acquisition Software and pneumatic rebound catch system to prevent multiple impacts for the same drop. Each specimen is impacted with an arbitrary incident energy- E_{in} until perforation of the specimen occurs and the number of impacts taken for perforation termed number of drops to failure- N_f is recorded. Table 1 shows the composite details, their characteristics, the overall impacting conditions & the incident energies to which these specimens were subjected. The composite constructions and the incident energies are chosen arbitrarily to induce experimental variations.

Table 1 : Impacting conditions for repeated drop tests on glass and carbon composites

Material details	**Thickness (mm)**	**Fibre weight fraction**	**Incident energies (joules) E_{in}**	**Impacting conditions**	
Twill woven glass epoxy (LY556-HY951) laminate (Room temperature cure)	2.03	0.69	3.2;5.4;6.5;7.0; 8.2;12.5	Test specimen type Support conditions Test specimen Dimensions Tup type Tup dia Impactor mass Drop height Incident energy Impact velocity Type of impact	Rectangular plate All round clamped 90 X 90mm Hemispherical 15.5 mm 5.42 Kgs Approx 0.094 - 0.282 mtrs Approx 3.5 to 15 Joules Approx 1.2 to 2.4m/s Repeated impacts until total penetration
Twill woven glass epoxy (LY556-HT972) laminate (120°C cure)	2.2	0.62	3.4;4.95;.5.5 ;7.6; 8.4;10.1;11.0; 14.7		
Twill woven glass epoxy (C14-K68-K112) laminate (180°C cure)	2.2	0.60	5.3;8.4;14.5		
Twill woven carbon epoxy (LY556-HT972) laminate (120°C cure)	2	0.59	3.7;5.0;7.0;10.1; 14.7		

4. Results and discussions

The quality of Resin impregnation in the composites can be seen from Figure 1 wherein the cross-sectional micrograph shows the merger of the matrix particles into the fibre bundles. Figure 2 shows the glass transition Temperature (Tg) obtained for 180°C cure composite using mDSc to check cure completeness. These tests and similar others such as ILSS, NDT by tapping have ensured quality composites for testing.

Composites when subjected to single impacts respond by absorbing the incident energy by any or all of the below modes of failure viz., Matrix cracking, delamination, fibre failure and total perforation [11]. The stages of energy absorbtion are mostly dependent on the conditions and intensity of impact. Repeated drop tests can be viewed as a delayed/staggered process of single drop tests, the advantage being, the possibility of demarcation of the above four stages. Figure 3 shows a typical energy absorption process in 120°C cure glass-epoxy composite subjected to repeated impacts. The number of drops to failure in this case is 98. From the figure it is seen that, with increase in drop numbers, a gradual increase in energy absorption can be seen. This behaviour can be explained as follows. After the initial stage of matrix cracking, the layers in the composite start delaminating, thereby absorbing the supplied energy. These delaminated layers without the brittle matrix act as resilient structures when subjected to impact, thereby, absorbing the supplied energy until a threshold point of each layer in the composite is reached at which point that particular layer fails. Continuing, during successive impacts, as each layer fails, the ensuing layer continues absorbing the supplied energy. This process continues till all the layers in the composite fails at which point there is a drastic drop in the energy absorption process as can be seen from the figure. The number of drops at which this occurs can be quantitatively obtained or easily identified from the E_{in} versus number of drops plot as can be seen from the figure 3 (marked as N_f). In the case of repeated drop tests carried out on sophisicated equipments with data acquisition support such as the one used here, N_f can be identified from the summarised plot of the Energy-time trace as shown in figure 3. This in brief, describes the response and evaluation of a polymer composite specimen when subjected to repeated drops.

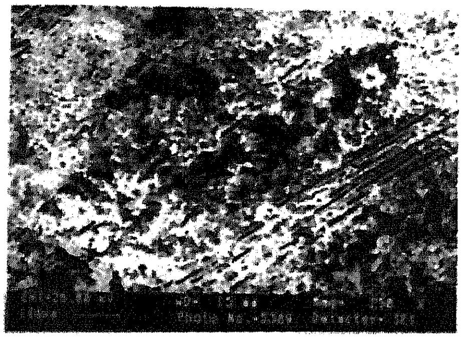

Figure 1 : Cross-sectional Micrograph showing resin transfer effectiveness by the merger of Matrix and fibre bundles

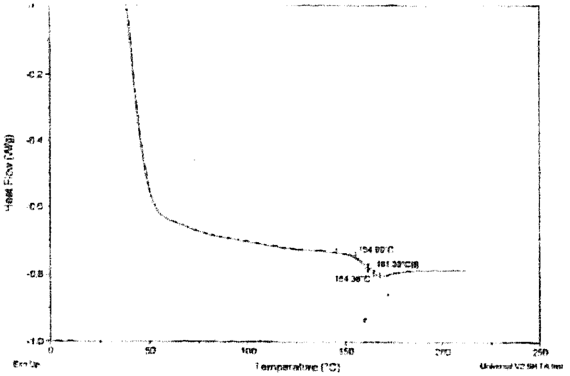

Figure 2:DSC scan of glass epoxy (180°C cure) composite

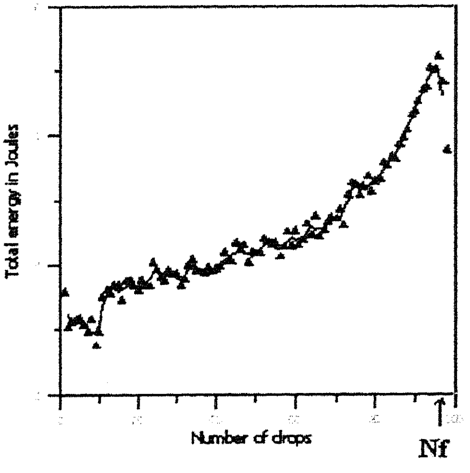

Figure 3 : Variation of energy absorption as a function of drop number in glass epoxy (LY 556 HT 972) composite. (E_{in}–5J, M – 5.42 Kgs)

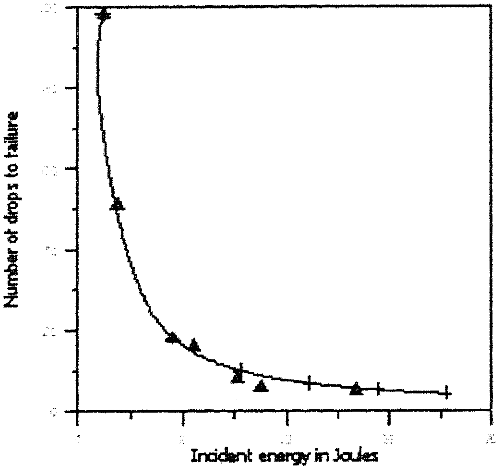

Figure 4 : E_{in} versus N_f curve for glass epoxy (LY 556 HT 972) composite.

Continuing, similar set of specimens from each composite class (described above) are subjected to varied E_{in} as depicted in table 1 and a range of E_{in} , N_f values has been obtained. A summarized plot of E_{in} versus N_f is shown in figure 4. Given the typicality of the curve, a relationship exists between E_{in} and N_f Viz., As E_{in} is varied in arithmetic progression, N_f varies as harmonic progression. For evaluation [more fully described in references 10,11], it is required that at least two set of E_{in} , N_f data values(preferably at lower incident energies) be obtained by way of experiments. These data points can then be used to predict the other E_{in} , N_f values from which the characteristic curve as shown in figure 4 can be obtained. Since N_f is a whole number, the results obtained by the above calculations should be rounded off to the nearest whole number. The usefulness of this relationship lies in the fact that, the characteristic E_{in} , N_f curve can be obtained with minimum experimentation and that this E_{in} , N_f curve is the basis for the assessment of impact damage tolerance described in the next section.

5. *Impact damage tolerance assessment*

Impact damage tolerance assessment here has been carried out by

- Identifying the threshold energy(termed as Critical Incident Energy- E_c) level in the composite
- Mapping of the damage caused using delamination area maps

5.1 *Critical Incident Energy Evaluation*

On close observation of the E_{in} , N_f curve (referring to Figure 4 as example), two phases can be demarcated. In the first phase, at lower incident energies (say < 7J), the number of drops to failure is high. It can be seen that, in this portion of the curve there will be large differences in N_f values for even small differences in E_{in} values. At very low E_{in} values, the specimen takes infinite drops. Generalising and defining this as a limits problem [10,11],

$$\text{As } E_{in} \rightarrow 0,\ N_f \rightarrow \infty \qquad \text{Equation (1)}$$

In the second phase, at relatively higher incident energies(say > 7J), the number of drops to failure is low. In this portion of the curve, there will be small differences in N_f values for even large differences in E_{in} values. At high E_{in} values, the specimen fails in a single drop. Generalizing and defining this also as a limits problem [10,11],

$$\text{As } E_{in} \rightarrow \infty,\ N_f \rightarrow 1 \qquad \text{Equation (2)}$$

The above two equations gives the governing limits within which the concept of repeated drops works and is true for any composite construction or variants of impacting conditions.

Now, from the E_{in} , N_f curve, tangents drawn from the vertical and horizontal portions of the curve is shown to intersect at a point on the X-axis. This intersection point has been designated E_c. Figure 5 shows the E_c value obtained from the E_{in} , N_f curve of glass epoxy (180°C cure) composite. It is to be noted that calculated values (+) in the plot are those values obtained by the previously described relation governing E_{in} , N_f curves. Experimental values(Δ) in the plot are those values obtained by carrying out repeated drop tests at the particular incident energies. Further, E_c values for all the composites considered here are obtained as described previously (Refer Table 2).

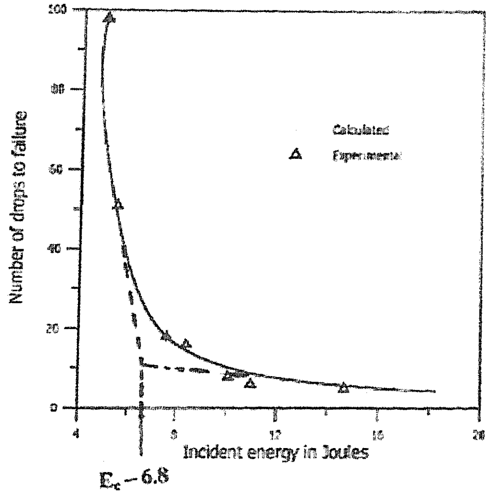

Figure 5 : E_c value obtained from the E_{in} , N_f curve for glass epoxy (LY 556, HT 972)composite

Table 2 : Critical incident energy values for composites

Specimen Details	***E_c(Joules)***
Glass epoxy (LY 556, HY 951) composite	*4.7*
Glass epoxy (LY 556, HT 972) composite	*6.8*
Glass epoxy (C14,K68,K113) composite	*7.3*
Carbon epoxy (LY 556, HT 972) composite	*5.3*

From the table, it can be seen that, the critical energy values are in the range 4.7J to 7.3J, though the superiority of glass-epoxy composite over the carbon- epoxy composite is quite visible. This critical energy value turns out to be the threshold value, below which the composite takes infinite drops to fail, and above which, it fails after very few drops. This is a good input to designers as a practical index of impact damage tolerance of the composites, since below this critical energy value, it can be safely assumed that no perceivable damage occurs that affects the composite integrity for the configurations considered here. Conversely, it can be said that, for all the impact energies above this critical value, the damages are visible and hence could be addressed through appropriate and timely repair schemes. It should be noted that the value of E_c varies for different composite constructions and has to be arrived on a case-to-case basis prior to design of the component

5.2 *Damage mapping using final delamination area maps*

In the case of polymer composites damage assessment is a special field by itself encompassing from the simple visual inspection of surface damages to the more advanced SEM studies wherein matrix cracking, fractography of the fibres can be undertaken in detail. In this work, as part of damage assessment, during repeated drop tests, final delamination area maps were obtained as explained below.

The impacted specimen is placed on an open window below which, illumination is provided by means of a table lamp. A tracing paper with graphical squares on it, is placed on the specimen. Using the illumination from below, the impacted area is carefully marked. Figure 6 shows the marked delamination area maps for different E_{in} of glass epoxy (LY 556, HT 972) composite. It is seen that each delamination area map, comprises of three traces. The innermost trace refers to the plan view of the cavity formed during impact, the second trace shows the extensive damage undergone by the layers. The outer trace shows the final delamination area of the impact damaged specimen. Here, all the layers may or may not have delaminated but nevertheless damage is made. From the traces, delamination areas termed F_{del} can be obtained as shown in figure 6.

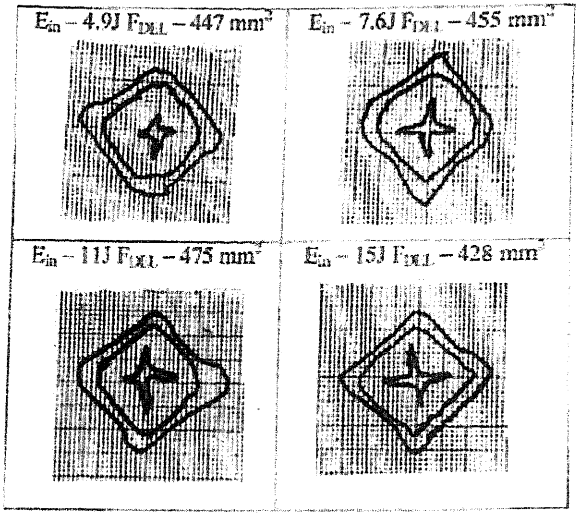

Figure 6 : Delamination area maps for glass epoxy (LY 556, HT 972) composite

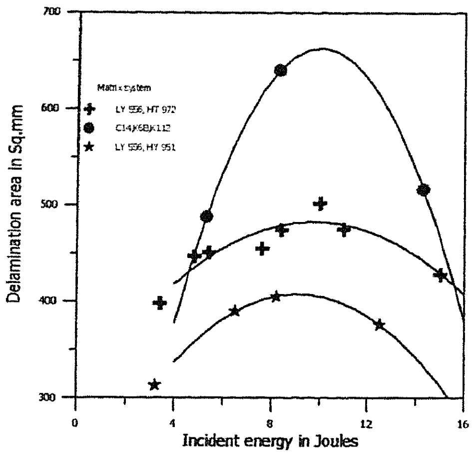

Figure 7: Super imposed plots of Final delamination areas of glass epoxy composites

Figure 7 shows the superimposed plot of Final Delaminate areas at varied incident energy in the three matrix systems of glass-epoxy composites. It can be seen that, delamination is highest at intermediary incident energies. This can be explained as follows. At low incident energies and lower impact velocities, damage propagation, hence delamination would be restricted due to the ability of the material to absorb the supplied energy without extensive damage. At intermediary energy levels and corresponding velocities, there would be ample time for the propagation of stress waves and therefore increased delamination of the layers can be found here. At higher incident energies, velocity of impact being comparatively higher, there would be no time for the stress waves to propagate laterally and hence damage would be extensive but highly localized thereby limiting the peripheral delamination area. In the case of carbon composites, the above explained damage mapping process of using delamination areas cannot be resorted to due to its opaqueness

6. Conclusions

This work has given a new approach route for understanding the impact behaviour of polymer composites by the use of repeated drop tests. Failure criteria in the case of repeated drop tests has been defined and arrived at for select composite constructions. A relationship governing incident energy and failure of composites when subjected to repeated drops has been defined and verified. Further, a well quantifiable impact damage tolerance criteria in composites in terms of a critical energy parameter that is of great value to composite designers has been arrived at for some sample constructions. A simple way of damage assessment using delamination area maps caused by impact is demonstrated which can be adopted for damage quantification. Finally, this approach route can be adopted to any type of composite construction for design of impact damage tolerant composites.

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8. References

1. D.S.Cairns and P.A.Lagace.,Jnl. of Reinforced Plastics and composites., 11(1992)395-412
2. K.D.Challenger., Composite structures., 6(1986) 295-318
3. E.Demuts, R.S.Whitehead and R.B.Deo., Composite Structures., 4(1985)45-58
4. M.O.W.Richardson and M.J.Wisheart., Composites Part A., 27A(1996)1123
5. A.Wyrick and D.F.Adams.,Composites.,19-1(1988)19-27
6. Rotem.A.,Journal of Composites Technology and Research.,10-2(1988)74-79
7. M.S.Found and L.C.Howard.,Composite Structures.,32(1995)159-163
8. Bijoysri Khan, RMVGK Rao and N.Venkataraman, Jnl. of Reinforced Plastics and composites.,14(1995)1150-1159
9. Rachid Boukhili, Chakib Bojji and Raymond Gauvin., Jnl. of Reinforced Plastics and composites.,13(1994)856-870
10. B.S.Sugun, "Drop Weight impact studies on polymer composites" Ph.D Thesis,2004, Mysore University
11. B.S.Sugun, R.M.V.G.K.Rao, Jnl. of Reinforced Plastics and composites.,23(15)(2004)1583-1599