Resistance of Composite Laminates to the Initiation and Propagation of Delamination under Low Velocity Impact

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ABSTRACT

A key factor affecting the use of carbon fibre reinforced composite laminates is the low velocity impact (LVI) damage which may be introduced accidentally during manufacture, operation or maintenance of the component. Among the various failure mechanisms involved in the damage process, delamination is the dominant failure mode and may reduce the post-impact compressive strength of the component significantly. The resistances to delamination initiation and propagation of the material are key material properties for damage tolerance design of aerospace structures. This paper presents an experimental study of the resistance of composite laminates to delamination initiation and propagation under low velocity impact. The impact force history obtained from the instrumented drop-weight impact test is used to detect the delamination threshold load (DTL) which is a parameter representing the material resistance to the initiation of delamination. Repeated impact test is carried out to characterise the resistance to delamination propagation under LVI. Good damage tolerance capacity of the composite laminates is demonstrated by the observation that the peak impact force under the repeated impact is higher than the one under the first impact when the impact energy is kept the same. The multiple delamination initiated under the first impact may act as subsequent impact energy absorbers and help to stop the propagation of the delamination. The effect of delamination initiation on the damage tolerance capacity of the composite laminates should be investigated further for the design and application of composite materials in aerospace industry.

KEYWORDS: *low velocity impact, composite laminates, delamination threshold load*

1 INTRODUCTION

The desire to reduce structural weight has been the driving force behind the research and development of new technologies and materials in the aerospace industry. A popular and effective solution to the ever-demanding weight-saving requirement is to replace the conventional metal alloys with composite materials for aircraft primary structures. Compared with conventional metal alloys, composite materials have higher specific strength and specific stiffness due to their high strength, high stiffness, and low density. They can also be formed into virtually any shape and offer optimized mechanical properties through a combination of fibre, matrix and interface conditions. The overall structural weight of the aircraft can therefore be reduced without compromising the stiffness and strength of its structure by using composite materials. The further application is however restricted by the susceptibility of current fibre reinforced plastic system to low velocity impact (LVI) damage, which may cause significant strength reduction even if the damage is barely visible [1-6]. It is well recognized that the damage mechanisms of carbon fibre reinforced plastic material are more complicated than those of engineering alloys. This can be attributed to the inherent brittleness of both the carbon fibre and the matrix materials. Composite laminates absorb impact energy mainly through elastic deformation and damage mechanisms, not via local plastic deformation as most conventional ductile alloys do [5-6]. Delamination and matrix cracking are the dominant failure mechanisms which interact with each other and contribute up to 60% degradation in compressive strength of composite laminates even if the damage is barely visible [7-8]. This paper presents an experimental study to develop further knowledge on the resistance of composite laminates to delamination initiation and propagation under LVI, which is valuable to the design and application of composite structures in aerospace industry.

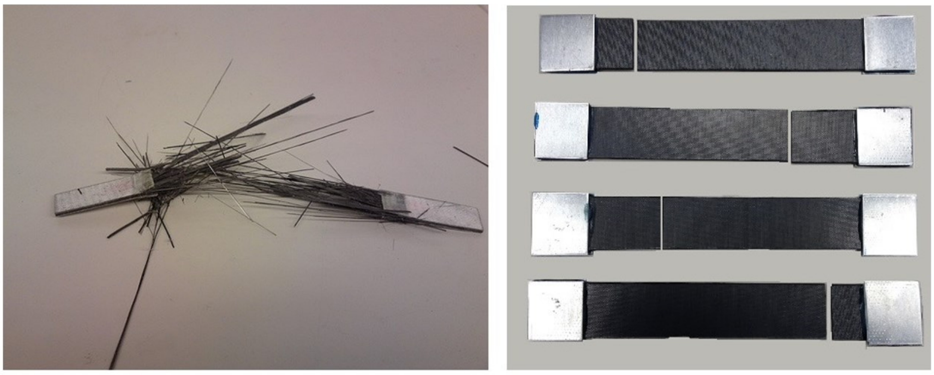
2. SPECIMENS PREPARATION AND EXPERIMENTAL PROCEDURE

2.1 Mechanical properties of the UD prepreg

The composite laminate is made of unidirectional (UD) carbon/epoxy prepreg *HexPly UD/M21/35%/268/T700GC/300* supplied by the Centre of Composites, Airbus UK. Test specimens were cured in an autoclave with curing temperature of 180°C and holding time of 120 minutes. Basic mechanical properties of the prepreg were determined with the electrical strain gauges on specimens prepared in accordance to the corresponding ASTM standards [9-11]. The tensile and in-plane shear material properties of the unidirectional materials are summarized in Table 1. Fig.1 shows examples of tested specimens for the determination of mechanical properties of the prepreg.

Table 1 Mechanical Properties of the UD prepreg.

Mechanical Properties	Notation	Test result
Longitudinal modulus (GPa)	E_1	132.0
Transverse modulus (GPa)	E_2	7.5
In-plane shear modulus (GPa)	G_{12}	4.2
Longitudinal tensile strength (MPa)	σ_{1t}	2117.0
Transverse tensile strength (MPa)	σ_{2t}	45.0
In-plane shear strength (MPa)	τ_{12}	85.0
Interlaminar shear strength (MPa)	ILSS	83.0
Major Poisson's ratio	ν_{12}	0.253
Minor Poisson's ratio	ν_{21}	0.0127



(a) (b)

Fig. 1 Examples of tested specimens under (a) longitudinal tensile test, and (b) transverse tensile tests.

2.2 Low velocity impact test

Table 2 shows the layup configurations of the instrumented drop-weight test for the study of the resistance to delamination initiation and propagation of composite laminates under LVI. Cross-ply laminates and quasi-isotropic laminates of thickness of 2mm and 4mm are used in the current study.

Table 2 Layup configurations for impact test specimens

Laminate thickness (mm)	Cross-ply layup	Quasi-isotropic layup
2	$[0/90_2/0]_s$	$[\pm45/0/90]_s$
4	$[0_2/90_3/0_2/90]_s$	$[\pm45/0_2/90_2/\pm45]_s$

Low velocity impact tests have been performed in accordance with the ASTM-D7136 [12]. Fig.2 shows the setup of the instrumented drop-weight impact test. The impactor used has a mass of 11.8 kg and a semi-spherical geometry with a diameter of 20 mm. The samples were clamped as prescribed by the ASTM standard with a supporting plate having a rectangular cutout of 75mm x 50mm. The impact force is determined through the pre-calibrated relation between the force and the strain of the impactor measured by strain gauges on the impactor surface. The impact force history is recorded by the Picoscope 3000 series oscilloscope

(a) (b)

Fig. 2 (a) Instrumented drop-weight test rig, and (b) base plate with the sample.

3. RESULTS AND DISCUSSION

The impact force history obtained during the low-velocity impact test provides important information regarding the resistance of composite laminates to delamination initiation and propagation. It has been documented by many investigators that the load drop in impact force history was associated with the stiffness reduction of laminate due to the initiation and propagation of delamination during the impact [1-6]. The first noticeable sudden drop of the impact force is defined as the delamination threshold load (DTL) which is a parameter representing the material resistance to the initiation of delamination. In this study, detailed impact force histories were obtained for the cross-ply and quasi-isotropic specimens under various impact energy levels following the test procedure as described in Section 2.2. The resistance to delamination propagation was investigated by conducting repeated impact on the same specimen at the same impact position and under the same impact energy level.

3.1 Initiation and propagation of delamination of cross-ply laminates under LVI

Fig.3 shows the first and repeated impact force histories of 2mm cross-ply specimens under various impact energy levels. No noticeable load drop can be observed to define the DTL of the laminate. It can be seen clearly that the repeated impact on the same specimen does not affect the impact duration. The repeated impact force history and the first impact force history are almost identical, especially under the relatively lower impact energy levels of 1J, 3J, and 6J. This indicates that little damage has been introduced into the laminate by the first impact under the relatively lower energy level, which can be explained by the fact that most of the impact energy is absorbed through the elastic deformation, not through the damage mechanism, in the thin laminate under the relatively lower impact energy level. It is however interesting to note that the maximum impact force has been increased by about 0.35kN (~8.7%) during the repeated impact under the relatively higher energy level of 9J. This is unexpected and tests were hence repeated. Similar results were obtained. This is associated with the introduction of impact damage under the relatively higher energy. The existence of the initial delamination and other damage types in the laminate affects the impact responses of the repeated impacts. As such, the information on the difference between the dynamic response of the first and the repeated impact can be used to identify the DTL level of the laminate.

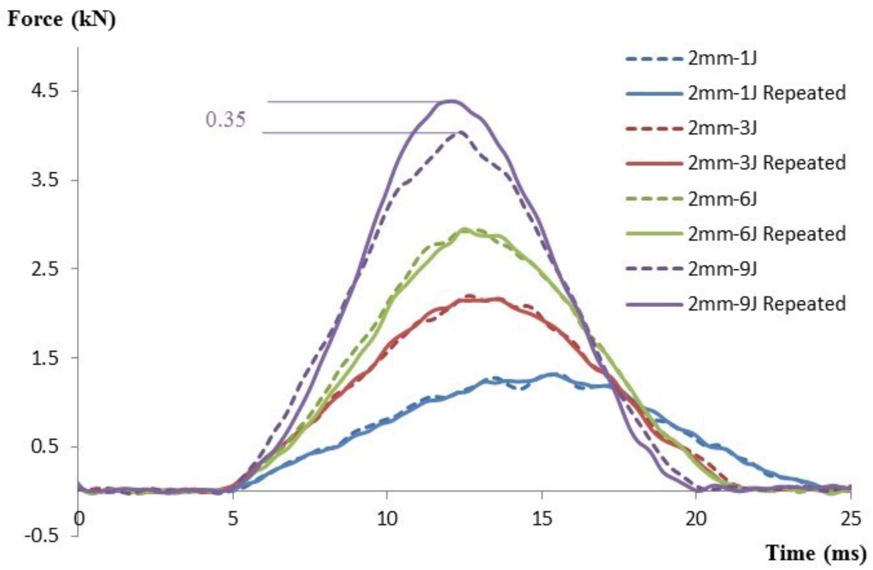


Fig. 3 First and repeated impact force histories of 2mm cross-ply laminate.

Fig.4 shows the first and repeated impact force histories of 4mm cross-ply specimens under various impact energy levels. Noticeable load drop occurs at about 4.3kN from the impact force histories of the first impact when the impact energy level is 6J and above. As such, 4.3kN is the DTL of the 4mm cross-ply laminate.

It can be seen clearly that DTL plays an important role in affecting the impact response of composite laminate under repeated impact. For the impact case under the 3J impact energy level, the maximum load of the first impact is less than the DTL value. There is no delamination initiated by the first impact. Similar to the observations from the 2mm specimens, the first and the repeated impact force histories are almost identical under the low impact energy of 3J. Clear difference between the first and the repeated impact force histories can be observed for the 4mm specimens when the delamination threshold load is exceeded during the first impact under higher impact energy level. Compared with the 2mm specimen results, it is noticed that the impact force curve of the repeated impact becomes smoother in terms of the impact history of the first impact, which could indicate that there is no propagation of the initial delamination caused by the first impact during the repeated impact under the same impact energy level.

Similar to the results of the 2mm specimen under high impact energy, the maximum impact force has been increased during the repeated impact when DTL level has been exceeded. Compared with those of the first impact histories, the maximum loads of the repeated impact histories under 6J, 12J, and 18J were increased by 0.61kN (~13.0%), 0.82kN (~12.5%), and 0.37kN (~4.4%), respectively.

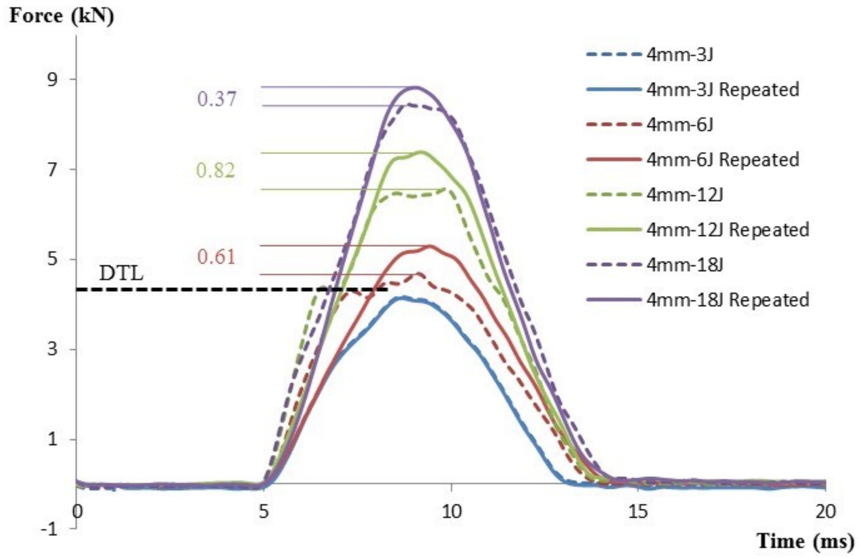


Fig. 4 First and repeated impact force histories of 4mm cross-ply laminate.

3.2 Initiation and propagation of delamination of quasi-isotropic laminates under LVI

The dynamic response of the cross-ply laminates under LVI varies with laminate thickness and is different between the first impact and the repeated impact when the peak force exceeds the DTL. To investigate this further, specimens with the quasi-isotropic lay-up configurations of $[\pm 45/0/90]_s$ (2mm) and $[\pm 45/02/902/\pm 45]_s$ (4mm) were tested under various impact energy levels.

Fig.5 shows the first and repeated impact force histories of 2mm quasi-isotropic laminate under various impact energy levels. It can be seen that the repeated impact force history fits well with the first impact force history, for the results of 3J and 6J impacts. This result further confirms that the delamination is hardly initiated in the thin laminate by the impact under the low impact energy due to the flexibility of the thin laminate. Severe damage has however been introduced under high energy impact, which occurs simultaneously with the initiation of the delamination. The severe damage causes significant reduction in the laminate stiffness. The increment in the maximum force of the repeated impact is around 0.35kN under impact energy of 9J. The specimen was significantly damaged by the first impact under the relatively high energy level (e.g. 12J). The maximum impact force of the repeated impact thus decreases as a result of the serious material degradation caused by the first and the second impacts. This is consistent with the results in Fig.4 where the increase of the peak force has been reduced to 4.4% under 18J impact energy compared with 13% increase under 6J impact energy and 12.5% increase under 12J impact energy.

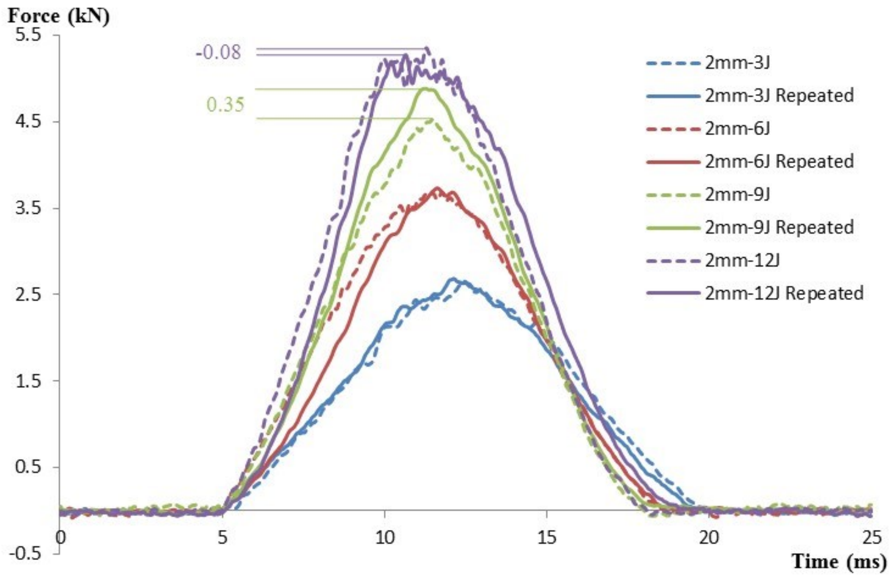


Fig. 5 First and repeated impact force histories of 2mm quasi-isotropic laminate.

Fig.6 shows the first and repeated impact force histories of 4mm quasi-isotropic laminate under various impact energy levels. The overall trend in the test result is similar to that from the 4mm cross-ply laminate. Noticeable load drop occurs at about 4.8kN from the impact force histories of the first impact when the impact energy level is 6J and above. As such, 4.8kN is the DTL of the 4mm quasi-isotropic laminate.

The correlation between the first impact force history and the repeated impact force history is dominated by the DTL value and the peak impact force of the first impact. If the DTL value has not been exceeded in the first impact, no initial delamination will be induced by the first impact. The damage resistance is therefore high enough and will prevent any further damage caused by the repeated impact under the same impact energy level and the repeated impact force history is very similar to the one of the first impact. If the maximum force of the first impact reaches the DTL value, the repeated impact force history will significantly deviate from the first impact force history. Similar to the observation from the cross-ply laminate, the load curve of the repeated impact is smoother than the first impact force history, which indicates that the damage introduced in the first impact is not further propagated during the repeated impact under the same energy level. The maximum impact force has been increased during the repeated impact when DTL level has been exceeded. Compared with those of the first impact histories, the maximum loads of the repeated impact histories under 6J, 12J, and 18J were increased by 0.61kN, 0.67kN, and 0.83kN, respectively. The increased peak force of the repeated impact force history also indicates that the load bearing capacity of the damaged specimen is not reduced by the repeated impact under the same energy level. In other words, the resistance of the delaminated laminate to further damage is actually improved or at least not reduced if the energy level of the repeated impact is not too high (below 18J for the 4mm quasi-isotropic laminate based on the current test data).

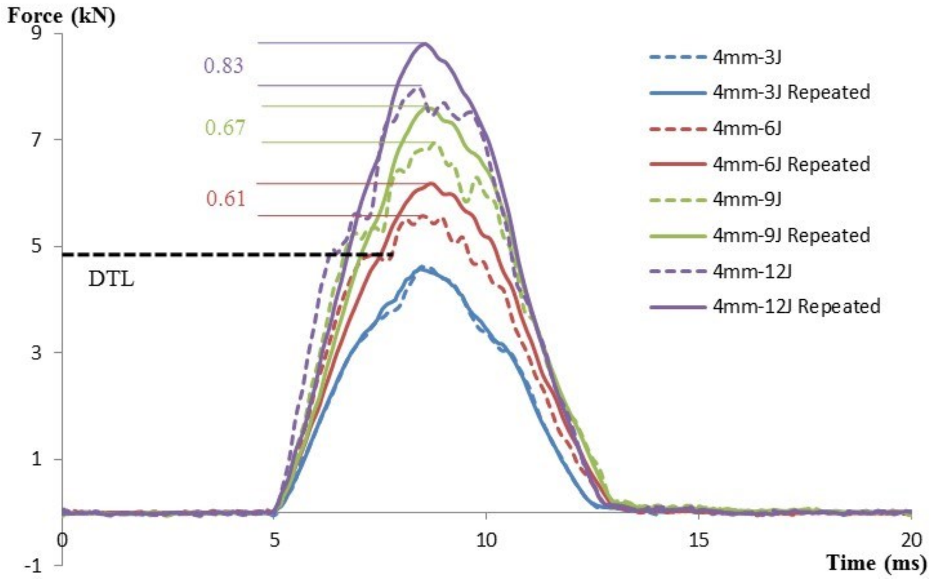


Fig. 6 First and repeated impact force histories of 4mm quasi-isotropic laminate.

Based on the results in Figs. 3-6, it has been observed that the resistance of the composite laminates to delamination initiation and propagation is dependent on the laminate thickness and layup configurations. The mechanism of absorbing impact energy is different between laminates of different thickness. The dominant energy dissipation mechanism in thin laminates is the elastic deformation. No noticeable load drop can be detected from the impact force history of the 2mm thick laminate while damages including delamination are easily visible under high impact energy. For thick laminate, the dominant energy dissipation mechanism is material damage including delamination with noticeable load drop of the impact force history during the impact. The resistance to delamination initiation is dependent on the layup of the laminate. The DTL of 4mm quasi-isotropic laminate is 4.8kN, which is 12% higher than the DTL (4.3kN) of the 4mm cross-ply laminate.

The impact force history of the repeated impact under the same impact energy is very similar to the one of the first impact when the impact peak force is below DTL. This is expected as the laminate is virtually undamaged during the first impact if the peak force is below DTL. An interesting observation is that the impact peak force of the repeated impact is consistently higher than that of the first impact when the impact peak force exceeds the DTL under higher impact energy. The increase of the peak force of the impact force history during the repeated impact is however unexpected as the initiation of the delamination during the first impact is generally believed to reduce the stiffness of composite laminate, which should lead to the reduction, rather than increase, of the impact peak force during the repeated impact under the same impact energy level. Another interesting observation of the test result is that the impact force history of the repeated impact under the same impact energy level becomes smoother than that of the first impact. This could be explained by the fact that the laminate is able to withstand the repeated impact without introducing any significant further delamination if the impact energy level is not too high. The elimination of the load drop in the impact force history of the repeated impact may thus cause a higher peak force compared with the one under the first impact when load drop occurs due to the initiation of delamination.

It is interesting to note that the composite laminate tested in the current study demonstrated a good damage tolerance capacity by resisting the propagation of delamination after the initiation of delamination. This could be explained by the fact that the existence of the initial delamination acts as additional sources for impact energy absorption and hence improves the damage tolerance of composite laminate under the repeated impact. The initial delamination, as a small gap at the interface of laminas with different fibre orientations, may improve the flexibility of the original brittle composite laminate and provide additional sources to absorb impact energy. The global deformation of the laminate under the repeated impact will be greater due to the initiation of delamination that will absorb extra impact energy. Additional energy will also be required to open the delamination area to a critical level before the delamination can be propagated. Hence, it makes the delamination difficult to propagate during the repeated impact under the same energy level. In other words, the increased peak force in the repeated impact force history is not caused by the increased laminate stiffness, but by the improved damage tolerance of the delaminated laminate.

The fact that all the specimens show different impact force history under repeated impact when the peak force exceeds the DTL has provided an alternative technique in detecting DTL. Repeated impact test could be carried out under different energy levels to determine at which level the impact force history starts to deviate from the one of the first impact. The peak impact force under this particular energy level should be the one close to DTL. This technique is particularly useful for thin specimens in which load drop phenomenon is not clear from the impact force history as mentioned earlier. A carefully designed repeat impact test will therefore enable the researcher to capture the DTL value of the laminate, at least the upper bound of the DTL.

4. CONCLUSIONS

Following conclusions can be drawn on the basis of above experimental results:

- The resistance of the composite laminates to delamination initiation and propagation is dependent on the laminate thickness and layup configurations. The DTL corresponding to delamination initiation can be detected from the load drop of the impact force history of thick laminates. No noticeable load drop can be observed for thin laminates even though the laminate is clearly damaged. This is associated with the difference in absorption mechanism of impact energy between thin laminates and thick laminates.
- The layup configuration of the composite laminate has a large effect on the resistance to delamination initiation. The DTL of 4mm quasi-isotropic laminate is 4.8kN, which is 12% higher than the DTL (4.3kN) of the 4mm cross-ply laminate.
- It has been observed that the impact force history of the repeated impact under the same impact energy level becomes smoother and the peak force of the repeated impact is consistently higher than that of the first impact when the impact peak force exceeds the DTL. This indicates that the laminate is able to withstand the repeated impact without introducing any significant further delamination if the impact energy level is not too high. The elimination of the load drop in the impact force history of the repeated impact leads to the increase of the impact peak force. The composite laminates tested in the current study demonstrate good damage tolerance capacities by resisting the propagation of delamination after the initiation of delamination.
- The difference in impact force histories between first impact and the repeated impact when the peak force exceeds the DTL has provided an alternative technique in detecting DTL of thin laminates where no noticeable load drop can be observed.

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