Abstract

Due to their superior weight-specific mechanical properties, carbon fibre epoxy composites (CFRP) are commonly used in aviation industry. However, their brittle failure behaviour limits the structural integrity and damage tolerance in case of impact (e.g. tool drop, bird strike, hail strike, ramp collision) or crash events. To ensure sufficient robustness, a minimum skin thickness is therefore prescribed for the fuselage, partially exceeding typical service load requirements from ground or flight manoeuvre load cases. A minimum skin thickness is also required for lightning strike protection purposes and to enable state-of-the-art bolted repair technology. Furthermore, the electrical conductivity of CFRP aircraft structures is insufficient for certain applications; additional metal components are necessary to provide electrical functionality (e.g. metal meshes on the outer skin for lightning strike protection, wires for electrical bonding and grounding, overbraiding of cables to provide electromagnetic shielding). The corresponding penalty weights compromise the lightweight potential that is actually given by the structural performance of CFRP over aluminium alloys.

Former research attempts tried to overcome these deficits by modifying the resin system (e.g. by addition of conductive particles or toughening agents) but could not prove sufficient enhancements. A novel holistic approach is the incorporation of highly conductive and ductile continuous metal fibres into CFRP. The basic idea of this hybrid material concept is to take advantage of both the electrical and mechanical capabilities of the integrated metal fibres in order to simultaneously improve the electrical conductivity and the damage tolerance of the composite. The increased density of the hybrid material is over-compensated by omitting the need for additional electrical system installation items and by the enhanced structural performance, enabling a reduction of the prescribed minimum skin thickness. Advantages over state-of-the-art fibre metal laminates mainly arise from design and processing technology aspects.

In this context, the present work focuses on analysing and optimising the structural and electrical performance of such hybrid composites with shares of metal fibres up to 20 vol.%. Bundles of soft-annealed austenitic steel or copper cladded low carbon steel fibres with filament diameters of 60 or 63 µm are considered. The fibre bundles are distinguished by high elongation at break (32 %) and ultimate tensile strength (900 MPa) or high electrical conductivity (2.4×10^7 S/m). Comprehensive researches are carried out on the fibre bundles as well as on unidirectional and multiaxial laminates. Both hybrid composites with homogeneous and accumulated steel fibre arrangement are taken into account. Electrical in-plane conductivity, plain tensile behaviour, suitability for bolted joints as well as impact and perforation performance of the composite are analysed. Additionally, a novel non-destructive testing method based on measurement of deformation-induced phase transformation of the metastable austenitic steel fibres is discussed.

The outcome of the conductivity measurements verifies a correlation of the volume conductivity of the composite with the volume share and the specific electrical resistance of the incorporated metal fibres. Compared to conventional CFRP, the electrical conductivity in parallel to the fibre orientation can be increased by one to two orders of magnitude even for minor percentages of steel fibres. The analysis, however, also discloses the challenge of establishing a sufficient connection to the hybrid composite in order to entirely exploit its electrical conductivity.

In case of plain tensile load, the performance of the hybrid composite is essentially affected by the steel fibre-resin-adhesion as well as the laminate structure. Uniaxial hybrid laminates show brittle, singular failure behaviour. Exhaustive yielding of the embedded steel fibres is confined to the arising fracture gap. The high transverse stiffness of the isotropic metal fibres additionally intensifies strain magnification within the resin under transverse tensile load. This promotes (intralaminar) inter-fibre-failure at minor composite deformation. By contrast, multiaxial hybrid laminates exhibit distinctive damage evolution. After failure initiation, the steel fibres extensively yield and sustain the load-carrying capacity of angularly (e.g. ±45°) aligned CFRP plies. The overall material response is thus not only a simple superimposition but a complex interaction of the mechanical behaviour of the composite's constituents. As a result of this post-damage performance, an ultimate elongation of over 11 % can be proven for the hybrid laminates analysed in this work. In this context, the influence of the steel fibre-resin adhesion on the failure behaviour of the hybrid composite is explicated by means of an analytical model. Long term exposure to corrosive media has no detrimental effect on the mechanical performance of stainless steel fibre reinforced composites. By trend, water uptake increases the maximum elongation at break of the hybrid laminate.

Moreover, the suitability of CFRP for bolted joints can partially be improved by the integration of steel fibres. While the bearing strength basically remains nearly unaffected, the bypass failure behaviour (ε_{max}: +363 %) as well as the head pull-through resistance ($E_{a,BPT}$: +81 %) can be enhanced. The improvements primarily concern the load-carrying capacity after failure initiation. Additionally, the integrated ductile steel fibres significantly increase the energy absorption capacity of the laminate in case of progressive bearing failure by up to 63 %.

However, the hybrid composite exhibits a sensitive low velocity/low mass impact behaviour. Compared to conventional CFRP, the damage threshold load of very thin hybrid laminates is lower, making them prone for delamination at minor, non-critical impact energies. At higher energy levels, however, the impact-induced delamination spreads less since most of the impact energy is absorbed by yielding of the ductile metal fibres instead of crack propagation. This structural advantage compared to CFRP gains in importance with increasing impact energy. The plastic deformation of the metastable austenitic steel fibres is accompanied by microstructural transformation from paramagnetic γ-austenite to ferromagnetic α'-martensite. This change of the magnetic behaviour can be used to detect and evaluate impacts on the surface of the hybrid composite, which provides a simple, non-destructive testing method. In case of low velocity/high mass impact, integration of ductile metal fibres into CFRP enables to address spacious areas of the laminate for energy absorption purposes. As a consequence, the perforation resistance of the hybrid composite is significantly enhanced; by addition of approximately 20 vol.% of stainless steel fibres, the perforation load can be increased by 61 %, while the maximum energy absorption capacity rises by 194 %.