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Impactor Mass effects in polymer Matrix Composites under Low Velocity Conditions: A Repeated Drops Test Approach

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Abstract: This paper utilizes the concept of repeated drop tests to understand impactor mass effects under low velocity test conditions on Polymer Matrix Composites. Twill woven glass fabric reinforcements and epoxy matrices(three variants) with differing cure schedules were used to prepare composite specimens. These specimens were then subjected to Repeated Drop Tests using an instrumented Impact test facility. Judicious combinations of Mass and Height were used to simulate equivalent incident energies (E_{in}) ranging from 3J to 15J. Number of Drops to failure data (N_f) was obtained for the varied impactor mass in each case. $E_{in} - N_f$ plots and the Threshold Incident Energy (E^*_{in}) values obtained from the overlay of these plots, showed, clear demarcable failures at lower incident energies, i.e., the specimen impacted with heavier impactor failed in less number of drops as compared to the specimen impacted with lighter mass for the same E_{in}. Also, E^*_{in} obtained, clearly identified the point below which impactor mass effected earlier damage in composites. The hallmark conclusion that has been inferred from this research work is that "It is preferable to use lighter tools during routine service and overhauling of aircraft/ similar structures, so that they inflict minimum impact damage during work execution/ accidental drops".

Keywords: Repeated Drop Tests, Polymer Matrix Composites, Impactor Mass effects, Threshold incident Energy, service and overhauling of aircraft structures

INTRODUCTION

Thermoset polymer matrix composites (PMC's) are increasingly used in the aircraft industry, both as secondary and primary structures (e.g.control surfaces, wings, fuselage, etc.,), in view of their attractive low weight, high specific strength/stiffness properties, corrosion resistance as well as amenability to design, tailorability, reparability and maintenance. The extensive use of PMCs in several frontline aircraft, both civil and military, is a testimony to the growing acceptability of composites in advanced aerospace applications.

It is known that, several tests need to be carried out on these materials prior to their usage. Of the broad range of properties that are routinely evaluated in the case of composites, the understanding of its impact behaviour has become increasingly important. Impact behaviour of polymer composites is a large and diverse field. The impact response of a structure depends largely on a number of parameters both at the instrument level (incident energy, impactor mass, impactor configuration, impactor material etc.,) and specimen level (thickness, Configuration, construction, constitution etc.,). Several researchers have been trying to address these issues, some of which has been outlined below. Jackson and Poe [1], have described a methodology for using impact force as a scale parameter for delamination damage of simple plates. Perverosek *et al.*, [2], have focused their study on the penetration resistance of fibre reinforced composites. A. P. Christoforou and A. S. Yigit[3], have developed a new contact law incorporating damage effects due to local contact stresses. Peter *et al.*,[4], have tried to optimize the impact phenomenon and other factors, such as material properties influence on the impact response. Dorey *et al.*, [5], have clearly distinguished two explorable areas viz., low velocity impact by a large mass (Charpy, izod, drop weight, hydraulic test machines) and high velocity impact by a small mass (Hopkinson bar technique, gas gun impact). Differing from the above, this paper discusses about the effects of impactor mass under low velocity test conditions using repeated drop test approach. The paper is outlined as below. The concept of repeated drop tests and its usefulness in evolving the impact damage tolerance criteria is given briefly in the next section. Subsequently, the concept of impactor mass effects, experimental details and the results obtained are discussed. Finally, demarcation of the Threshold Incident energy, its evaluation and importance has been put forth followed by conclusion.

1. Concept of Repeated Drop Tests (RDT) and its Usefulness in Impact Damage Tolerance Assessment [6,7]

Contrary to single drop tests, repeated drop tests 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 specimen

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for perforation can be obtained and is termed as N_f. For a given material, a range of E_{in} and N_f values can be obtained from different but identical specimens. Subsequently, from the E_{in} and N_f values, E_{in} - N_f curve for the particular material can be obtained. The governing limits within which the above concept of repeated drop tests work in any material and its configuration is best represented by the equations [6] :

$$\text{As } E_{in} \rightarrow 0,\ N_f \rightarrow \infty \ \&\ \text{As } E_{in} \rightarrow \infty,\ N_f \rightarrow 1$$

It is well known that, the anisotropic behaviour of composites, makes their failure processes very complex, both to visualize and predict precisely, especially under a combination of static and dynamic loads. Extensive experimental data coupled with complex theoretical analysis is needed to understand and design with composites. The damage tolerance in composites, as such, has a complex understanding and evaluation process. In this context, a novel and simpler technique of assessing and assigning an impact damage tolerance index by means of a new criteria (termed E_c-Critical incident energy) has been arrived at from the E_{in}-N_f curve and detailed in reference[7]. The E_c parameter thus obtained, defines the incident energy level below which the material will be impact damage tolerant and above which there would be rapid failure. Figure 1 shows the Critical Incident Energy obtained in the case of glass-epoxy composite[7].

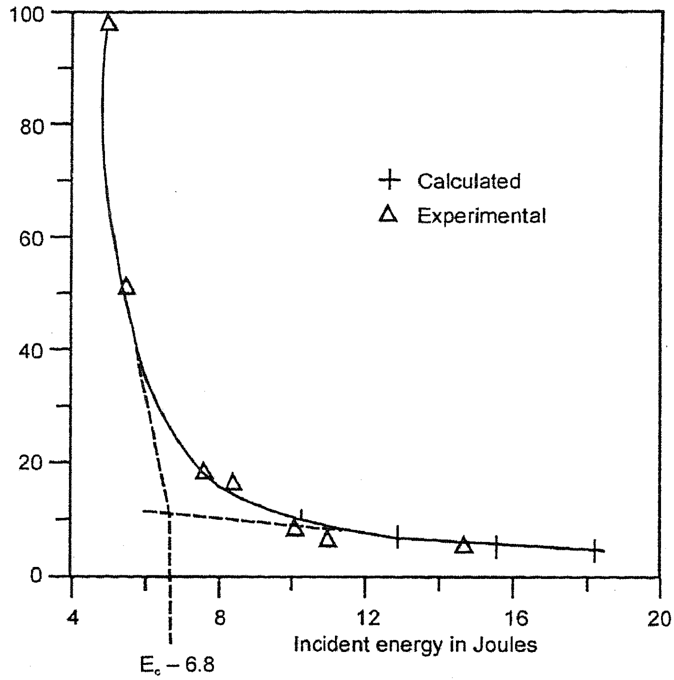


Figure 1: Evolution of Critical Incident Energy (Criteria for Impact Damage Tolerance)in Glass-epoxy composite[7]

2. Use of Repeated Drop Tests in Understanding the Impactor Mass Effects

From the relation, E = mgh or E = ½ mv², m and h are inversely proportional to each other. Here, the symbols have their usual notations. Keeping either M or h constant (in turn velocity as $v = \sqrt{2gh}$) and changing the other, will correspondingly change the amount of incident energy. As a result of this, the associated effects can be logically inferred. Further, it is also quite possible that a judicious combination of m and h can be arrived at, keeping E constant. i.e., A pre-defined incident energy on the specimen can be either imparted using a heavier mass from a lower height or a lighter mass from a higher height. The damaging effects in such cases cannot be logically inferred and therefore, the essence of this paper is to experimentally evaluate the effects arising out of these mass-velocity combinations.

3. Experimental Work

2 × 2 Twill woven E-glass fabrics and 3 variants of epoxy resin systems were used to prepare composite laminates. The epoxy resin systems used were: Room Temperature cure (LY 556, HY 951), 120 °C cure (LY 556, HT 972) and 180°C cure (C14, K68, K112). The laminates were prepared using Resin Ingression Technique (Figure 2)[8], a variant of RTM process. The laminates were then taken to their pre-defined cure schedules as defined by the manufacturer. The laminates were all of 0.60 ± 0.02 fibre weight fraction and 2.1 ± 0.1mm thick. 90 × 90 mm test specimens prepared from these laminates were used for impact testing. Table 1 gives the combinations of mass, height and impacting conditions that

was used to carry out the impact tests. The mass combinations were chosen depending on the availability of the standard weights (2.74, 5.42 and 12.28 Kgs) provided with the drop weight impact test equipment. Repeated impact tests at E_{in} given in table 1 were carried out on specimens with different impactor mass and the corresponding failure data (N_f) was obtained in each case. Select load-time and energy-time traces were also obtained from the data acquisition system. The experimental variations in the impact incident energy for the varied impactor mass was within ± 0.2*J*.

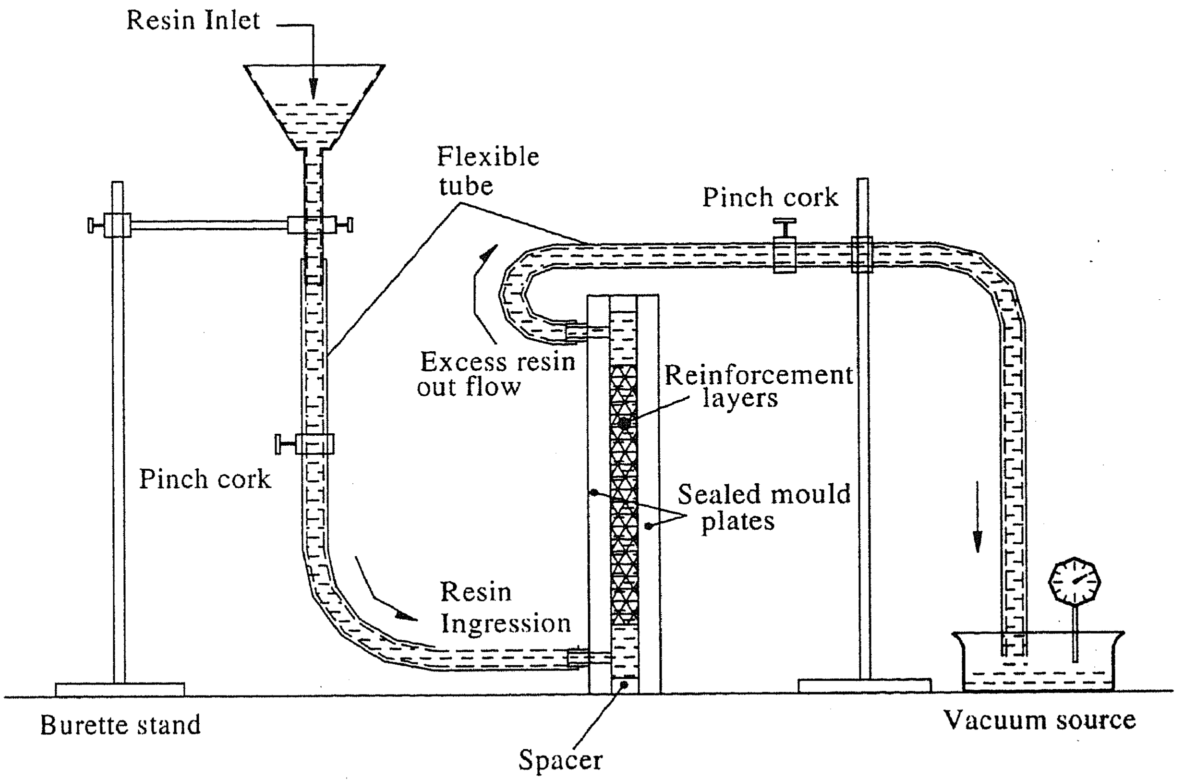


Figure 2: A Schematic of Resin Ingression Technique used to Prepare Composite Specimens [8]

Table 1
Mass-height Combinations and Impacting Conditions used to Carry Out Impact Tests for Understanding Impactor Mass Effect[9]

Material details	*Impacting conditions*	*Mass in kgs→* *Incident energy (Joules)* ↓	*2.74*	*5.42*	*12.28*
			Impactor height in Mtrs		
Twill woven glass epoxy	Tup shape : Hemispherical	3.2	0.119	0.06	-
(LY556 HY951)	Tup diameter : 15.5mm	6.5	0.242	0.122	0.054
laminate (RT cure)	Boundary conditions :	12.5	0.465	0.235	0.104
Twill woven glass	Clamped on all four sides	3.4	0.127	0.064	-
epoxy (LY556-HT972)	Drop conditions :	5.5	0.205	0.103	0.046
laminate (120°C cure)	Gravity assisted free fall	7.6	0.283	0.143	0.063
Twill woven glass epoxy	Others : Pneumatically assisted	11.0	0.409	0.207	0.091
(C14-K68-K112)	rebound break to prevent multiple	5.3	0.197	0.1	0.044
laminate (180°C cure)	impacts during any specified drop	8.4	0.312	0.158	0.070
	Type of test: Repeated drop	14.0	0.521	0.263	0.116

4. RESULTS AND DISCUSSIONS

Table 2 shows the summarised results of N_f values for the three composite systems studied here. From the table, it can be seen that at low incident energies, there is large difference in N_f values. Ex. In RT cure composite, at 3.2 J of incident energy, N_f value with 2.74Kg impactor mass is 430 while it is only 230 with 5.42 Kg mass. Figure 3 shows the load-time-energy trace obtained from the instrument for the 230th drop number of both the above impactor mass for the same

E_{in}(3.2J). It can be seen from the load-time plot that the specimen impacted with 5.42 Kg does not take any load indicating failure, as compared with the specimen impacted with 2.74 Kg mass. This, clearly depicts the loss of structural integrity of the specimen in the case of the former. As we go to the next higher incident energy i.e., 6.5 J the margin in N_f values has drastically reduced viz., 20,18 and 15 for 2.74, 5.42 and 12.,28 kg impactors, respectively. This shows the waning off, of the mass effects. At still higher incident energy ie., 12.5 J all the specimens impacted with different impactor mass failed at 6 drops, totally nullifying the effects of impactor mass.

Table 2
Failure Data for varied E_{in}-Mass Combinations

Material details	*Mass in kgs →*	*2.74*	*5.42*	*12.28*
	Incident energy (Joules) (E_{in})	*Number of drops of failure (N_f)*		
Twill woven glass expxy	3.2	430	230	
(LY 556 HY 951) laminate	6.5	20	18	15
(RT cure)	12.5	6	6	6
Twill woven glass epoxy	3.4	506	316	
(LY 556-HT 972) larninate	5.5	57	51	41
(120 °C cure)	7.6	26	18	16
	11.0	6	6	6
Twill woven glass epoxy	5.3	102	85	60
(C 14-K68-K 112) laminate	8.4	13	11	5
(180 °C cure)	14.0	5	5	5

The above analogy can be seen even with the 120°C and 180°C cure composites as well (refer Table 2). Figures 4 and 5 show the above experiment carried out with three different impactor mass for a 180°C cure composite. Figure 4 shows the Load-Time and energy-time plots for 60th drop number. It can be seen that, the composite impacted with 12.28

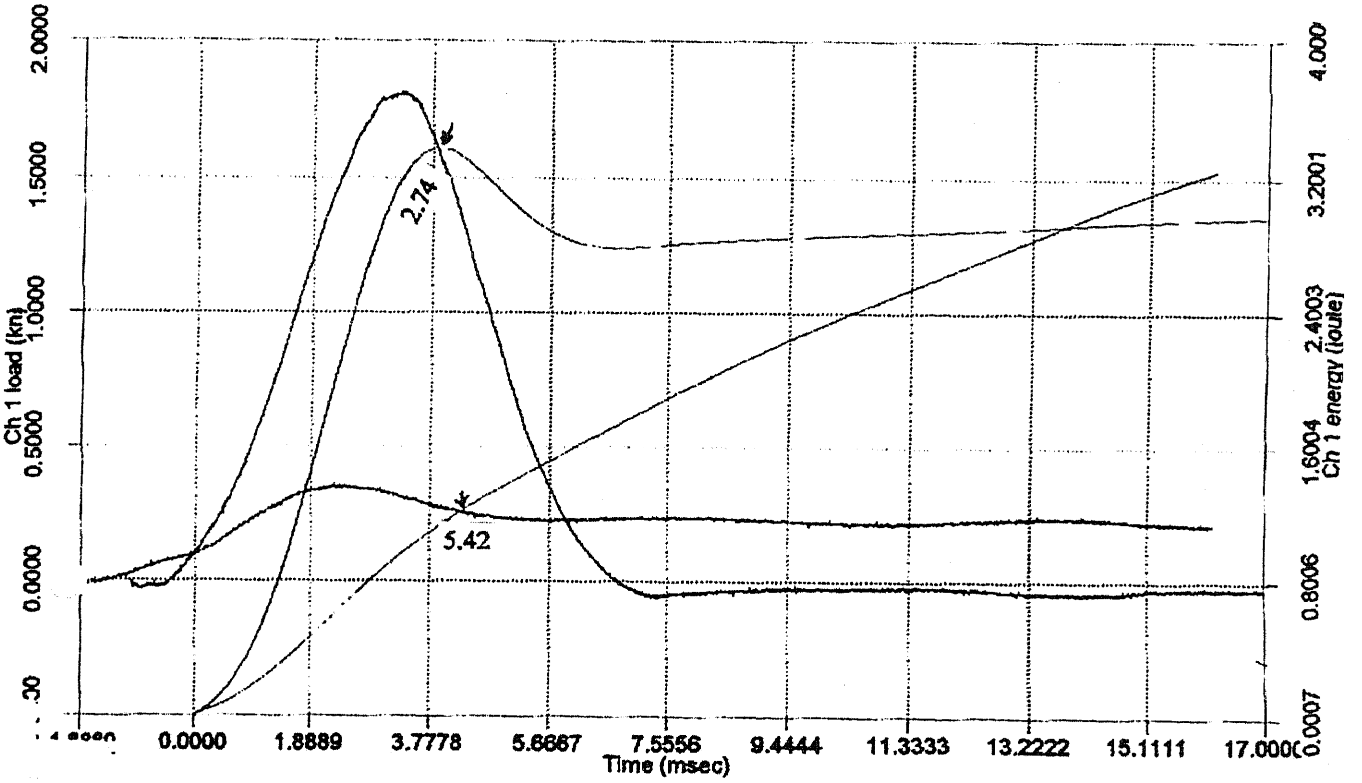


Figure 3: Load-Time-Energy Trace of RT Cure Composite for Varied Impactor Mass (E_{in} – 3.2J, Drop Number- 230). Numbers on the Curve Indicate Impactor Mass in Kgs.

Kg mass has totally failed (Drastic reduction in the load taken by the laminate). Continuing further, figure 5 shows the load-time-energy plot for 85th drop number. Here again, it can be seen that the specimen impacted with 5.42 Kg mass has failed. The specimen impacted with 2.74 Kg mass has taken 102 drops to fail (table 2). Figure 6 shows the load-time-energy plot of specimens impacted with the three impactor mass for 120°C cure composite. The specimens were impacted at a relatively higher incident energy (11.0 Joules). From the figure, it can be seen that all the specimens have been failing in a synchronized manner showing that the impactor mass does not really matter at this energy level. The plots are given for 10th (top) and 15th drop number.

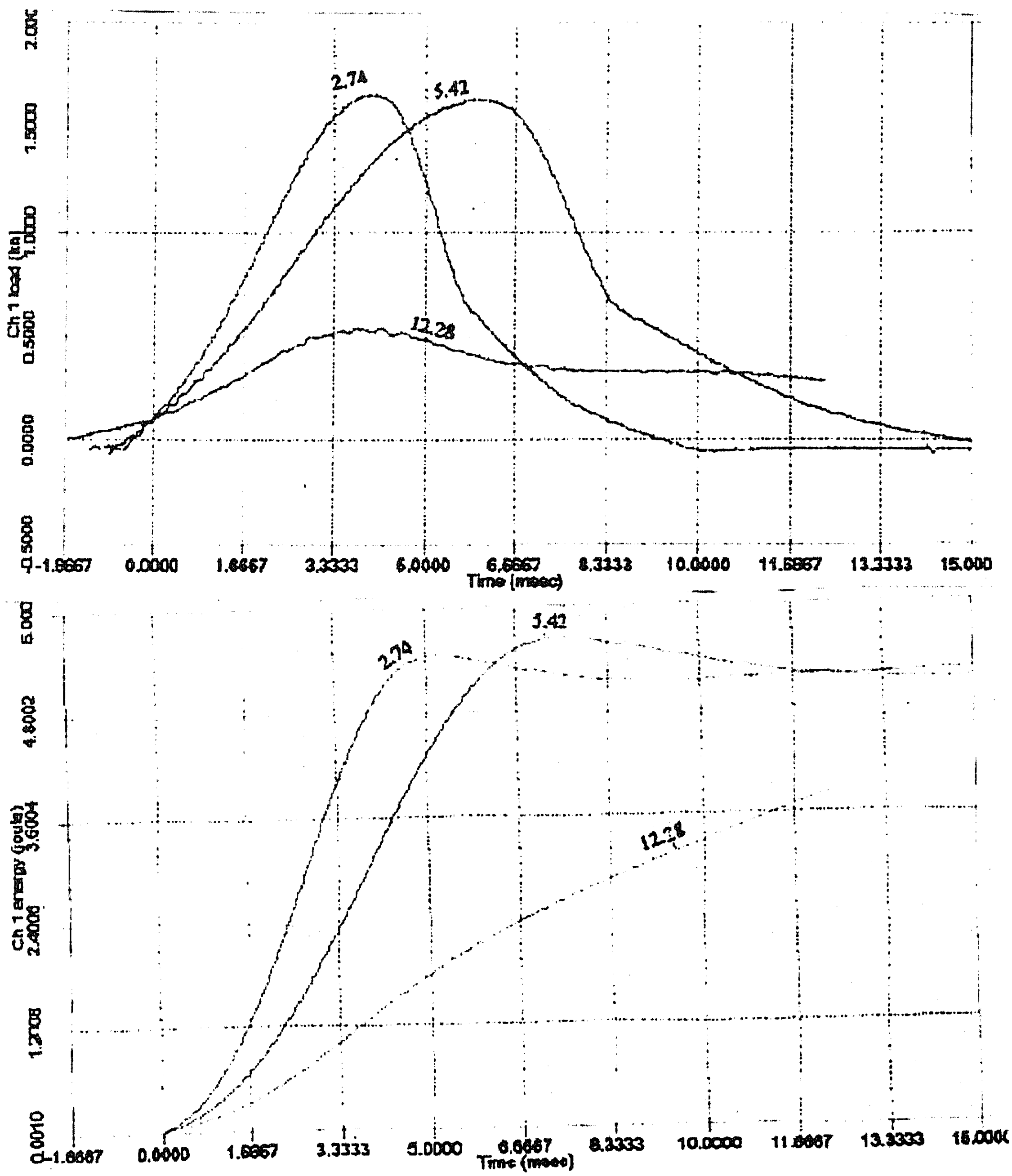


Figure 4: Load-Time and Energy-time Trace of 180 °C Cure Composite for Varied Impactor Mass (E_{in} – 5.3J, Drop Number- 60). Numbers on the Curve Indicate Impactor Mass in Kgs.

These experiments clearly depict that, at low incident energies, impactor mass becomes an important criteria in impact damage tolerance studies of composites. i.e., Lighter impactors inflict less damage and delays the failure process in these materials. The practical inference therefore, that can be ascertained from these studies, is that, it would be preferable to use lighter tools during routine service and overhauling of aircraft structures, so that they inflict less damage during work execution/ accidental drops.

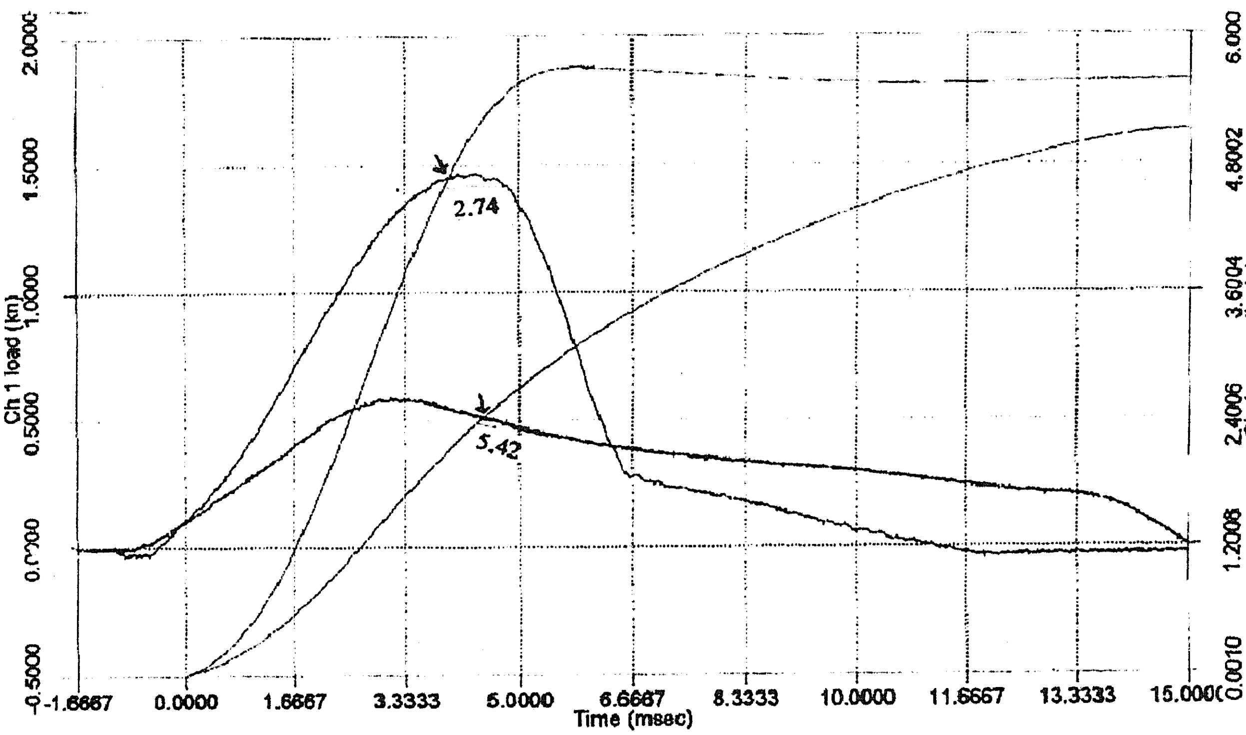
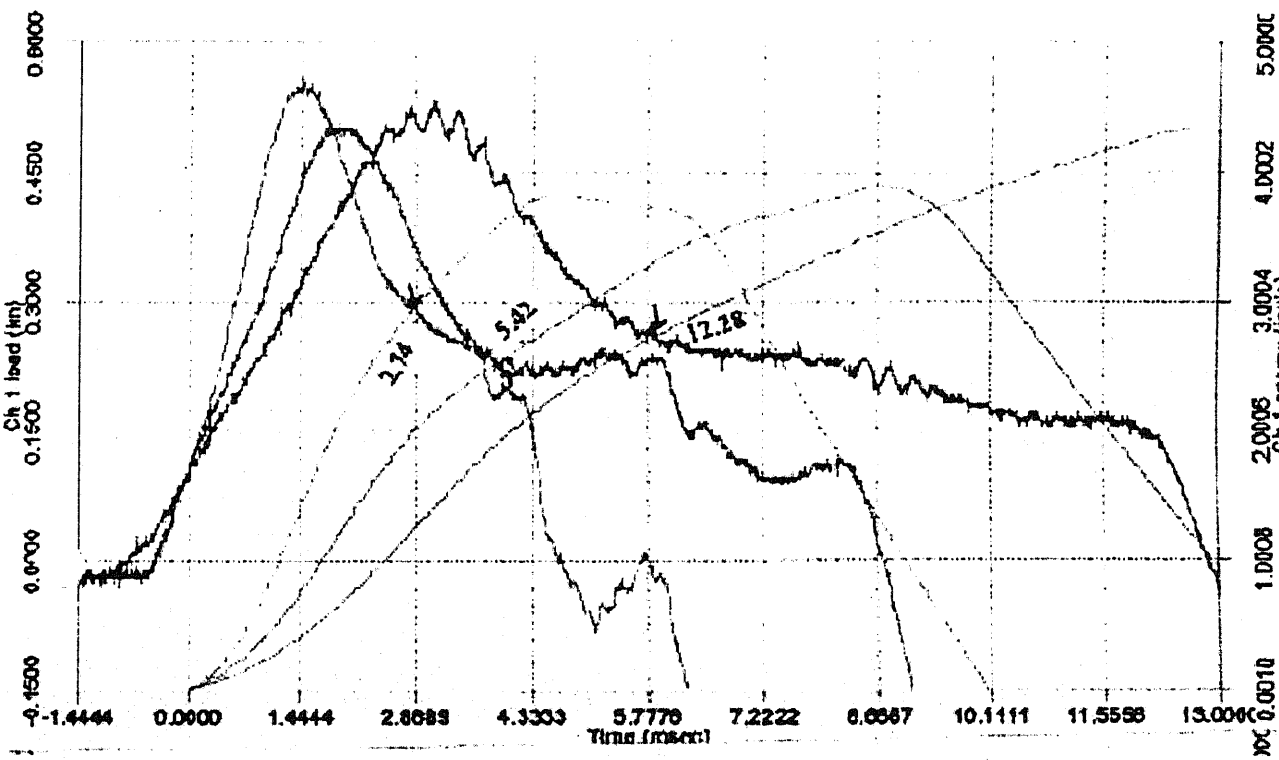


Figure 5: Load-Time-Energy Trace of 180 °C Cure Composite for Varied Impactor Mass (E_{in} – 5.3J, Drop Number- 85). Numbers on the Curve Indicate Impactor Mass in Kgs.

5. EVOLUTION OF THRESHOLD INCIDENT ENERGY (E^*_{in})

From the table 2, referring to 120°C cure composite, overlapping E_{in}-N_f plots for the three incident energies can be obtained as shown in figure 7. The threshold incident energy is the meeting point of the curves in the E_{in}-N_f plot (Refer figure 7) identified as E^*_{in}. Figure 8 shows the Threshold incident energy obtained for RT cure and 180°C cure composites. It can be observed that hot cured composites have higher threshold incident energies, meaning that they have better sustainability when subjected to impact. This threshold incident energy can be arrived at in the laboratory on any representative class of aircraft structure/ material by the above described experimental process.



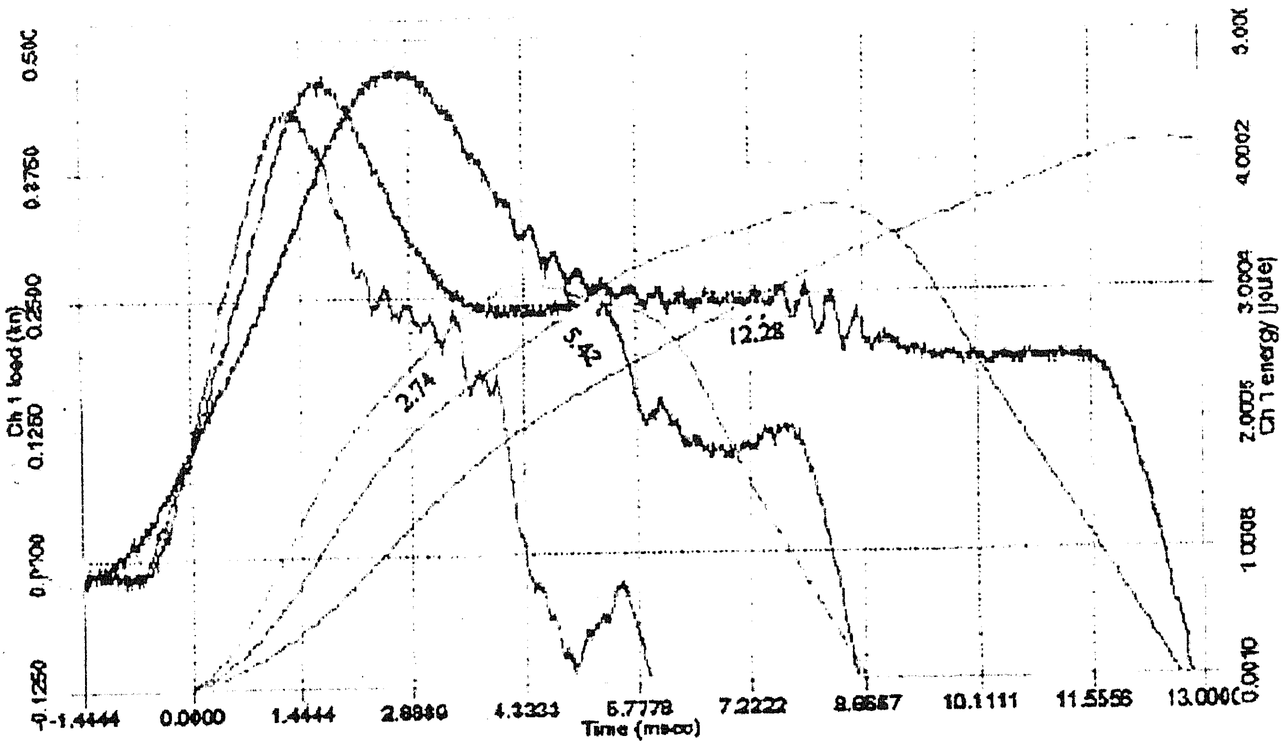


Figure 6: Load-Time-Energy Trace of 120 °C Cure Composite for Varied Impactor Mass (E_{in} – 11J, Drop Number- previous Page -10, Above : 15). Numbers on the Curve Indicate Impactor Mass in Kgs.

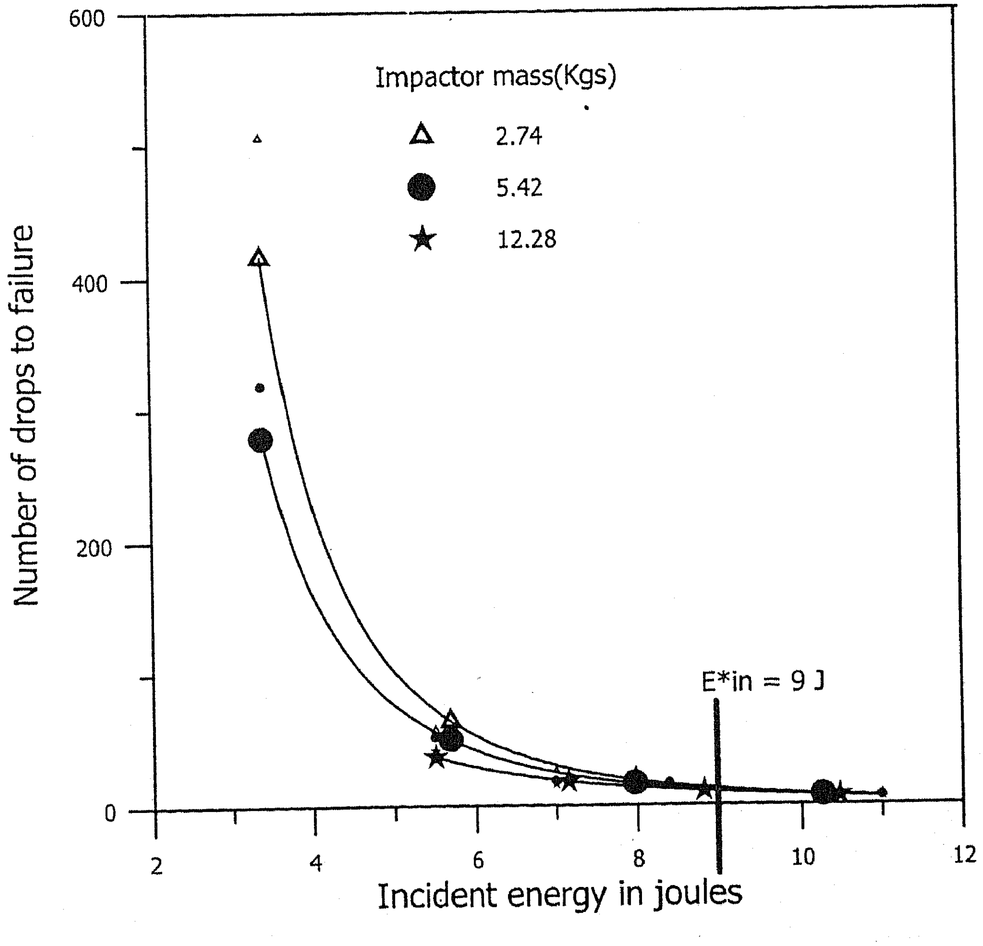


Figure 7: Identification of E^*_{in} in 120 °C Cure Glass-epoxy Composite

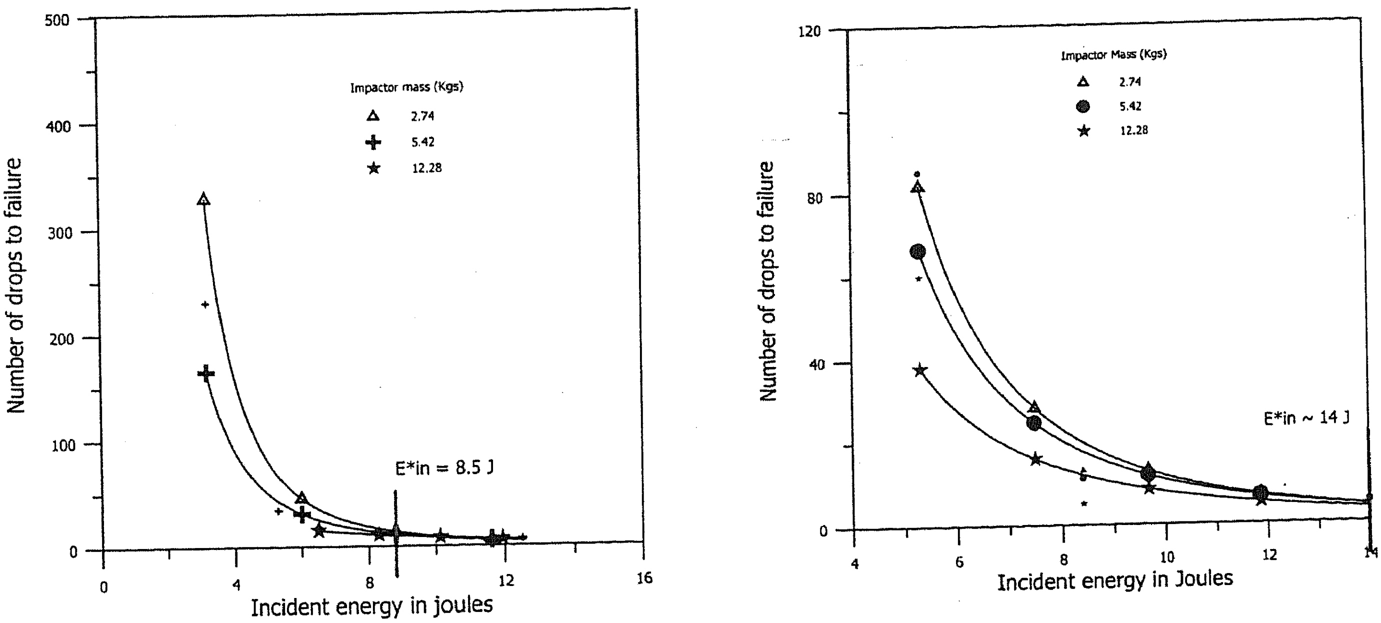


Figure 8: Identification of E^*_{in} in RT Cure(Left) and 180 °C(Right) Cure glass-epoxy Composite

6. SUMMARY AND CONCLUSIONS

This work has aimed at understanding the impactor mass effects in polymer composite materials using the concept of Repeated Drop Tests under low velocity test conditions. Highlights of impact damage tolerance assessment, experimental studies on glass-epoxy composites to understand impactor mass effects, identifying the threshold incident energy from E_{in}-N_f curves and finally, the practical significance of this research work has been put forth. Summarising, the following inferences are arrived at

- Impactor mass plays a pre-dominant role in impact damage of polymer composites. At very low incident energies, heavier impactors causes more damage leading to earlier failure. The effect wanes off with increasing incident energies.
- On a case-to-case basis, Threshold Incident Energy (E^*_{in}) can be identified, which demarcates the point below which impactor mass influences early damage and rapid failure of the composite.
- It is imperative that at low incident energies, impactor mass need to invariably be mentioned in all impact related experiments.

The crucial input that stems from this research study is that *"Preference need be given to the usage of lighter tools during routine service and overhauling of aircraft/ similar structures, so that they inflict minimum impact damage during work execution or accidental drops"*.

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