

**Project title**                      Lightweight structures based on hierarchical composites

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**Keywords**                            Hierarchical structures, carbon fibre reinforced polymers, carbon nanotubes

**Background**

Carbon fibre reinforced polymer (CFRP) composites have gained great importance as lightweight materials in many applications in space, aerospace, automotive and renewable energies. Their high strength- and stiffness-to-weight ratio makes them ideal for highly tailored engineering applications, while outperforming conventional metallic solutions. Such CFRPs are supremely effective when exploiting their tensile properties in the unidirectional fibre direction. Nevertheless, the failure of a state of the art CFRP laminate is almost always governed by compressive failure in fibre direction (driven by the comparatively low matrix stiffness, resulting in buckling of single fibres at the microscopic level) or transverse strength (driven by the matrix strength at the fibre to matrix interface). Therefore, there has always been a high interest to enhance the properties of the fibre to matrix interface.

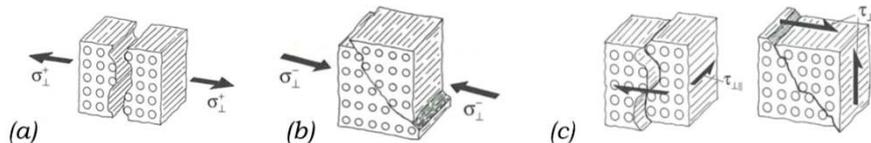


Figure 1: Interface and matrix dominated failure modes from CFRPs; (a) transverse tensile, (b) transverse compression, (c) shear. These failure modes are an order of magnitude lower than the strength in fibre direction [1].

A novel and promising approach to the challenge of the fibre-matrix disparity of properties is the development of multi scale, or hierarchical composites. Such materials contain reinforcing fibres at typically two length scales; the nano- and micro-metre [2]. The reinforcing fibres in the nanometre length scale are typically carbon nanotubes (CNT) with their extraordinary intrinsic mechanical properties, and complement the micron sized ( $\varnothing 7 \mu\text{m}$ ) carbon fibres.

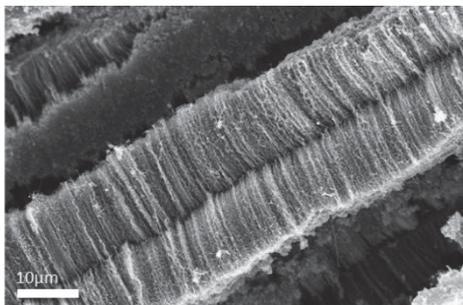


Figure 2: SEM Image of highly aligned CNT's grown on carbon fibre. The CNT length exceeds the fibre diameter. It becomes apparent the CNTs from neighbouring fibre start interact leading to novel mechanisms of load transfer (Source: S. Vogel - unpublished).

Stable growth of CNTs on the carbon fibre substrate was achieved by applying an oxide layer on the fibre by atomic layer deposition, prior to application of a metal catalyst, followed by the CNT growth via chemical vapour deposition (CVD), as demonstrated by Perrin et al.[3]. The  $\text{Al}_2\text{O}_3$  layer protects the carbon fibre and thereby solves the reported [4] fundamental problem, as of generated defects in the carbon fibre and its substantial reduction of tensile strength during CVD processing. However, the interface between the oxide layer and the carbon fibre is stressed by temperature loads during the CVD process and may debond, therefore requiring restrictions of processing temperatures. These mechanisms were identified [5] such that carbon fibre with strength values close to their virgin state and a well-conditioned interface with highly aligned CNT growth can be realized. The applicants have built up infrastructure in fibre coating, catalyst deposition techniques, CNT growth and characterization, which will be available for the proposed PhD project.

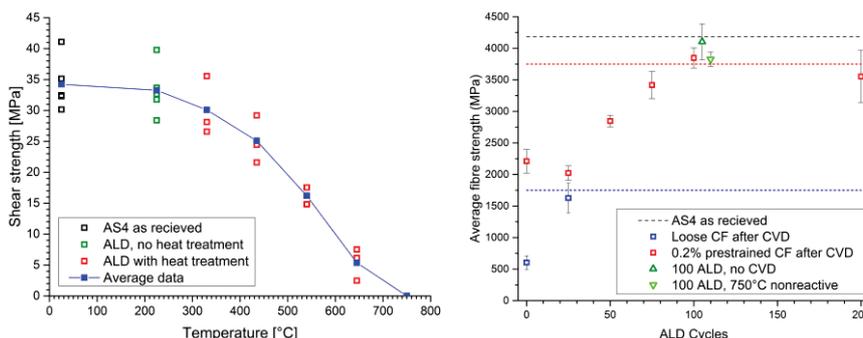


Figure 3: Left - the oxide layer is subjected to thermal stresses during the subsequent CVD process, which reduces the interfacial strength. Right - an optimum thickness of the oxide layer (corresponding to 10.5 nm) reconstitutes the original strength of the reference fibre [6].

## Objective

Having understood fundamental aspects and properties of a single fibre with densely grown CNT's on their surface, the aim of this PhD project is to understand i) the influence of the interlacing growths of the CNTs on the properties on a lamina level, which represents the next assembly step in the hierarchical architecture, ii) to investigate and understand the detailed filling mechanisms of the structure by the matrix material on the nanometer scale and iii) to understand the failure mechanisms of the hierarchical composite structures, where today only little knowledge exists. Preliminary work has demonstrated, that the distance between the carbon fibre layers increases through the growing CNTs, which is attributed to the CNT envelope separating the fibres. This might limit the benefits in the interaction between fibres. It is therefore intended to develop methods allowing confined growth of CNTs, potentially leading to an entanglement, respectively intimate interaction.

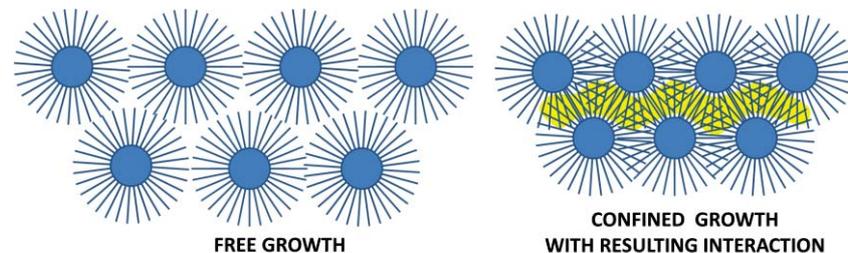


Figure 4: Confining the space of the fibres at lamina level during CNT growth is expected to lead to an interaction or entanglement of the CNTs from neighbouring fibres, leading to new mechanisms of load transfer (Source: C. Dransfeld - unpublished).

## Research Plan

Such hierarchical carbon fibre architectures will be prepared as in [6] and impregnated with a diglycidether-bisphenol-A based epoxy system. Such processes are subject to dual scale flow: the bulk flow progression being determined by permeability of the reinforcement primarily between fibre bundles (tows) and the micro scale permeability of the tows being determined by capillary forces [7]. In hierarchical composites, wetting will also have to be understood at the nanometer scale between the radially aligned CNT; with free volume approaching the molecular scale close to the fibre surface, appropriate models need to be developed to describe the formation of the interphase and expected separation of resin and hardener molecules. Advanced analytical methods (TEM, synchrotron-based SAXS) will be used to study and understand the details of the matrix wetting and interphase formation. Standard tests for the investigation of the mechanical properties of the lamina samples will be applied.

In year one, we will aim at understanding the CNT growth restrictions in confinements and hence the control over their hierarchical architecture. In year two, the impregnation and wetting will be investigated up to the nanometer scale; the third year will be dedicated to understanding the structure property relationship from such hierarchical composites.

## Impact

Next to their mechanical properties, such hierarchical architectures are of high interest for electrical energy storage, such as for battery electrodes or supercapacitors and might therefore lead to novel multifunctional materials beyond the primary scope described above. This work would also contribute to teaching at FHNW and Uni Basel in Polymer Engineering respectively Nanoscience disciplines.

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