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Correlation of Dent Depth to Maximum Contact Force and Damage of Composite Laminates

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Abstract. A major concern affecting the efficient use of carbon fibre reinforced composite laminates in the aerospace industry is the low velocity impact damage which may be introduced accidentally during manufacture, operation or maintenance of the composite structures. It is widely reported that the contact behavior of composite laminates under low-velocity impact can be obtained under quasi-static loading conditions. This paper focuses on the study of the correlation of the dent depth to the maximum contact force and damage of composite laminates under quasi-static loading. Analytical and finite element simulation approaches were employed to investigate relations between the contact force and the dent depth. Experimental investigations on the correlation between dent depth, maximum contact force and damage include quasi-static indentation testing, optical and scanning electron microscopic examination of the damage under different loading levels. The effect of damage initiation and growth on the contact behaviour has been discussed. Results show that consistent correlations between the dent depth, maximum contact force and damage exist and can be predicted with the analytical and numerical approaches. Dent depth can be used as an engineering parameter in assessing the severity of damage for composite structures that are subjected to low-velocity impact. This may lead to the development of a cost-effective technique for the inspection and maintenance of composite structures in aerospace applications.

Introduction

Composite laminates have been increasingly used to replace conventional metal alloys for aircraft primary structures to meet the ever-demanding weight-saving challenge in the aerospace industry. This can be attributed to their higher specific stiffness/strength and the unique design capacity of forming into virtually any shape and offering optimized mechanical properties through a combination of fibre, matrix and interface conditions. A major concern affecting the more effective use of composite laminates is the substantial reduction in the structural strength due to the low-velocity impact which can be introduced accidentally during the manufacture, operation or maintenance of composite structures [1-6]. This can be attributed to the inherent brittleness of both the carbon fibre and the epoxy matrix materials which can only absorb impact energy through elastic deformation and damage mechanisms, not via plastic deformation as most conventional ductile alloys do. 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 [7-8]. It is therefore important for the industry to identify some parameters which can not only be used to predict the damages but also be measured easily in real life engineering applications.

This paper presents a study of the correlation of the dent depth to the maximum contact force and damage of composite laminates under quasi-static loading through analytical, numerical and experimental investigations. Efforts are made to assess the feasibility of using dent depth as an engineering parameter in assessing the severity of damage for composite structures that are subjected to low-velocity impact. This may lead to the development of a cost-effective technique for the inspection and maintenance of composite structures in aerospace applications.

Approaches

Dent depth has been chosen as the potential engineering parameter in assessing the severity of damage for composite structures subjected to low-velocity impact. It has been reported that contact behaviour of composite laminates under low-velocity impact can be obtained through the quasi-static indentation tests [7, 9-12]. In the present study, quasi-static indentation tests performed under ASTM D6264/D6264M-12 test standard [13] have been used to reduce the number of samples in establishing the relation between the indentation force and the dent depth. 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 $[\pm 45/0/90]_s$ and $[\pm 45/0_2/90_2/\pm 45]_s$ corresponding to laminate thicknesses of 2mm 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 semispherical indenter of a diameter of 20mm under the displacement control of 2mm/min. Fig.1(a) shows the set-up of the quasi-static indentation test with no composite laminate between the semi-spherical indenter (above the laminate) and the dial gauge (below the laminate). The total dent depth under the indentation force is the difference between the displacement of the indenter and backface deflection of the composite laminate measured by the dial gauge.

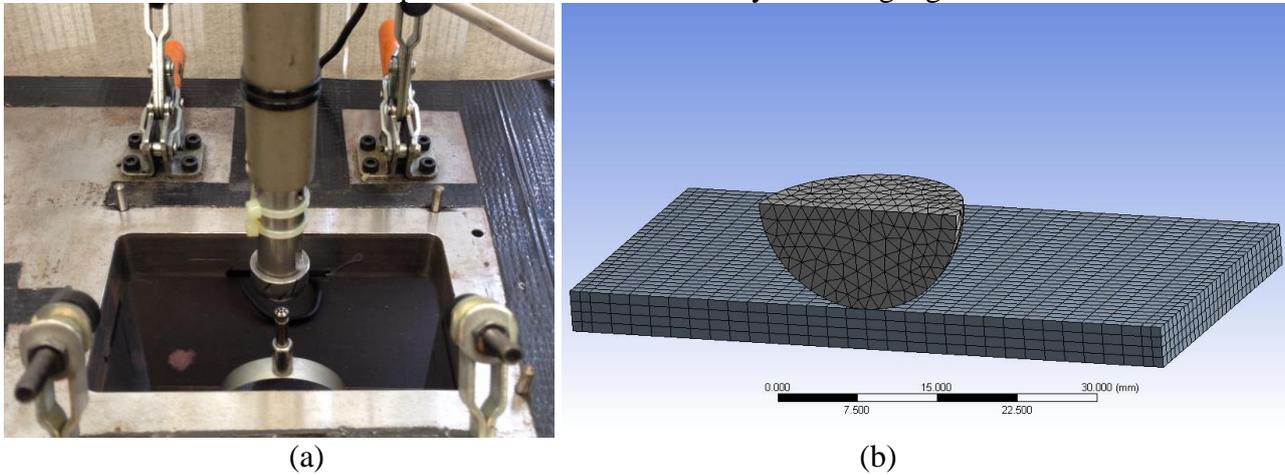


Fig.1 (a) Set-up of the quasi-static indentation test (no laminate shown), (b) finite element model.

It has been reported that the material behaviour of the composite laminate in the transverse direction is governed by the properties of the matrix [14-15]. Permanent deformations are introduced when the indentation exceeds a critical value associated with the laminate thickness and properties of the matrix material. Fig.1(b) shows the finite element model used to simulate the indentation of the same composite laminate under the indentation force with the commercial software ANSYS R14.5. Considering the fact that indentation is a local phenomenon, the layer of the matrix material of the same thickness as that of the composite laminate has been bonded to a rigid substrate.

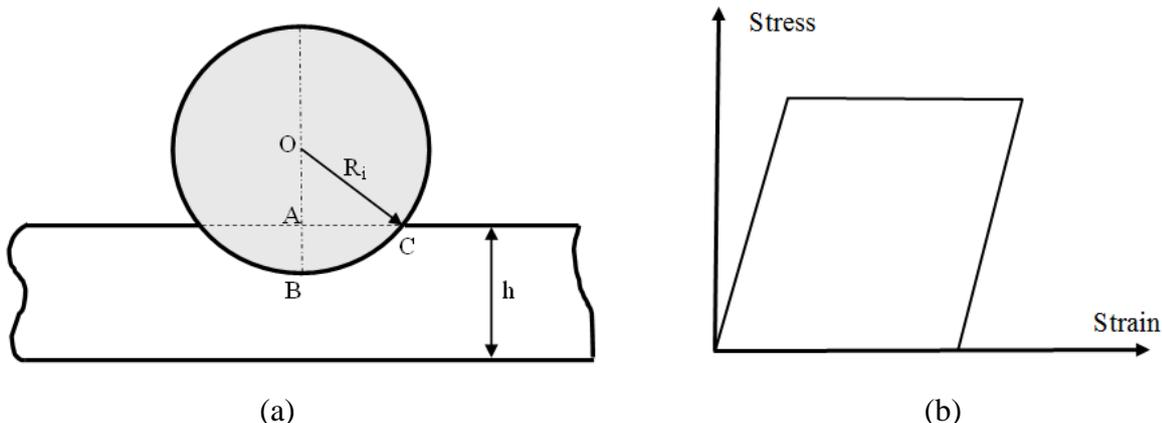


Fig.2 (a) Analytical model for the prediction of the indentation, (b) stress-strain relation for a simple elastoplastic analysis.

Fig.2(a) is a schematic illustration of the analytical model to carry out the simple analytical prediction of the indentation of a composite laminate under the indentation force. Similar to the finite element simulation, the properties of the matrix material has been used for the layer of material bonded to the rigid substrate [14-15]. The material is first assumed to deform elastically until a critical indentation is reached. The contact area is then divided into a plastic zone immediately under the indenter and an elastic zone as the loading increases. A simple elastic-perfectly-plastic stress-strain relation is assumed for the matrix material. The relation between the dent depth and the indentation force acting on the composite laminate is derived based on the force equilibrium analysis.

Results and Discussions

Fig.3 shows the correlation between the dent depth and the indentation force obtained from the finite element simulation, quasi-static indentation test, and the analytical prediction. Similar trends have been observed between the 2mm thick laminate (Fig.3(a)) and the 4mm thick laminate (Fig.3(b)). The simple analytical model overestimates the dent depth compared with the results measured from the quasi-static indentation test. The finite element simulation results agree well in general with the quasi-static indentation test results but fail to capture some key points representing different phases of damages identified in previous work [10].

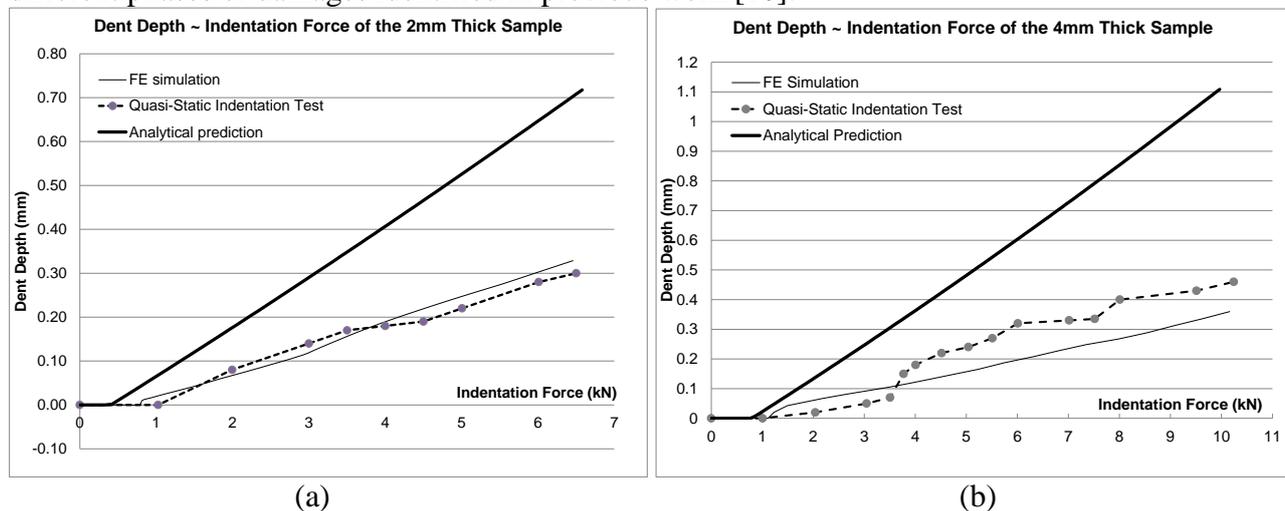


Fig.3 Dent depth versus indentation force of: (a) 2mm thick laminate, and (b) 4mm thick laminate.

It is however worth noting that both the analytical approach and the numerical simulation show great potential in predicting the dent depth for composite laminates under low-velocity impact. This is due to the fact that a very simple material model has been used for the material properties of the laminate in the current study. The results from the analytical and numerical simulation approaches can be improved significantly when more advanced material models are introduced. More realistic stress-strain curve for the material should be used for the matrix material. The reinforcing effect of the fibre to the matrix material in the transverse direction should be accounted for properly to improve the prediction results. Furthermore, the effect of damages at different phases identified in [10] has to be considered properly in the model in order to link the dent depth to the severity of the impact damage. Fig.4 shows the through-thickness damages of the 4mm thick composite laminate under 8kN indentation force. Fig.4(a) shows the dent depth/profile at the top surface of the laminate obtained with the optical microscope. Fig.4(b) shows the distribution of matrix cracking and delamination obtained with scanning electron microscope. It is clear that matrix cracking interacts with delamination and this failure sequence needs to be modelled properly to predict the material behaviour of composite laminates under low-velocity impact.

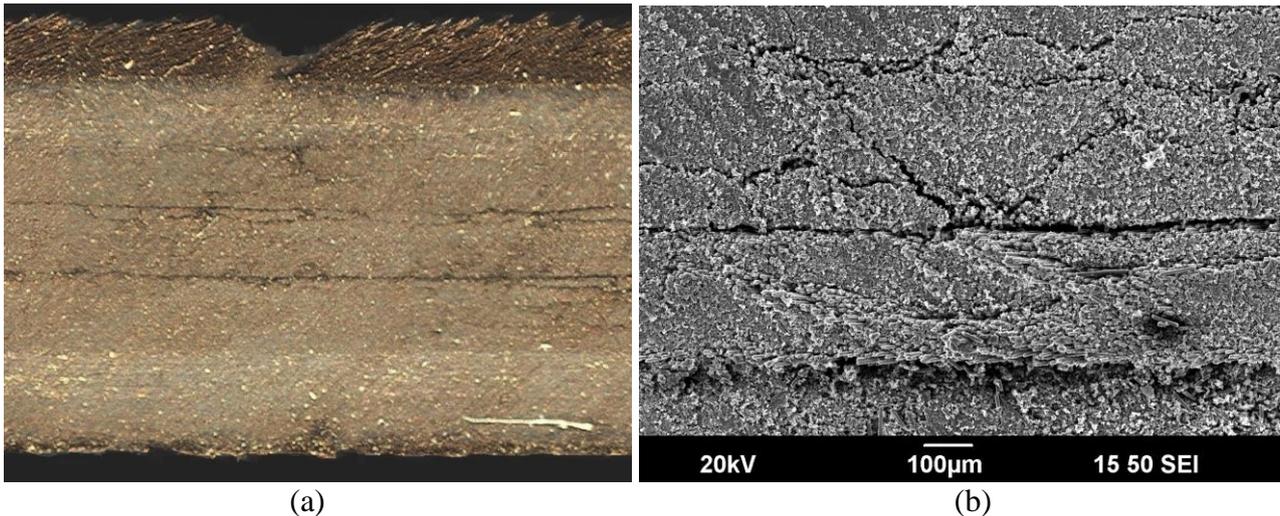


Fig.4 (a) optical microscopic observation of damage, (b) scanning electron microscopic observation of damage.

Conclusions

Relations between the dent depth and the indentation force have been investigated through quasi-static indentation test, finite element simulation, and analytical analysis. Following conclusions can be drawn from the results:

- Dent depth can be used as the engineering parameter in assessing the severity of damage for composite structures that are subjected to low-velocity impact.
- Analytical and numerical approaches can be used to correlate dent depth to the maximum contact force and damage level when more advanced material models are used.

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