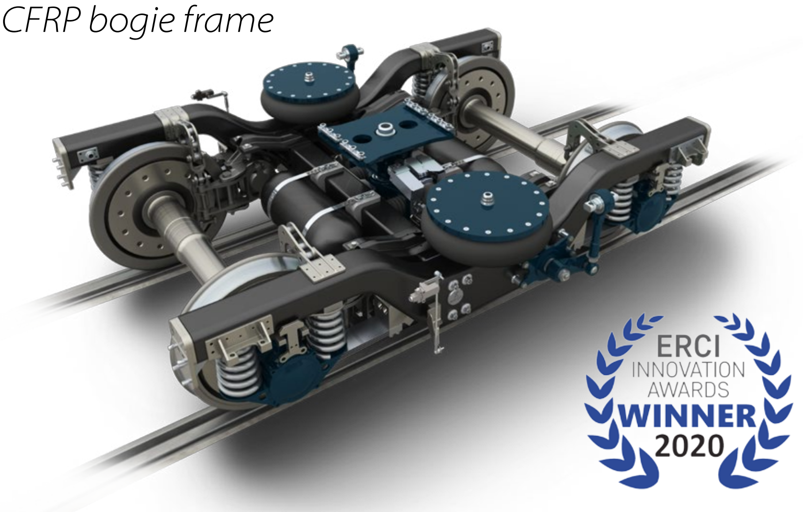
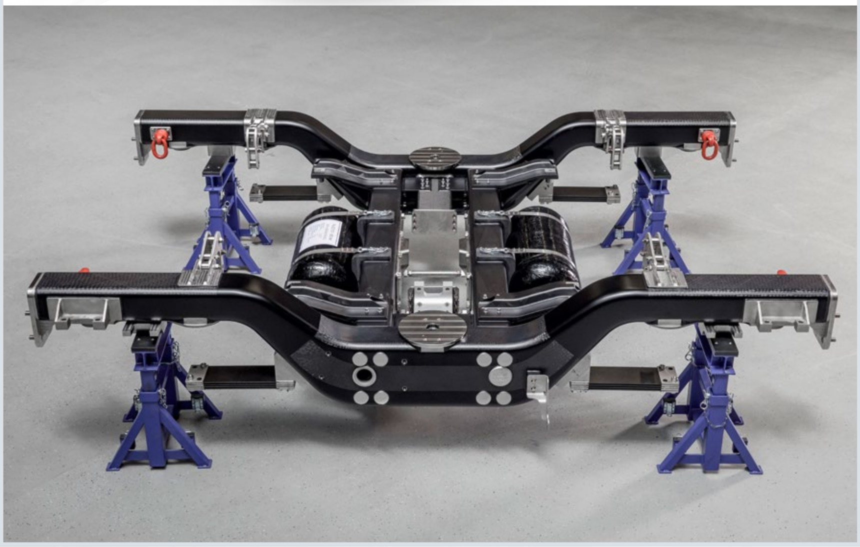
CFRP pantograph platform

CFRP bogie frame





DER EI
EISENBAHN
INGENIEUR
INTERNATIONALE FACHZEITSCHRIFT
FÜR SCHIENENVERKEHR & TECHNIK

6|21

CFRP lightweight solutions for rail vehicles

Material-specific use of carbon fibre-reinforced plastics (CFRP) in highly stressed rail vehicle structures opens up enormous lightweight potentials

ANDREAS ULBRICHT | FRANZ BILKENROTH | SEPP RENNER

CG Rail

CG Rail GmbH
Freiberger Straße 33
D-01067 Dresden
www.cgrail.de
info@cgrail.de

SPECIAL PRINT

CFRP lightweight solutions for rail vehicles

Material-specific use of carbon fibre-reinforced plastics (CFRP) in highly stressed rail vehicle structures opens up enormous lightweight potentials

PROF. DR.-ING. ANDREAS ULBRICHT
DIPL.-ING. FRANZ BILKENROTH
DIPL.-ING. SEPP RENNER

Current trends in rail vehicle technology such as the accomplishment of hybrid drives for greater operational flexibility or the integration of additional comfort and information systems for passengers are leading to increasing structural masses. However, the total mass of the vehicles is limited by the maximum permissible wheelset loads. Here, the development of modern lightweight CFRP solutions for fully loaded structures offers an attractive opportunity for significant mass reduction, although railway vehicles are still a comparatively young field of application for CFRP materials. The lightweight potential of CFRP and the solution of associated challenges have already been successfully demonstrated by CG Rail GmbH for various rail vehicle structures.

Potentials of CFRP in the rail vehicle sector

The material-specific use of continuous fibre reinforced plastics for highly stressed load-bearing structures in rail vehicles allows the exploitation of enormous lightweight potentials. The technical significance of glass fibre and carbon fibre reinforced plastics (GFRP and CFRP) stands out because of their exceptionally high specific strengths and stiffnesses compared with metallic structural materials. The diagram in Fig. 1 compares density-related lightweight indicators for different materials, whereby the values for composites are only valid if applied in fibre direction. When developing GFRP or CFRP lightweight solutions, the directional dependence (anisotropy) of the material properties must be given special consideration in the development of GFRP or CFRP lightweight solutions to exploit the full material potential. In addition, special manufacturing and joining restrictions of continuous fibre reinforced GFRP or CFRP must be considered throughout the entire design process, from the first concept to the detailed design phase [1].

However, the structural application of fibre reinforced composites in rail vehicle technology has so far mainly been limited to components with low loads, such as front cabin structures or cladding components for interiors and exteriors. In these cases, GFRP with either short, long or continuous fibre reinforcement is usually applied. Compared to metallic materials, the main advantages of GFRP are an exceptional freedom to design, combined with low material and production costs including an excellent corrosion resistance.

Compared to metals and GFRP, the adequate use of CFRP permits mass reductions of up to 50% in highly stressed rail vehicle structures – a fact that has already been successfully demonstrated in extensive studies and basic research projects (see [2, 3, 4]). Furthermore, in contrast to metals, fibre composites such as CFRP allow direct integration of sensor elements into the material during the primary production process (see [5, 6]). This means that the sensor elements are excellently protected from environmental influences ensuring component strains to be reliably measured during operations. Continuously monitoring online structures also provides the opportunity for condition-based maintenance of CFRP structures. Other advantages of CFRP and GFRP materials compared with metallic materials include high material damping, lower heat conduction perpendicular to the fibre direction (thermal insulation), excellent corrosion resistance and mostly benign failure behaviour.

Selected challenges for the application of CFRP in the rail vehicle structures

However, the commercial series use of CFRP materials in rail vehicles is currently limited to only a very few applications such as lightweight antenna carriers on bogies. It seems that CFRP is still being used hesitantly because of the high material costs for carbon fibres (CF), which, along with the plastic, constitute the main part of the composite material CFRP. The main cost drivers for CF production result from the precursor – the polyacrylonitrile fibre (PAN) – contributing around 50%, and the energy costs for stabilisation, carbonisation and optional graphitisation of the PAN-fibre during CF production which contribute about 20% [7]. However, the steadily increasing CF production capacities worldwide and the associated economies of scale have already led to a significant fall in prices for pure carbon fibre of up to less than 20 €/kg in recent years [8]. In addition, there are promising developments regarding a successive replacement of the expensive, petroleum-based precursor PAN with cost-effective and sustainably produced materials such as lignin, which is a waste product from paper production. As a result, further cost

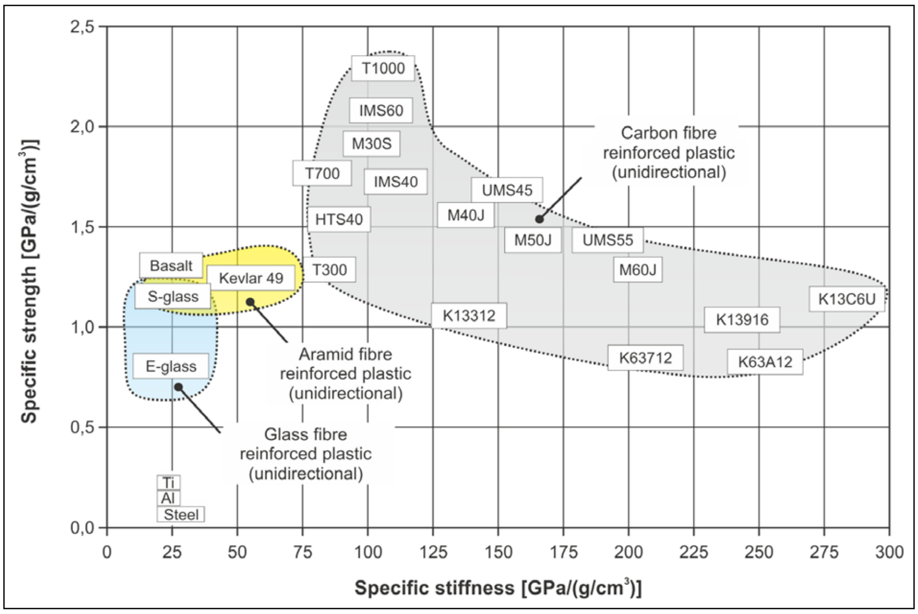


Fig. 1: Comparison of the lightweight potential of different materials

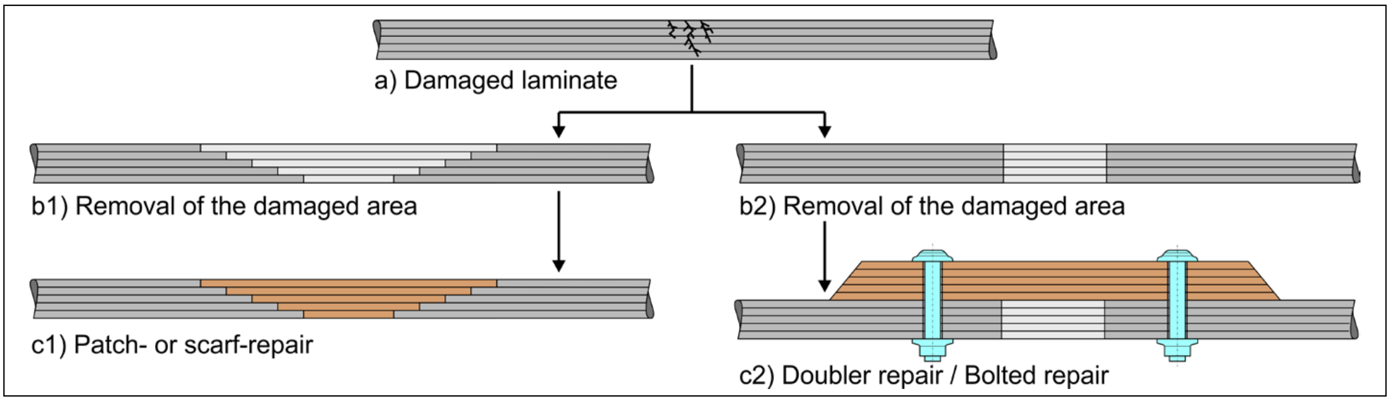


Fig. 2: Basic principles of selected repair processes for CFRP materials

reductions can be expected in future [9].
High manufacturing costs due to labour-intensive manual processes are also often mentioned as a critical point in practice. These can be significantly reduced through a higher degree of automation, which simultaneously improves component quality and reproducibility. However, the economic profitability of process automation should always be examined in view of the higher initial investment considering the planned production scenario. In addition, a planned automated production should have been considered before, in the early conceptual design phase of CFRP components, as the selected manufacturing process usually influences important factors such as usable, semi-finished products and realisable shape [1].
In general, however, the monetary evaluation of lightweight CFRP construction measures for rail vehicles should not only be carried out in a limited manner for the manufacturing costs, but in a systemic manner for the entire life cycle costs, whereby the material price and the manufacturing costs usually only form a subordinate part. For example, the application of CFRP lightweight structures to material-adapted designs can lead to a significant reduction in energy costs (mass reduction), maintenance costs (wear reduction on the rail vehicle, excellent corrosion resistance) and track charges (reduction of stress on the track superstructure) (see [10, 11]).
The fulfilment of fire protection requirements according to the European standard EN 45545 is often considered another challenge for CFRP in rail vehicles. It has been in place since 2016, especially for the highest hazard class HL 3, e.g. in metros [12]. To this end, CG Rail GmbH has carried out extensive fire tests on various CFRP structural materials with both thermoset as well as thermoplastic matrix, whereby even the highest requirements according to HL3 R7 in accordance with EN 45545-2 are fulfilled through special fire protection measures. On the one hand, this is achieved by using inherently flame-retardant plastics such as phenolic resins. On the other hand, the market offers many different flame retardant additives, which, added to plastic and depending on their chemical composition, influence fire behaviour with different modes of action. Another possibility is integrating special fire protection-modified fibre layers or resin layers (so-called gel coats) on the outer side of fibre composite components directly during the main manufacturing process (see [13]). Finally, fire protection coatings can also be applied after manufacturing fibre composite components, although this leads to additional manufacturing steps and therefore additional costs.
Another focus during the development of lightweight CFRP structures for rail vehicles is on impact behaviour and fatigue behaviour. In the exemplary case of lightweight CFRP structures in rail vehicles exposed to impacts by flying gravel, especially adapted layer structures with high impact tolerance and energy absorption capacity can be achieved. CG Rail GmbH, for example, has developed a novel underfloor cladding in lightweight CFRP design with high impact resistance. The CFRP claddings that were applied achieved a mass saving of 55% compared to the metallic reference components and, at the same time, require less space for design [14]. The fatigue behaviour of CFRP materials with continuous fibre reinforcement is influenced by many different factors, such as the CF fibre type, the plastic (thermoplastic, thermoset), the manufacturing process and the component quality (see [15]). As an example, in CFRP components with continuous fibre reinforcement, stresses should predominantly only occur in the fibre direction under all load conditions to exploit the excellent fatigue strength of CFRP materials in this direction. If this basic principle is considered during design

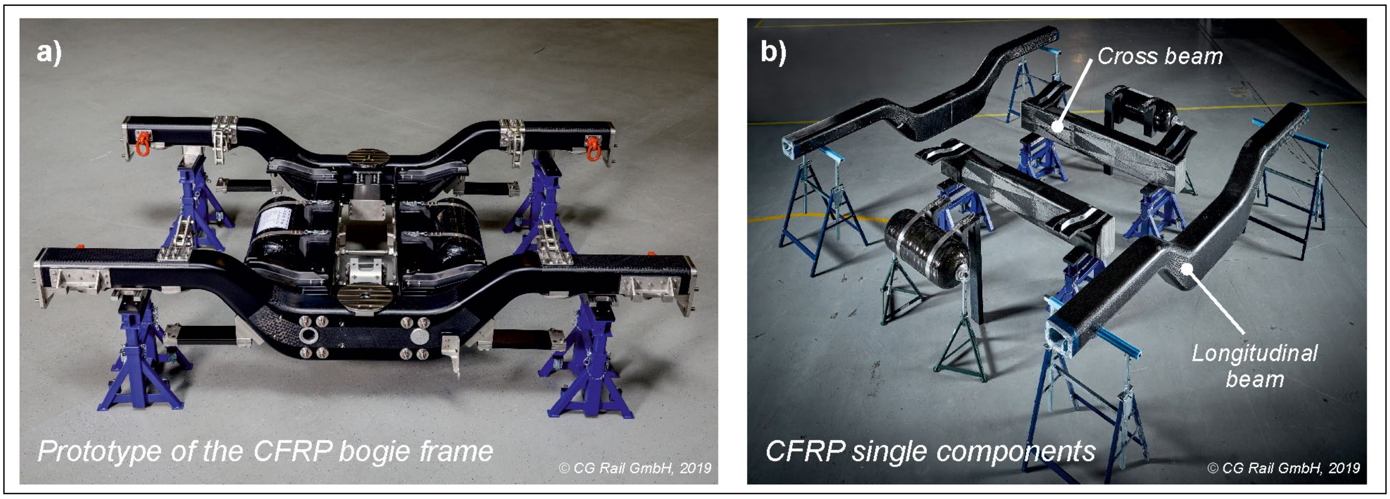


Fig. 3: CFRP lightweight bogie frame in differential design

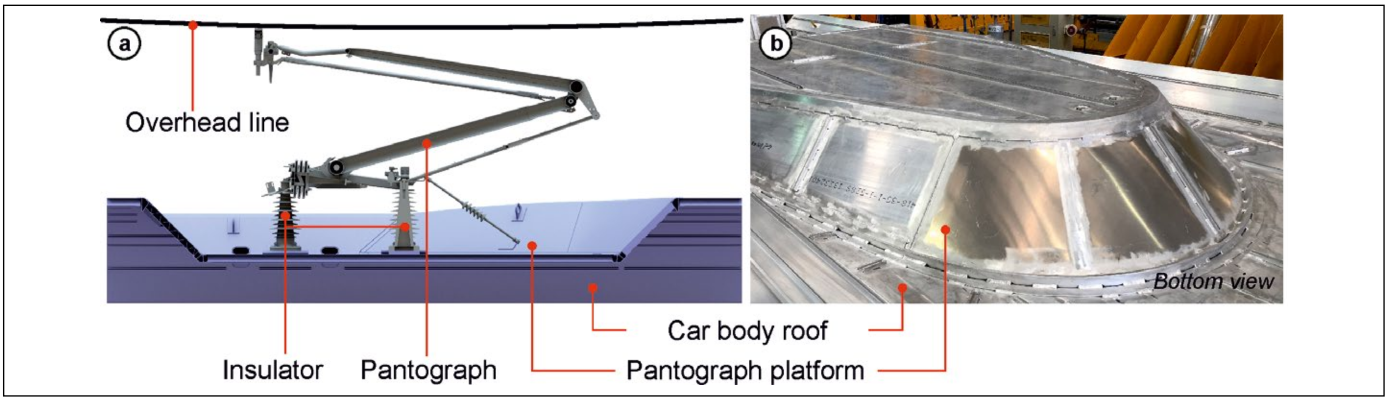


Fig. 4: Pantograph platform

and dimensioning of the components, a long service life can be achieved.

In the area of damage detection and repair of CFRP lightweight structures, the aviation sector provides several established technologies that can be partly transferred to the rail vehicle sector in a synergetic manner. Suitable technologies for damage detection in CFRP structures include the ultrasound method, acoustic emission testing, thermography or the X-ray method. However, these methods differ regarding various criteria, e.g. detectability of different types of damage (see for example [16]). Furthermore, the integration of sensor elements with different operating principles offers great potential for continuous structural monitoring of CFRP lightweight components (see [17]). For repairing CFRP components with a thermoset matrix in the aerospace sector, various certified technologies have been established, too, such as milling out the damage and subsequently laminating a repair patch (also known as "scarf repair" or "patch repair") or the so-called doubler repair (also known as "bolted repair"). The basic principles of these methods are shown in Fig. 2 (see [18, 19, 20]).

The exceptional lightweight potential and the resolvable challenges in the structural use of CFRP in rail vehicles provide many approaches for development and technology solutions for innovative lightweight components. In the following, two novel CFRP lightweight structures, developed under the leadership of CG Rail GmbH from Dresden, are presented as examples.

Lightweight CFRP bogie frame

Innovative lightweight CFRP solutions for bogies can lead to multiple advantages such as improved running dynamics due to reduced inertia forces, reduced wheel-rail wear due to lower loads and lower energy consumption. An impressive example of the beneficial use of CFRP in bogies is the lightweight bogie frame developed by CG Rail, offering a mass reduction of almost 50% compared to the steel reference frame [21]. This innovation has been awarded with the European "ERCI Innovation Award 2020".

The classic H-shape of this lightweight bogie frame results from the requirement to adopt all interfaces, installation spaces and add-on components from the steel reference frame (Fig. 3a). The intended highly automated production was already considered at an early development stage during the conceptual design phase. As an example, a new kind of CFRP differential design with an intelligent division into four CFRP single components using simpler geometry was developed, because the complex H-frame shape makes producing a one-piece CFRP integral design technically and economically almost impossible (Fig. 3b). The automated production of the single components enables a very high component quality with low production costs at the same time.

The new CFRP bogie frame was successfully tested in extensive tests under static as well as cyclic loading. The cyclic testing was carried out in accordance with the DIN EN 13749:2011 standard over a total of 12 million load cycles. The load level was gradually increased from 100% to 160% during the test after the successful completion of 6 million load cycles (see also [21]).

Lightweight CFRP pantograph platform

In high-speed trains, the pantograph can be mounted either directly onto the car body roof or in a recessed position. In both cases, additional claddings are usually provided to reduce air resistance and turbulence (see [22]). Mounting the pantograph into a roof recess can reduce the cross-sectional area of the car body and thus contribute to a reduction in aerodynamic drag, especially at very high speeds of over 300 km/h (Fig. 4a). An aerodynamically favorable design of the recess can also reduce turbulence and the resulting noise emissions generated by the pantograph, especially at higher speeds (see [23, 24, 25, 26]). Therefore, the shape of this so-called pantograph platform has to be adapted to its special aerodynamic requirements. This usually results in complex geometry on outer surfaces which, in classic metal design, can usually only be produced using very complex welded constructions with a large number of individual parts (see Fig. 4b). In addition to the related very high-subsequent extensive manufacturing costs, complying with the required tolerances is a further challenge.

The extremely high design freedom in the primary molding process and the possibility of producing an integral component in just one manufacturing step predestine the use of CFRP to produce the pantograph platform. In addition, CFRP offers the possibility of a significant reduction in mass and thus also in the moment of inertia in the particularly relevant roof area. Another aspect is the possibility of noise reduction in the interior through improved sound insulation. The acoustic properties of CFRP can be adjusted especially by the layer structure and fibre orientation in the layers to reduce structure-borne noise.

As part of a research project, CG Rail GmbH therefore developed and technologically implemented the world's first CFRP pantograph platform in a new integral design, which has a mass saving of 30% compared to the aluminum reference platform (Fig. 5). The aerodynamically designed outer surface of the platform was specified by the customer [23]. The one-piece CFRP sandwich structure of the platform, in a maximum dimension of 3.80 meters, is manufactured by means of a vacuum infusion in just a single process step. The use of the one-step infusion process has significantly reduced the amount of work and fixturing required in production. With a tolerance of just ±2 mm, the finished component also exhibits high dimensional accuracy. In addition, a specially adapted sandwich structure has significantly improved sound insulation in the audible frequency range. Compliance with the required fire protection class HL3 R8 in accordance with standard EN 45545-2 was achieved using fire protection systems and demonstrated in extensive fire protection tests. The platform in integral lightweight CFRP construction was also successfully tested in extensive tests under static and cyclic loads over 10 million load cycles.

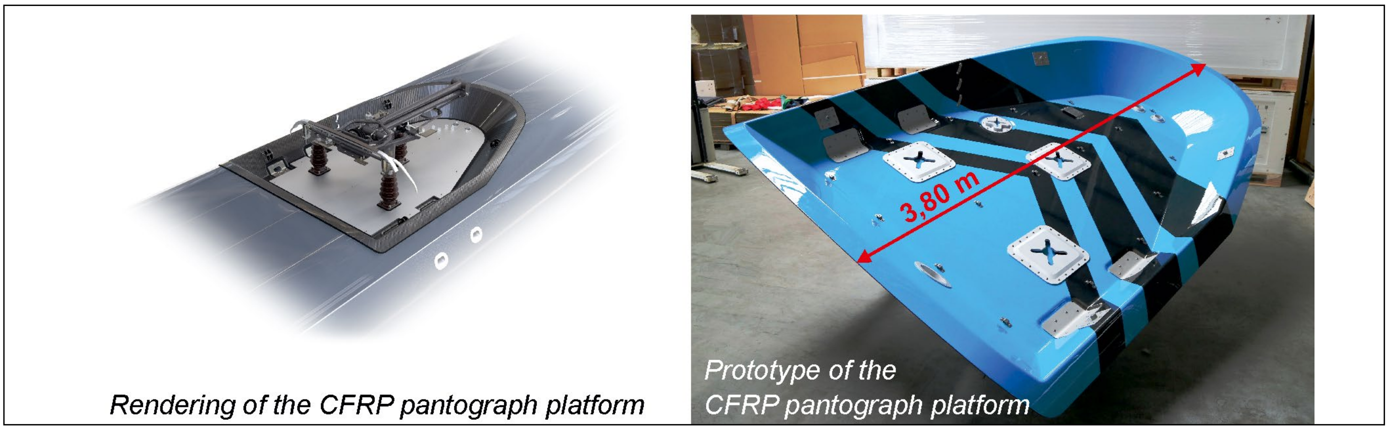


Fig. 5: Prototype of the CFRP pantograph platform

Source (all Fig.): CG Rail GmbH

Summary

CG Rail GmbH and its renowned partners have successfully demonstrated the enormous lightweight potential of CFRP materials for application in load-bearing structures of rail vehicles in the framework of several projects. These include a CFRP pantograph platform in an integral design with a mass saving of 30% and a CFRP lightweight bogie frame in a differential design with a mass saving of almost 50%. All specific requirements for rail vehicles such as those relating to fire protection or operational stability were considered throughout the development process, from the conceptual design phase through to the technological realization of the prototypes. The knowledge gained in the projects on the use of continuous fibre reinforced CFRP in rail vehicles is an important foundation for the future realization and approval of series applications for new vehicles as well as modernization measures. ■

BIBLIOGRAPHY

[1] Hufenbach, W.; Helms, O. Zum methodischen Konstruieren von Leichtbaustrukturen aus kohlenstofffaserverstärkten Kunststoffen. Konstruktion – Zeitschrift für Produktentwicklung und Ingenieur-Werkstoffe 62, 2010, Volume 10, pp. 69-74.

[2] Nickel, J.; Fischer, F. et al. Einsatz von CFK Leichtbau-Faserverbund-Technologien im Schienenfahrzeugbau. Projektstudie des Deutschen Zentrum für Luft- und Raumfahrt (DLR), 2016.

[3] Seo, S. I.; Kim, J. S.; Cho, S. H. Development of a hybrid composite bodyshell for tilting trains. Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 222 (1), 2008, pp. 1–13.

[4] Hillebrecht, M.; Orlo , S.; Brandhorst, M.; Kuhn, D. Leichtbau durch Multimaterialsysteme im ultraleichten Wagenkasten. Lightweight Design, 2016, Volume 9 Issue 4, pp. 32-37.

[5] Geller, S.; Gude, M. Process-Integrated Manufacturing and Embedding of Novel Piezoelectric Sensor Modules into Glass Fibre-Reinforced Polyurethane Composite Structures. Materials Science Forum 825–826, pp. 563-570, 2015.

[6] Hufenbach, W.; Böhm, R.; Thieme, M.; Tyczynski, T. Damage monitoring in pressure vessels and pipelines based on wireless sensor networks. Procedia Engineering 10, 2011, pp. 340-345.

[7] Lässig, R. et al. (2012). Serienproduktion von hochfesten Faserverbundbauteilen – Perspektiven für den deutschen Maschinen- und Anlagenbau. Roland Berger Studie für den VDMA. Retrieved March 3, 2021, from https://www.industrial-production.de/upload_weka/Studie_894791.pdf

[8] Schüppel, D. 18 EURO/KG CFK - Spitzencluster MAI Carbon erreicht Kostenziel. Carbon Composites Magazine, 1, 2018, pp. 21-22.

[9] Al Aiti, M. et al. Dry-Jet Wet Spinning of Thermally Stable Lignin-Textile Grade Polyacrylonitrile Fibers Regenerated from Chloride-Based Ionic Liquids Compounds. Materials 13(17): 3687, 2020.

[10] Wennberg, D.; Stichel, S.; Wennhage, P. Lohnt sich eine Gewichtsreduzierung bei Hochgeschwindigkeitsfahrzeugen. ZEVrail, 3, 2013, pp. 77-87.

[11] Mannsbarth, H. (2014, December 9). Moderne innengelagerte Drehgestelle für den Vollbahnbereich. Speech at IFS-Seminar at RWTH Aachen. Retrieved February 28, 2021, from: http://www.dmg-berlin.info/page/downloads/vortrag_mannsbarth.pdf

[12] DIN EN 45545-2 Bahnanwendungen – Brandschutz in Schienenfahrzeugen – Teil 2: Anforderungen an das Brandverhalten von Materialien und Komponenten. Beuth Verlag GmbH, 2020, Berlin.

[13] Bünker, J. Brandhemmend ausgerüstete Faserverbundbauteile nach DIN SPEC 91326. EI-Eisenbahningenieur, July 2016, pp. 44-48.

[14] Ulbricht, A. et al. Entwicklung von Leichtbaustrukturen in CFK-Sandwichbauweise mit hoher Impactbeständigkeit. ZEVrail, 6-7, 2020

[15] Alam, P. et al. The fatigue of carbon fibre reinforced plastics - A review. Composites Part B: Engineering, Volume 166, 2019, pp. 555-579.

[16] Towsyfyan, H.; Biguri, A.; Boardman, R.; Blumensath, T. Successes and challenges in non-destructive testing of aircraft composite structures. Chinese Journal of Aeronautics, Volume 33, No. 3, 2020, pp. 771-791.

[17] Giurgiutiu, V. Structural Health Monitoring of Aerospace Composites. Academic Press Verlag. 2015

[18] Wang, C.-H.; Duong, C.-N. Bonded Joints and Repairs to Composite Airframe Structures. Elsevier-Verlag, 2016.

[19] Dutton, S.; Kelly, D.; Baker, A. Composite Materials for Aircraft Structures. American Institute of Aeronautics & Astronautics, 2004.

[20] Sinapius, M.; Holzhüter, D. (2011, February 23) Infusion Technology for Bonded CFRP Repairs. 11. DECHEMA Kolloquium „Gemeinsame Forschung in der Klebtechnik", Frankfurt a.M. Retrieved Febuary 26, 2021, from https://elib.dlr.de/69524/1/CFRP-Repair_Vortrag_DLR.pdf

[21] Ulbricht, A. Entwicklung und technologische Umsetzung eines Schienenfahrzeugs in neuartiger Faserverbund-Leichtbauweise. ZEVrail, 6-7, 2019, pp. 220-227.

[22] Thompson, D.-J.; Iglesias, E.-L.; Liu, X.; Zhu, J.; Hu, Z. Recent developments in the production and control of aerodynamic noise from high-speed trains. International Journal of Rail Transportation, Vol. 3, No. 3, 2015, pp. 119-150.

[23] Lin, P.; Zhang, Y.; Guo, D. Optimal Design of Pantograph Platform for High-Speed Trains. International Journal of Mechanics Research, Vol. 7 No. 2, 2018, pp. 27-35. Retrieved February 20, 2021, from www.hanspub.org/journal/PaperInformation.aspx?paperID=25347

[24] Thompson, D. Railway Noise and Vibration: Mechanisms, Modelling and Means of Control. Elsevier-Verlag, 2009.

[25] Böhm, J. et al. (2017). Review on the results of the requirement analysis and assessment. Projektbericht des Shift2Rail Projekts DESTINATE. Retrieved Febuary 10, 2021, from https://projects.shift2rail.org/s2r_ipCC_n.aspx?p=DESTINATE

[26] Kümmritz, S. (2020). Emissionsortdetektion im Schienenverkehr mit einer akustischen Kamera. Berichte des Deutschen Zentrums für Schienenverkehrsforschung (DZSF), Report Nr. 4. Retrieved March 1, 2021, from https://www.dzsf.bund.de/SharedDocs/Textbausteine/DZSF/Forschungsberichte/Forschungsbericht_2020-04.html;jsessionid=1D1A9FBF3DE0FAFCA80E00B419DED50B.live11312?nn=2203708

Prof. Dr.-Ing. Andreas Ulbricht
Managing director
CG Rail GmbH
andreas.ulbricht@cgrail.de

Dipl.-Ing. Franz Bilkenroth
Project leader
CG Rail GmbH
franz.bilkenroth@cgrail.de

Dipl.-Ing. Sepp Renner
Project leader
CG Rail GmbH
sepp.renner@cgrail.de