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Influence of matrix toughness and ductility on the compression-after-impact behavior of woven-ply thermoplastic- and thermosetting-composites: A comparative study

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ABSTRACT

This study was aimed at comparing the residual compressive strength and behavior of TS-based (epoxy) and TP-based (PPS or PEEK) laminates initially subjected to low velocity impacts. Provided that the impact energy is not too low, the permanent indentation is instrumental in initiating laminates local buckling under compressive loadings. CAI tests revealed that matrix toughness is not the primary parameter ruling the damage tolerance of the studied materials. However, matrix ductility seems to slow down the propagation of transverse cracks during compression thanks to plastic micro-buckling which preferentially takes place at the crimps in woven-ply laminates. It could therefore justify why the matrix toughness of TP-based laminates does not result in significantly higher CAI residual strengths. Finally, the compressive failure mechanisms of impacted laminates are discussed depending on matrix nature, with a particular attention paid to the damage scenario (buckling and propagation of 0° fibers failure).

1. Introduction

Low velocity impact is one of the most detrimental solicitations for laminates because it drastically reduces the residual mechanical properties of the structure [1–3]. It is well established that polymer matrix composite laminates are prone to delamination when impacted, resulting in low damage tolerance, which is of great concern for load carrying applications. To discuss the damage tolerance of polymer matrix composites it is initially helpful to consider the nature of constitutive materials and the reinforcement type [4]. Thus, high-performance thermoplastic (denoted TP) resins (e.g. polyetheretherketone – PEEK – and polyphenylene-sulfide – PPS) are increasingly considered in composite structures mainly for damage tolerance reasons. Semi-crystalline TPs resins offer a number of advantages over conventional thermosetting (denoted TS) resins (such as epoxies): a high degree of chemical resistance, excellent damage and impact resistances, and they may be used over a wide range of temperatures.

1.1. About damage tolerance of TS- and TP-based laminates

Very few authors have compared the impact behavior of TS- and TP-based composite structures, and their effects on residual strength [5–10], as well as the damage tolerance of UD-ply and woven-ply laminates [10–12]. From a general standpoint, it appears from literature that TP-based composites display a better resistance to the impact damage than epoxy-based composites. The brief literature review, herein, is not aimed at giving a general overview of the impact behavior of TS-based laminates for which a great number of references are available in the literature [1,13–15]. In the early 90s, the impact performance and damage tolerance of TP-based composites had been studied in order to understand why such materials were often more damage tolerant than TS-based composite materials [16–17]. To this aim, a few authors have investigated the influence of matrix type and morphology on the ability of TP-based composites to withstand penetration [18–19], absorb energy, and sustain damage at different temperature levels. Most of the studies about the impact performance, and damage tolerance of TP-based composites deal with PEEK-based composites [8,9,20–24]. However, only very few references report the impact behavior of PPS-based laminates [7,20,25–28]. The impact energy adversely affects the impact performance of the laminates, whereas the effect of impact velocity is found to be insignificant. Among the properties governing the impact behavior of laminated composites, the mode I and mode II critical energy release rates G_{IC} and G_{IIC} (see Table 1) are of the utmost importance [29–32]. In addition, higher Compression After Impact (CAI) strengths are generally observed in C/PEEK compared to C/Epoxy (see Fig. 1a), and the reason has already been explained [8,28].

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Table 1
Interlaminar fracture toughness of tested materials [43].

	C/PEEK	C/PPS	C/Epoxy (914)
G_{Ic} (kJ/m^2) neat resin	4	0.5–0.9	0.1
$G_{Ic,initiation}$ (kJ/m^2) carbon fiber woven-ply polymer	1.1–2.1	0.85–1	0.35–0.5
$G_{IIc,initiation}$ (kJ/m^2) carbon fiber woven-ply polymer	2–4.9	1.8	1.5

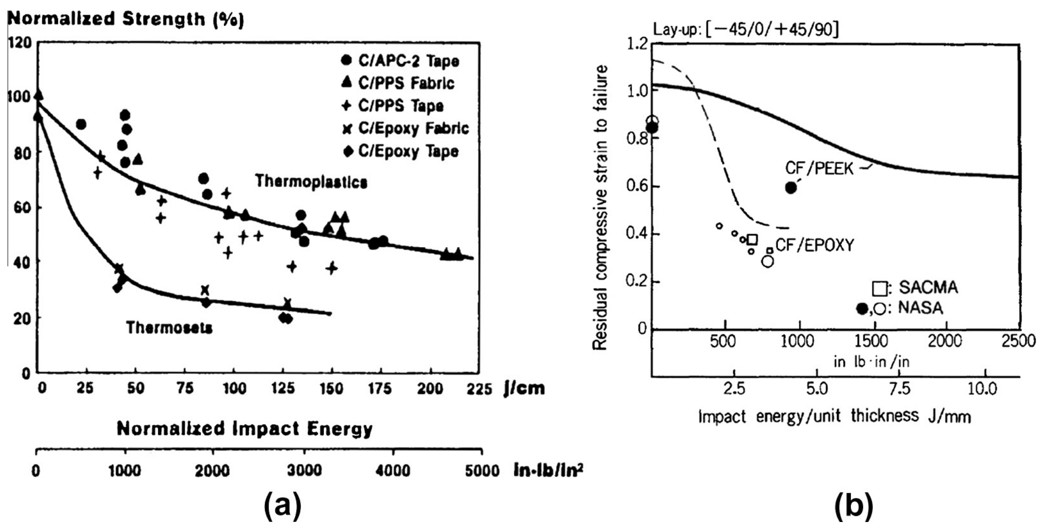

Fig. 1. Comparison of the CAI properties of TP- and TS-based laminates as a function of the impact energy: (a) normalized strength [33] – compressive strain to failure [8].

The process of delamination propagation in the final stage of C/Epoxy CAI tests is well understood: delamination causes buckling deflection reverse in the impact side and reduces the load carrying capacity of the delaminated plates. Due to the ability to arrest delamination, the CAI strain of C/PEEK laminates is almost twice that of C/epoxy (see Fig. 1b), whereas the CAI residual strength is 70% reduced in TS-based laminates and 50% reduced in TP-based laminates at higher impact energy [33].

1.2. About damage tolerance of woven-ply laminates

In addition to the contribution of the matrix toughness to the impact performance of a composite system, the impact behavior and the damage tolerance are also importantly influenced by the reinforcement architecture. The issue of the specific impact behaviors of UD-ply laminates and woven-ply laminates has been well addressed in [10–12,19,20,33–40]. An illustration of the significant contribution of fiber reinforcement to impact behavior is given by Ghasemi Nejhad and Parvizi-Majidi who studied the impact behavior and damage tolerance of carbon-fiber woven-ply TP-based (PEEK and PPS) laminates [20]. The CAI strength of PEEK-based composite remained at 47% of the value for virgin material even after sustaining an impact of 29 J. The features and failure mechanisms are identified [41–42]: inherent toughness of the fabric; the availability of matrix-rich regions at the fiber bundles crimps where plastic deformation can develop along with micro-buckling; crack propagation along the undulating pattern of the yarns creating a large fracture surface area; and multiple crack delaminations on the impacted side [12]. Thus, woven-ply laminates generally exhibit a lower peak load, a smaller damage area, a higher ductility index, and a higher residual CAI strength than UD cross-ply laminates [34], because they show much higher G_{IC} values (often more than 4–5 times) than the UD counter-parts. As a result, the damage tolerance of woven-ply laminates is better, but the overall mechanical properties of non-impacted UD-ply laminates are higher. From this brief literature review, it seemed necessary to look further into matrix's specific contribution (toughness and ductility) to the impact performance, and damage tolerance of different types of woven-ply laminates. To this aim, low velocity impact tests have been conducted at different impact energies [43]. In this work dealing only with the impact behavior, C-scan inspections and a fractography analysis showed that C/TP laminates are characterized by reduced damage (C/PPS laminates in particular), confirming that a tougher matrix can possibly be associated with better impact performance. In addition, the reinforcement weave structure limits extensive growth of delamination, but fiber breakages are more common and appear at lower impact energies because of fiber crimps. The permanent indentation (representative of local matrix crushing or plasticization, and local fiber breakage) can be ascribed to specific mechanisms. In TP-based laminates, the matrix plasticization seems to play an important role in matrix-rich areas by locally promoting permanent deformations. Fiber-bridging also prevents the plies from opening in mode I, and slows down the propagation of interlaminar and intralaminar cracks. Both mechanisms seem to reduce the extension of damages, in particular, the subsequent delamination for a given impact energy. In epoxy-based laminates, the debris of broken fibers and matrix get stuck in the cracks and the adjacent layers, and create a sort of blocking system that prevents the cracks and delamination from closing after impact [44].

1.3. Objectives of the study

In order to assess the severity of damage on the compressive residual strength and behavior, CAI tests were carried out on specimens impacted in [43]. To the authors' knowledge, most of the previous studies focused on the values of residual strength, but do not shed light on a detailed understanding of damage mechanisms leading to the final failure under compressive loading. In general, the compressive residual strength is determined by the