Composite Structures 147 (2016) 25–32

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

An investigation of the damage tolerance of carbon/Benzoxazine composites with a thermoplastic toughening interlayer

N.H. Nash, T.M. Young, W.F. Stanley *

Irish Centre for Composites Research (IComp), Materials and Surface Science Institute (MSSI), University of Limerick, Castletroy, Co. Limerick, Ireland

ARTICLE INFO

Article history:
Available online 09 March 2016

Keywords:
Benzoxazine
Out of autoclave
Damage tolerance
Toughening
Impact damage

ABSTRACT

The results of an experimental analysis of the damage tolerance of carbon/Benzoxazine laminates subjected to a 30 J impact, compression after impact (CAI) and open-hole compression (OHC) are presented herein. Four configurations of quasi-isotropic laminate with interlaminar polyamide (PA) fibre veils are studied. Damage areas were examined using X-ray imaging and micro-computed tomography (μCT). It was found that interlaminar veils decreased damage area by up to 36% for a 30 J impact. The veils, however, caused the formation of long, cylindrical voids due to retention of the resin within the veils which did not permit percolation into the fibre tows. Despite this, the veils increased the CAI strength from 45% of the undamaged compressive strength to 64%. The OHC response of three types of laminates was found to compare well with commercially available carbon/epoxy systems qualified for use in aircraft structures, but was not significantly affected by the interlaminar veils.

1. Introduction

The use of carbon fibre reinforced polymers (CFRPs) in primary aircraft structures can often be limited by the poor impact performance that is exhibited by laminates with a thermosetting matrix. This is particularly problematic for damage caused by low-velocity impacts (e.g. a tool dropped during maintenance, repair and operations) as impact loads often induce considerable subsurface damage (matrix cracks, fibre/matrix debonding and delamination) in composite laminates, with very limited visible surface damage [1], which can considerably reduce structural performance. Impact damage is mostly a concern for compressive properties, as delaminations and fibre–matrix debonding makes the laminate more susceptible to failure due to buckling. The compressive strength of CFRPs that have been subjected to an impact is, therefore, a minimum performance requirement for their selection as structural materials – hence the concept of damage tolerance. Damage tolerance is vital for aircraft structural materials in order to ensure safe operation of the aircraft; a composite structure must maintain its structural performance despite the presence of damage that is not easily identifiable on the surface in order to be considered damage tolerant.

Damage tolerance of a structure is largely influenced by its damage resistance, i.e. its ability to withstand the formation of damage. Damage resistance and damage tolerance are two important aspects of a composite material's structural performance, as a structure that is damage resistant and damage tolerant will require fewer repairs and will contribute to the safer operation of the aircraft. There have been many experimental investigations [2–9] into, and numerical simulations [10–16] of, the formation of impact damage and the role that this damage plays in the post-impact structural performance [17–22] of composite laminates. It is known that low velocity impacts cause barely visible impact damage (BVID) which consists of matrix cracking, delaminations and fibre/matrix debonding that is not visible on the surface. Davies and Zhang [23] commented on the nature of delaminations after an impact as resembling a characteristic peanut shape with varying orientations at different interfaces resulting in a spiral effect. Delaminations can be quite large near the back face of the laminate due to the large flexural stresses caused by bending of the laminate. Bull et al. [21] observed that impact damage consists mostly of matrix cracks and two key types of delaminations: delaminations that are confined between two matrix cracks of the same orientation and delaminations that grow away from the impact site, constrained at the interface between two matrix cracks 45° apart. These 45° delaminations form a "spiral staircase" of damage around an undamaged cone of material directly below the impact site and are particularly significant for subsequent compressive behaviour. Delaminations that propagate into the undamaged cone during compressive loading increase the unsupported length of the sub-laminates, and hence increase the likelihood of failure due to buckling of the sub-laminates [21]. Therefore,

* Corresponding author.
E-mail address: walter.stanley@ul.ie (W.F. Stanley).

http://dx.doi.org/10.1016/j.compstruct.2016.03.015
0263-8223/

toughening systems which prevent the propagation of delaminations during an impact and subsequent compressive loading into the undamaged cone have a clear advantage in improving the damage tolerance of a composite laminate. However, the increased toughness of a matrix system that suppresses delamination to a large extent can result in fibre fracture due to the high tensile stresses on the rear surface of the laminate. This could cause detrimental reductions in both residual tensile and compressive strengths, therefore tough matrix systems should be used with high-strength carbon fibres in order to compensate for this change in damage mechanism.

The use of a third, toughening component within the composite has shown to be an effective method to increase the damage tolerance of composite structures [24]. The toughener can be incorporated in three different ways: through the thickness, in the matrix or at the interlaminar region. Through-thickness reinforcements include Z-pins and stitching; these mechanical reinforcements are inserted through the preform that have been shown to prevent the growth of delamination due to impact [25–28]. Unfortunately, this type of toughening method can reduce in-plane properties of the structure, for example in tension, due to fibre crimping and a risk of micro-cracks at the pins or stitches. Resin modification through the incorporation of thermoplastics to create a blend [29–33], rubber particles [34–38], block co-polymers [39,40] and hyper-branched polymers [41–44] is an effective way to increase the resistance to damage and improve subsequent mechanical performance. This type of toughening technique is suitable for use in prepreg materials as the resin is not required to flow large distances during consolidation of the laminate; therefore, any increase in viscosity does not significantly affect the final porosity of the finished component.

With the advent of out-of-autoclave (OOA) manufacturing techniques, which allows for composite part manufacture at increased volume and reduced cost, it is important to develop techniques that can ensure a cost-effective and damage tolerant structure. Liquid resin infusion (LRI) manufacturing is a term used to describe a group of manufacturing techniques that involves the introduction of a liquid resin into a dry fibre preform through the application of vacuum or positive pressure. These techniques require resins to maintain a low viscosity when a toughening technique is employed, to ensure ease of infusion. The use of thermoplastic fibres co-woven in the fibre preform that are soluble in the infusing resin is a technique used by Cytec to increase the damage tolerance of the laminate without altering the viscosity of the resin. Once the resin is infused, it interacts with the thermoplastic toughener to form a phase separated, toughened morphology. This concept is similar to the use of electrospun nano-fibres which are placed at the interlaminar regions of the preform, and interact with the resin once the resin has been infused. There have been many reported increases in damage tolerance and interlaminar fracture toughness (ILFT) using this technique [45–54]. A review of the inclusion of a thermoplastic phase to improve impact and post-impact performance of CFRPs is available in the literature [24].

One toughening technique that has been suggested as a low-cost method of improving the ILFT and damage tolerance of composites is the use of interlaminar veils. Impact tests have shown that carbon/epoxy prepreg laminates with interlaminar nylon fibrous veils contain less damage than baseline laminates [55]. Interleaving is observed to generate localised damage while the unmodified laminate experiences significant global damage suggesting that the fibrous veils contribute more to arresting damage propagation rather than preventing damage formation. Increases in compression after impact (CAI) strength, Mode-I ILFT and Mode-II ILFT have been reported without any concomitant reduction in other mechanical properties [56–63]. Interlaminar veils also offer the potential for multi-functionality in terms of increased conductivity, damping and as an aid for resin flow in LRI manufacture. However, despite the numerous benefits of this toughening technique, very few investigations have been conducted to fully understand its effect on the performance of the laminate. These investigations have generally been limited to carbon/epoxy laminates, and more studies are necessary to assess the effect of this toughening technique on the properties of laminates with other matrices. Benzoxazines, for example, have the potential to outperform epoxies in terms of cost-efficiency, hot-wet behaviour and damage tolerance; however, very little has been published on the use of Benzoxazine as a composite matrix.

The purpose of the current investigation is to quantify the effect of the incorporation of interlaminar thermoplastic veils on the impact and post-impact behaviour of carbon/Benzoxazine laminates. In order to assess this behaviour, undamaged compressive strength will be quantified using a combined loading compression (CLC) test method and damage tolerance will be assessed using the compression after impact (CAI) test. Damage areas will be measured using X-ray imaging and μCT imaging. This study intends to examine the damage that exists in the BVID region of damage. Therefore, the use of X-ray scanning, which requires the aid of a penetrant dye, is not completely reliable in generating images of the internal damage as inter-connecting cracks are not always present within the laminate. Finally, as CAI tests on toughened laminates are not representative due to the potential for a large variation in damage area (i.e. specimens may not be tested with the same degree of impact damage), the compressive strength of specimens with a centrally drilled hole will be also be studied using the open-hole compression (OHC) test.

2. Experimental

2.1. Materials

Carbon fibre laminates were manufactured using 0°/90° Non-Crimp Fabric (NCF), with an areal weight of 559 g/m^2, based on high tensile strength carbon fibres (TENAX® E HTS40 F13 12 K 800tex) supplied by Saertex GmbH (Germany). The resin is a commercially available Benzoxazine resin, developed specifically for use in liquid composite moulding technologies – Loctite® BZ9120 AERO – supplied by Henkel AG & Co. KGaA (Germany). To increase the damage tolerance of the laminates, thermoplastic veils are incorporated at the interlaminar regions. Non-woven PBN-II polyamide (PA) veils, with an areal weight of 34 g/m^2, supplied by Cerex Advanced Fabrics Inc. (USA) were used in this study. The PA fibres have a nominal diameter of 23 μm and the nominal thickness of the veils is 0.1 mm when cured within the laminate.

2.2. Laminate manufacture

Carbon/Benzoxazine laminates were manufactured using the double-bag Vacuum Assisted Resin Transfer Moulding (VARTM) process. Prior to resin infusion, the resin was degassed in a vacuum oven at 110 °C, 850 mbar (absolute) for two hours to remove any entrapped air. All PA veils were dried in a vacuum oven at 90 °C for one hour at 850 mbar to remove any moisture that may have been absorbed while in storage. The degassed resin was heated to the infusion temperature of 110 °C and infused using vacuum pressure through a heated inlet tube into the dry fabric preform, which was placed on a heated mould. The temperature of the mould was controlled using three proportional integral derivative (PID) controllers located under the mould. Once the infusion was complete, a second vacuum bag was placed over the infused area for the curing process. To cure the laminates, the tool was heated to 180 °C for a dwell time of 90 min.