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Development and technological realisation of the world's first CFRP high-speed metro in novel lightweight design

Design and realisation of advanced process technology with high automation potential

CG Rail
World Trade Center Dresden
Freiberger Straße 33, 01067 Dresden
E-Mail: info@cgrail.de
Internet: www.cgrail.de

Development and technological realisation of an innovative lightweight rail vehicle in composite design

Entwicklung und technologische Umsetzung eines Schienenfahrzeugs in neuartiger Faserverbund-Leichtbauweise

Prof. Dr.-Ing. Andreas Ulbricht, Dresden (Deutschland)

Abstract

The increasing complex demands on rail vehicles regarding multi-system capability, crash behavior and passenger comfort result in ever greater structural masses. Thus, lightweight design with high-tech materials like carbon fibre reinforced plastic (CFRP) is becoming increasingly important in the rail-vehicle industry. But high costs and low repeatability resulting from commonly used manual manufacturing processes usually form an obstacle for a wider application of CFRP. CG Rail GmbH and its Dresden based partners developed the world's first complete metro train in carbon-intensive lightweight design and built it as a prototype using manufacturing processes with a very high degree of automation in a pilot project on behalf of Chinese rail-vehicle manufacturer CRRC. This work presents impressive examples for the technological progress like the novel braiding process for CFRP components of the bogie frame and the innovative pultrusion technology for complex CFRP beams of the railcar body.

Zusammenfassung

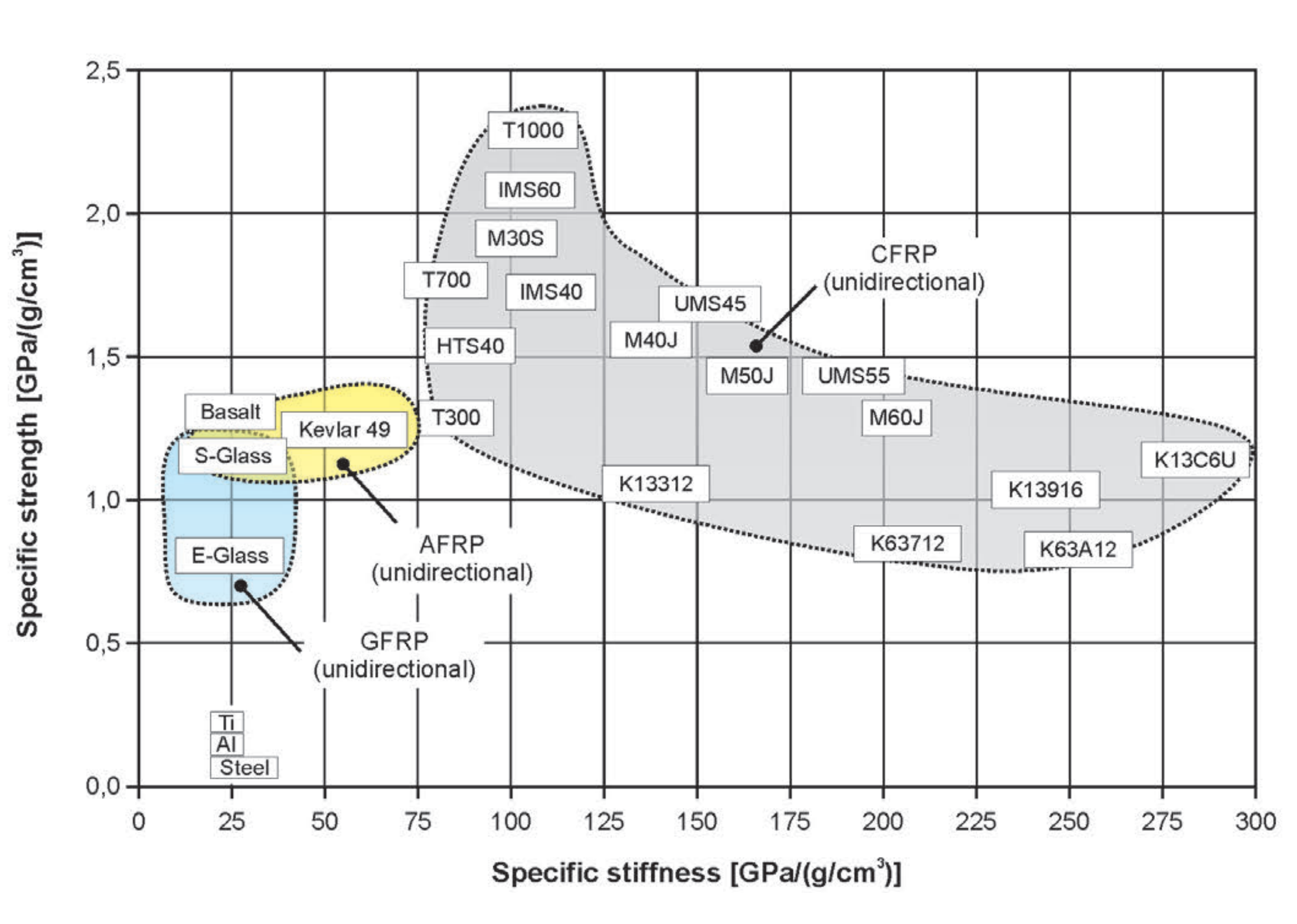
Ständig steigende Anforderungen an Schienenfahrzeuge wie etwa Mehrsystemfähigkeit, Crashverhalten und Passagierkomfort führen zu immer größeren Strukturmassen. Deshalb gewinnt der Systemleichtbau auch in der Schienenfahrzeugindustrie zunehmend an Bedeutung. Allerdings sind die oft noch manuellen Fertigungstechnologien bislang mit hohen Prozesskosten und unzureichender Reproduzierbarkeit verbunden. Die CG Rail GmbH und ihre Partner in Dresden haben im Auftrag des chinesischen Schienenfahrzeugherstellers CRRC weltweit erstmals eine komplette U-Bahn in carbonintensiver Leichtbauweise als Prototyp umgesetzt, wobei insbesondere hoch automatisierte Fertigungstechnologien eine wichtige Zielsetzung darstellten. Ein neuartiger Flechtprozess für CFK-Komponenten des Drehgestellrahmens sowie ein innovatives Pultrusionsverfahren zur kontinuierlichen Fertigung von multiaxial verstärkten CFK-Mehrkammerprofilen für den Leichtbau-Wagenkasten bilden eindrucksvolle Beispiele für den technologischen Fortschritt.

1 Lightweight design in the rail vehicle sector

The increasing and ever more complex demands on rail vehicles, such as multi-system capability, crash behaviour and passenger comfort, lead to ever greater structural masses [1]. However, the total mass of the vehicles is limited by the maximum permissible axle loads of the infrastructure, so that a higher structural mass usually leads to lower payloads. Furthermore, an increase in structural mass usually also leads to higher energy consumption and wear on the superstructure. Therefore, lightweight system design is becoming more and more important in the rail vehicle industry [2 to 3].

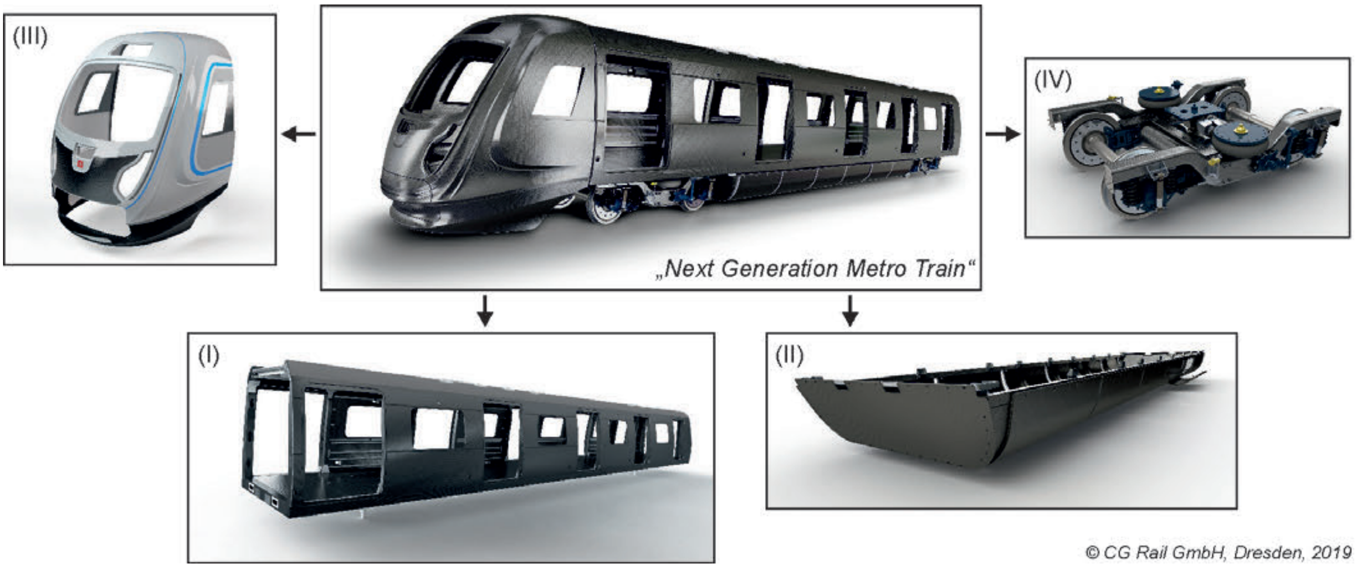
The development and technological realisation of pioneering lightweight system solutions for rail vehicles offers enormous advantages in both technical and economic terms, depending on the respective operational profile (commuter, regional, intercity and high-speed traffic) [4 to 7]. Important technical properties such as energy consumption and payload, but also vehicle dynamics, can be significantly improved. Furthermore, the use of fibre composites for structural components also opens up new possibilities for sensor integration for structural monitoring during operation. Also, from an economic perspective, intelligent lightweight solutions can significantly reduce assembly costs as well as operating and maintenance costs.

The development of high-tech lightweight solutions for rail vehicles requires the symbiotic application of different lightweight design strategies, mainly structure, material and conditional lightweight design. In the field of material lightweight design, the use of continuous fibre-reinforced plastics for structural components



I Figure 1: Lightweight potential of different materials

in rail vehicle technology – in contrast to other innovative sectors such as the aircraft and automotive industries - still plays a subordinate role. Especially for modern, innovative rail vehicle construction, carbon fibre-reinforced plastics (CFRP) with their exceptionally high specific strengths and stiffnesses open up new, and as yet unexploited, lightweight potential compared to classic metallic materials (steel, aluminium). *Figure 1* shows those density-related lightweight coefficients for various materials. In the case of unidirectionally reinforced plastics, the mechanical properties are directionally dependent (see, for example, [6 to 8]). This so-called anisotropy must be especially considered and utilised in the material-adapted design of lightweight CFRP components (see, for example, [11 to 12]). The use of fibre-reinforced plastics in rail vehicle construction has so far been limited mostly to components for the interior and exterior, which are usually made of glass fibre-reinforced plastic (GFRP) due to their complex shape and low mechanical requirements at the same time. However, the widespread use of CFRP for highly stressed load-bearing structures has not yet become established in rail vehicle construction, although detailed studies and basic projects on CFRP lightweight solutions have already demonstrated the technical feasibility and economic viability over the entire service life in principle (see, for example, [13 to 16]).
Major obstacles to the wider use of CFRP for structural applications in rail vehicle construction still include manufacturing costs and reproducibility. For this reason, the use of highly automated manufacturing processes with high efficiency and quality, in addition to mass savings, formed another important objective during the development of a novel underground train made of CFRP within the framework of the „Next Generation Metro Train“ (NGMT) project. When designing the load bearing CFRP lightweight structures, the intended manufacturing processes had to be already considered during the early concept design phase, since in particular with fibre composites, the selection of the manufacturing technology is also associated with specific restrictions, for example regarding the realisable shape or the fibre orientation [17].
In the NGMT project, CG Rail GmbH from Dresden, together with German and European partners from science and industry, successfully developed novel CFRP lightweight designs for the four essential subsystems of a metro and realised them technologically as prototypes (*Figure 2*): Car body (I), underfloor cladding (II), front cabin (III) and bogie frame (IV). Important parameters for the design and dimensioning, such as the train configuration, the design of the outer hull, the design spaces and interfaces as well as the load cases and standards were predetermined by a customer specification, which formed the basis for the development. The freedom to modify all parameters influencing the lightweight degree was limited by these specifications to the material-adapted design of the main load bearing CFRP structures.
Especially for the two particularly safety-critical subsystems „car body“ and „bogie frame“, highly automated production



I **Figure 2: NGMT subprojects**

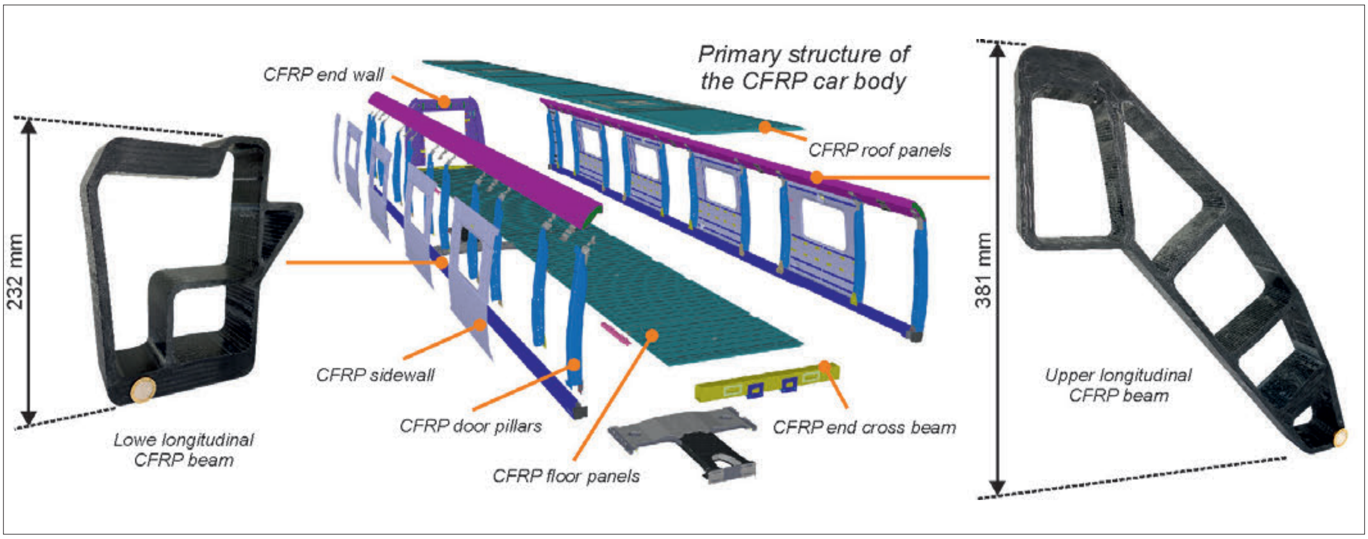
processes were used and, in some cases, newly developed for the manufacture and assembly of the highly stressed individual CFRP components, which are presented in more detail below.

2 Lightweight car body made of CFRP

The lightweight car body mainly made of CFRP was realized in a multipart differential design after detailed discussion and evaluation of all relevant criteria [18]. The primary structure of the car body, which serves to transfer the main loads, has a frame structure made of CFRP profiles, which is stiffened by two-dimensional CFRP sandwich elements acting as shear stiffeners (*Figure 3*). The outer skin in the roof and side wall area represents the secondary structure of the car body and consists mainly of thin-walled CFRP panels. They were joined to the primary structure of the car body using low distortion joining processes and specially developed auxiliary devices. This significantly reduces the usually high cost of preparatory work for the subsequent painting process, such as filling and sanding. The tertiary structure of the car body consists mainly of functional elements such as the metallic grounding cage and a large number of smaller connecting elements that form the interfaces between the load bearing CFRP primary structure and the interior components such as seats and handrails. The total mass share of CFRP materials in the primary, secondary and tertiary structure is approximately 70 %.

2.1 Novel pultrusion process

The frame structure of the CFRP primary structure of the car body is characterized by the special CFRP multi-chamber profiles in the corners of the floor and roof area, which are essential for transferring the high loads in the longitudinal direction as well as for bearing the high bending loads (*Figure 3*). These straight CFRP profiles with a constant cross-section are particularly predestined for a technological realisation using the efficient pultrusion process, which also has potential for



I **Figure 3: Structure of the lightweight car body**

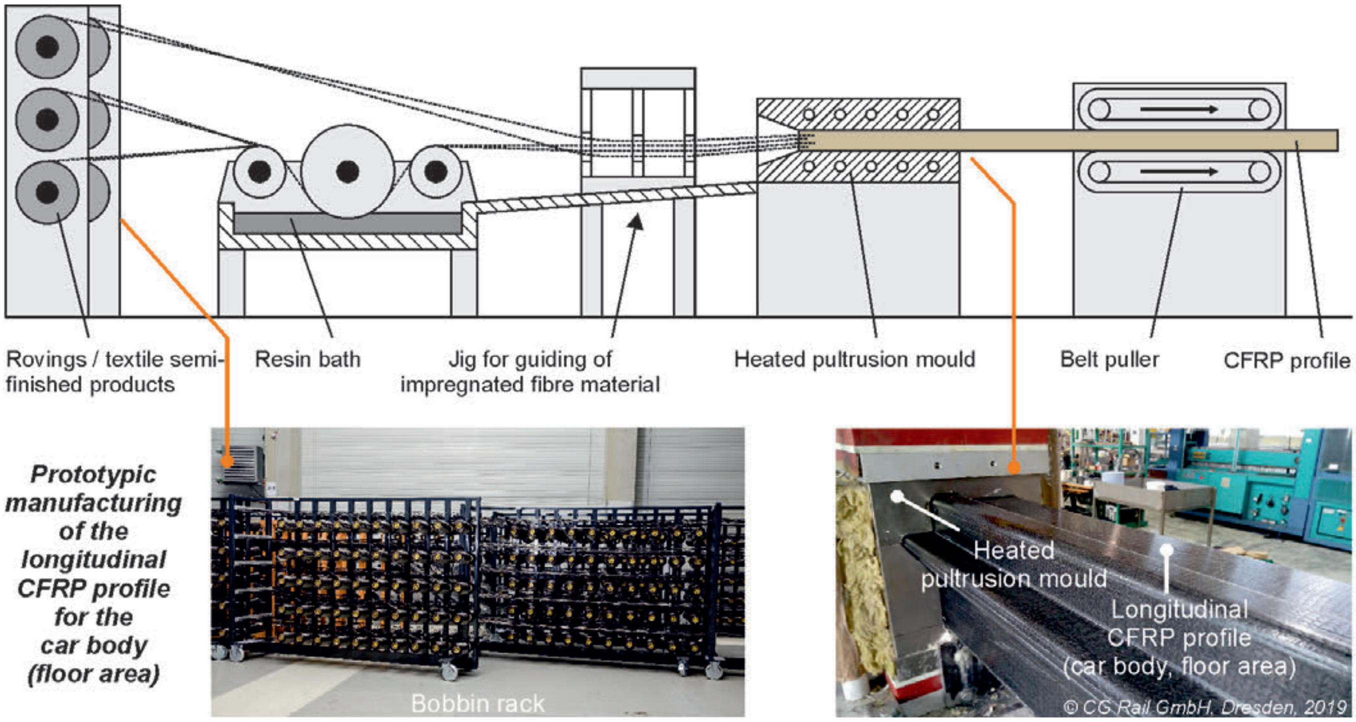


Figure 4: Pultrusion of composite profiles

a broader application in CFRP structural components in rail vehicles [19].
Pultrusion is a continuous process to produce continuous profiles made of GFRP or CFRP. In this process, „dry“ rovings („fibre bundles“) are fed directly from the spool first through a resin bath for impregnation and then through a heated metal mould for forming and curing (*Figure 4*). So far, this process has typically been used to produce simple smaller hollow or solid profiles with only unidirectional reinforcement in the longitudinal direction. However, in the case of CFRP longitudinal profiles, the occurring multi-dimensional stress states as well as the multiple joining areas with other components require the fibres to be arranged in different directions. In addition, the limited design space and other functional requirements in the NGMT project led to complex cross-sectional geometries of the longitudinal CFRP beams with several chambers and varying wall thicknesses from 7 mm to 25 mm. For this reason, CG Rail GmbH and its partners have enhanced the pultrusion process for the first time worldwide in such a way that extremely complex multi-chamber profiles with textile reinforcement in the form of multiaxial fabrics can be realized with the help of special feeding devices and core systems. The feasibility of this process was successfully demonstrated in a first step by the prototype production of the upper and lower CFRP longitudinal members of the lightweight car body with a length of more than 20 meters (*Figure 4*).

2.2 Efficient assembly processes

Another important challenge in the development of the lightweight car body was the realisation of an efficient and precise assembly process, which – like the manufacturing technologies – had to be considered already during the early conceptual design phase of the car body. During the assembly of the CFRP components of the primary structure, combined riveted/adhesive joints are used for joining. Here the adhesive joints are primarily used for purely functional reasons to seal against media.
The developed differential design of the car body allows an efficient and ergonomic pre-assembly of the two side walls (CFRP longitudinal beams, CFRP door pillars and CFRP sidewall modules) in a horizontal position in the first step, using assembly jigs specially developed by CG Rail GmbH (*Figure 5 A*). These assembly jigs allow the individual components to be joined in a pre-curved state of the sidewall in order to achieve a visually straight appearance of the car body under subsequent loading by its own weight. In a second assembly step, the side walls are erected and fixed in a final assembly jig, where the remaining components of the primary structure, such as CFRP floor and roof panels, are assembled (*Figure 5 B*).
All work steps for the pre-assembly of the side walls and the final assembly of the primary structure can potentially be automated and digitized for future series production in line with the guiding principle of Industry 4.0.
The feasibility and efficiency of the developed manufacturing technologies and assembly processes as well as the predicted mass saving of the CFRP car body of 30 % compared to the classic metal design were successfully proven on several prototypes (*Figure 6*). The produced prototypes are already in China to gain further knowledge from practical running tests on the test track.

3 Bogie frame in CFRP lightweight design

In rail vehicles, the bogie frame represents an extremely safety-critical component in the running gear and must accordingly meet the most stringent requirements in terms of component quality. Furthermore, as in most train configurations, two bogie frames are installed per rail car body of the NGMT train. This results in a higher number of identical parts being produced.

Figure 5: Final assembly of the lightweight car body

Figure 6: Lightweight car body made of CFRP

These two factors favour the use of automated manufacturing processes with excellent reproducibility and high efficiency, particularly in the production of the lightweight bogie frame. This objective was therefore consistently pursued during the conceptual design phase and detailed design phase.

The requirement to retain the interfaces and design spaces of the reference steel bogie frame could only be met by realising a classic H-frame design. Already in the early conceptual design phase, a detailed evaluation of the design of this H-frame in a one-piece CFRP integral design or in a multi-piece CFRP differential design was carried out considering the intended automated production. However, the complex shape of an H-frame makes the technological realisation of a CFRP integral construction using automated manufacturing technologies such as automated tape laying (ATL) technically and economically almost impossible. For this reason, a new type of CFRP differential design was developed with an intelligent division into four individual CFRP components with a simpler geometry that allows an automated production. The worldwide unique bogie frame consists of two straight CFRP cross beams and two double cranked CFRP longitudinal beams, which are joined together by specially developed, detachable joining technologies (*Figure. 7*).

3.1 Selection and development of manufacturing technologies

The individual components of the bogie frame are accordingly thick-walled multilayer CFRP profiles with a hollow cross section whose outer surfaces must be defined with high precision for accurate assembly. In addition, the fibres in the single layers must have different orientations in order to withstand the occurring load conditions. Furthermore, the fibre volume content must be as high as possible in order to achieve a high lightweight degree. For the automated production of CFRP hollow profiles with such properties, a two-step process is suitable in fibre composite technology. In the first step, the dry textile reinforcement structure made of carbon fibres (CF) – the so-called preform – is produced using a CNC-controlled process. In this case braiding or winding is predestined for thick-walled hollow profiles with different fibre orientations. The second step is so-called resin transfer moulding (RTM), where the preform is inserted into an all-side closed RTM mould with an integrated heating system to infiltrate and cure the thermoset plastic. This ensures the realisation of highly precise outer surfaces. Furthermore, the additional compression of the preform inside the RTM mould permits the achievement of a very high fibre volume content and thus very good mechanical properties with a low mass at the same time.

For the first process step – the so-called preforming – extensive experimental preliminary tests for braiding as well as for winding were carried out for the CFRP longitudinal beam with its more complex geometry in order to identify the most suitable process (*Figure. 8 A and B*). These preliminary tests showed that the strong cranking of the longitudinal beam would restrict the realisable fibre orientations in the winding process too much. The reason for this is the undesirable lateral slippage of the dry fibres on the winding core at more complex shapes, as the fibres do not have any strong textile weave among each other, in contrast to braiding [20 to 22]. Therefore, the braiding process was selected to produce the textile preforms of the longitudinal beams. The total amount of ten longitudinal beams was produced on a high-speed radial braiding machine with a total of 288 bobbins with a robot-guided braiding core at the TU Dresden (*Figure 8 C and D*).

After the final RTM process was completed, the deflection for some of the manufactured CFRP longitudinal beams was determined in a 3-point bending test under a load of 100 kN in order to verify the simulation models and prove the reproducibility of the developed manufacturing technology. The deflection of 3.54 mm determined in the finite element (FE) simulation differs by only about 9% from the value of 3.25 mm determined experimentally at the prototype (*Figure 9*). Furthermore, a comparison of the experimentally determined deflections of the prototypically manufactured longitudinal beams shows only extremely small variances of no more than 5% from the mean value. These results demonstrate both the high quality of the material and simulation models as well as the excellent reproducibility of the manufacturing technology developed for the CFRP longitudinal beams.

3.2 Experimental testing of the CFRP bogie frame

The lightweight bogie frame in novel CFRP differential design was successfully tested in comprehensive tests under static and cyclic loads at an external partner in Dresden. The fatigue testing was based on DIN EN 13749:2011 and was performed over a total of 12 million load cycles, with a subdivision into intervals of 1 million load cycles each followed by an inspection of the structural condition. After the successful completion of 6 million load cycles, the load level was gradually increased from 100% to 160% of the test load.

The strains were permanently measured at several positions during the fatigue test by using strain gauges. *Figure 10* shows the development of the measured strains at some selected positions over the entire test series of 12 million load cycles. The gradual increase of the load level after 6 million load cycles results in proportionally increasing strains at the affected structural areas. However, all strains are still at a clearly subcritical level in spite of the increased load. One effect could be observed repeatedly, where the strains at the start of the new interval were lower compared to the previous interval, although the load was the same. This can be attributed to non-critical creep effects after a longer pause between two inspection intervals, such as after 2 million load cycles. In addition to the strain gauges, acoustic sensors were installed on the CFRP bogie frame to allow continuous location and identification of potential damage events [23].

After completion of the fatigue test over 12 million load cycles – 6 million of which were at highly excessive load levels – no system-critical damage was detected. The results obtained confirm the exceptionally robust design of the CFRP bogie frame developed and its enormous application potential. The achieved mass saving of the first prototypes is almost 50% compared to the reference bogie frame made of steel. Based on the excellent test results, the further lightweight design potential is already becoming evident.

4 Summary

CG Rail GmbH and its renowned partners successfully developed and realized a prototype of an entire train in a novel lightweight CFRP design for the first time within the framework of the NGMT project. Mass savings of up to 50% were achieved for the main load-carrying subsystems of the train. For the technological realisation of selected CFRP components, specially adapted automated manufacturing processes were developed to achieve high component quality and cost efficiency, like the braiding process for manufacturing of the textile reinforcement structure for the CFRP longitudinal beams of the lightweight bogie frame. In addition, many series-ready joining and assembly technologies with associated fixtures for carbon-intensive large-scale rail vehicle structures were developed and successfully implemented. The necessary requirements for the implementation of these manufacturing processes as well as joining and assembly technologies were considered already at an early stage in the

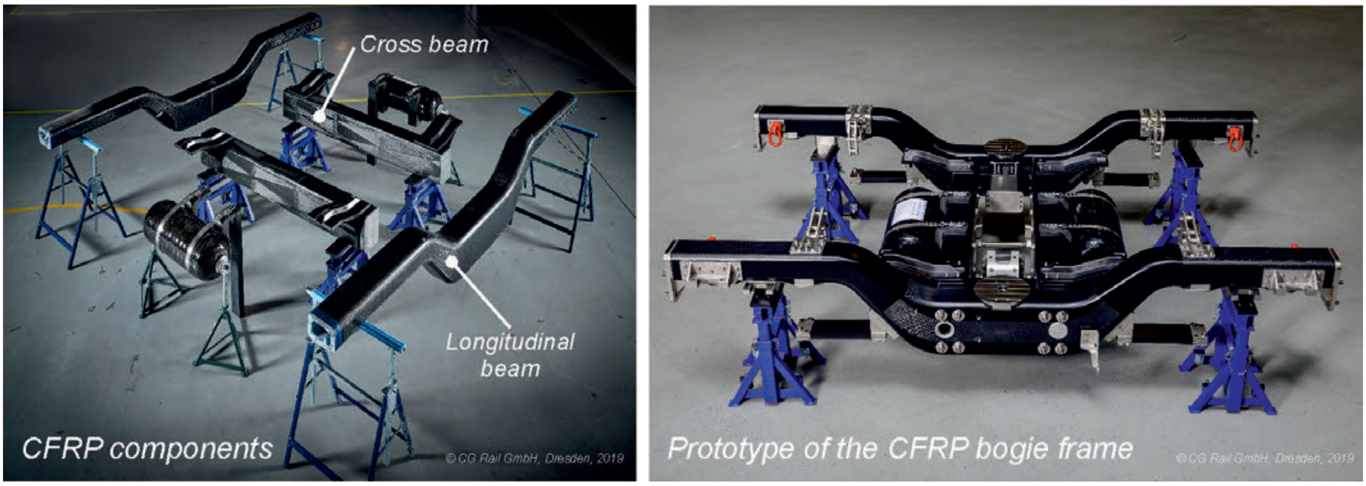


Figure 7: Lightweight bogie frame made of CFRP

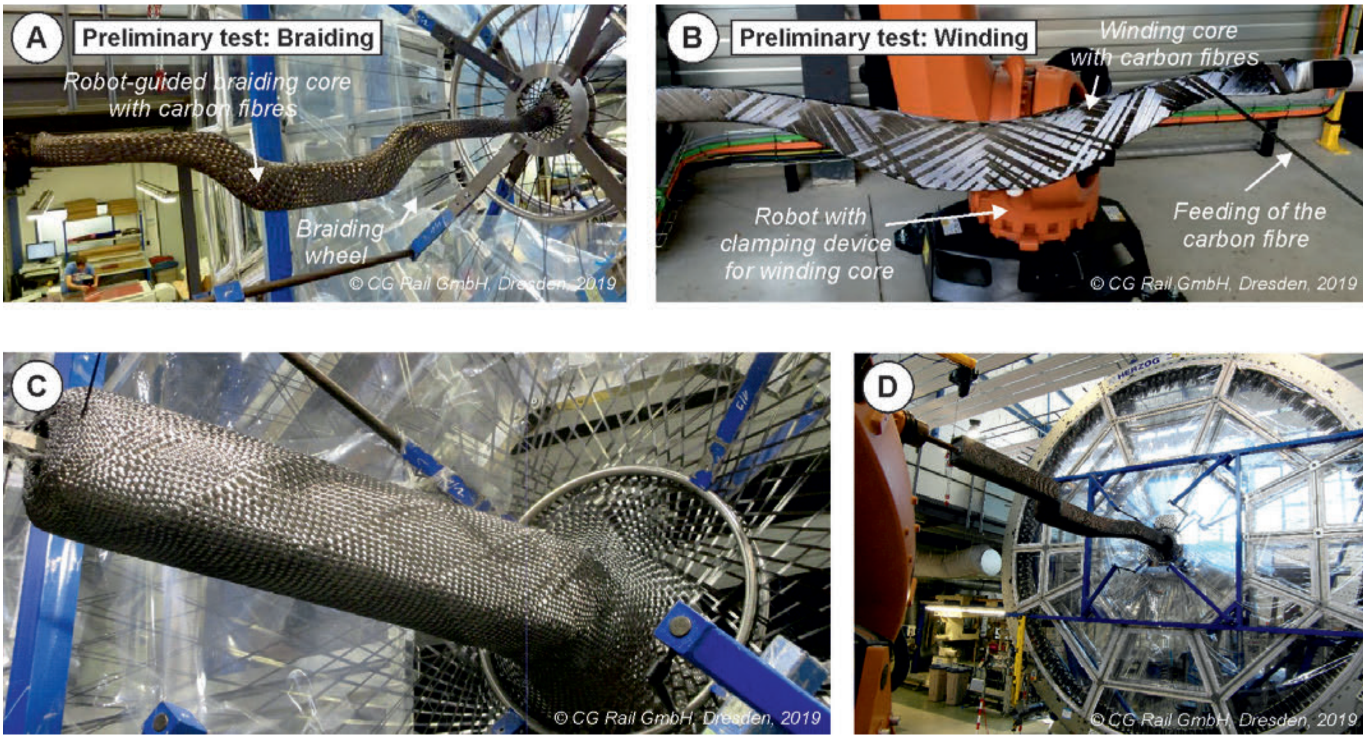


Figure 8: Manufacturing of longitudinal CFRP beam

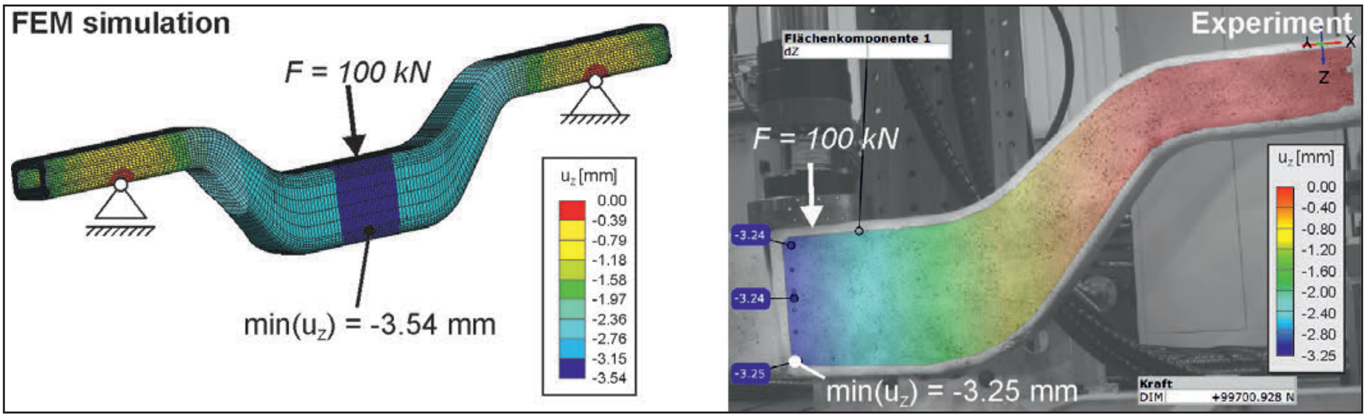


Figure 9: Test of longitudinal CFRP beam

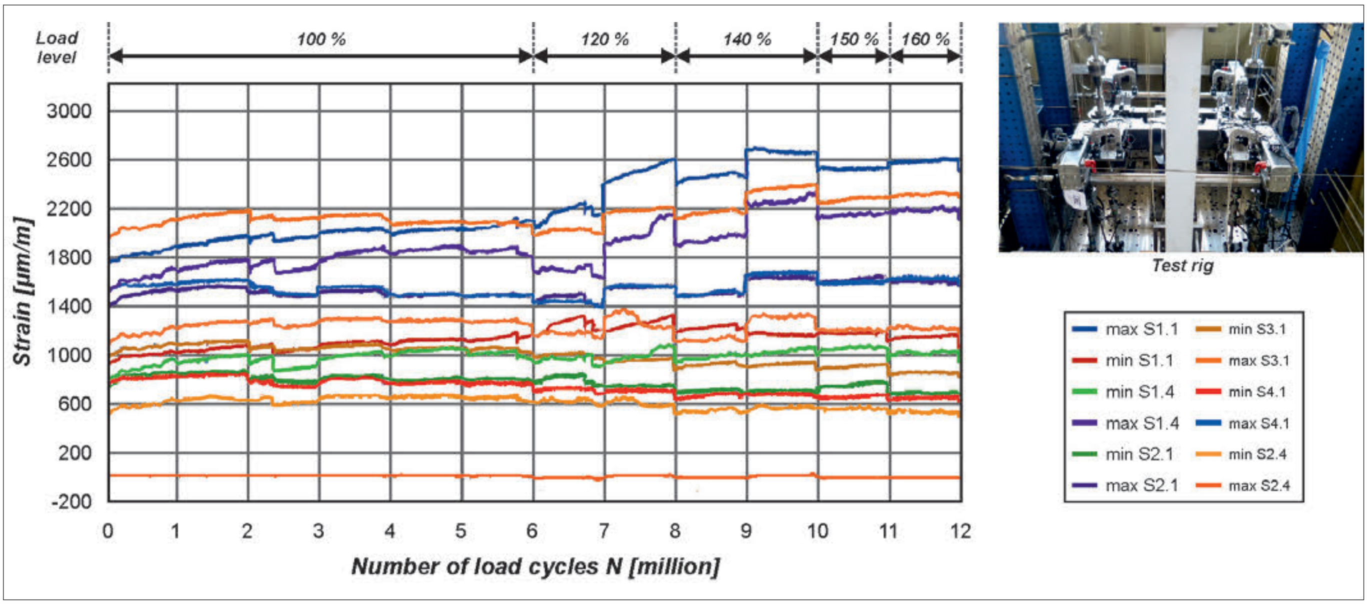


Figure 10: Measured strains during fatigue test

conceptual design phase and subsequently consistently throughout the entire development process. These developments are also reflected by 15 patent applications. This gained knowledge can also be used synergistically for other fields of application, such as for large commercial vehicles (trucks, buses).

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(Picture credits: 1 to 10; Author)

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Prof. Dr.-Ing. Andreas Ulbricht (40), studied industrial engineering, with specialisation in lightweight design, at TU Dresden. Research assistant at the Institute of Lightweight Engineering and Polymer Technology (ILK) of the TU Dresden until 2011, doctorate (Dr.-Ing.) in 2011. Project group leader at Leichtbau-Zentrum Sachsen GmbH (LZS) from 2012 to 2015. Managing director of CG Rail GmbH since 01.11.2015. Since 01.07.2018 visiting professor at Tongji University in Shanghai, China.
Address: CG Rail GmbH, Freiberger Straße 33, 01067 Dresden, Germany.
E-Mail: andreas.ulbricht@cgrail.de