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An Analysis of CFRP Application in the Construction of Rail Vehicles

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Summary
The aim of this article is to provide crucial information on CFRP composites and examples of their use in rail vehicle construction. The first part outlines the key characteristics of CFRP composites and compares their properties with conventional structural materials. Implementation examples of this group of composites for structural components of rail vehicles are discussed further. The final section of the article analyses the reasons for introducing composites of this type into the engineering practice of railways.

Keywords: CFRP composites, carbon fiber, rail vehicle body, mass reduction

1. Introduction

Carbon Fibre Reinforcement Plastics (CFRP) are an interesting group of engineering materials. Their main advantage over conventional materials applied in mechanical engineering is their high specific strength, i.e., the tensile strength-to-weight ratio. Due to their physical properties and the developments in the economics of their production, there has been a steady growth in their use in vehicle construction in recent years, as demonstrated by the increasing implementation of this material in many structural assemblies of rail vehicles.

2. Characteristics of CFRP composites

CFRP composites belong to the group of carbon fiber reinforced plastics. The combination of high-strength fibers with a soft, ductile and light matrix creates a material with high specific strength and rigidity [1]. In CFRP composites, the matrix is essentially a thermosetting polymer, such as polyester or epoxy resin. Carbon fibers are synthesized by pyrolysis, most commonly of polyacrylonitrile (PAN) or mesogenic pitch [2, 3]. They are very thin, ranging from 8–10 μm, which increases the complexity of their subsequent processing. The characteristics of carbon fibers are their relatively low density (1.7–2.2 g/cm^3), excellent tensile strength (2500–6000 MPa) and modulus of elasticity (207–1035 GPa) [4]. The polymer matrix ensures that the carbon fibers are adequately bonded and that the loads from the matrix are transferred to them. The density of the polyester or epoxy resin matrix is 1–1.2 g/cm^3 [5]. By bonding carbon fibers to a polymer matrix, high strength is achievable with relatively low mass. The strength properties of CFRP composites depend primarily on the proportion of fibres in the complete composite, as well as their web.

The qualities of CFRP composites include high rigidity, damping capacity, high specific and fatigue strength, low coefficient of linear expansion, and the ability to form complex shapes. In addition, they exhibit high chemical resistance and do not absorb water. The main disadvantages of this type of material are its relatively high production and processing costs, its limited repair options and its conductance, which may be undesirable in certain applications [6]. Due to their characteristics, they are most commonly applied in the construction of components requiring high rigidity and corrosion resistance [7]. Table 1 compares the properties of a group of CFRP composites, a typical CFRP composite and conventional materials used for standard rail vehicle structural components.

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Table 1

A comparison of the properties of engineering materials for standard structural components of a rail vehicle

Properties of materials	CFRP composites collectively [8]	Epoxy resin + carbon fibers, (60% fibres, unidirectional web) [5]	S355 steel [9]	Aluminium AL6082-T6 [10]
Density [g/cm³]	1.5–2.1	1.5	7.85	2.7
Yield strength [MPa]	–	–	295–355	250–260
Ultimate strength [MPa]	600–3900	1600	450–680	290–310
Modulus of elasticity [GPa]	37–784	120–200	190–210	69

Based on this comparison, a conclusion can be drawn that the main advantage of CFRP composites over conventionally used materials for rail vehicle construction is their higher mechanical strength with significantly lower density. Consequently, as the economic and technological barriers associated with the production of such composites are being removed, they are becoming an alternative to conventional engineering materials. Due to the roughly 3 times lower density of CFRP composites compared to steel, it can be assumed that one kilogram of carbon fiber replaces 3 kg of steel in the construction of a structural component, however, given the difference in density compared to aluminum alloys, 1 kg of CFRP composite replaces 2 kg of aluminum.

3. Examples of CFRP application in railways

The evolution of materials used in the construction of rail vehicles can be divided into 3 stages [11]:

- all-steel structures,
- structures with aluminum alloys, and
- structures with light alloys and composites.

Since the end of the 1990s, the introduction of composites into the construction of rail vehicles has been observed, with the greatest share enjoyed by Fiber Reinforcement Plastics (FRP) composites. In this group, in addition to glass-fiber-reinforced polymer composites, carbon-fiber-reinforced composites are used as a structural material for rail vehicles. Due to a crucial property, i.e., high specific strength, such composites can be used for components carrying high static and dynamic loads while reducing mass compared to conventional materials, such as steel or aluminum. In addition, the ability to form complex geometries makes them applicable to a wide range of vehicle components, thereby making them a multipurpose construction materials.

In rail vehicle construction, CFRP composites are generally applied in two forms – as panels or sandwich composites consisting of CFRP sheets with a lightweight and durable core between them, usually made of aluminum [12]. Table 2 shows the application of CFRP composites in the construction of rail vehicles along with information on the mass reduction compared to a component made of a conventional material.

When discussing the use of CFRP composites in the construction of rail vehicles, it is important to mention the experimental attempts to implement them into the bodies of high-speed vehicles operated in Japan in the early 1990s. One example of this is an initiative led by the Railway Technical Institute, Nippo Sharyo and Toray Industries, in which a prototype

Table 2

Overview of rail vehicle construction based on CFRP components

Design / vehicle	Structural components	Mass reduction of a CFRP component compared to conventional material [%]
Korean Tilting Express Train (TTX)	body	38
CRRC CETROVO	body	30
	bogie frame	40
CRRC Optics Valley Quantum	body	30
Kawasaki efWING®	leaf spring	40 (compared to the mass of a complete bogie)
	bogie frame longitudinal beam	
CaFiBo	bogie frame	36
HMC axle (NEXTGEAR)	road axle	4–60

body was constructed in the form of CFRP composite panels reinforced with an aluminum frame. The bonding between the composite panels and the frame was achieved through rivets and epoxy adhesive. The thickness of the composite panels was 300 mm [13].

The Korean Tilting Express Train (TTX) was one of the first rail vehicles to use a high proportion of CFRP–type composite material in the body construction, i.e. a combination of the epoxy resin matrix and carbon fiber [14, 11]. A sandwich composite was used for the body construction with a system of composite panels with a hexagonal (honeycomb) core made of A3031 aluminum. In key sections, such as the windows and roofing, an internal frame made of stainless steel profiles was placed between the CFRP panels, attached to the CFRP composite panels by adhesive bonding or riveting [15]. The body as a whole was made as a single piece to avoid joints between its segments [16]. A diagram of the connection between the body and the bogie frame is shown in Fig. 1.

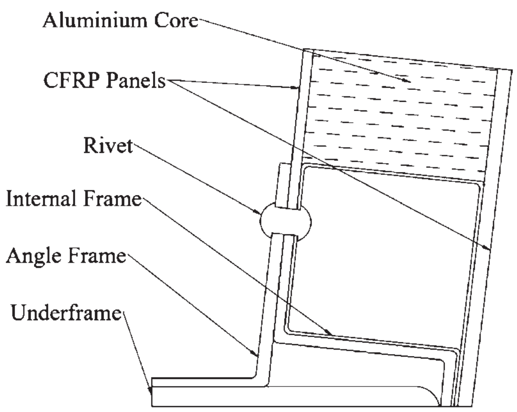

Fig. 1. Diagram of the body / bogie frame connection; author's own study based on [15]

The use of a sandwich composite formed of CFRP panels and a hexagonal aluminum core achieved a mass reduction of 38% compared to a conventional steel body. Reducing the vehicle body mass allowed the center of gravity to be lowered, which is important for a vehicle's dynamic performance when cornering, especially on tilt-body vehicles, such as the TTX. Economic analyses of the composite body use showed savings in energy consumption at 42% compared with a stainless steel body and 21% compared with an aluminum body [12].

The Chinese rolling stock manufacturer CRRC is making interesting attempts to introduce CFRP composites into rail vehicle construction. In 2018, the company, in collaboration with CG Rail – a Chinese-German team, came up with the concept of a modern underground vehicle called CETROVO as part of the "Next Generation Metro Train" project [11]. The proportion of CFRP composite material in the body of this vehicle is 70%, representing a mass reduction of 30% compared with conventional aluminum designs [17]. In addition, a length of 30 years is guaranteed for the absence of corrosion and fatigue damage, which is an argument for reducing vehicle operating costs [11]. Single-piece, multi-chamber profiles were used for the body, as well as panels up to 25-mm thick [17]. The use of large-size panels reduced the number of components and the connections between them. Composite panels with different fiber orientations were used to ensure the appropriate mechanical and technological properties for individual components. The vehicle's front wall, also in CFRP material, is innovative because it is separated from the rest of the body with the elements not being connected by the underframe [18]. The floor panel across the front cabin is 90% CFRP [19]. The bogie frame is also made of CFRP composite. In the vehicle proposed by CG Rail, the longitudinal beams and crossbeams of the bogie frame are made of CFRP to reduce mass by 40% compared to the conventional steel structures. The frame itself is also more flexible, which has a positive effect on the vehicle's dynamic performance.

Another CRRC vehicle that uses a significant proportion of CFRP composite in its body design is the Optics Valley Quantum tram for the municipal rail service in the Chinese city of Wuhan. Comparing the body mass of this vehicle to the mass that would be obtained by building a steel body, the reduction is approximately 30%. The reduction in mass translates into a greater range, which is an important feature since this tram is a vehicle that also travels using only the electrical energy stored in supercapacitors, charged for 2 minutes to cover a distance of 10 km [20, 21].

An attempt to redefine the bogie design of a rail vehicle using carbon fiber has been made by Kawasaki with its efWING® (environmentally friendly Weight-saving Innovative New Generation truck) project [22, 23]. The innovative application of the CFRP material involves producing an element that acts as both the longitudinal beam of the bogie frame and the leaf spring, which acts as the primary suspension spring. Figure 2 shows the concept of this solution. By replacing two components with one, as reflected in the reduction in the number of fasteners and the introduction of a CFRP composite into the design, a mass reduction of 40% has been achieved compared to the steel bogie frame design, resulting in a mass reduction of 400 kg [22].

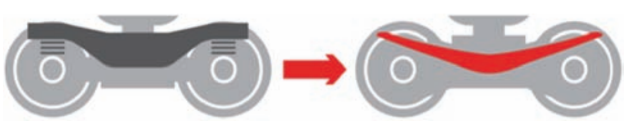

Fig. 2. Visualization of the efWING® bogie concept [22]

In addition, the use of a single spring with a limited number of fasteners has simplified the design, consequently reducing manufacturing process costs, maintenance operations and eliminating potential failure points. The Kawasaki efWING® bogie is used in the wagons of Japan Railways Shikoku or Kyushu Railway Company [24]. A distinctive external feature of the efWING® family of bogies is the bright color of the leaf spring to emphasize the innovativeness of the design.

A prototype concept for a composite bogie frame for the Alstom Class 180 vehicle is being developed in the UK as part of the CaFiBo (Carbon Fiber Bogie) project and is expected to reduce the negative impact of the vehicle on the track through mass reduction and increased flexibility compared with conventional steel design. The mass reduction compared with a steel bogie frame design is 36%. The simulations show that it is feasible to reduce the lateral forces applied to the track by 40%. In addition, the fuel consumption is reduced by 20% owing to the reduced mass of the bogie and, consequently, of the entire vehicle. Both recycled CFRP composite materials from structures used in aviation and the arms industry and completely new materials have been used in the construction of the bogie frame [25]. The use of recycled composite material will reduce the environmental impact of the technological process, as well as the production costs of the component. The carbon fiber reinforcement in the case of the recycled composite is in the form of fabric, while in the case of a new composite it is in the form of unidirectional fibers. The matrix is made of highly flame retardant resin [26]. An interesting innovation is the use of optical fibers in the frame that are responsible for monitoring the structure in real-time to validate the results obtained by numerical simulation methods. Economic analyses show that a mass reduction of 590 kg compared with a steel bogie frame design translates into annual vehicle operating savings of between £8,000 and £62,000. The existing prototype version still incorporates steel components in the form of connectors and fasteners to work properly with corresponding components in other segments of the vehicle. For this reason, further work will be targeted at creating an all-composite structure to achieve an even greater level of mass reduction and, as a result, a lower environmental impact from the vehicle.

In addition to components such as body segments and bogie frames, the applicability of CFRP materials for the construction of wheelset axles is being tested. An axle with composite components was created by experts involved in the NEXTGEAR project [6]. Three Hybrid Metallic Composite (HMC) axle concepts were presented, each assuming a composite axle, i.e., an axle center section made of a CFRP composite, with components such as wheel seats and journals made of steel. The reason for this is that a conventional material, such as steel, works much more effectively with the inner rings of the bearings and can also be connected by thermocompression bonding, as is the case with axle/wheel connections. The mass reduction is 4%, 23% or 60% depending on the axle version.

Fig. 3. Hybrid axle concept [6]

Various options for connecting the two parts of the axle are being analyzed. Depending on the solution suggested, the connection between the CFRP part and the steel part is made either by adhesive bonding or by joining with a fastener. According to the team of researchers involved in the Shift2Rail project, the most promising concept is to use a composite tube along the entire length of the axle (Fig. 3). The bonding between the composite part and the metal part is implemented by means of adhesive bonding. In addition, to prevent any possible decomposition of the axle, a connection between the two metal parts is routed along its entire length. The mass reduction of this axle concept, compared to a steel axle, is 60%.

4. The reasons for the use of CFRP in the construction of rail vehicles

4.1. Reduction of vehicle mass

From the examples of the use of CFRP composites in rail vehicle construction presented earlier in this text, it can be concluded that they are being applied in the construction of the following rail vehicle components:

- body components,
- bogie frames, and
- wheelset axles.

By implementing CFRP composites in the construction of these components, it is feasible to reduce the mass by approximately 30–40% compared to steel or aluminum structures. Although the mass reduction is not an end in itself in the construction of rail vehicles, due to the hauling capacity and high track adhesion that a rail vehicle should have, there are some reasons why it should be minimized. When considering the mass fraction of individual components in the vehicle mass fraction, it is possible to use the results presented in [6]. The mass distribution was tested for a 6-set underground vehicle and is shown in Fig. 4.

The analysis obtained shows that the vehicle's bogies have the largest mass fraction. Their mass fraction is almost double that of the body, which accounts for 24% of the total vehicle mass.

Design trends in recent years have contributed to a significant increase in the mass of the bogie as an assembly of components, as rail vehicle design has evolved into one providing a high level of safety and comfort. This is due to the fact that it is fitted with various types of damping elements or devices to improve running safety. Based on the use of conventional materials, such as steel and aluminum for a bogie construction, further mass reduction is no longer achievable. An option to reduce the bogie mass and consequently the mass of the entire vehicle, which has increased due to the installation of new components, is to use composite materials, such as carbon-fiber-reinforced polymer matrix composites, which have high strength properties at a significantly lower mass [22]. When analyzing the benefits of a lighter rail vehicle, the following should be highlighted:

Reducing wear and tear on vehicle components and damaging infrastructure

Reducing the mass of the entire vehicle effectively reduces the intensity of the forces acting at the wheel/rail contact, and consequently limits their wear, while also reducing vibration and noise. The reduction in lateral forces, due to the lower mass of the vehicle acting on the track when cornering, reduces wear on the rails. Reducing the unsprung mass of the wheelset also makes a positive contribution to reducing the intensity of damaging interactions of the vehicle on the track in the form of impacts and, as a result, reducing the occurrence of wheelset or rail imperfections. Reduced vehicle and track damage intensity contribute to reduced maintenance costs for rolling stock and infrastructure, as well as to increased vehicle operating safety [12].

Reducing emissions of harmful substances into the environment

Since the early 21st century, efforts have been made to reduce the harmful impact of transport on the environment, including by reducing the carbon footprint generated by each mode of transport, including rail-

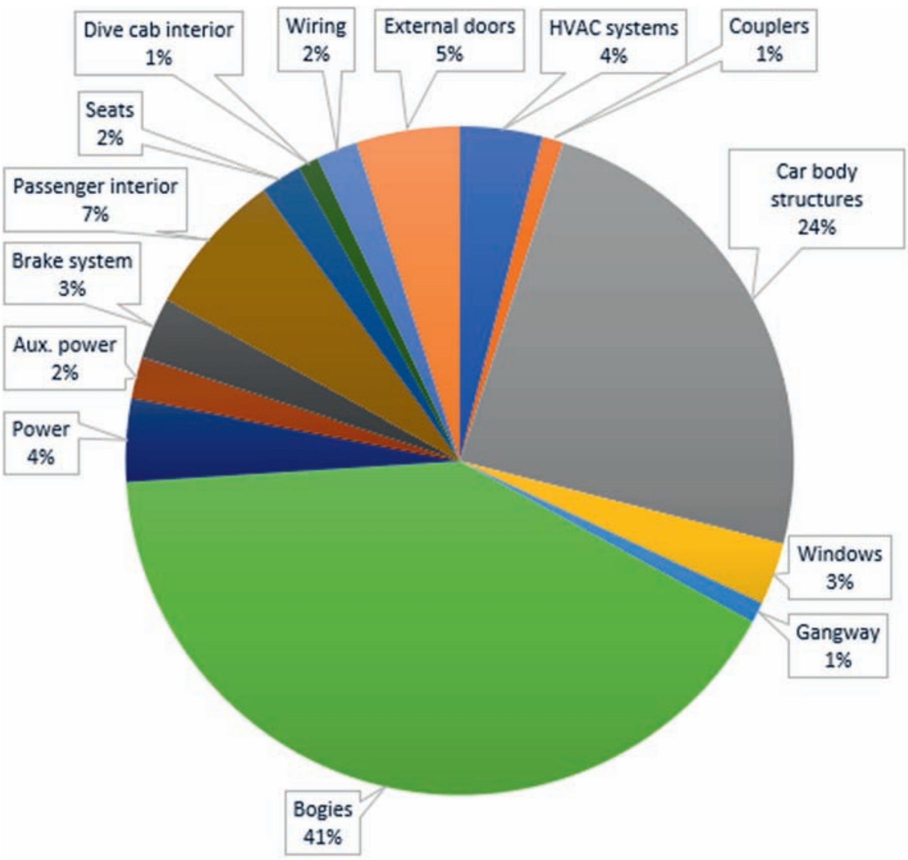

Fig. 4. Mass distribution of a rail vehicle; author's own study based on [6]

ways. The 2015 UIC report states that the transport sector is responsible for 24.7% of global CO_2 emissions, while the share of transport sector emissions generated by rail vehicles is 4.2% [27]. It is reported that the use of composite as a material for a rail vehicle body allows a 30% mass reduction, resulting in a reduction in CO_2 emissions during operation by approximately 5% [12].

Minimizing emissions of harmful substances into the environment can be achieved both during the production process of the vehicle and its subsequent operation. A crucial feature is the energy efficiency of a vehicle, i.e., its fuel consumption during operation. By reducing vehicle mass through high-specific-strength materials, such as CFRP composites, it is feasible to achieve lower energy requirements and consequently save energy. It is estimated that a 10% reduction in vehicle mass corresponds to an 8% reduction gain in fuel consumption [27].

Figure 5 shows a comparison of the CO_2 emissions of bogies with different proportions of composite elements in their design. From this analysis, it is apparent that the greater the proportion of composite materials and the elimination of steel, the lower the CO_2 emissions into the atmosphere. It has been calculated that for an all-composite bogie with a composite equalizer there is a 3.8% reduction in emissions compared to a conventional steel design [25].

Enhanced vehicle dynamic behavior

By constructing a vehicle body incorporating materials from the CFRP composite group, it is possible to reduce its mass by approximately 30%, resulting in a lower center of gravity. A lower vehicle center of gravity improves vehicle dynamics, especially when cornering by high-speed vehicles. The reduced mass also contributes to enhanced acceleration performance and braking requirements. In addition, it allows the use of either lower traction power or the same power with the option of a higher payload or better acceleration of the vehicle [28].

4.2. Complicated geometries obtainable

Forming complex geometries with CFRP composites is facilitated due to their anisotropic nature. Compared to the plastic working of metals (steel, aluminum), composites of this type offer much wider machining options. Thus, it is possible to achieve complex shapes that are required, for example, in the front panels of high-speed vehicles. These units, due to their high speed, must have good aerodynamics. In addition, they generate a high-pressure wave when passing through tunnels. To reduce this, it is desirable for the nose cone of a vehicle to have a refined and aerodynamic shape – as a result of this geometry, a reduction in the compression of the air at the entrance to the tunnel is achieved, which results in a smaller pressure wave when a vehicle exits the tunnel and a reduction in the stresses acting on the body [29].

In addition, large-scale components can be produced. For example, the technological resources used in the production of the CETROVO vehicle enable components of up to 77 m in size to be produced [17]. This reduces the number of vehicle components and the connections between them, making the construction and maintenance process considerably easier. Fewer connections between vehicle segments eliminate potentially hazardous areas.

4.3. Higher energy storage capacity and flexibility than metals

Another property of some CFRP composites is that they have higher elasticity than steel or aluminum. The relatively high flexibility and energy storage capacity of CFRP composites is a feature used in the production of bogie frames and springs. Table 3 shows a comparison of the strain energy accumulated by CFRP composites and structural steel [5].

A conservative approach to bogie frame design assumes that the rigidity of the component is high,

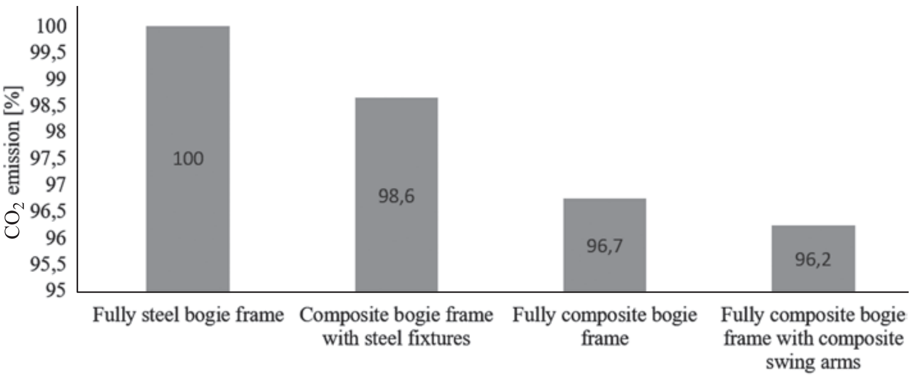

Fig. 5. Comparison of CO_2 emissions for bogies with different proportions of composites in their design; author's study based on [25]

however, bogie frames are now being designed to have a degree of flexibility to improve running characteristics and track impact [30]. Leaf springs were previously widely used in the railway industry, but nowadays they are only applied in the construction of freight wagons and old types of locomotives in the form of standard or parabolic leaf springs with progressive damping characteristics [31]. The main characteristics of leaf springs that have pushed them outside the design of modern rail vehicles include the high mass and external dimensions of the flat spring assembly, due to the use of steel as the construction material. By using a leaf spring made from a CFRP composite, it is possible to eliminate these defects because of the two main advantages of this material over steel – higher flexibility and specific strength.

Table 3

Comparison of the strain energy storage capacity by structural steel and CFRP composites [9]

Material	Strain energy accumulated by the material [kJ/kg]
EN37 steel	0.33
Epoxy resin + carbon fibre	2.45
Polyurethane + carbon fibre	4.12

4.4. Enhancing the economic competitiveness of CFRP composites

Despite the expensive production technology of carbon fiber-reinforced composites, due to the widespread use of this material in engineering practice, a reduction in production costs is expected, which is also an argument for the increasing competitiveness of CFRP in relation to conventional engineering materials [32]. In addition to the high level of recovery (recycling) of CFRP, the amount of waste produced at the end of the vehicle lifecycle is reduced [27]. According to [27], for a CFRP material, the ratio of the weight of an entire component to the mass recovered that can be recycled into a vehicle component, and the ratio of the weight of a component to the energy that can be generated from it, for typical components, such as a bogie frame or a rail vehicle body, are both 95%.

Figure 6 shows the global demand for carbon fiber over the period from 2010 to 2022. It shows that from 2010 to 2022, demand for this type of fiber increased almost fourfold. Carbon fibers are the most expensive components of CFRP composites due to their high level of production sophistication. Due to the increasing demand for this material, a dependency is created that causes the price of this material to decrease because of its increased popularity.

5. Conclusions

In recent years, there has been a large increase in the implementation of CFRP materials in engineering practice for rail vehicle construction. The numerous advantages of CFRP composites along with the improved technology of their production mean that their significance and share in railway vehicle construction are constantly growing, and the material itself has become competitive to the two most frequently used materials in vehicle construction – steel and aluminum. An important issue is the components for which CFRP material is used. In the structure of a standard rail vehicle, the body and bogie account for the highest mass fraction. For this reason, these are structural components in which the standard metals are replaced by CFRP composites. By applying this group of materials, in addition to reducing the mass of a component, it is also possible to benefit from other advantages of these composites – good workability or greater flexibility than metals. Given the

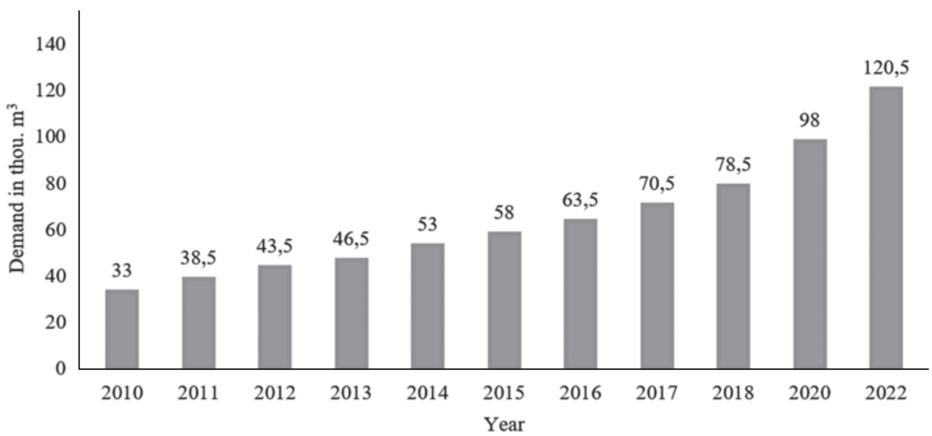

Fig. 6. Global demand for carbon fiber from 2010 to 2020; author's study based on [33]

trend towards reducing CO_2 emissions generated by rail transport, here too CFRP composites are becoming a material group with great potential for increasing application in rail vehicle construction.

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