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Design and characterisation of high performance, pseudo-ductile all-carbon/epoxy unidirectional hybrid composites

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ABSTRACT

A variety of thin-ply pseudo-ductile unidirectional interlayer hybrid composite materials comprising high modulus and high strength thin carbon fibre/epoxy prepregs was investigated. The central high modulus carbon plies fragmented and delaminated stably from the outer high strength carbon layers under uniaxial tensile loading in the hybrid materials. These pseudo-ductility mechanisms resulted in favourable, metal-like stress-strain responses featuring pseudo-yielding, a stress plateau and further rise in stress before final failure. The high initial elastic modulus of up to 240 GPa, the early warning and the wide safety margin between damage initiation and final failure make the new hybrids advantageous for safety-critical applications where ultimate performance and low density are key design drivers. A hybrid effect with an increase in the failure strain of the high modulus carbon material was highlighted for very thin plies.

1. Introduction

Carbon fibre/epoxy composites offer high stiffness and low density resulting in some of the highest achievable specific elastic moduli and tensile strengths among structural materials. These desirable properties make them suitable for applications such as aero-structures, spacecraft, motorsports, high specification sports equipment, where ultimate mechanical performance and lowest possible weight are crucial. Besides their high strength, carbon/epoxy composites generally exhibit unfavourable sudden and brittle failure without sufficient warning and residual integrity, which currently limits their use in many high-volume and safety-critical applications such as mass-produced automotive and construction, therefore improvements are required. The sudden failure characteristic of fibre reinforced composites is usually compensated for by conservative design limits, which hinders component manufacturers from fully exploiting their excellent mechanical properties. The possibility of creating pseudo-ductile carbon fibre reinforced composites assuring safe, progressive failure mechanisms similar to metals' yielding and strain hardening with detectable warning and a wide margin between damage initiation and final failure is therefore of high interest.

The most obvious approach to add ductility to fibre reinforced composites is to replace their intrinsically brittle constituents (i.e. glass, carbon fibres and thermosetting polymer resins) with new, more ductile materials, but the choice of suitable materials is very limited. The focus has been on fibre development as the properties of high performance composites are usually fibre-dominated. Although there are promising new materials such as nanotube fibres [1], the development to make them suitable for structural applications is extremely challenging and their verification and commercialisation is a long process. Low diameter stainless steel fibres with tensile failure strains well beyond 10% were also investigated recently as a new reinforcement for ductile composites with various matrix materials by Allaer et al. [2] and Callens et al. [3–5]. Excellent ductility was reported although the density of the obtained composites was at least twice as high as that of carbon/epoxy, which renders them less suitable for lightweight applications.

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Architecture modification of laminated composites made of traditional constituents to generate additional strain using different ductility mechanisms is an alternative approach offering improvements in a shorter time scale. The additional strain can be realised e.g. by realignment of off-axis fibres and shearing of the matrix [6] [7], or from excess length due to out of plane waviness [8]. Interface modification on the fibre [9] [10], and on the ply level [11] as well as designed discontinuities [12–14] are also suitable for delaying fracture and generating stress-strain non-linearity through controlled damage before final failure.

Hybridisation of commercially available fibres is an established approach to increase the initial modulus of the high strain component and potentially introduce a gradual failure, although it usually results in an unfavourable major load drop when the low strain constituent breaks. Our intention is to use various high stiffness (low failure strain) and high strain (lower stiffness) carbon fibre/epoxy prepregs in thin format to address this issue and fully exploit the benefits of hybridisation for progressive, pseudo-ductile failure. The extensive literature on hybrid composites accumulated since the early 1970s is summarised in a few reviews [15–20]. The most practical approach based on the literature is the layer-by-layer or interlayer hybridisation, as intimate mixing of individual continuous fibres (also called intermingling) is not feasible on an industrial scale at the moment. However excellent intermingling and pseudo-ductility was presented recently with aligned discontinuous fibres [21], [22]. The vast majority of the works presenting mechanical test results of hybrid composites deal with the typical combination of continuous glass and carbon fibres to improve the relatively low failure strain and brittle fracture of carbon fibre composites. A load drop at the low strain component failure and a significant improvement in the carbon component failure strain-usually referred to as a “hybrid effect”- has generally been reported. Different aspects of the hybrid effect are extensively discussed in Refs. [20] and [23]. The importance of the correct baseline for carbon layer strain improvement was also emphasised in Ref. [23].

The authors recently demonstrated desirable stable pseudo-ductile failure in tension by hybridising uni-directional (UD) standard thickness glass and thin carbon prepreg plies [24], [25], exploiting the fragmentation and stable delamination of the carbon layer. Up to 170% increase of the baseline glass composite modulus and 2.6% pseudo-ductile strain (defined between the final failure strain and the strain on the extrapolated initial slope line at the failure stress, see Table 4) was achieved. A design framework for the hybrids was also developed in the form of both numerical [26] and analytical tools [27], [28]. These glass/carbon hybrids comprised some of the recently introduced thin-ply carbon prepregs which have generated high interest and have been studied extensively on their own [29–36] because of their unique potential to allow for highly dispersed lay-up designs resulting in favourable damage suppression properties.

There are only a few studies in the literature reporting the mechanical behaviour of hybrid composites made of different types of carbon fibres which will be referred to as all-carbon hybrids in this manuscript. Curtis and Browne [37] proposed a hybrid composite architecture where higher performance carbon fibres (T800) are put in the directions in which high stresses are expected (primary direction), and cheaper, lower performance carbon fibres (T300) are utilised in the less important directions (secondary direction). Up to 20% cost saving was anticipated while the mechanical properties of the hybrid composites were maintained at almost the same level as that of the high performance fibre reinforced baseline composites. Naito et al. [38] studied UD interlayer hybrids made of standard thickness (around 0.14 mm) prepreg plies of high strength (HS) and ultra-high modulus (UHM) carbon fibre/epoxy composites. A major load drop at the low strain component fracture was reported for hybrids with approximately 50 vol% of both components, with some load carrying capacity retained. The interlaminar fracture properties of the composites were also examined using specimens with pre-cut UHM carbon plies and release film of various lengths around the cuts. Montagnier and Hochard [39] considered high modulus (HM) and HS carbon reinforced composites for their design study of a drive shaft system. It was concluded that a hybrid composite design may reduce the number of shafts in the complete system and the total weight of the examined helicopter tail rotor driveline. Tsampas et al. [40] studied the compression performance of HS and intermediate modulus (IM) carbon hybrids in a quasi-isotropic lay-up sequence by utilising different types of prepreg plies in specific directions. No clear effect of the hybridisation on the failure loads was identified. Amacher et al., [41] and Czél et al. [42] both presented initial results at the same conference showing pseudo-ductility in quasi-isotropic hybrid laminates made of different types of carbon/epoxy. Different fibre types and stacking sequences were investigated by the two groups and both strategies yielded interesting material behaviours.

The aim of this research is to demonstrate that pseudo-ductility can be achieved with all-carbon hybrids to generate high stiffness composites exhibiting gradual failure. This will allow for high specific stiffness by a large increase in the elastic modulus and a significant decrease of the density of the new pseudo-ductile hybrid composites compared to existing glass/carbon ones. The developed materials may be suitable for some of the most demanding safety-critical applications such as aerospace, motorsports and pressure vessels where ultimate stiffness and low weight are key design drivers.

2. Material and configuration design

This section gives details of the overall concept, the applied materials and the design considerations to assure a stable pseudo-ductile failure of the hybrid laminates.

2.1. Concept

The basic concept behind pseudo-ductility in thin-ply UD interlayer hybrid composites is the exploitation of two damage mechanisms i.e. *fragmentation* of the low strain material (LSM) and dispersed, *stable delamination* or *stable pull-out* of the LSM from the high strain material (HSM) layers local to the LSM cracks as presented earlier in Refs. [24], [28]. Fragmentation in this paper refers to the damage process where multiple fractures take place stably in a UD composite ply or layer loaded in tension parallel to the fibres. The fractures in the carbon plies were observed earlier [24] in UD glass/carbon hybrids visually through the translucent glass plies, which is not possible in the all-carbon/epoxy composites. It can be detected here as an almost horizontal plateau in the stress/strain response, when more and more fractures take place in the LSM upon further increase of displacement accompanied by only a small increase in stress. The fragmentation of the LSM is only achievable if the energy release rate at first LSM fracture is lower than the mode II fracture toughness of the interface between the LSM and HSM layers so that global unstable delamination of the layers is prevented. Instead, delamination may either be completely absent, or present in a dispersed, stable, localised form due to the low energy available to drive it. Therefore thin constituent prepregs are utilised to limit the energy released at the first LSM fracture. The resulting expected stress-strain responses of the studied UD hybrids are given in Fig. 1. The key features of the expected response are a quasi-linear initial part, a flat, wide stress plateau and a second rising part before final failure. This metal-like failure character