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Novel composite design approaches for structural lightweight components of railway vehicles - development, technological realization and test

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Abstract

The constantly increasing demands on railway vehicles with regard to important properties such as high operational flexibility by use of battery-electric hybrid drives or multi-system capability by use of multiple electric systems result in ever greater structural masses. However, the total mass of the vehicles is limited by the maximum permissible axle loads for the infrastructure, so that a higher structural mass usually results in lower payloads. In addition, energy consumption and the related carbon emissions as well as the wear on the track and related track charges usually increase with a higher structural mass.

Here, the application of carbon fibre reinforced plastic (CFRP) with its superior specific strength and stiffness for structural components of railway vehicles opens up new lightweight potentials compared to the use of classic metallic materials like steel or aluminium. But the wider structural use of CFRP in railway vehicles requires the development of suited design approaches considering the rail specific requirements and standards as well as the development of related automated and cost-effective manufacturing processes for large and thick-walled one-piece CFRP-components.

These tasks have already been handled and successfully solved by CG Rail GmbH within the scope of various projects. One example is the so-called Next Generation Metro Train (NGMT) project, where a complete metro in carbon-intensive lightweight design was developed, built and tested for the first time worldwide. A highlight of this train is the successfully developed and tested lightweight bogie frame with a novel differential design, consisting of four main CFRP components that can be manufactured using automated and cost-efficient winding and braiding technology. This bogie frame is 50% lighter than the steel reference frame. In the framework of another project a novel lightweight pantograph platform made of CFRP was developed for a highspeed train achieving a mass reduction of 30 % compared to the welded aluminium reference structure.

The developed and experimentally proven composite design approaches at CG Rail GmbH open up the chance for the achievement of substantial mass saving at future railway vehicles. Due to the extremely long lifetime of railway vehicles of usually 40 years and more the mass savings can lead to significant reduction of operational costs depending on the operational profile of the train resulting from the lower energy consumption, the lower wear of the track, the better corrosion resistance compared to metals and many other factors.

Keywords: Structural lightweight design, railway vehicle, composite materials, carbon fibre reinforced plastic.

1 Introduction

The increasing and ever more complex demands on railway vehicles, such as multi-system capability, operational flexibility, crash behaviour and passenger comfort lead to ever larger structural masses (e.g. [1]). However, the total mass of the vehicles is usually limited by the maximum permissible axle loads of the infrastructure, so that a higher structural mass generally leads to lower payloads. In addition, an increase in structural mass usually also leads to higher energy consumption and wear on the track. For this reason, lightweight system design is becoming increasingly important in the rail vehicle industry.

The development of future-oriented lightweight system solutions for railway vehicles opens up enormous technical and economic advantages, depending on the respective operational profile (local, regional, intercity and high-speed traffic) (e.g. [2,3]). Important technical properties such as energy consumption, payload and driving dynamics can be significantly improved.

The development of lightweight solutions for railway vehicles requires the symbiotic application of various lightweight design strategies like shape optimization and lightweight material design. In the field of lightweight material design, the use of carbon fibre reinforced plastics (CFRP) for structural components in rail vehicle technology - in contrast to other sectors such as the aircraft industry - has so far played a subordinate role in spite of their extraordinarily high specific strengths and stiffness and subsequent lightweight potential compared to metals (Figure 1). Furthermore, various studies and research projects have already proven the technical feasibility and economic efficiency of CFRP application for structural components over the entire service life of railway vehicles (e.g. [4,5]). But the current application of composite materials is usually limited to non-structural components like interior claddings, where mostly glass fibre reinforced plastics are used due to the complex shape and low mechanical requirements.

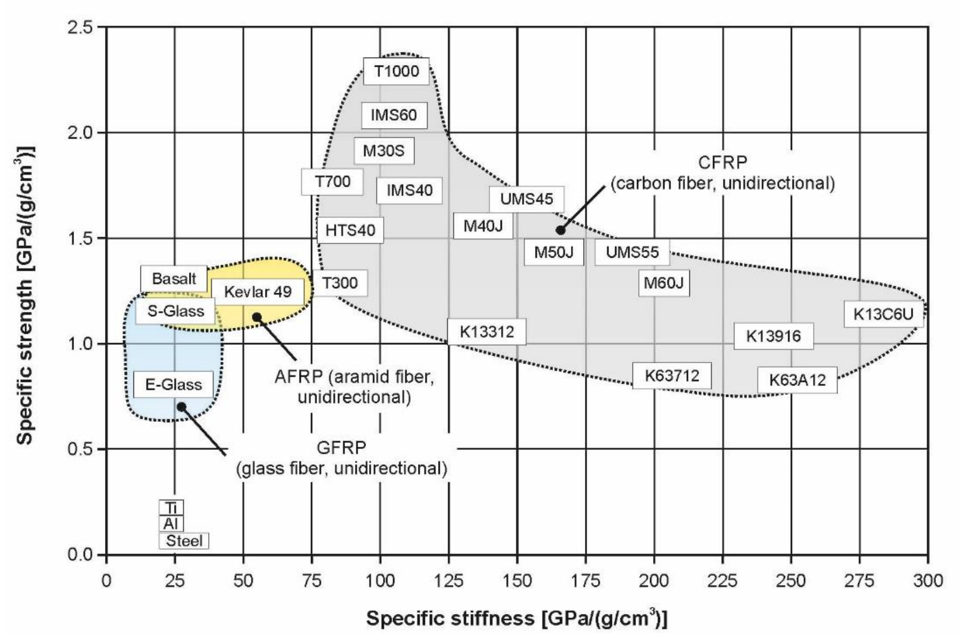

Figure 1: Lightweight potential of materials.

One of the main hurdles for a wider structural application of CFRP in railway vehicles is the lack of suitable composite designs that meet the specific railway standards and can be manufactured in a highly efficient and reproducible manner. Thus, specially adapted CFRP lightweight designs for a wide range of highly stressed structural systems in railway vehicles have been successfully developed, realised and tested, which are exemplarily presented here for (A) car body, (B) bogie frame and (C) underfloor panelling of the NGMT as well as a (D) pantograph platform of a highspeed train (Figure 2).

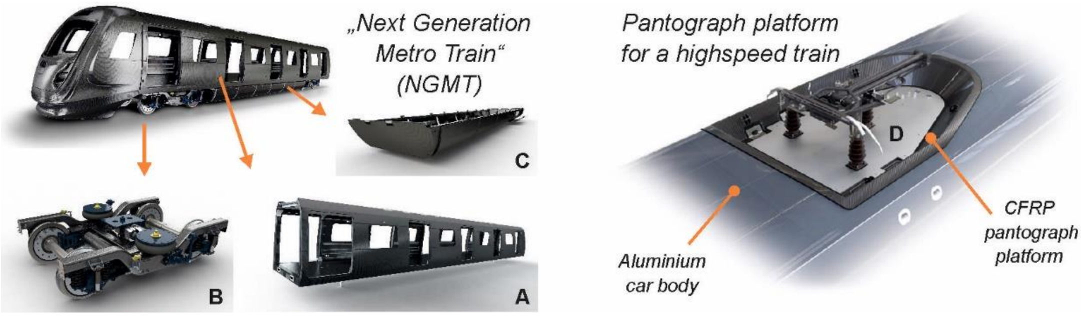

Figure 2: Overview composite structures.

2 Methods

The design of those highly stressed lightweight CFRP structures for railway vehicles has to consider a lot of different requirements - especially the challenging railway specific standards related to strength and stiffness requirements, which are often based on the assumed use of metallic materials (e.g. [6]). In this context special attention was given to the anisotropic material properties of CFRP during the design of the components (e.g. [7]). Furthermore, the aimed use of – as far as advantageous – highly automated manufacturing technologies with high efficiency and reproducibility on realizable shapes and layups was already regarded during the early conceptual design.

A special challenge arose from the high impact resistance requirements especially for the underfloor panelling, which protects the equipment under the car body. The CFRP sandwich structure must withstand an impact of a concrete ball with a mass of about 500 g and a speed of 250 km/h and an impact angle of 90° without penetration of the impactor. After impact, the side facing the impact must still have an intact surface. Furthermore, no pieces may be detached. Extensive experimental impact tests have been made to develop a sandwich layup with high impact resistance. Furthermore the test results served for the validation of a non-linear finite element (FE) models, which can be used for cost-efficient determination of lay-ups with high-impact resistance in future without expensive testing.

Another challenge for composite materials arises from challenging fire resistance requirements in railway industry according to DIN EN 45545 [8]. Extensive tests of different CFRP materials and coatings have been conducted to meet these requirements. Figure 3 shows CFRP specimen after test for determination of heat release according to ISO 5660-2 for the pantograph platform. The chosen material system achieved all requirements for HL3 R8 according to DIN EN 45545-2.

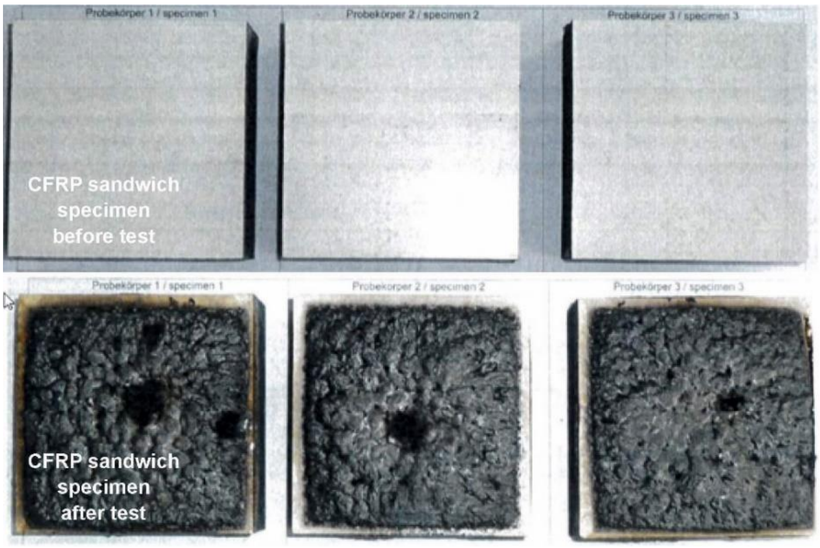

Figure 3: Fire resistance tests.

Another important aim was the development of highly automated manufacturing processes, which allow the cost-effective and reproducible production of large one-piece CFRP components. Focussed manufacturing technologies were computer numerical controlled braiding, winding and pultrusion processes. As an example, the pultrusion process for thick-walled CFRP-profiles with multi-chamber cross section for the car body is shown in Figure 4.

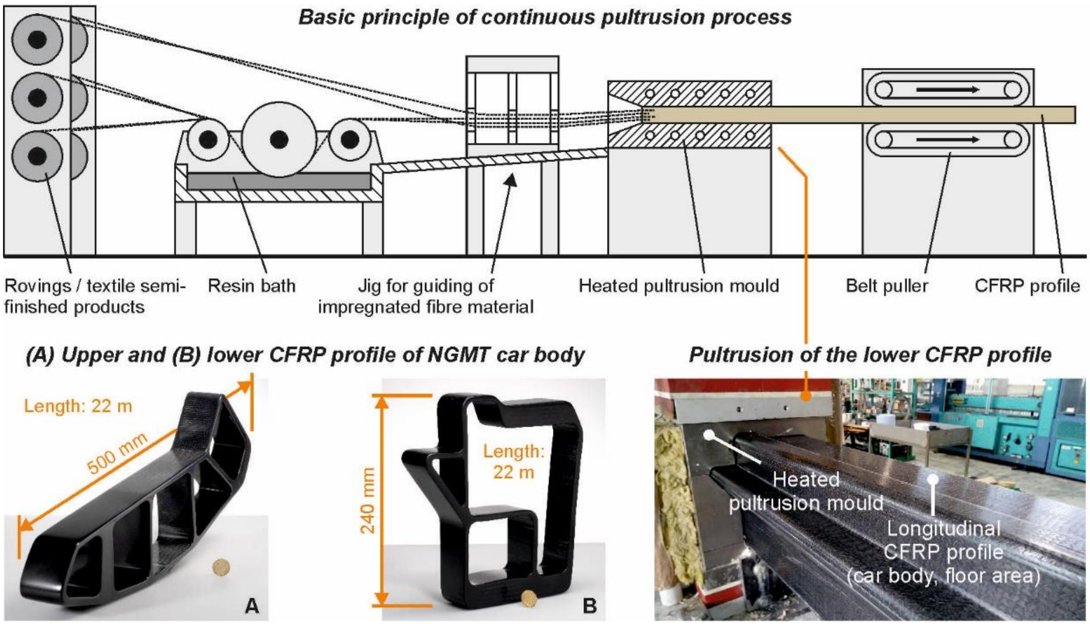

Figure 4: Pultrusion of CFRP-profiles.

The innovative CFRP lightweight structures have been finally tested under static and cyclic loading for validation of the simulation models as well as verification of the novel lightweight design approaches with composite materials.

3 Results

A differential design approach was realized for a metro's car body, bogie frame and underfloor panelling, which offers many advantages compared to integral design approaches like high-efficient manufacturing of the single CFRP-components with simple geometries and easy replacement of damaged components.

The differential design of the car body is characterized by a load-bearing frame made of pultruded CFRP profiles, which is stiffened by CFRP sandwich elements acting as shear fields ([9,10]). The CFRP components are joined by means of combined riveted/bonded joints, whereby the bonding is mainly used for functional reasons to ensure the tightness. The predicted mass saving of 30% of the CFRP car body compared to metal design was successfully demonstrated (Figure 5).

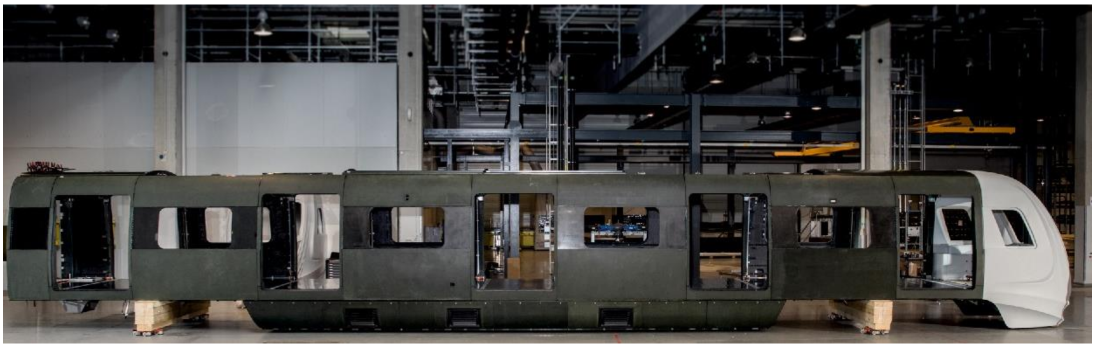

Figure 5: CFRP car body.

The structural base frame of the underfloor panelling forms a frame structure of predominantly pultruded CFRP profiles, to which sandwich structures are attached (Figure 6). Extensive non-linear crash simulations and corresponding impact tests were used to determine sandwich layups with high impact resistance. Test- and simulation-results showed a very good agreement (Figure 7). With the CFRP underfloor panelling a mass saving of 30% was achieved compared to aluminium design [9].

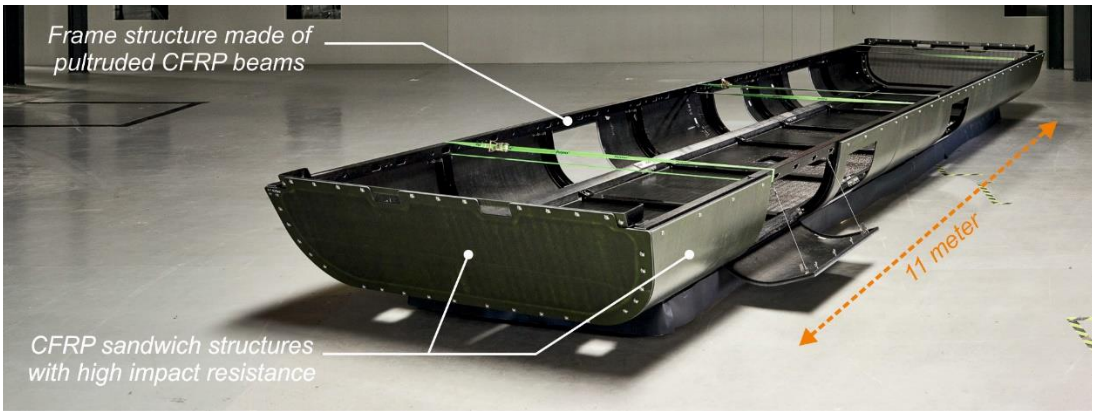

Figure 6: CFRP underfloor panelling.

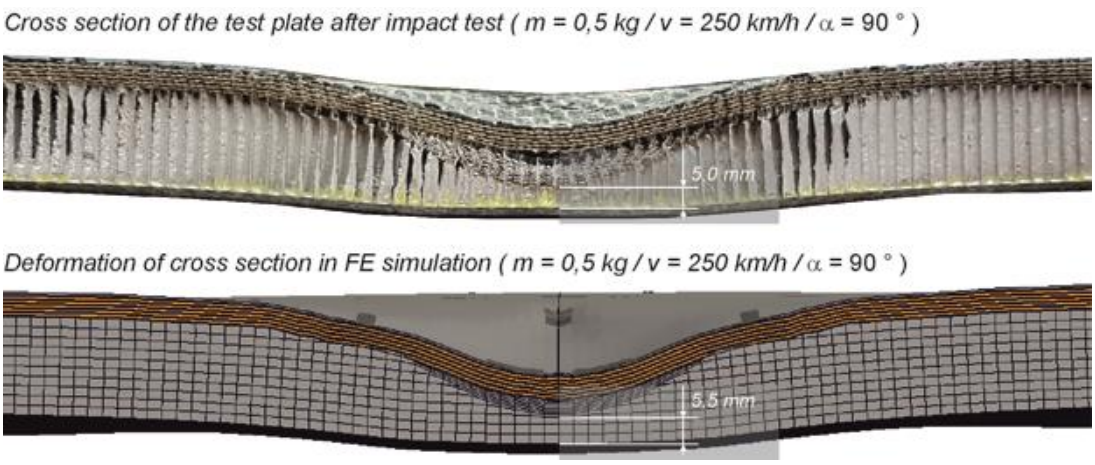

Figure 7: Comparison of test and simulation results.

The novel CFRP differential design of the bogie frame features two straight CFRP cross members and two double-elbowed CFRP longitudinal members, both of identical geometry, which are joined together using specially developed detachable joining technologies. The preforming process of the dry textile reinforcement structure from carbon fibres forms the first production step, which is done completely using CNC-controlled processes (braiding and winding) [10]. In a second step, both components are infiltrated with the thermosetting resin using resin transfer moulding (RTM). The lightweight bogie frame was successfully tested both statically and cyclically (based on EN 13749:2011 over 12 million load cycles) [11]. The mass saving achieved in comparison to the reference steel bogie frame is about 50% (Figure 8).

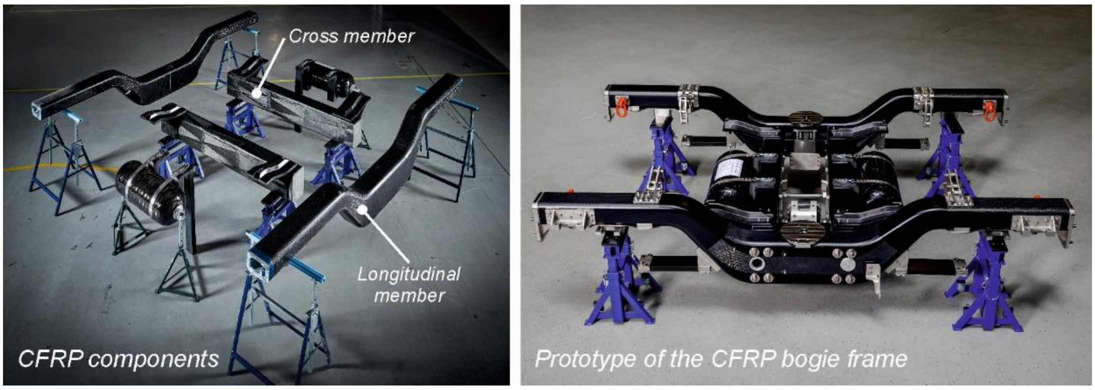

Figure 8: CFRP bogie frame.

The pantograph platform of a highspeed-train was realized as an integral CFRP composite design with a mass reduction of 30 % compared to the welded aluminium reference structure (Figure 9). Additional advantages of the integral composite solution are the design freedom allowing the realization of an aerodynamic outer shape with low noise and the more efficient and precise one-step manufacturing process compared to the multi-step welding process [12].

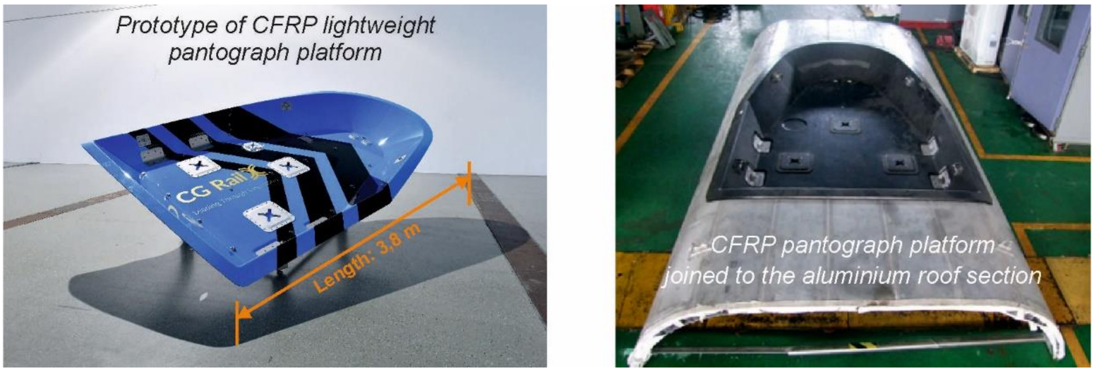

Figure 9: CFRP pantograph platform.

4 Conclusions and Contributions

CG Rail GmbH and its renowned partners have successfully demonstrated the enormous lightweight potential of CFRP materials for application in load-bearing structures of railway vehicles in the framework of several projects. Mass savings of up to 50 % have been achieved for main structural subsystems (car body, bogie frame, underfloor cladding) of a metro in the NGMT project. A mass saving of 30 % has been realized with a lightweight CFRP pantograph platform for a highspeed train.

All rail vehicle-specific standards, such as those relating to operational strength criteria or fire protection, were considered throughout the development process, from the conceptual design phase up to the technological realization of the lightweight components taking into account the special material properties of CFRP. The entire development process was accompanied by detailed FE-simulations including stress analysis under static and cyclic loading using specific failure criteria, non-linear simulation of crash and impact load cases like gravel from the track as well as residual stress analysis resulting from curing. The developed FE-models have been validated by extensive tests so that they can be used for more cost-efficient and fast development of CFRP lightweight structures for railway vehicles in the future.

The development and realization of highly automated manufacturing processes for composite components played an important role during the whole development process - especially for material choice, component design and definition of laminate layup - due to the strong interdependencies of these factors. These automated manufacturing technologies have been successfully realized at large structural CFRP-components like the bogie frame on a prototypic level. All developed manufacturing processes can be potentially integrated as flexible manufacturing cells into a smart factory for later volume production.

The developed and experimentally proven composite design approaches with CFRP open up the chance for the achievement of substantial mass saving at future railway vehicles leading to reduction of operational costs over lifetime resulting from the lower energy consumption, the lower wear of the track, the better corrosion resistance compared to metals and many other factors. The gained knowledge in carbon-intensive lightweight structures and production-ready manufacturing and assembly technologies for very large CFRP structures in railway vehicles also forms an important basis for the future realization and approval of series applications for new vehicles as well as modernization measures too. This knowledge can also be used synergistically in other application areas, such as for large commercial vehicles (trucks, buses).

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