Contact Behaviour of Composite Laminate under Quasi-Static Indentation Load

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Abstract. A viable solution to the ever-demanding weight-saving target in aerospace industry is the replacement of conventional engineering alloys with composite materials in primary structures. A major concern to the effective use of composite laminates is the substantial reduction in the compressive strength when the contact force has exceeded the delamination threshold load (DTL). This paper focuses on the study of the contact behavior of composite laminates under quasi-static indentation (QSI) forces. The effect of damage initiation and growth on contact behavior has been investigated via detailed assessment of the relation between the indentation force and the dent depth. Different phases corresponding to undamaged, local damage, global damage, and final failure of the laminate have been identified. A modification to the classical Hertz contact law has been proposed to account for the matrix material resistance to plastic deformation.

Introduction

Composite material has been widely used to replace the conventional metallic material for aircraft primary structures due to its higher specific stiffness and strength. The further application is however restricted by the susceptibility of current carbon-fibre/epoxy system to low velocity impact (LVI) damage, which may cause enormous strength reduction [1-4]. 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 can absorb impact energy mainly through elastic deformation and damage mechanisms, not via local plastic deformation as most conventional ductile alloys do [5]. 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 [6-7].

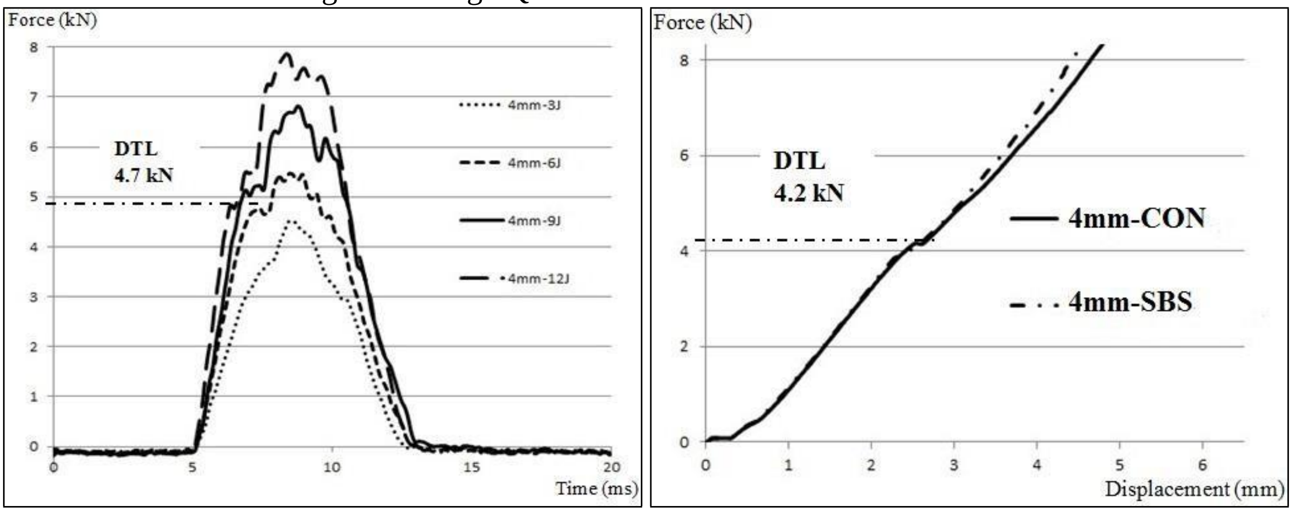
This paper presents a study of the contact response of composite laminates through a series of instrumented quasi-static indentation tests. The indentation force and dent depth are measured carefully to characterize the damage process of the composite laminate. A main focus of the study is the effect of the dent depth on the damage initiation and propagation.

Experimental Procedure

It has been reported that LVI tests can be approximated by the QSI tests [6, 8-9]. QSI tests can significantly reduce the number of samples in getting the contact force/dent depth data. In the present study, a series of instrumented indentation tests had been carried out using ASTM D6264-98 test standard [10] to characterise the damage resistance of the composite laminate. The unidirectional material is the carbon/epoxy prepreg *HexPly UD/M21/35%/268/T700GC/300* supplied by the Centre of Composites, Airbus UK. Layup configurations of $[\pm45/0/90]_s$, $[\pm45/0_3/90]_s$, and $[\pm45/0_2/90_2/\pm45]_s$ corresponding to laminate thicknesses of 2mm, 3mm, and 4mm were cured in an autoclave with curing temperature of 180°C and holding time of 120 minutes. The indentation force was applied to a hemispherical indenter of a diameter of 20mm under the displacement control of 2mm/min. Two loading approaches were used during the test. In a continual loading approach, indentation force was applied continuously until the final failure of the specimen. In a step-by-step loading approach, the specimen was loaded up to the predetermined level and then unloaded to measure the dent depth. The process was repeated for different load levels until the final failure of the same specimen.

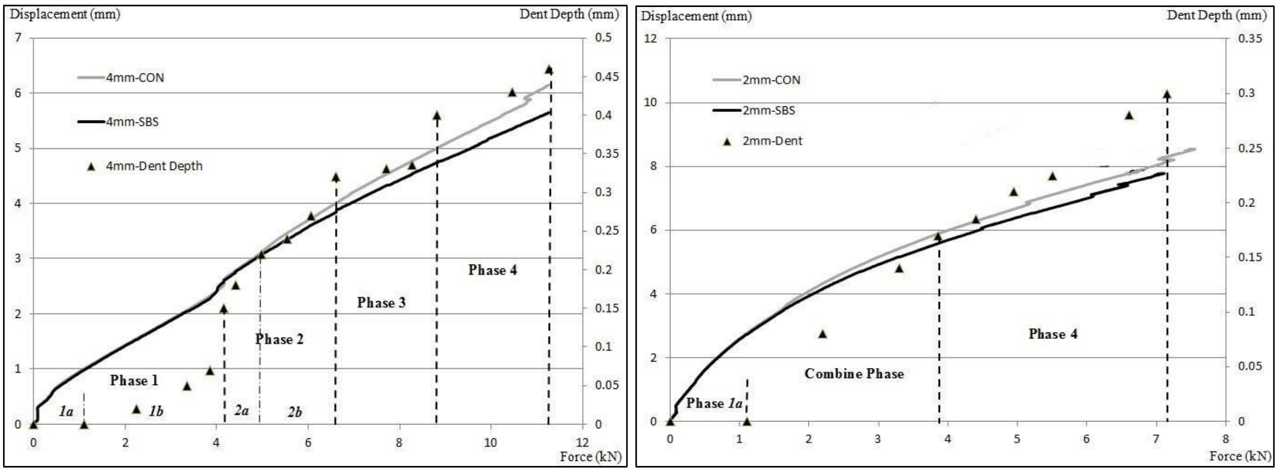
Results and Discussions

The concept of delamination threshold load (DTL) is well documented [5-7]. The DTL is linked to the first sudden load drop in the impact force history associated with the delamination initiation. Fig. 1(a) shows the filtered impact load historie under different impact energy levels. The DTL value for the 4mm laminate is about 4.7kN. Fig. 1(b) shows the contact force versue displacement curves obtained under both the continual loading approach and the step-by-step loading approach. The solid line in Fig. 1(b) represents the test results from the continual loading approach. The dotted line represents the overall loading curve by piecing together all the individual load curves under different loading levels in the step-by-step loading approach. The existence of the knee point is clear in both curves in Fig. 1(b) and the DTL so obtained is around 4.2kN, which is close to the value determined in LVI tests. The 10% difference is considered acceptable due to the complexity in determining the DTL. The result demonstrates that the contact behaviour of composite laminates under LVI can be investigated through QSI tests.



(a) (b)

Fig. 1 4mm thick laminate: (a) LVI test result; (b) QSI test result.

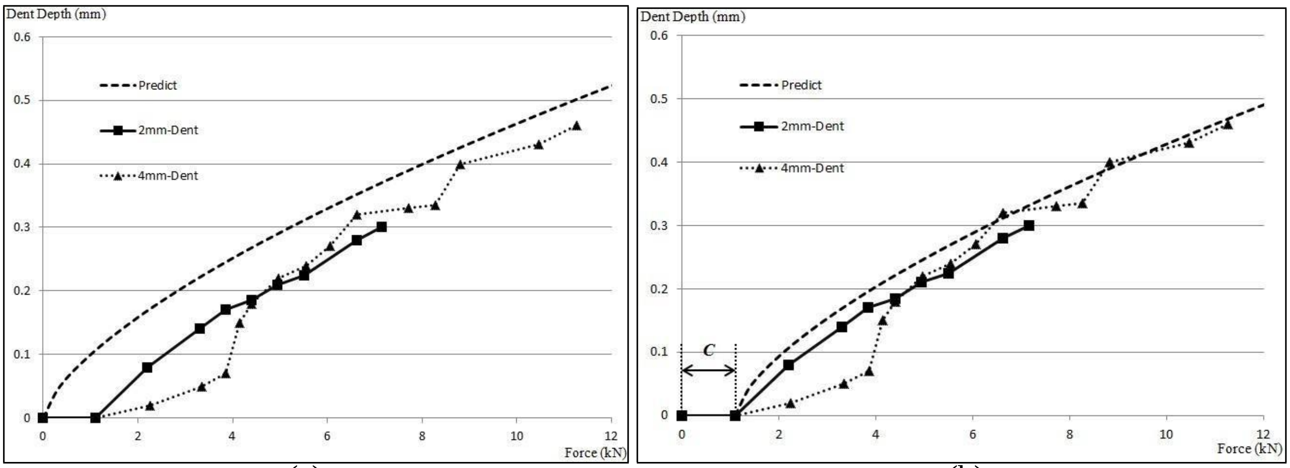


(a) (b)

Fig. 2 Indentation force *vs.* dent depth /displacement: (a) 4mm laminate and (b) 2mm laminate.

Fig. 2(a) shows the QST test results of the indentation force against the dent depth and the indenter displacement of the 4mm laminate. In general, the dent depth increases as the indentation force increases to its maximum. The rate of increase in the dent depth is quite different over the whole loading regime. The whole indentation response of the 4mm laminate can be divided into four phases corresponding to undamaged, local damage, global damage, and final failure, respectively. The first undamaged phase can be further divided into two sub-phases. When the indentation load is less than a certain level, which is about 1kN for the 4mm laminate, the matrix material resistance to plastic deformation is high enough to prevent any damage. There is no detectable dent in Phase 1a

as a result. Phase 1b has the indentation load greater than 1kN in which the contact stress exceeds the yielding stress of the matrix in the upper layer. The dent depth increases linearly with the indentation force but has no direct influence on the overall peformance of the laminate in this phase. Phase 2 is the phase when the local damage including the delamination initiation and local growth has been introduced in the laminate. Phase 2a is the sub-phase when delamination is initiated after the DTL value has been exceeded. The local stiffness under the indenter has been significantly reduced due to the initiation of local matrix cracking and delamination, which explains the sharp increasing in the dent depth in Phase 2a. The damage is accumulated stably in Phase 2b and the delamination has been extended from a local region under the indenter to the whole laminate. Phase 3 is the global damage phase which shows a plateau in the dent depth measurement. This phenomenon can be linked to the global stiffness reduction triggerd by the cumulative damage from previous stage. The reduction in global stiffness makes the laminate more flexible which will increase the contact area between the indenter under the same dent depth. This explains the plateau of the dent depth under the increase of the indentation load. Phase 4 is the final phase in which the matrix is extensively damaged under the indenter. Widespread carbon fibre breakage has been observed after losing the protection from the matrix, which is the indication of the final failure.
Fig. 2(b) shows a similar study of the 2mm laminate. It is found that the contact behaviour of the thinner sample is different from that of 4mm thicker specimen. The damage process of the 2mm laminate can be separated into three phases. The first phase is same as the first sub-phase of the 4mm laminate. The matrix material resistance to the plastic deformation is high enough to prevent any damage in this phase. No dent has been introduced in this phase as a result. It is however worth noting that the proportion in energy absorption due to the delmination in thinner laminates is relatively small compared with thick laminates [5]. As a result, the effect of delamination initiation on the contact behaviour of the 2mm thin laminate is less obvious compared with that of the 4mm laminate. Consequently, the second phase of the 2mm laminate is actually a combination of local and global damage phases as in the response of the 4mm laminate. The final phase of the 2mm laminate is the same as that of the 4mm laminate in which widespread fibre breakage and severe delamination occur after the fibres losing the protection from the matrix.
Yang and Sun [11] proposed a Hertz contact law based empirical relation between the contact force, F, and the indentation depth α: $F = k\alpha^{1.5}$ (1) The Hertzian contact stiffness k is determined by: $k = \frac{3}{4}\sqrt{R}\,E_3$ (2)
where E_3 is the Young's modulus of the top layer in the thickness direction which is 7.52GPa for the laminate tested. R is the radius of the rigid spherical indenter which is 20mm.



(a) (b)

Fig. 3 Comparison between QSI test results and (a) Hertzian contact law, (b) modified contact law.

Fig. 3(a) shows the comparison between the QSI test result and the prediction from the classic Hertzian contact law. There is a large discrepency between the test and the prediction results. Both test results of the thin and thick laminates are shifted to the right by a certain value of around 1kN.

This value is independent of laminate thickness and can be treated as a constant depending on the matrix material property of the upper layer. The relation between the contact force and the indentation depth can therefore be modified as: $F = k\alpha^{1.5} + C$ (3)

Fig. 3(b) shows the comparison between the QSI test results and the prediction from the modified contact law. Eq. 3 has a good agreement with the test results of the 2mm laminate. For the 4mm laminate, there is however a noticeable difference between the prediction and the test result when the indentation force is below 4.5kN. The complex interactions among various damage mechanisms for the thick laminate can be the reason for the discrepancy. Further detailed investigation is required to improve the prediction.

Conclusions

Contact behavior of composite laminates has been investigated through a series of instrumented quasi-static indentation tests. Following conclusions can be drawn from the results:

- Contact behavior of composite laminates under LVI can be obtained through the quasi-static indentation test. DTL can be determined from the curve of the indentation force versus the displacement of the indenter.
- Contact process can be separated into a number of phases corresponding to different damage status of the laminate. The effect of damage initiation and growth on contact behavior of the laminate is dependent on its thickness.
- A modification to the classical Hertz contact law has been proposed to account for the matrix material resistance to plastic deformation. Modified contact law agrees well with the QSI test result of the laminate of 2mm thickness. Further investigation is required to improve the prediction result further for the laminate of 4mm thickness.

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