IMPROVED MECHANICAL AND ELECTRICAL PROPERTIES OF CFRP MULTIAXIAL LAMINATES BY EMBEDDED METAL FIBERS

B. Hannemann[1], S. Backe[2], S. Schmeer[1], F. Balle[2], U. P. Breuer[1]

[1]Institute for Composite Materials (IVW GmbH)
Erwin-Schroedinger-Str., Bldg. 58, 67663 Kaiserslautern, Germany
Email: benedikt.hannemann@ivw.uni-kl.de, web page: http://www.ivw.uni-kl.de

[2]Institute of Materials Science and Engineering (WKK)
University of Kaiserslautern, P.O. Box 3049, 67653 Kaiserslautern, Germany
Email: balle@mv.uni-kl.de, web page: http://www.uni-kl.de/wkk

Keywords: damage tolerance, electrical conductivity, hybrid composites, multifunctionality, steel fibers

Abstract

Distinctive attributes of CFRP led to an increasing share of this composite in aviation industry. However, its comparatively poor electrical conductivity and limited damage tolerance require additional systems and elements, compromising today's CFRP lightweight potential. Former research attempts dealing with modified polymer systems could not prove sufficient enhancements. Against this background, a novel hybrid composite material consisting of reinforcing carbon and metal fibers embedded in an epoxy matrix is investigated. Basic idea of this concept is to merge electrical and load-bearing functions by incorporating highly conductive and ductile austenitic CrNi steel fibers.
Researches on unidirectional reinforced hybrid composites with steel fiber fractions between 10 and 20 vol.% already proved significant enhancements of the electrical and mechanical properties. Compared to conventional CFRP, the electrical conductivity of the hybrid composites is up to five times higher. At the same time, the deformability and damage tolerance of the composite can essentially be risen. The results suggest that an allocation of the steel fibers in core and top layers is advantageous over a homogenous steel fiber distribution. This knowledge is transferred to multiaxial laminates with aeronautical stacking sequences. The present paper is focused on the mechanical properties of this novel hybrid composite.

1. Introduction

Due to their superior mechanical properties, carbon fiber reinforced polymers (CFRP) are commonly used in lightweight applications, e.g. aviation or car industry. High structural performance to mass ratio, utilization of anisotropy for tailored strength, stiffness and stability design, excellent fatigue behavior and corrosion resistance are distinguished attributes of CFRP.
However, compared to advanced light metal alloys, such as aluminum-lithium or aluminum-magnesium-scandium, CFRP offers poor electrical conductivity. Additional metal elements are necessary to fulfill certain electrical functions (e.g. copper mesh on the outer skin for lightning strike protection, wires for electrical grounding and bonding, overbraiding of cables to provide sufficient shielding). In addition, CFRP shows brittle failure behavior, limiting the structure integrity in crash load cases. The necessary damage tolerance against impact events like hailstone, bird impact, tool drop or tire debris as well as state-of-the-art rivet repair technologies require a minimum wall thickness for substantial areas of the airframe. All these tasks cause additional mass, limiting the lightweight potential that is given by the structural performance of CFRP.

Excerpt from ISBN 978-3-00-053387-7

Former research attempts tried to overcome these drawbacks by modifying the polymer matrix system. By introduction of conductive particles like carbon nano tubes (CNT), the specific conductance of CFRP could be enhanced [1-2]. However, a sufficient level of conductivity which would guarantee electrical function integration for the modified CFRP similar to that of aluminum alloys or GLARE airframe structures could not be demonstrated. The impact damage tolerance of thin-walled CFRP structures has gradually been improved by the addition of polymer toughening agents [3-4]. Thermoplastic polymers and rubber particles were introduced in epoxy resin systems, enabling substantial improvements of fracture toughness and residual strength. However, even for CFRP airframe structures fabricated with the latest generation of toughened prepreg systems, the prescribed minimum wall thickness criteria can still be the limiting design driver.

2. Fiber hybrid laminates

Different to former research attempts dealing with modified polymer matrix systems, the metal fiber incorporation is a promising new approach. Research results in [5-8] show significant improvements in terms of energy absorption, fail safe behavior and structural integrity, when classical composites were reinforced by steel. The metal fibers can either be distributed homogenously in the composite (“homogenized layer concept”) or locally concentrated in individual layers (“separated layer concept”).
Unlike fiber-metal-laminates such as GLARE, the fiber based approach enables stress tailored composite design and multiple shaped structures. Moreover, fully automated manufacturing technologies can be explored by means of processes that are already available and in service for CFRP, e.g. weaving processes for non-crimped fabrics, automated tape laying, fiber placement or resin transfer molding.
However, potential metal fibers have to meet various requirements, in particular superior electrical conductivity, distinctive failure strain, high strength, high stiffness, corrosion resistance, appropriate thermal expansion, availability and low costs.
Copper fibers offer high electrical conductivity and good corrosion resistance, but high density and poor mechanical properties. Fibers made of Aluminum are distinguished by superior weight specific electrical conductivity and reasonable mechanical properties. However, in contact with carbon fibers, aluminum tends to ineligible galvanic corrosion. This is of no relevance for stainless steel fibers. Stainless steel fibers are commercially available with a wide range of mechanical properties and appearance. Furthermore, the stiffness of standard modulus carbon and stainless steel fibers is comparable. Compared to a standard high tenacity ex-PAN carbon fiber, the electrical conductance of stainless steel fibers is approximately 23 times higher. Due to less alloying, low carbon steel fibers have even better specific mechanical properties. By nickel or copper cladding, the electrical conductivity can be further enhanced. In addition, the cladding enables a sufficient corrosion resistance.

Table 1. Selected properties of the processed fibers

	Carbon fiber[1)]	**Steel fiber[2)]**
Density / g/cm^3	1.77	7.95 ± 0.01
Tensile strength / MPa	4 806 ± 125	897 ± 2
Failure strain / %	1.85 ± 0,04	32.31 ± 2.01
Electr. resistivity / Ωm	1.6×10^{-5}	$(6.97 \pm 0.02) \times 10^{-7}$
Filament diameter / µm	5	60.0 ± 0.4
Roving size	12k	7

[1)] Manufacturer information, [2)] Own measurements on fiber bundles

Excerpt from ISBN 978-3-00-053387-7

Within the present study, twisted bundles of metastable austenitic chrome-nickel steel fibers are considered. The bundle consists of seven filaments, each with a diameter of 60 µm. Furthermore, standard modulus/high tenacity carbon fibers of type Toho Tenax HTS40 and epoxy resin of type Cytec CYCOM 977-2 are processed. Selected properties of the fibers are summarized in table 1.

3. Researches on unidirectional laminates

In a first step, the mechanical properties of unidirectional reinforced laminates are analyzed. Hybrid composites (MCFRP) with a volume share of 10.4 and 18.8% steel fibers are tested and compared with state-of-the-art CFRP [10].

In case of pure tensile load in parallel to the fiber orientation, both CFRP and the hybrid composites show brittle material behavior with similar ultimate strains to failure. Increasing the steel fiber content slightly lowers the tensile strength and stiffness of the composite. Despite the incorporation of highly ductile fibers, a pronounced post failure cannot be observed. This brittleness is caused by a homogenous stress state in the loaded composite. The reinforcing fibers generate elastic energy in the entire volume of the specimen. During failure of the carbon fiber, most of this energy is abruptly released and transferred by the matrix to the ductile steel fibers, causing yielding of the metal. However, the steel fibers plastify only in a narrow area around the fracture, causing merely a slight macroscopic elongation of the specimen. Improvements are expected by higher steel fiber fractions (i.e. the elastic energy can be absorbed by a bigger amount of plastifying steel fibers), but would cause higher material densities. Furthermore, a reduced fiber-resin-adhesion could enable unhindered deformation of the metal fibers over larger areas, but would certainly impact other important properties, e.g. the transverse tensile strength.

Improvements of the composite failure by incorporation of steel fibers become apparent in case of combined bending and tensile load, figure 1. Conventional CFRP shows a brittle material behavior. Failure occurs abruptly and singularly. By contrast, the hybrid composites exhibit a noticeable post failure behavior. Accompanied by a significant load drop, initial failure occurs at a deflection similar to that of CFRP. Afterwards, the composites can be further loaded at a reduced level of load. In case of the hybrid composites with a homogeneous steel fiber distribution (MCFRP 10 UD and MCFRP 20 UD), the maximum deflection until final failure is doubled compared to conventional CFRP. Further improvements can be achieved by localizing the metal fibers exclusively in the top (MCFRP 20a UD) or core layers (MCFRP 20i UD) of the laminate. Compared to MCFRP with homogenously distributed steel fibers, the maximum deflection is further enhanced, while the bearable load remains on an even higher level. In case of the combined bending and tensile load, stress and deformation are inhomogenously distributed in the coupon. Stress peaks occur in the outer plies at the area of

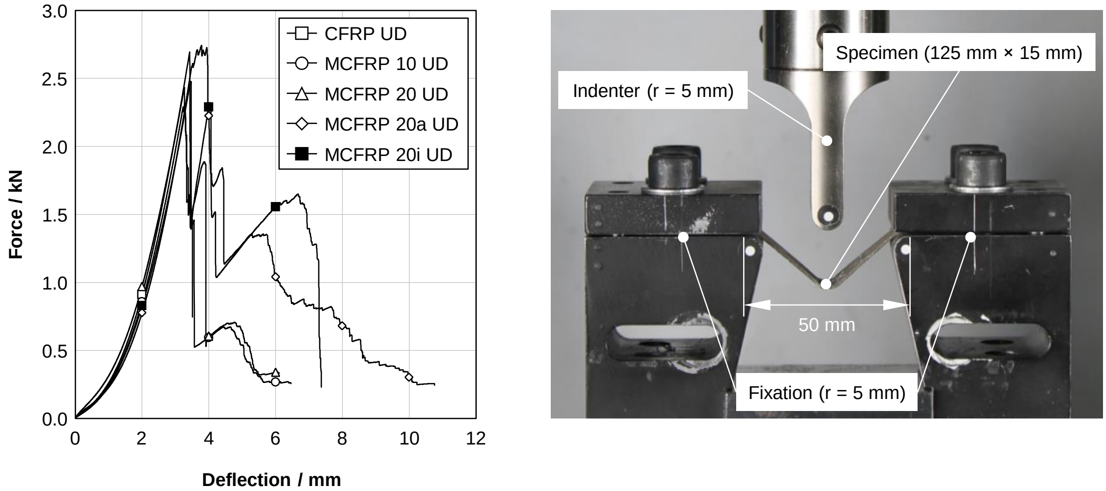


Figure 1. Tensile-bending tests on unidirectional (hybrid) composites

Excerpt from ISBN 978-3-00-053387-7

maximum bending, while local stresses in the remaining regions are significantly lower. Compared to the pure tensile stress state, the carbon fibers consequently store less elastic energy. After failure of the carbon fibers and the corresponding energy release, the steel fibers continue to yield and bear further deflections. By this means, the energy absorption and hence the structure integrity can significantly be enhanced.

5. Researches on multiaxial laminates

The awareness of concentrated steel fibers in selected plies of the composite to achieve a beneficial material behavior is transferred to multiaxial laminates. As reference materials, a 13- and a 17-layered CFRP laminate with typical aeronautical stacking sequences are manufactured. For benchmark reasons, a 13-layered CFRP laminate with an additional copper mesh for lightning strike protection purposes (Dexmet 3CU7-100FA, 195 g/m²) is prepared. The hybrid composite consists of a 13-layered CFRP core and four additional, pure steel fiber reinforced top layers, figure 2. The laminates are tested in regard to their notched properties and their penetration resistance. For this purpose, bearing stress, filled hole tension and penetration tests are conducted.

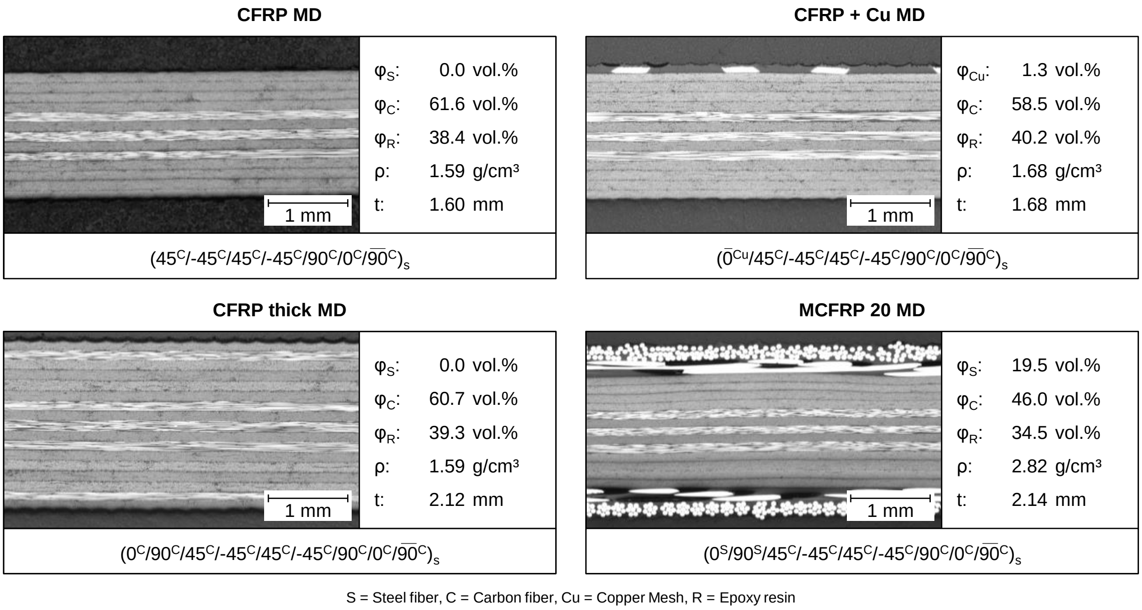
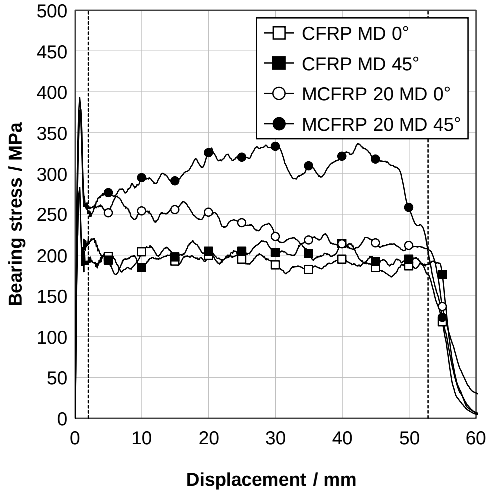


Figure 2. Microstructure of the analyzed multiaxial (hybrid) laminates

5.1. Dynamic bearing stress tests

A metal pin with a diameter of ¼ inch is continuously pulled in in-plane direction through composite specimens with a loading speed of 1 m/s. All tested laminate configurations show a similar material response: After exceeding an initial trigger load (σ_{trig}), the bearing stress remains on a lower, but nearly constant level (σ_{mean}), figure 3. Intergrating the force vs. displacement data yields the energy (AE) which is absorbed by the material.

Excerpt from ISBN 978-3-00-053387-7



Material	σ_{trig} / MPa	σ_{mean} / MPa[1)]	AE / J
CFRP MD 0°	292 ± 16	191 ± 8	106 ± 5
CFRP MD 45°	288 ± 14	200 ± 5	113 ± 2
MCFRP 20 MD 0°	402 ± 52	233 ± 16	177 ± 13
MCFRP 20 MD 45°	408 ± 46	302 ± 11	220 ± 6

[1)] Determined between 2.000 and 52.825 mm pin displacement

Figure 3. Results of the dynamic bearing stress tests

However, compared to CFRP more extensive areas lateral to the track of the bolt are degraded in case of MCFRP, figure 4. In consequence of the spacious plastification of the steel fibers, the mean bearing stress is increased 22% compared to CFRP. Loading the hybrid composite (i.e. the embedded steel fibers) at an angle of 45° (MCFRP 20 MD 45°), both steel fiber plies equally restrain the movement of the pin. Consequently, further enhancements of the bearable load can be achieved. Compared to CFRP MD 45°, the mean bearing stress rises 51%. As a consequence of the plastic deformation of the steel fibers, the hybrid composite can absorb more energy during failure than CFRP.

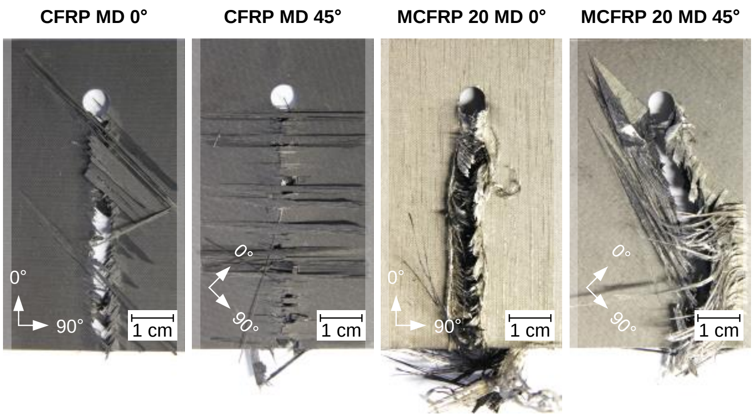
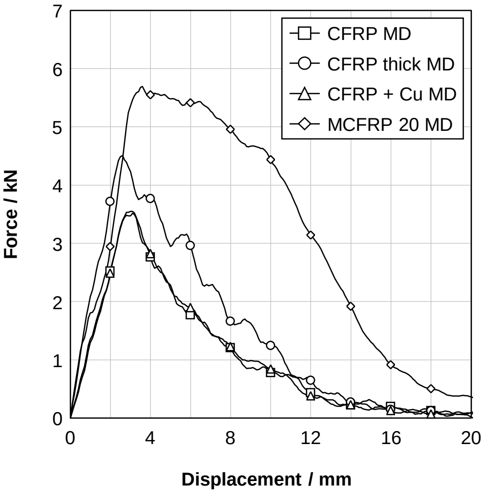


Figure 4. Typical failure modes after bearing load

5.2. Dynamic penetration tests

Dynamic penetration test are conducted according to DIN EN ISO 6603-2. A metallic indenter with a diameter of 20 mm and an impact energy of 193 J is dropped on the flat side of composite plates. The plates are circular clamped with a free gauge length of 40 mm. The material response is characterized by the maximum force (F_{max}), the displacement, in which the force has fallen to half its maximum value (l_p) and the ratio of the absorbed energy after to the absorbed energy before the maximum load (R_E). Figure 5 summarizes the obtained results.

Excerpt from ISBN 978-3-00-053387-7



Material	F_{max} / N	l_p / mm[1)]	R_E[2)]
CFRP MD	3 558 ± 336	5.76 ± 0.57	2.92 ± 0.57
CFRP thick MD	4 523 ± 91	6.95 ± 0.35	3.66 ± 0.16
CFRP + Cu MD	3 598 ± 65	6.07 ± 0.60	2.71 ± 0.37
MCFRP 20 MD	5 737 ± 46	12.55 ± 0.18	4.11 ± 1.06

[1)] Displacement, in which the force has fallen to half of the maximum force

[2)] Ratio of the energy after to the energy before maximum load

Figure 5. Results of the dynamic penetration tests

CFRP exhibits a brittle failure behavior. The failure mode is dominated by delamination and cracking. After exceeding a certain peak load, cracks grow free of energy absorption, mostly at an angle of ±45°, i.e. in direction of the majority of fibers (cf. figure 6). Only a few carbon fibers break. Increasing the thickness of the composite causes only a slight increase of the maximum load. An additional copper mesh on the impacted side of the specimen has no significant influence on the penetration behavior.
By contrast, MCFRP shows a distinctive ductile behavior. The failure mode on the entry side of coupons resembles a deep drawing process. On the rear side, bundles of steel fibers of the outer ply delaminate from the laminate and plastify. More pronounced deformations are only hindered by the grip of the specimen. Nevertheless, compared to CFRP, the hybrid composite can bear larger deformation, while the load remains on a higher, slightly decreasing level. The displacement, in which the load has fallen to half of the load maximum rises 117% compared to CFRP MD and 80% compared to CFRP thick MD.

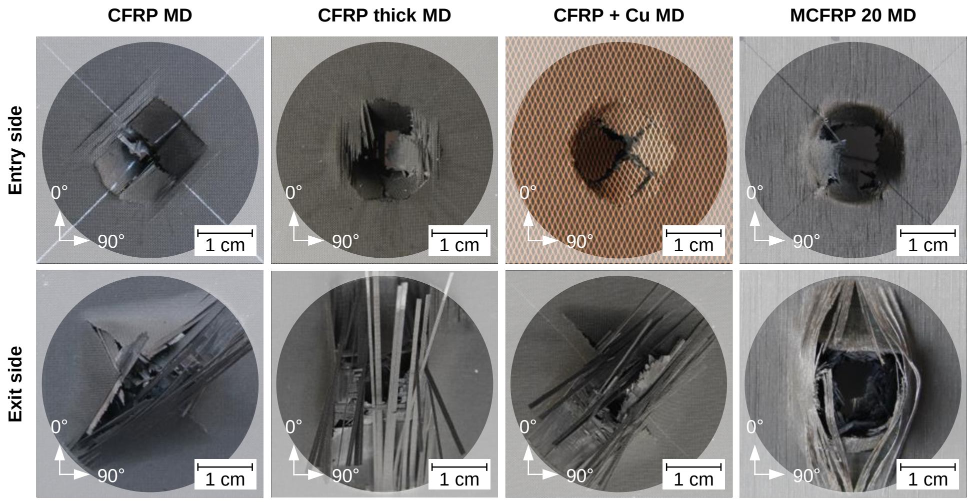
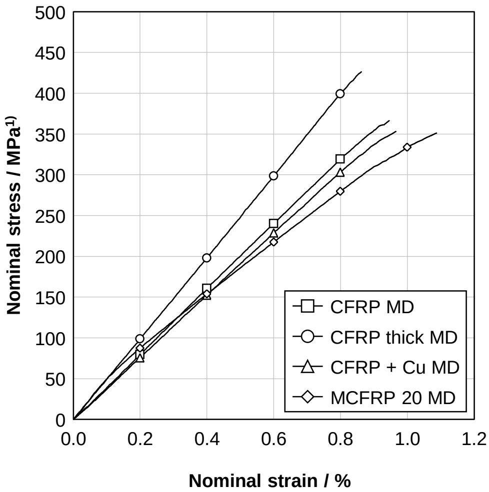


Figure 6. Typical failure modes after penetration load

Excerpt from ISBN 978-3-00-053387-7

5.3. Filled hole tension tests

Filled hole tension tests are conducted in compliance with AITM 1-0007. Rectangular specimen with a width of 32 mm and a ¼ inch centered bold (tightening torque: 7.5 Nm) are monotonically loaded with a crosshead speed of 2 mm/min. The elongation of the specimen is analyzed within a gauge length of 150 mm by a DIC system.
Both CFRP composites show brittle material behavior. The thick CFRP configuration is stiffer and stronger due to its additional 0° top layers. Again, the influence of an additional copper mesh can be neglected. Integration of steel fibers into CFRP decreases the tensile strength (σ_{max}) and the mean stiffness (E), while the ultimate strain to failure (ε_{max}) rises 26%, compared to CFRP thick MD, figure 7.



Material	E / GPa[1) 2)]	σ_{max} / MPa[1)]	ε_{max} / %
CFRP MD	40.6 ± 0.5	366 ± 6	0.95 ± 0.02
CFRP thick MD	49.6 ± 0.8	426 ± 14	0.86 ± 0.01
CFRP + Cu MD	38.4 ± 0.6	353 ± 9	0.97 ± 0.02
MCFRP 20 MD	34.4 ± 0.3	351 ± 8	1.09 ± 0.03

1) Considering the nominal width of the specimen

2) Determined by linear regression between 10 and 50% of σ_{max}

Figure 7. Resultes of the filled hole tensile tests

6. Conclusions

Several advantages of CFRP in comparison to aluminum alloys led to an increasing share of this composite structures in aviation industry. However, its comparatively poor electrical conductivity and limited damage tolerance require additional systems and elements, compromising today's CFRP lightweight potential. For this reason, efforts concentrate on modifying CFRP in order to guarantee the necessary electrical functionality for system installation purposes and to improve its damage tolerance.
Unlike former research attempts dealing with modified polymer matrix systems, this study analyzes the potential of a hybrid composite consisting of reinforcing carbon and stainless steel fibers embedded in an epoxy resin.
Researches on unidirectional reinforced (hybrid) composites prove that in case of combined tensile-bending load, the structure integrity can significantly be improved. The hybrid composites reveal a distinctive post failure behavior. After initial failure, the composites can sustain further loads. The bearable deflection is increased up to 181%. The test results suggest that an allocation of steel fibers in core or top layers is advantageous over a homogenous steel fiber distribution.
In case of multiaxial laminates, hybrid composites with embedded steel fibers exhibit a higher resistance against bearing failure. After failure initiation, the hybrid material enables better energy absorption capabilities than conventional CFRP. Furthermore, the penetration resistance of CFRP can be enhanced by incorporating steel fibers. The hybrid composite reveals complex failure modes. Spacious areas of the material can be addressed to absorb impact energy by plastification of the steel fibers. By contrast, state-of-the-art copper mesh for lightning strike protection purposes has no

Excerpt from ISBN 978-3-00-053387-7

influence on the penetration resistance of the composite. Regarding the bypass failure behavior, the incorporation of steel fibers into CFRP leads to a significant increase of the bearable strain.
Future work will focus on optimizing the laminate stacking sequence with regard to certain electrical and mechanical applications by further analysis, e.g. compression after impact, fatigue, fastener pull-through. Furthermore, the usability of integrated austenitic metastable CrNi steel fibers for in-situ health monitoring (based on phase transformation and change of the electrical resistivity) and inductive heating for advanced manufacturing processes will be investigated.

Acknowledgments

The financial support of the German Research Foundation (DFG) within the projects BR 4262/2-1 and BA 4073/6-1 is gratefully acknowledged. Prepreg and resin film was kindly supplied by Cytec Engineered Materials GmbH (Östringen, Germany).

References

[1] A. Noll, K. Friedrich, T. Burkhart, U. P. Breuer. Effective multifunctionality of poly (p-phenylene sulfide) nanocomposites filled with different amounts of carbon nanotubes, graphite and short carbon fibers. *Polymer Composites,* 34(9):1405-1412, 2013.

[2] Z. Spitalsky, D. Tasis, K. Papagelis, C. Galiotis. Carbon nanotube-polymer composites: Chemistry, processing, mechanical and electrical properties. *Progress in Polymer Science*, 35(3):357-401, 2010.

[3] C. Garg, Y.-W. Mai. Failure mechanisms in toughened epoxy resins - A review. *Composites Science and Technology*, 31(3):179-223, 1988.

[4] R. M. Medina Barron. Rubber toughened and nanoparticle reinforced epoxy composites. *IVW Schriftenreihe*, 84, 2009.

[5] A. Radtke, V. van Wassenhove, K. van Koert, F. Vöge, D. Moors, O. Geiger, D. Fertig. Reinforcing with steel cord. *Kunststoffe*, 11:67-71, 2012.

[6] S. Schmeer, M. Steeg, M. Maier, P. Mitschang. Metal fiber reinforced composite - potentialities and tasks. *Advanced Composites Letters*, 18(1):45-52, 2009.

[7] S. Vandewalle. Multifunctional steel fibre reinforcement. *Proceedings of the Wolfsburg Innovations in Automotive Textiles*, Wolfsburg, Germany, October 7th 2010.

[8] M. G. Callens, L. Gorbatikh, I. Verpoest. Carbon nanotube–polymer composites: Chemistry, processing, mechanical and electrical properties. *Composites Part A: Applied Science and Manufacturing*, 35(3):357-401, 2014.

[9] Toho Tenax Europe GmbH. Product data sheet for Tenax® HTS filament yarn. 2014.

[10] B. Hannemann, S. Backe, S. Schmeer, F. Balle, U. P. Breuer. New Multifunctional Hybrid Polymer Composites reinforced by Carbon and Steel Fibers. *Proceedings of the 20th International Conference on Composite Materials*, Copenhagen, Denmark, July 19th-24th 2015.

Excerpt from ISBN 978-3-00-053387-7