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Pseudo-ductility and reduced notch sensitivity in multi-directional all-carbon/epoxy thin-ply hybrid composites

Gergely Czél [a,b,*], Tamas Rev [b], Meisam Jalalvand [b,c], Mohamad Fotouhi [b,d], Marco L. Longana [b], Oliver J. Nixon-Pearson [b], Michael R. Wisnom [b]

[a] Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
[b] Bristol Composites Institute (ACCIS), University of Bristol, Queen's Building, BS8 1TR Bristol, United Kingdom
[c] Department of Mechanical and Aerospace Engineering, University of Strathclyde, 75 Montrose Street, Glasgow G1 1XJ, United Kingdom
[d] Department of Design and Mathematics, University of the West of England, Bristol BS16 1QY, United Kingdom

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ABSTRACT

Un-notched and notched tensile response and damage accumulation of quasi-isotropic carbon/epoxy hybrid laminates made of ultra-high modulus and intermediate modulus carbon fibre/epoxy thin-ply prepregs were studied. It was confirmed that the ply fragmentation demonstrated previously in unidirectional hybrids as a successful pseudo-ductility mechanism can be transferred to multi-directional laminates. Furthermore, reduced notch sensitivity was demonstrated in quasi-isotropic specimens for both open holes and sharp notches as a result of local ply fragmentation around the notch.

1. Introduction

High performance composites reinforced with carbon and glass fibres exhibit high specific strength and stiffness, which makes them desirable for lightweight applications including spacecraft, aero-structures, motorsports and recreational equipment. In line with the commonly observed trade-off between strength and ductility [1–5] in metals and other structural materials, stiff and strong composites generally fail suddenly without sufficient warning and residual load bearing capacity. The catastrophic failure of composites is usually compensated for by cautious design and high safety-factors which leads to significant overdesign hindering the full exploitation of their mechanical properties. High performance pseudo-ductile composites exhibiting a safe, progressive failure process similar to yielding and strain hardening of metals accompanied by detectable damage which can serve as a warning sign well before final failure are therefore of high interest.

The ideal approach to provide fibre reinforced composites with ductility would be to replace their intrinsically brittle constituents (carbon, glass etc. fibres, thermoset polymer matrix) by more ductile ones. There are two different directions of new material development: There is significant interest in finding tougher and more crack-resistant resins (mainly thermoplastic polymers) which can improve matrix-dominated properties such as delamination resistance. However the brittle failure of unidirectional (UD) composites needs to be addressed by focussing on fibre development as the tensile stress-strain response of high performance composites is usually fibre-dominated. Although there are some promising ductile fibres developed recently such as nanotube [6], regenerated cellulose [7] and other polymeric fibres, their typical elastic modulus and strength are significantly lower than those of conventional carbon fibres. It is also noted that the development to make a new fibre suitable for structural applications is extremely challenging and the verification and commercialisation is a long process. Excellent ductility was reported recently by Allaer et al. and Callens et al. using low diameter stainless steel fibres combined with various matrix materials [8–11]. However the relatively high density of the obtained composites may limit their application in lightweight structures.

Another approach to generate additional strain in laminated composites is the design and modification of the architecture of materials made of commercially available constituents. A few mechanisms were identified and investigated within the High

* Corresponding author at: Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary.

E-mail address: czel@pt.bme.hu (G. Czél).

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Performance Ductile Composite Technologies (HiPerDuCT) programme such as: additional strain from realignment of off-axis fibres and shearing of the matrix [12]. Interface modification on the fibre [13–15] and on the ply level [16] as well as designed discontinuities [17,18] were also found to be suitable for delaying fracture and generating stress-strain non-linearity through controlled damage before final failure.

Hybridisation of fibre types at different levels (laminate, ply, tow) is a mature approach for increasing the elastic modulus of the high strain component and introducing a gradual failure process with final failure close to the failure strain of the high strain fibres. However hybrids usually show an unfavourable major load drop at the failure of the low strain constituent if the level of dispersion is too low and/or the volume fraction of the low strain fibres is too high. A few reviews [19–23,3] summarise the extensive literature on hybrid composites accumulated since the early 1970s. Based on the literature, the most successful approach is the interlayer or layer-by-layer hybridisation partly for its simplicity, as intimate mixing (or intermingling) of different continuous fibres providing high dispersion is currently only feasible on a small scale. If an interlayer hybrid is made of very thin plies of a single layer of fibres, modelling has shown that the dispersion can be even higher than that for random packing [24] resulting in a favourable stable failure process. Aligned short fibre hybrid composites [25] however demonstrated excellent dispersion of the constituent fibres, stiffness close to that of continuous fibre composites and pseudo ductility with highly non-linear stress-strain curves. The so-called hybrid effect commonly reported for glass/carbon fibre reinforced hybrids as a significant improvement in the carbon component failure strain was investigated in [26] and the importance of the correct carbon composite baseline strain achievable with delaminating UD hybrid specimens [27] was highlighted.

The authors of this paper have demonstrated pseudo-ductility in both glass-carbon/epoxy [28] and all-carbon/epoxy [29] thin-ply UD interlayer hybrid composites in tension earlier with high initial modulus, pseudo-yielding, a flat (or rising) stress plateau and further increase in load towards final failure. Fragmentation of the low strain layer and stable delamination were identified as the key damage mechanisms and implemented in the dedicated numerical [30] and analytical [31] modelling and design tools developed for the UD hybrids. The reported pseudo-ductility was achieved by hybridising some of the recently introduced thin-ply carbon prepregs, which are studied extensively for their unique properties [32–39]. These include their low thickness enabling highly dispersed lay-up designs, significantly decreasing the minimum thickness of multi-directional e.g. quasi-isotropic (QI) plates and favourable intrinsic damage suppression properties due to the low energy released upon fracture of thin plies. The general conclusion of the studies is that early damage in thin-ply QI laminates (transverse matrix cracking, splitting, free-edge delamination) is suppressed, therefore the strength may be increased but the failure of non-hybrid thin-ply plates becomes more brittle than that of standard ply-thickness laminates.

The aim of the present study is to demonstrate pseudo-ductility in multi-directional hybrid laminates which have a lot higher merit in structural applications than unidirectional ones. To this end, the benefits of UD hybrid composites (i.e. fragmentation of the low strain component) is combined with the favourable general damage suppression due to having thin plies in a laminate. Our composite architecture design approach is based on thin-ply all-carbon (intermediate modulus- IM/ultra-high modulus- UHM carbon) UD hybrid sublaminates as building blocks stacked together into symmetric quasi-isotropic plates. The expected tensile response features the suppression of unwanted damage (transverse cracking, delamination) and exploitation of controlled fragmentation within the 0° sublaminates starting at a known strain (i.e. the failure strain of the low strain carbon plies). Some of the initial results were presented recently in a conference by the authors [40], but this more complete study includes one more material configuration and a comprehensive damage analysis. Amacher et al. [41] also presented their work on quasi-isotropic thin-ply all-carbon/epoxy hybrids with a different design concept and architecture at the same conference and indicated the scope for pseudo-ductility.

The damage development in the QI hybrid plates was monitored with various state of the art techniques. Delaminations and fibre fractures in the tested specimens are detected and analysed by X-ray computed tomography (X-ray CT) after tests interrupted at pre-defined typical damage states. The damage was segmented by defining certain grey-scale thresholds using the software Avizo® 7.0 in the same manner as in Refs. [42,43]. Stress concentrations around two different notch types (open hole and sharp notch) were investigated by digital image correlation (DIC). Acoustic emission events originating primarily from fibre fractures were recorded on-line during selected tests to monitor the damage accumulation in the hybrid laminates.

2. Material and configuration design

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

2.1. Concept

The basic concept of this study is to use thin UD pseudo-ductile interlayer hybrid laminates comprising low strain and high strain materials (LSM and HSM respectively) as building blocks for multi-directional plates as highlighted in Fig. 1. The ultimate goal is to transfer the safe and progressive failure process of the UD sublaminates to a multi-directional laminate and provide pseudo-ductile tensile response in all loading directions. To this end, the beneficial pseudo-ductile failure mechanisms i.e. LSM *fragmentation* (stable, multiple layer fractures) and *stable pull-out* (stable intra-sublaminate delamination) are promoted and exploited in the multi-directional hybrid plates, but other less stable damage mechanisms i.e. splitting and unstable inter-sublaminate (free-edge) delamination are suppressed until a given, higher strain.

The most important damage mechanism putting pseudo-ductile failure at risk is unstable delamination, which can happen at two different levels in the designed laminates as explained in Fig. 2. (i) *Intra-sublaminate delamination* could take place within the sublaminate if the LSM releases more energy at its first fracture than the mode II fracture toughness of the interface. (ii) *Inter-sublaminate delamination* could occur due to the free-edge stresses at the interface between neighbouring hybrid-sublaminates caused by their different orientations. This is a mixed mode delamination and therefore its prediction and control is more challenging than those of the other pure mode II intra-sublaminate one analysed in our previous works on UD hybrids [28,30]. The inter-sublaminate delamination would take place at the specific interfaces (symmetrically to the mid-plane in symmetric laminates) where the energy release rate is the highest in relation to the fracture energy within the laminate.

2.2. Materials

The materials considered for design, and used for the experiments were thin carbon/epoxy prepregs from North Thin Ply Technology and SK Chemicals made of different type intermediate