Received: 16 May 2023 | Revised: 24 August 2023 | Accepted: 21 September 2023

DOI: 10.1002/pc.27817

REVIEW ARTICLE

spe INSPIRING PLASTICS PROFESSIONALS Polymer COMPOSITES WILEY

Recent advancements in the applications of fiber-reinforced polymer structures in railway industry—A review

A. Saeedi | M. Motavalli | M. Shahverdi

Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland

Correspondence
A. Saeedi and M. Shahverdi, Empa, Swiss Federal Laboratories for Materials Science and Technology, Dübendorf, Switzerland.
Email: ali.saeedi@empa.ch; moslem.shahverdi@empa.ch

Abstract

The application of fiber-reinforced polymer (FRP) composite materials and structures in various industrial sectors is expanding significantly to meet the rising demand for efficient, reliable, and functional building materials. Using FRPs can be an excellent strategy for enhancing railway structures and equipment because of their high strength-to-weight ratio, tailorable mechanical properties, and suitable long-term characteristics. However, the railway industry appears to be hesitant to adopt composite materials compared to other transportation sectors like aerospace. It seems that there is still a long way to go before FRPs reach their full potential in railway applications. The goal of the current study is to explore the current uses of FRPs in the railway industry and the significant challenges, obstacles and difficulties that must be overcome to put FRP-based concepts into practice for structural and rail vehicle applications.

Highlights

- Applications of FRPs in railway vehicles and rail lines are reviewed.
- Main challenges for utilization of FRP in railway industry are studied.
- Future trends and applications of FRPs in the railway sector are introduced.

KEYWORDS

bogies, car bodies, fiber-reinforced polymers, rail vehicles, railway industry, sleepers

1 | INTRODUCTION

Over the past few decades, fiber-reinforced polymer (FRP) composite structures have taken the place of conventional metallic components in a wide range of industrial applications. As an illustration, the demand for carbon fiber reinforced polymers (CFRPs) has recently increased at a compound annual growth rate (CAGR) of around 6% in the key industries, such as air and ground transportation and wind energy.[1] With such a growth rate, it is anticipated that the global market for CFRPs would expand from 26 billion USD in 2018 to 41 billion USD in 2025. The aerospace sector is renowned as a pioneer in adapting advanced FRPs for structural and transportation purposes due to the crucial necessity of weight reduction in air transportation. The steadily expanding use of composites in the aerospace industry is illustrated by Rana and Fangueiro's review of the use of advanced polymer composites in aircraft structures.[2] In another study, Jawid and Tariq[3] considered the sustainability of using polymer composites in aerospace components. Following the aerospace applications, the automobile,[4,5] marine,[6,7] and railway industries[8,9] have all worked to improve the functionality of their products by utilizing the FRPs throughout the past several years. As reviewed by Ravishankar et al.,[4] polymer composites can be used in a variety of automotive applications, such as automotive piston applications, brake friction materials, and automotive anti-roll bars. Additionally, composites can be employed in body parts, trunk lids, door panels, engine hoods, engine frames and joints.[5] Regarding marine applications, composites are widely used in the construction of boats, ships, and submarines, both for the body and for internal components.[10] FRP composites have also been used in pressure vessels, repairing patches, tidal turbines, FRP risers, and so forth.[11]

With their high strength-to-weight ratio, excellent corrosion resistance, and superior fatigue properties over conventional materials, composites are able to accelerate the development of ground transportation. Considering the growing need for a safe, rapid, and efficient transportation system, utilizing FRP composite structures can be considered a high-rate solution to improve the rail transportation and to meet such rising demands. Jagadeesh et al.[12] conducted a review study on the use of polymer composites in railway applications and took into account information regarding the employment of FRP in different countries. Figure 1 depicts FRP composite applications in the railroad industry. Composite structures can be employed both in railway vehicles and in infrastructures. A detailed discussion on the potential structural and non-structural uses of FRP composites will be presented in the following section. A number of potential advantages of utilizing FRP composites in the railway sector and the remaining barriers to such FRP-metal replacements are presented in Table 1. Due to potential advancements in manufacturing processes and materials, and outweighing the potential benefits of the FRPs against the aforementioned barriers, a dramatic increase in the FRP applications in the railway industry can be expected.

The current study examines the uses of FRP composites in the railway industry. Applications in car bodies, bogies, and wheelsets as well as other railway structural components such as rail sleepers are fully discussed. The potential advantages of using the FRP components are highlighted in each section. The literature survey implies that, in contrast to the aerospace and marine sectors, the full capabilities of composite structures have not yet been substantially utilized in the railway industry. The challenges and barriers to utilization of composites in the railway industry are investigated and prospective solutions are also discussed.

TABLE 1 Potential benefits and barriers for utilizing FRP composites in railway industry.

Potential benefits of utilizing FRPs in railway industry	Barriers to replacing metals with FRPs
• Significant weight reduction • Reduced energy consumption	• Lack of standard specifications and performance history
• Flexibility control of the structure	• High cost of raw material
• Tailorable mechanical properties	• High cost of product fabrication
• High corrosion resistance	• Complexity in design and analysis of FRP structures
• Intrinsic damping behavior	• Fire resistance and high temperature behavior
• High damage tolerant	• Transverse impact resistance

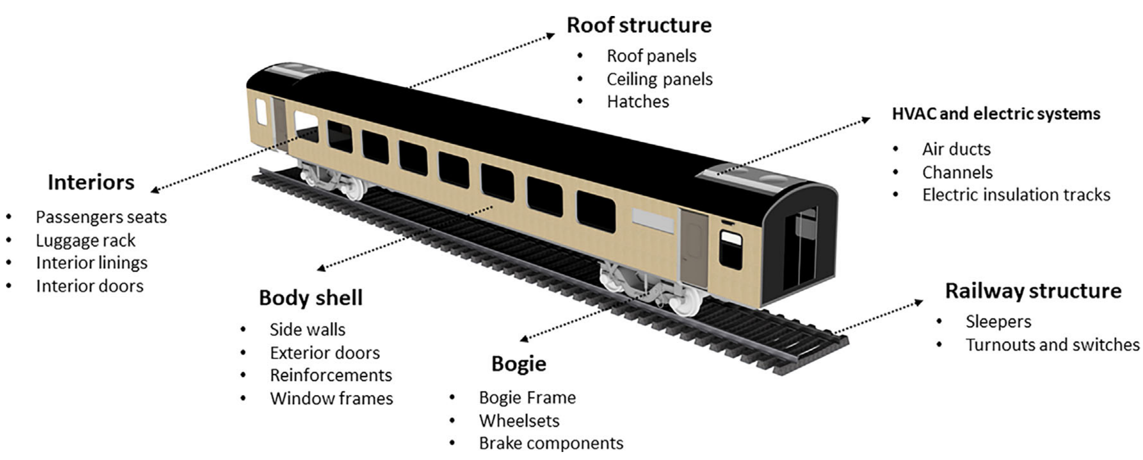


FIGURE 1 Applications of FRP composites in railway industry.

2 | APPLICATIONS OF FRPS IN RAILWAY VEHICLES

High-priority candidates for the adoption of FRPs in railway industry include bogies, wheelsets, and car bodies, which make up the man parts of the railway vehicles. The economic and technical efficiency of the railway transportation system is greatly impacted by their total weight and life-cycle characteristics. The efforts to use FRPs for these high-priority candidates are studied in this section. The general procedures for designing and analyzing FRP parts for railroad vehicles, such as bogies and car bodies, are shown in Figure 2. The required steps from a conceptual design to a manufactured component are demonstrated.

2.1 | Application of FRPs in vehicle bogies

Bogies are multi-component structures that serve a variety of purposes in the railway transportation systems. These structures support the weight of the train and connect it to the rails. In addition, bogies offer a suspension system to improve ride comfort, control the wheelset alignment, and regulate vehicle steering behavior. Various kinds of bogies have been developed for different applications, such as freight wagons, passenger trains, or metro wagons. Whatever the case, the bogie comprises a significant portion (30%–40% based on the vehicle type and bogie class) of the total weight of the vehicle[13,14]; therefore, the lighter the bogies, the higher the transport efficiency in the railway system is. A model of the conventional class of freight bogies and its components is shown in Figure 3.

Advanced composite materials and structures allow the designers not only to reduce the total weight of the bogie but also to take advantage of their high damping properties to reduce the system noise and enhance the comfort of passengers. From 1983 until now, scientific and industrial efforts have been made to provide more efficient, more functional, and cost-effective bogies for use in the railway industry using FRP composite materials and structures. By using FRPs, the mechanical properties of the bogie can be tailored concerning complex loading cases. Three models of previously developed FRP bogies are illustrated in Figure 4. A summary of the previously published scientific and industrial investigations on replacing traditional metallic bogies with lighter composite ones is presented in Table 2. According to the reported results, 25% up to 60% bogie weight reduction can be expected by exploiting FRP composites in the bogie design and manufacturing. The following sections provide specific details of the previously introduced FRP bogies.

2.1.1 | Messerschmitt-Bolkow-Blohm (MBB) FRP bogie

FRP composite bogie frame for the first time were designed and manufactured by MBB[16,17,23] in 1980s. Project participants included the German Federal Railway and Deutsche Bahn (DB). They employed a step-by-step approach to reduce the risks associated with developing novel materials for load-bearing components of the bogie. Compared to the similar steel bogie (for ICE V train) they reported a significant weight reduction of 25% for the overall bogie weight. Such a weight reduction permits reductions in power requirement, energy consumption, wear, and noise emission. They considered static and dynamic parameters, including structural stability, guidance behavior, ride comfort, and resistance to derailment in the composite bogie design. The fabricated FRP-based bogie frame is shown in Figure 4A.

2.1.2 | GFRP sandwich bogie frame FRP bogie

Numerous studies have been carried out on GFRP sandwich bogie frame by the support of *Korean Railroad Research Institute (KRRI)* since 2010. At the beginning, Kim et al.[13,14] designed and fabricated a composite side beam for the bogie frame and performed static bending tests. The composite side beam consisted of four elements, including composite skin, chords, ribs, and foam core. Later on, in 2011, they fabricated the whole composite bogie frame for subway trains using glass fiber reinforced polymer (GFRP) composites and evaluated its structural safety by static,[14,25,26] and fatigue tests.[27,28] The composite bogie frame in the full bogie assembly is shown in Figure 4B. Numerical methods were also employed to optimize the geometrical parameters and the manufacturing process in the composite bogie frame.[29] They compared experimental and finite element (FE) results on the stress distribution in their presented bogie frame and reported good agreement. Subsequently, the structural integrity of the fabricated bogie frame was evaluated under dynamic loadings. Goo et al.[30] performed an experimental and numerical study on the composite bogie frame subjected to the ballast-flying impact phenomenon. According to their findings, after being subjected to impact, the composite bogie frame's structural integrity was not significantly damaged. Further investigations on the dynamic properties of the composite bogie frame showed that even by eliminating the primary suspension system in the composite frame, dynamic wheel unloading, wheel wear index, and ride comfort satisfy the design requirements.[24,31] More recently, distributed optical fiber sensors were employed

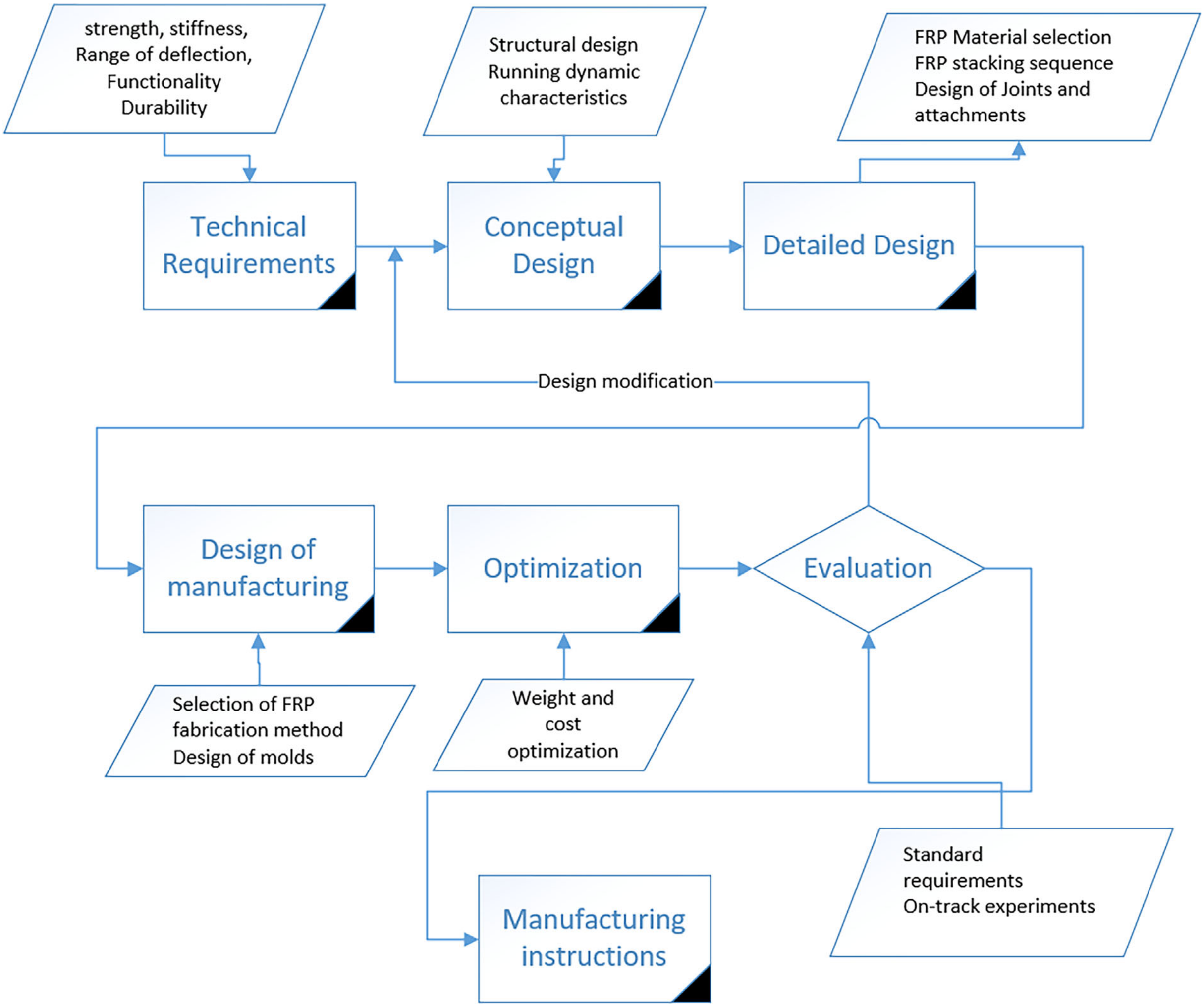


FIGURE 2 Flowchart of design and analysis of FRP components for railway vehicles.

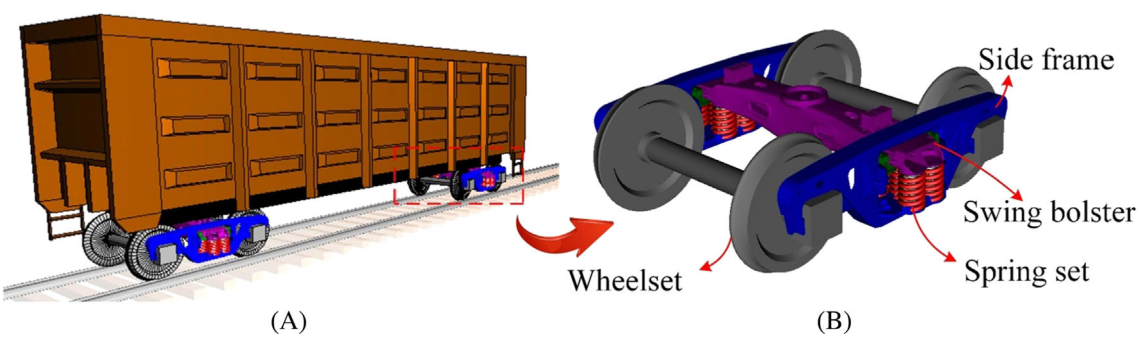
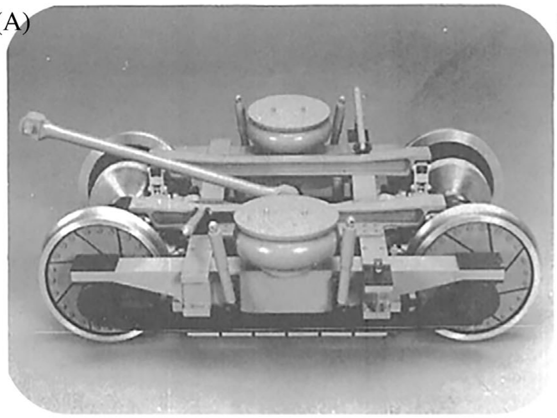


FIGURE 3 A model of (A) carriage and (B) bogie of the freight train, reproduced with permission from Reference 15.

to monitor the structural deformation of the developed composite bogie in real-time.[32] The presented monitoring method, represents a viable way for a real time evaluation of the composite structure's health status. This system makes it possible to determine whether delamination or cracks in composites happen during running time of the bogie.

2.1.3 | EUROBOGIE (Ecobogie)

As a completely different design for FRP composite bogies, Hou and Jeronimidis[19] introduced a novel composite bogie frame that consisted of two GFRP frames, and two composite axle ties (Figure 4C). The detailed analysis and characterization of the abovementioned



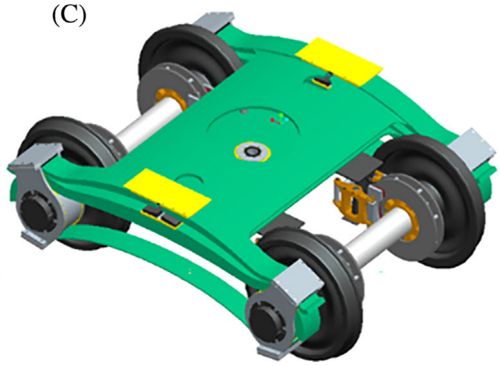


FIGURE 4 The previously designed and fabricated FRP based bogies: (A) AEG/MBB bogie (1988) reproduced with permission from Reference 23, (B) KRRI bogie (2010) reproduced with permission from Reference 24, and (C) Eurobogie (2012) reproduced with permission from Reference 19.

TABLE 2 Previously introduced FRP composite bogies and their properties.

No.	Institution/Company	Commercial name	Reported weight reduction	Country	Presenting date	FRP type	References
1	AEG Westinghouse MBB	-	25% (bogie weight)	Germany	1988	GFRP	16,17
2	Alstom	TER Bogie frame	30% (bogie frame weight)	France	2002	GFRP	18
3	Korean Railroad Research Institute (KRRI)	-	31% (bogie frame weight)	South Korea	2010	GFRP	13,14
4	Department of Trade and Industry (DTI)/Eureka Project	EUROBOGIE	1 Ton (bogie frame weight)	EU	2012	GFRP	19
5	Japanese Railway Technical Research Institute	efWING	40% (bogie frame weight)	Japan	2016	CFRP	20
6	UK Rail Research and Innovation Network/ Institute of Railway Research (IRR)	CaFiBo	36% (with metallic fixtures) 60% (with composite fixtures)	UK	2020	CFRP (recycled fibers)	21
7	CG Rail	-	50% (frame)	Germany	2020	CFRP	22

bogie design were carried out as part of the EUROBOGIE project (2012). The main idea of their developed bogie design was to integrate the primary and secondary suspensions in their bogie using the variable stiffness of the composite frame. Such a variable vertical stiffness is obtained before and after the contact between the two frames. They fabricated a one-fifth scale bogie and characterized its performance by static tests. However, the dynamic characteristics of the bogie, including the damping behavior and frequency analysis, were not considered. In another investigation on EUROBOGIE, Cerny[33] conducted an experimental study on the composite subcomponents of the bogie frame and evaluated their inter laminar shear properties as one of the major failure criteria in connection areas. Later on, the composite bogie was subjected to several experiments, including drop tests, shaker rig tests, sweep tests, and track profile for full static and dynamic characterization of the developed composite bogie system.[34]

2.1.4 | efWING FRP bogie

A new generation of CFRP-based composite bogies was introduced in 2016, by Kawasaki Heavy Industries of Japan. This bogie design, efWING, is the first developed composite bogie that employed CFRP spring beams.[20] The efWING composite bogie was designed to combine the primary suspension and load-bearing system into an integrated composite bogie system using CFRP leaf springs. The developed bogie, offered a 40% weight reduction of the bogie frame compared to the conventional metallic bogies and entirely met the running safety requirements, including derailment coefficient, decreased ratio of wheel load, and lateral force.

2.1.5 | CaFiBo FRP bogie

A new type of carbon fiber-based FRP bogie named as Carbon Fiber Bogie project (CaFiBo) was recently introduced by the Institute of Railway Research (IRR) at the University of Huddersfield (2020).[21] The recycled carbon fibers obtained from composite industry wastes along with the prime carbon fibers were used in the fabrication of the CaFiBo bogie to reduce the total costs. The embedded fiber optic system enables the real-time health monitoring of the composite bogie. A weight reduction of 36% is reported for the composite bogie compared to the conventional metallic bogie of the same type (class 180 bogies). In addition, even more weight reduction, of up to 60%, can also be obtained by replacing the metallic fixtures with composites. The on-track test results for the CaFiBo bogie have not been published yet.

2.1.6 | Optimizations of bogies, design of components and joints

Materials and structural optimization have been taken into consideration to increase weight reduction in the bogie and its components. In a recent study, Ma et al.[35] investigated the potential of braid-and-lay integrated CFRPs for use in metro bogies. Through structural optimization, they reported a 15.3% weight reduction in the bogie frame compared to the structure before optimization, while the deformation and stresses remained within acceptable limits.

In addition to the main beams for the FRP bogie frame, some elements of metal bogie frames can also be designed and manufactured using FRP composites. In this regard, Yao et al.[36] designed and manufactured a multi-cavity casting block to be employed with metal elements in metallic bogie for urban maglev train. They performed an experimental and numerical study on the designed FRP casting blocks and compared them with conventional metallic design. They reported a weight reduction of 30.9% for the fabricated composite element compared with the metallic one.

In the design step of multibody FRP composite structures, including bogies, special consideration should be paid to the attachments of the components. In general, the adhesively bonded and mechanically fastened joints are the critical regions in the design and analysis of the composite structures.[37–44] In this regard, Tserpes et al.[37] conducted a review study, taking into account the opinions of experts on the simulation and theoretical analysis of the adhesively bonded joints. Cameselle-Molares et al.[38] presented progressive damage modeling of the adhesively bonded joints between FRPs. The experimental findings of the adhesive joints of pultruded GFRP specimens and the developed model were in good agreement. The mixed-mode fracture behavior of adhesive joints of pultruded GFRPs was experimentally analyzed by Shahverdi et al.,[41] who also developed a method for mode partitioning in the experimental data. Using experimental, analytical, and finite element methods, they also established quasi-static,[42] and fatigue[43,44] failure criteria for the aforementioned joints. For the purpose of forecasting the mixed-mode bending fracture behavior of the adhesive joints of pultruded GFRP specimens, Cevcik et al.[39] created an analytical model. They looked into how the order of the laminate stacking and fiber breakage affected the results of mixed-mode fracture. In the GFRP joints that were subjected to mode I fracture, they also modeled the growth of fatigue cracks. The connection between the components in composite bogies is also a crucial issue that should be taken into consideration in the design process. In a numerical study on the joints, Kim et al.[45] used the finite element method and submodeling technique to optimize the mechanical properties of bolted joints in their developed composite bogies. In another study on the same composite bogie design, the behavior of adhesively bonded T-joints in the bogie frame was evaluated.[46,47]

Besides the detailed designs of connections and joints, some investigations on the possible reinforcing methods have been recently performed to enhance the durability and performance of the composite bogies. In this context, Liu et al.[48] introduced the design strategy of thin-ply on the composite bolster of a bogie system. Their obtained results revealed that using the thin-ply strategy significantly improves the static strength of the composite structure, especially at the bolts and holes areas. In another study, Rizzo et al.[49] introduced thermoplastic polyurethane composites as a coating to improve the impact resistance of composite parts against the impact of debris surrounding the tracks. Using this method, a major weakness of composite structures, that is, internal damage due to impact, can be addressed.

2.1.7 | Overview of the present state of FRP bogies in the railway industry

As reviewed in Section 2.1, the main advantage of using FRP bogies in comparison with conventional metal bogies is their significant weight reduction. There are also some potential advantages for such lightweight bogies in the operational, infrastructure, and environmental fields. These benefits result from the frame structure's lighter weight or increased flexibility. Potential advantages of FRP bogies can be listed as follows:

- Significant weight reduction in the bogies: A weight reduction of 25%[16] to 50%[22] of the bogie frame by replacing the metallic frame with FRP components.
- Less complex mechanical parts by removing suspension springs as performed for Eurobogie[19] and efWinng bogie.[20]
- Potential for improving running dynamic behaviors such as enhancements in steering properties.[19]
- Potential for reduction in infrastructures maintenance costs due to fewer damages: as a result of better steering.
- Potential for reduction in noise emission (as a result of better steering).
- Potential for reduction in fuel consumption of the railway vehicle (as a result of reduced weight and enhanced steering).

Despite of the presented advantages and potentials for enhancements of the rail transportation, no FRP bogie has yet been employed commercially, to the author's knowledge. Economic concerns and a lack of authoritative norms and certifications for using FRP bogies in the rail transportation system are two of the key obstacles to their industrial development. There are also other challenges regarding employment of FRP bogies in the industry that are discussed in Section 4. In summary, due to a lack of economic justifications and thorough characterizations of these novel types of bogies, it appears that the managers of the railway industry are not entirely convinced of the high serviceability of composite bogies.

2.2 | Application of FRPs in the wheelsets

Wheelsets form a considerable portion of the vehicle's weight; however, compared to the other vehicle's components, the research projects on employing FRP structures for light-weighting purposes are very limited. An investigation on the CFRP wheels was conducted by the Institute of machine tools and product engineering in Germany (IWF), and the possibility of over 50% weight saving was reported while retaining the proper mechanical behavior.[9] In another study, British Railways examined CFRP axle tubes that were fabricated using filament winding and resin injection techniques.[50] The fabricated FRP composite tubes provided a 70% weight reduction compared to steel structures. The main drawback of the presented FRP tubes was their poor impact resistance, while their mechanical behavior against static and fatigue loadings was satisfactory.

More recently, a feasibility study funded by the Swiss Federal Office for the Environment FOEN (BAFU) was performed in Switzerland on the application of FRP wheelsets in railway vehicles with the collaboration of Carbo-Link AG (Switzerland), PROSE AG (Switzerland), and Swiss Federal Laboratories for Materials Science and Technology (Empa).[51] The finite element method was employed for analyzing the static, vibrational, and acoustic behaviors of the wheelsets (Figure 5). The focus of the study was on the noise (and weight) reduction of the FRP wheelset compared to the conventional steel ones. The obtained results showed that using FRP wheelsets led to a considerable noise reduction of 23 dB (A) on the wheelset level and overall reduction of approximately 3 dB (A) considering the noise from both wheelsets and rail.

2.3 | Application of FRPs in car bodies

Car body structures account for 20%–30% of the total weight of rail vehicles which make them top priority components for the use of FRP structures and light-weighting. The cap fronts, carriage doors, and seat shells were the first

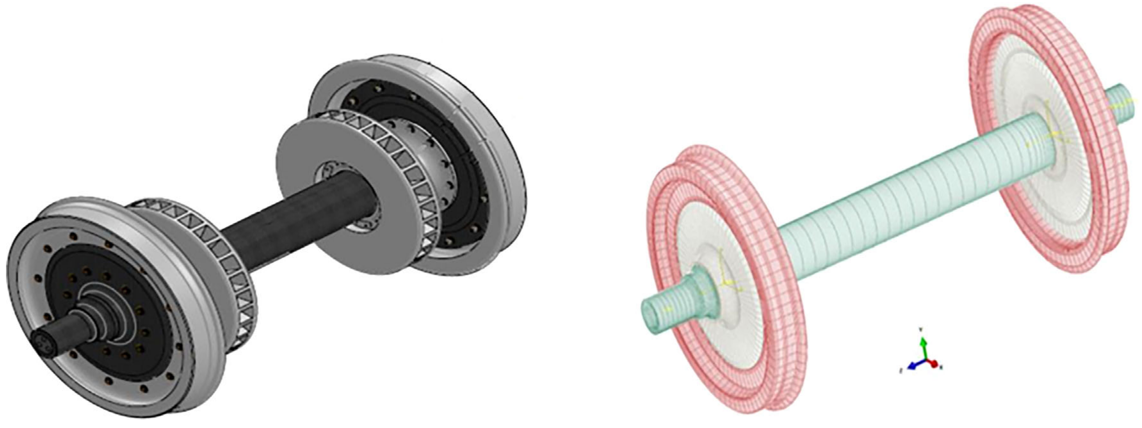


FIGURE 5 The FE model of the FRP wheelset.[51]

introduced applications of FRPs in railway car bodies.[50] As an example, Tang et al.[52] performed a design and optimization study of CFRP sandwich panels to be used in the car body of high-speed trains. A weight reduction of 35.7% was reported compared to a similar metallic structure. In another study, Jagadeesh et al.[53] designed and manufactured Areca/Sisal/Carbon reinforced epoxy resin hybrid composites, and the experimental findings demonstrated the design's suitability for use in interior carbody components. A summary of previously published investigations on using FRPs in car body structures is presented in Table 3. Such investigations centered on various components of the entire car body and reported different ranges of weight reduction. The presented studies will be reviewed in more details in the following sections.

2.3.1 | Schindler Wagon and Hardcore-Dupont car body

Schindler Wagon (Switzerland) introduced their FRP car body based on GFRP and CFRP, and filament winding manufacturing process in 1995, as one of the first developed main projects on utilizing FRP composites for car body structures.[54] According to their report, the car body shell that is being presented can reduce the total carriage weight by a total of 10%. At the same time, glass/polyurethane composites and resin infusion method were employed by Hardcore-Dupont for the fabrication of their prototype of the composite railcar. The largest 1-piece infusion-molded structure, as they claimed.[55]

2.3.2 | Tilting train express (TTX)

A sample of a full FRP composite car body structure was designed and manufactured by Korea Rail Road. Kim et al.[56,57] fabricated an FRP sandwich panel-based car body structure and investigated its mechanical behavior using experimental and FE methods. The car body structure and the FRP composite component are shown in Figure 6. The static characteristics,[60] vibrational behavior,[61] and low-velocity impact response[62] of the structure were also investigated on the manufactured FRP car body. They reported that the composite car body demonstrates a deflection pattern similar to the traditional car bodies and is designed in a way that unpleasant periodic motions can be avoided. The health monitoring algorithm for the fabricated structures was designed based on the Fiber Bragg Grating (FBG) method.[63] Experimental strain distribution was employed to verify the introduced health monitoring program. A numerical study on the crushing and local stiffness of the body sandwich panels showed that by filling the core of the panels with polyurethane foam, the energy absorption and local stiffness of the panel can be improved by 232% and 45%, respectively, with a weight addition of only 2% of the car body weight.[64]

2.3.3 | CFRP-based car body

More recently, a CFRP-based car body was manufactured and introduced by a US railway and shipping company, CG Rail (Dresden, Germany).[59] They used pultrusion technique for the fabrication of large and single-piece components of the car body. Their fabricated body showed a 30% weight reduction in comparison with conventional aluminum shells. CFRP composites form 70% of the car body structures and are mainly employed in the front cabin and underfloor panels.

2.3.4 | Hybrid FRP-metal car bodies

Heller et al.,[58] in a project sponsored by the Czech Ministry of Industry and Trade, introduced a hybrid car body

TABLE 3 Previously introduced FRP composite car bodies and their properties.

No.	Institution/Company	Reported weight reduction	Country	Presenting date	FRP type	References
1	Schindler wagon	10% (total rail vehicle's weight)	Switzerland	1995	GFRP & CFRP	54
2	Hardcore-Dupont		USA	1995	GFRP	55
3	Korean tilting train express (TTX)	38% (upper car body)	South Korea	2001	CFRP	56,57
4	Czech Ministry of Industry and Trade	19% (car body)	Czech republic	2015	CFRP	58
5	CG Rails	30% (car body)	Germany	2018	CFRP	59

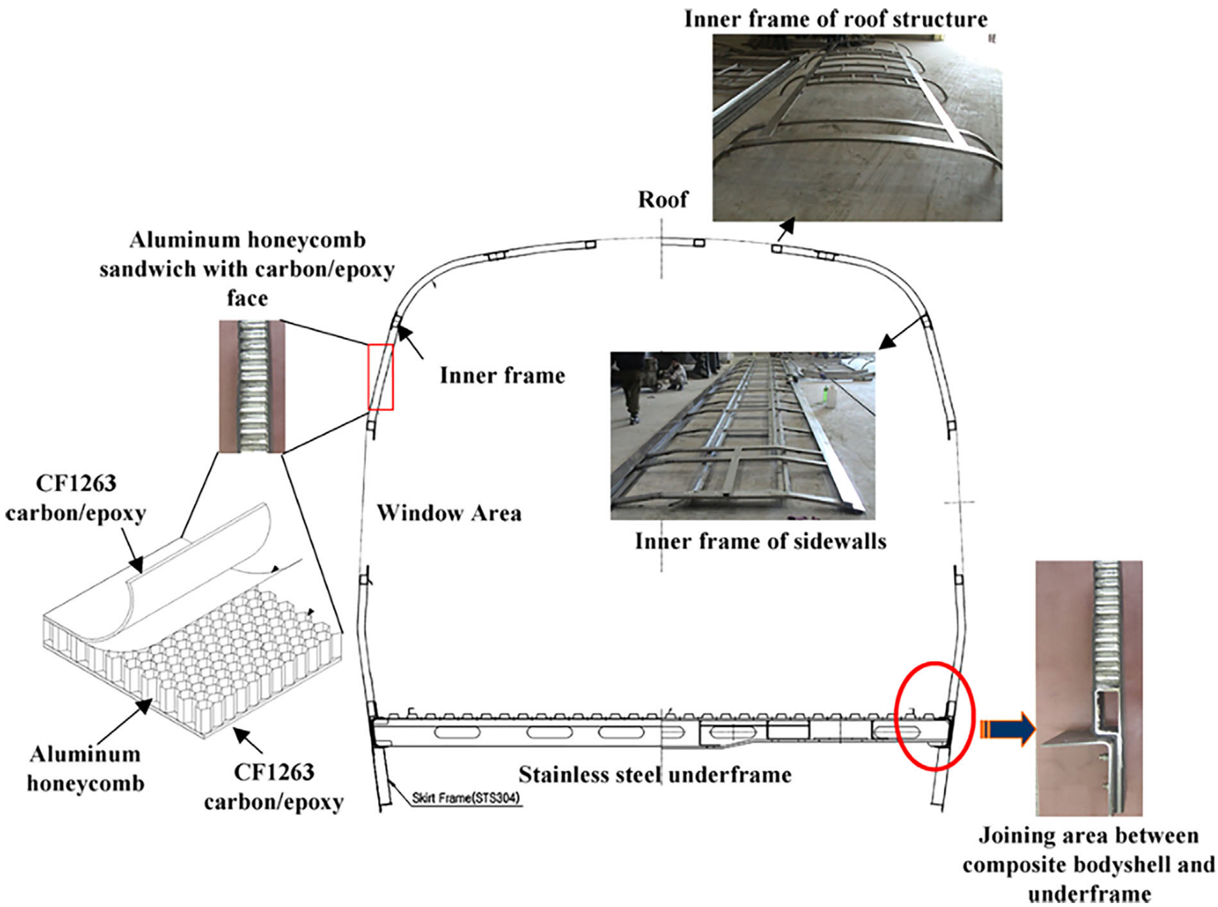


FIGURE 6 Car body structure of the Korean titling train, reproduced with permission from Reference 56.

for the underground train which consists of various materials and structures. Hybridizing GFRP sandwich panels and metallic parts in the car body resulted in a 19% weight reduction compared to the metallic car body shells. They offered local reinforcing methods for decreasing the unwanted deflections in the static loading. The feasibility of using lightweight pultruded GFRP panels for medium-speed railway vehicles was examined in a different study by Tang et al.[65] They employed an innovative method of fabric pultrusion manufacturing that made use of multi-axial fabrics. The constructed panel and the stiffeners are shown in Figure 7.

2.3.5 | XBODY lightweight car body

3A Composites Mobility (Switzerland), a division of Schweiter Technologies AG, develops lightweight

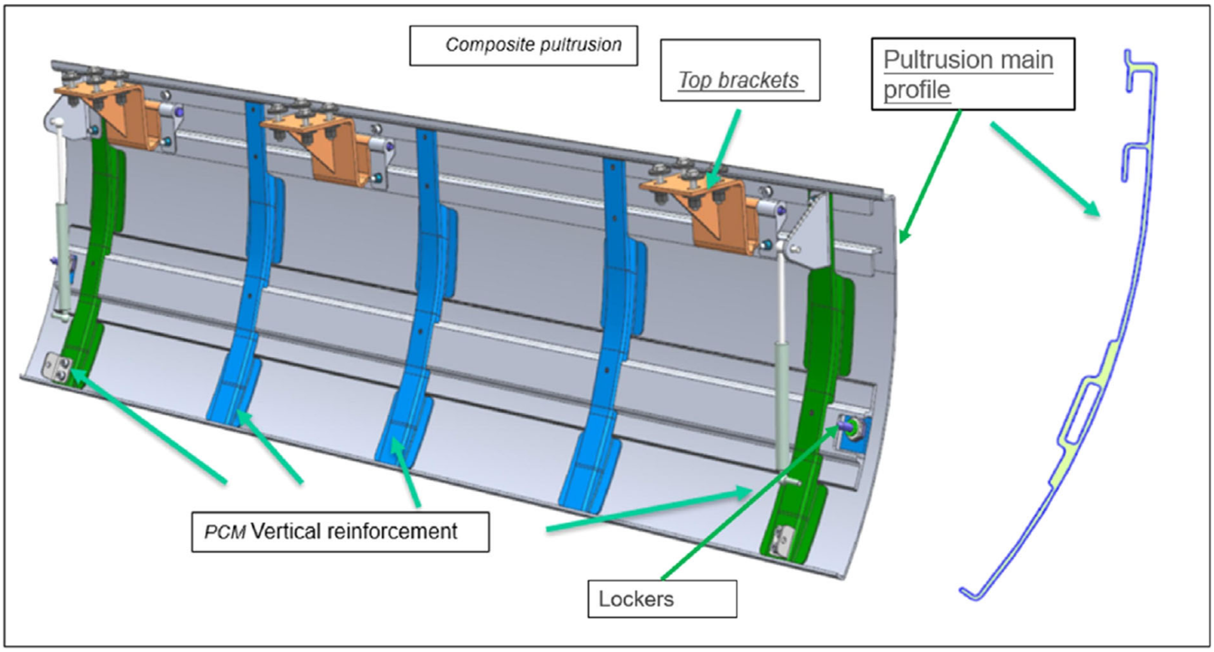


FIGURE 7 External GFRP panels with vertical reinforcements, reproduced with permission from Reference 65.

structures for rail vehicles. In 2000, they debuted their sandwich technology for whole car bodies and continued by manufacturing car bodies in bulk (XBODY). The fabrication of the roofs, floors, side walls, and chassis follows standards for both rail and road vehicles. Additionally, they used the vacuum assisted resin infusion (VAC) technique to produce a large set of FRP structural front ends (INNOCAB). 3A Composites created a lightweight modular flooring system for rail vehicles in 2008 (CONFLOOR). Such thin sandwich panels offer considerable weight reduction and enable uniform heat distribution within the car body. 3A Composites has more recently been working on the development and manufacturing of FRP front ends for high speed trains.[66]

2.3.6 | Design strategies and optimizations for car bodies

Along with the previously mentioned studies on FRP car bodies that can be considered the main applications of FTPs in the car bodies, there are several design strategies and optimization processes that have been undertaken to improve the functionality of FRPs in the car body structures.

Harte et al.[67] developed a multi-level optimization method for designing light weight body shell walls using FRP sandwich panels. Kim et al.[68] introduced an expert system for stiffness optimization of FRP composite laminates in train car bodies. In another study, Zinno et al.[69] developed a multiscale approach for sandwich structures that are used in the roof of a railway vehicle. They considered both technical and economic aspects in their research and employed experimental results to characterize their model. Hudson et al.[70] carried-out an optimization study on the sandwich panels for rail vehicle floors. They used ant colony optimization algorithm to define the design space and reported a possible weight reduction of 60% compared to the traditional poly-wood panels. Cuartero et al.[71] showed that by replacing the traditional aluminum roof with the FRP sandwich panels, a weight reduction of about 3.5% of the total rail vehicle's weight can be achieved.

A lightweight prototype of the rail vehicle driver's cap was designed and fabricated by Carruthers et al.[72] (DE-LIGHT project). Evaluation of the fabricated cab reveals that up to 40% weight reduction, 60% fewer parts, and 20% cost reduction are obtained using the FRP structure. Wennberg et al.[73] (KTH Royal Institute of Technology) proposed a multi-functional design and optimization for the FRP car body for high-speed trains. By considering structural, acoustic, thermal, and fire safety parameters, over 40% weight reduction was obtained in their optimum design. A design for an FRP composite car body roof was carried out in the framework of SCILLA-M project (Italy),[74] based on the innovative sandwich panels. Three types of sandwich panels including classic, rectangular blocks, and trapezoidal blocks, were compared according to their influence on the mechanical behavior of the FRP roof, that is, deformation and stresses.

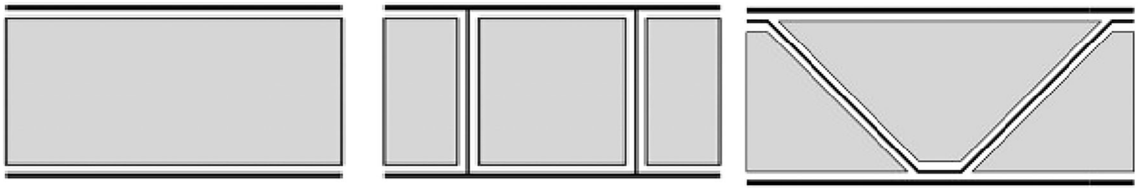


FIGURE 8 Three suggested types of sandwich panels for improving the mechanical behavior of car body's roof.[74]

A schematic of the examined composite structures is shown in Figure 8. According to the reported FE results, employing the trapezoidal type sandwich panels lead to a weight reduction of 36.5% compared to the traditional aluminum roofs. Moreover, an 11.5% reduction in the vertical deformation of the roof was reported for the FRP roof.

3 | APPLICATIONS OF FRPS IN RAIL LINES

FRP composites can be employed in the railway industry for structural purposes in rail lines, in addition to rail vehicles. Weight reduction may not always be the top concern in these kinds of applications. Instead, other FRP characteristics, such as high strength, high corrosion resistance, simplicity of installation, repair and maintenance, as well as economics, are factors that drive the use of composites in railway constructions. A discussion on one of the most practical FRP applications in the rail sector—railway sleepers—is taken into consideration in this sections.

Sleepers are transverse structural elements in the rail tracks that support the rails and transfer the loads from the rails to the ballast. Considering the very large number of employed sleepers in the train lines across the world, selecting the right material for them is of the highest importance in terms of costs, durability, and structural behavior.

The now-in-use sleepers are often made of timber,[75] concrete,[76,77] steel,[78,79] and more recently, FRP composite material.[80–83] In a review study, Manalo et al.[84] compared the alternative materials for replacing timber in rail sleepers. They came to the conclusion that considering the effective parameters like economic costs, weight, and structural behavior, steel and concrete have not shown to be reliable substitutes to be utilized in the new sleepers. In another review that specifically focused on the composite sleepers, Ferdous et al.[80] divided various FRP composite sleepers into three groups: sleepers with (1) short or no fiber reinforcements, (2) unidirectional reinforcements, and (3) bi-directional reinforcements. They reached the conclusion that the primary obstacles to using type-1 sleepers in railroad tracks are their low mechanical properties, low anchoring, creep deformation, and temperature-dependent characteristics. On the other hand, type-2 and type-3 sleepers alleviate the primary drawbacks of type-1 sleepers; however, their higher cost presents a problem that should be handled by optimizing the sleeper structures and utilizing economically advantageous fibers and production techniques.

Numerous experimental and numerical research have been done so far on the mechanical behavior and operation of FRP-based sleepers. Table 4 provides an overview of the studies that have been previously published on the FRP sleepers and their characteristics. The reinforced concrete sleepers are not taken into consideration because the present review focuses primarily on polymer-based composites. However, hybrid sleeper types made of any sort of FRP structure and concrete are also taken into consideration.

Since 1970s, Fiber-reinforced Foamed Urethane (FFU) has been one of the most popular materials used for railway sleepers. Such materials have a very long lifespan (estimated to be 50 years based on Reference 85), are lightweight, and can be drilled, but their main disadvantage is that they are substantially more expensive than traditional timber sleepers. In an effort to boost the sustainability of the new sleepers, natural fiber composites are being used to reinforce polymers in FRP sleepers.[81–83] According to the experimental results,[81] good mechanical properties can be obtained by using this sort of natural fiber composites. There are also several investigations on utilizing recycled materials in railway sleepers as reviewed by Arafat and Imam.[86]

By looking over the findings of the earlier studies on FRP sleepers that have been published, it is possible to do a qualitative comparison with other varieties of sleepers. New FRP sleepers are compared with traditional ones (i.e., wood, concrete-based, and metallic-based sleepers) in terms of effectiveness and costs, in Table 5. Temperature-dependent mechanical characteristics and expensive material and production costs are the main limitations of the FRP sleepers. The railway sector can gain from the various benefits of the FRP railway sleepers by resolving the aforementioned restrictions through advancements in composite science and technology

TABLE 4 Recent investigations on FRP based sleepers.

No.	Sleeper type	Outcomes	Reference
1	FFU based sleepers	• The Railway Technical Research Institute (RTRI) in Japan conducted research on FFU sleepers that were used in the track during routine train operations and found that they could still be utilized for the next 20 years	85
3		• Finite element analysis was performed for obtaining natural vibration frequencies of FFU sleepers • They concluded that the obtained vibrational parameters can be used for in-situ health monitoring of the railway sleepers	87
4		• A damage detection approach was developed for FFU sleepers based on acoustic emission • FFU sleepers show brittle failure behavior and the rupture occurs by delamination of fibers	88
5		• It was determined through experimental testing and finite difference analysis that composite sleepers create a more compliant sleeper/ballast interaction than concrete ones	89
6		• Test specifications of composite sleepers considering in situ conditions were investigated • For comparison, the impact of support and ballast conditions on the static flexural behaviors of composite sleepers were considered • The AS1085.14 test standard is more efficient than ISO 12856 for flexural test of FFU sleepers	90
7		• The moisture effects on damping behavior of FFU composite sleepers were investigated • According to the results, damping parameter can be varied within 4% while the natural frequencies can vary up to 7% under wet/dry conditions	91
8		• A comparison was conducted between concrete and FFU sleepers • At 2 mm of displacement, the lateral and longitudinal resistances of the ballast bed with the concrete sleeper were much higher than those with FFU sleeper • During the early stage of displacement of FFU and concrete sleepers, the longitudinal and lateral resistances of the composite sleeper varied more violently	92
9	Sandwich-based sleepers	• Experimental study was conducted on flexural and shear behavior of the glued laminated sandwich beams for turnout sleepers • Three types of sandwich sleepers made of glued laminated sandwich structures in flatwise, edgewise and combined directions were examined • It was concluded that the presented system for edgewise specimens has the potential to be considered as an alternative for rail sleepers	93
10	Hybrid FRP sleepers	• Experimental investigation was performed on flexural properties of rectangular pultruded profile filled with geo-polymer concrete • The new sleepers showed acceptable level of bending stiffness in addition to significant reduction of CO_2 emission, low shrinkage, low thermal conductivity, lower weight, and so forth	94
11		• The modal and harmonic response of CFRP/reinforced concrete sleepers were investigated • Experimental tests and FE analyses showed the desired static behavior of the sleepers in addition to their higher damping properties compared with traditional sleepers	95
12		• An analytic hierarchy process was used for obtaining optimum amount of filler to resin ratio for FRP sleeper coatings • Density, mechanical properties, thermal behavior UV resistance and costs were considered as the selection parameters • 30% and 50% filler ratio are the optimum amount of filler by giving the first priority to the mechanical properties and costs, respectively	96

TABLE 4 (Continued)

No.	Sleeper type	Outcomes	Reference
13	Natural fiber based sleepers	• Wood particles and bamboo strips were used as reinforcements and phenol formaldehyde as the matrix • A non-linear optimization program was developed to estimate composite sleeper mechanical properties • The modulus of rapture was found to be about 70 MPa by 15.5% resin content	81
14		• Sandwich structures for sleepers made of glass/epoxy composites and bagasse and coconut fibers fillers were presented • Mechanical tensile and flexural tests on the specimens show the proper performance of the sandwich structures for rail bridges	82
15		• The prospective utilization of the natural fiber composites for fabrication of FRP sleepers was reviewed	83
16	Recycled materials based sleepers	• The mechanical and physical properties of different types of sleepers and highlighting the potentials of recycled materials for using in composite sleepers were reviewed	86
17		• The screw pull-out strength of different type of sleepers including timber, synthetic composites, recycled plastic and particulate filled polymers was experimentally examined • According to the results, the particulate filled resin specimens showed the highest pull-out load, with large load drops during failure	97
18		• Composite sleepers by using recycled polyethylene, iron slag, calcium carbonate, polyester resin, glass ropes and glass woven fabrics were fabricated • Up to 39.3 MPa bending strength for the newly developed sleepers was obtained based on experiments	98

TABLE 5 Qualitative comparison of different types of sleepers.

Parameters	Timber	Concrete	Steel	FRP
Overall weight	Good	Poor	Moderate	Excellent
Anchorage	Moderate	Good	Excellent	Moderate
Static and dynamic behavior	Good	Moderate	Good	Good
Life cycle properties	Poor	Moderate	Good	Good
Corrosion resistance	Good	Good	Poor	Excellent
Electric insulation	Good	Good	Poor	Good
Replacement	Good	Poor	Moderate	Good
Repair and maintenance	Moderate	Poor	Good	Moderate
Temperature dependency	Good	Good	Good	Poor
Recyclability	Moderate	Poor	Good	Poor/moderate/good
Costs	Good	Moderate	Poor	Poor

(i.e., establishing effective material systems and fabrication methods).

4 | CHALLENGES FOR APPLICATION OF FRPS IN THE RAILWAY INDUSTRY

Even though FRP structures have excellent mechanical behavior, there are still some serious concerns about using such lightweight structures in the railway industry. Although the economic aspects appear to be the biggest obstacle, this section (Section 4) will also cover certain technical constraints. Despite the growing environmental concerns in all transport systems, restrictor rules for less noise, less wear, and lighter weights have not yet been stablished for the railway industry. Under these circumstances, railroad companies prefer to use less-optimized but cheaper products. As an example in this area, conventional metallic freight bogies (Y25 bogies) have been used on the lines for decades without being significantly improved in terms of total weight, noise emission, and wear behavior.[99] On the other hand, it appears that for railway companies, immediate cost reduction is more significant than reduction in life cycle costs. The major technical and financial obstacles that prevent FRPs from being used more widely in the railway sector are discussed in the Sections 4.1–4.7. Effective replacement of metallic structures with FRP ones cannot be anticipated in the absence of reasonable solutions to the problems relating to the utilization of FRPs for long service life applications in the railway industry.

4.1 | Economic challenges

One of the primary obstacles to replacing heavy-duty structures with lightweight FRP ones is considered to be the high manufacturing costs. FRP components typically have substantially higher initial prices than traditional metallic constructions, including the costs for raw materials and fabrication techniques.[100] Some strategies can be taken into consideration to optimize the FRP costs:

- hybridizing FRP components[101,102] by using low-cost fibers and resins (e.g., glass/polyester) along with expensive ones (e.g., advanced carbon/epoxy composites). In this regard, a design optimization study for the hybridization of glass and carbon fibers for a bumper beam was carried out by Kim et al.[101] Based on the findings, the final configuration has a weight reduction of 33% and improved impact resistance. In experiments on hybrid glass/carbon composite specimens, Bhagwat et al.[102] reported the tensile and compressive properties of the aforementioned composites,
- developing hybrid metal/composite designs,
- utilizing recycled fibers and polymers, as was reviewed by May et al.,[103] for the fibers to be used in various applications, the required material properties and recycling costs typically trade off,
- using cost-efficient fabrication methods for mass production of composites (e.g., pultrusion, pulwinding, etc.).

It should be noted that the higher initial costs for composites can be partially offset by a significant reduction in life-cycle costs. In most cases, FRP structures offer long service lives as well as low repair and maintenance costs. Moreover, in the case of rail vehicles, significant fuel consumption reduction can be accomplished by reducing the vehicle's weight. Accordingly, depending on the speed range, vehicle type, and path profile, a weight reduction of 10% for diesel railway vehicles can result in energy savings of up to 15%.[104] By considering 30 years of service life and the estimated price of the fuel, cost-saving in the range of 12 Euro/kg (for electrical vehicles) up to 76 Euro/kg (for diesel suburban vehicles) can be calculated.[104] Other effective parameters including less wear in the railway or wheelsets, longer maintenance periods, and possible government prizes for less noise and CO_2 emission, can also be calculated as cost savings.

4.2 | Flammability and fire resistance challenge

Considering the available standards for fire resistance behavior of the materials and structures in the railway industry, the design and fabrication of polymeric composites with acceptable fire resistance properties is a challenging issue. As a reference in this field, DIN EN 45545 standard[105] defines requirements for fire behavior of the materials in railway vehicles. In general, two choices are available for the FRP manufacturer for complying with fire behavior regulations: (1) Employing intrinsically flame redundant polymers, and (2) modifying commercial polymer systems with fire redundant agents. Table 6 presents a comparison between the abovementioned methods considering technical and economic aspects.[106,107]

4.3 | Low impact resistance challenge

In the railroad industry, composite structures may frequently be subjected to low-velocity impacts of the foreign objects. This may occur throughout the in-service period (for instance, the impact of debris) or maintenance (e.g., drop of tools). Due to the brittle nature of most composites, they are more vulnerable to possible damage against impact of foreign objects. Onder et al.[108] introduced a practical test method for impact damage assessment of flying ballast or debris in railway vehicles. They used quasi-static punch tests and FE simulations to obtain damage characteristics for high-velocity impact on the composites. Sakly et al.[109] conducted experimental and FE simulations for examining the low-velocity impact resistance of sandwich panels in railway applications. Their findings revealed matrix cracks and delamination, which seemed to be the major damage modes. Interlaminar damage from matrix cracking was also generated by successive impacts. A harmonized method for examining the impact resistance of glass/polyester composites for railway car bodies was developed by Onder and Robinson.[110] They used their model to unify the related standards on the impact resistance of components in the railway industry. As reviewed by Shah et al.,[111] the

TABLE 6 Fire resistant polymers for using in railway industry.

Fire behavior	Polymer systems		Fire redundant additives	Mechanical properties	Economic parameter
Intrinsically flame redundant	Thermosets	Phenolic resins	-	Relatively low mechanical properties	Generally higher price
		Cyanate esters			
		Bismaleimide			
	Thermoplastics	Polyphenylene sulfide	-		
		Polyetheretherketone			
		Polyethersulfone			
		Polyetherimide			
Embedding fire retardant agent	Thermosets	Epoxy	Halogenated	Good mechanical properties	Generally lower price
		Polyester	Metal compounds		
		Vinylester	Phosphorus-based		
	Thermoplastics	Polyamids	Nitrogen and silicon-based		
		Polypropylene			

impact resistance of composites is significantly affected primarily by the resin toughness and fiber architecture. Secondary parameters such as environmental effects, stacking sequence, and fiber and matrix hybridization also affect the damage tolerance behavior of composites. Intensive attempts have been done to improve the impact resistance of composites by enhancing both primary and secondary effective factors. Some reinforcing methods are as follow:

- embedding SMA alloy reinforcement for more energy absorption: according to Meo's review,[112] embedding SMA alloys within composite structures results in a significant amount of impact energy absorption due to the superplastic behavior of SMA. It was demonstrated that a composite beam can experience a 56% reduction in deformation when only a 0.2% volume fraction of SMA is embedded in the beam,[113]
- using 3D fibers: according to Wang et al.'s experiments[114] on 3D woven basal/aramid composites, the reinforced interplay properties increased energy absorption by up to 67%,
- Z-pinning: according to Mouritz,[115] using a relatively small amount of z-pinning can increase the impact damage resistance of composites by 50% or more. Z-pinning can significantly increase the laminate resistance to growth of the existing delamination during impact tests, according to experimental studies by Francesconia and Aymerich,[116]
- using protective coating: Rizzo et al.[49] demonstrated that applying a protective thermoplastic polyurethane coating to CFRP laminates improves the material's ability to withstand damage from impacts by halting the spread of damage throughout the laminate,
- using Nano-reinforcements: Cetin et al.[117] employed multi-walled carbon nanotubes to enhance the impact behavior of sandwich laminates with FRP faces and an aluminum core. The result showed enhancement in energy absorption for shear and bending deflection by adding nanoparticles to the adhesive.

4.4 | Challenge for stablishing proper structural health monitoring system

Advanced composite structures are mainly designed based on damage tolerant criteria. In this regard, detection of the presented damage within the structure is of high importance. On the other hand, due to more brittle nature of the most structural composites in comparison with metals, they are more vulnerable to internal defects. There are several structural health monitoring methods that are proposed to be employed in FRP structures, including: vibration based sensors, embedded optical and piezoelectric sensors, acoustic emission, and Lamb wave method.[118] For an FRP bogie or car body structure, embedded sensors can be employed for online health monitoring during their working time. As an example, the real-time health monitoring using optic fibers was employed for CaFiBo.[21] The required number of embedded sensors, their location, and direction should be designed in such a way that they provide optimum detection of various damages within the structure. Moreover, embedding the health monitoring sensors within the structures, increases the manufacturing cost and complexity. Therefore, this can be seen as a challenge for switching to FRP structures on railways and should be properly addressed in the design and analysis stage.

4.5 | Recycling challenges and waste management

As their use in industrial applications rises, recycling of FRPs can be seen as a significant environmental challenge. Even though several recycling techniques have recently been developed (including mechanical, chemical, and thermal recycling), recycling is still a challenging problem for thermoset-based composites, which are utilized to create the majority of FRPs used in the railway. High recycling process costs, average mechanical characteristics of recovered materials, and a lack of markets for recycled products are the key issues in this area. As an example, each FRP-based bogie frame consists of approximately 400–800 kg of CFRPs and/or GFRPs.[14,19] Given the required number of bogies for railway transportation, thousands of tons of FRPs should be considered to be managed after their working life. This problem has already been brought up in other FRP applications, such as wind turbines, and recycling and disposal techniques have already been suggested, such as grinding up FRP waste and using it as fillers or reinforcements.[119,120]

4.6 | Challenges due to mechanical degradation and chemical aging

There is still a lack of experimentally obtained data source on the durability of FRPs used in different branches including railway transportation systems. Differences in the materials, fabrication methods and working conditions used have even been recognized as potential causes of discrepancies between the results of several durability studies.[121] For majority of railway applications, high life-cycle is expected for the structures (e.g., over 30 years for bogies). On the other hands, such structures are being exposed to different environmental conditions with different levels of temperature, UV emission, and humidity. It is therefore necessary to predict the FRP mechanical properties as a function of long-term environmental conditions. Estimating the remaining life of FRP structures would also be possible by using such data. The long-term mechanical degradation of FRPs should be considered for the structural applications in the design step by the selection of the proper matrix, reinforcements, and possible additives and fillers to improve the long-term performance of the FRP structure. Mechanical degradation and chemical aging may pose a challenge for the replacement of metallic structures with FRP structures, given the required data for material characterization, the cost of required reinforcements, and the need to predict life expectancy.

4.7 | Repair challenges and maintenance process

Composite structures can typically be repaired (e.g., using flexible or rigid bonded patches[122,123]). Depending on the FRP type, damaged component and required applications, repairing is generally more cost-effective than replacing the whole structure. However, just like the design and analysis phases, repair and maintenance of FRP structures are more complicated than those of the metallic ones. The main steps for repairing FRP structures are: Damage detection (using the health monitoring system), design of the repair method (adhesively bonded or mechanically bolted patches), analysis of the structural performance and durability using numerical, analytical or experimental methods, and finally performing the repair process on the structure. Prior to using bonded patches, adhesive or mechanically bolted joints, their structural impact and expected durability should be considered. Standards for maintenance of railway industry components should also be modified for FRP materials. An alternative would be to develop new standards based on FRP structures for maintenance specifications. Without clear repair and maintenance procedures, it is impossible to replace metallic structures with FRP ones in railway transport systems.

5 | FUTURE TRENDS FOR FRP APPLICATIONS IN RAILWAY INDUSTRY

Due to the increased need for rapid travel in today's transportation industry, rail transportation is experiencing dramatic improvements. Considering the strong competition with other transportation systems such as air transportation, the research and engineering in the railway industry must plan ahead by investing in new technologies in order to reach the future objectives. Developing autonomous systems, green railways, high-speed trains, and providing more passenger comfort can be considered some of the expected improvements in the rail sector. In this sense, the hyperloop project[124] (the evacuated tube, high-speed transportation system) and passive magnetic levitation systems[125] are examples of railway transportation advancements.

Composite science and technology can contribute to the evolution of the railway industry by providing appropriate materials and structures as well as design approaches for the upcoming needs. The future rail industry's possible benefits of composites are discussed in the following.

- In comparison to conventional railway systems, weight reduction may be more crucial for modern high-speed trains and battery-powered rail vehicles. Advanced composite constructions can be the key in this situation to achieving the necessary weight reduction.
- Function integration through the use of composite technology, such as the incorporation of damping and suspension systems into FRP load-bearing structures, results in less complex assemblies, reduced noise emission, and lighter weight.
- Future rail industries can use smart composite materials and structures as both sensors and actuators. For instance, shape-memory alloy reinforced composites that can adjust their mechanical characteristics in response to environmental stimuli can be utilized to strengthen structures, improve energy absorption, and even build motorless actuators that can be used for autonomous systems.
- Advanced manufacturing technologies such as 3D printing of composite materials can be used as a functional, rapid, and reliable fabrication method for producing complex geometries for advanced high-speed rail vehicles. Currently, the load bearing parts' technical specifications might not be completely met by the mechanical properties of the 3D printed FRP component. However, a substantial improvement in additive manufacturing techniques for FRP structures is expected because of the advancements in 3D printing technology and printing parameter optimization.
- Using natural and recyclable fibers and resins to build the functional composite constructions may greatly reduce greenhouse gas emissions and create more sustainable railway systems.

6 | CONCLUSIONS

The present study of FRP structures' applications in the railway industry reveals the high potential of FRP composites to be used to increase rail transportation efficiency. It can be inferred from the review that FRPs have so far been primarily trusted for structural applications, such as the reinforcement of infrastructures (like railway bridges) or the replacement of traditional timber sleepers. The situation is, however, different for railroad vehicles, particularly for bogies and wheelsets. For instance, despite the fact that investigations into FRP bogies date back to the 1980s, there is not a working example of one of these bogie designs that has been successfully commercialized in the railway industry. The complete or partial replacement of traditional metallic components with novel FRP structures is hindered firstly by economic barriers and second, by the technical challenges as reviewed in Section 4.

In the upcoming years, it is expected that FRPs will play a larger role in railway applications as a result of developments in the materials and fabrication methods used in the FRP composite industries, as well as the increased attention that businesses and governments are giving to environmental issues like greenhouse gas emissions and noise production. Restrictive rules concerning the environmental aspects in the railway sector are expected to be stablished, that prevent employing outdated and non-eco-friendly structures (e.g., old design of bogies) in the railway transportation.

ACKNOWLEDGMENT

Open access funding provided by ETH-Bereich Forschungsanstalten.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

A. Saeedi https://orcid.org/0000-0002-3413-5435

REFERENCES

1. Zhang J, Chevali VS, Wang H, Wang C-H. Current status of carbon fibre and carbon fibre composites recycling. *Compos B Eng*. 2020;193:108053.
2. Rana S, Fangueiro R. *Advanced Composite Materials for Aerospace Engineering*. Woodhead Publishing; 2016, ch. 1.
3. Jawaid M, Thariq M. *Sustainable Composites for Aerospace Applications*. Woodhead Publishing; 2018.
4. Ravishankar B, Nayak SK, Kader MA. Hybrid composites for automotive applications – a review. *J Reinf Plast Compos*. 2019;38(18):835-845.
5. Muhammad A, Rahman MR, Baini R, Bakri MKB. *Advances in Sustainable Polymer Composites*. Woodhead Publishing; 2021, ch. 8.
6. Selvaraju S, Ilaiyavel S. Applications of composites in marine industry. *J Eng Res Stud*. 2011;2(2):89.
7. Neşer G. Polymer based composites in marine use: history and future trends. *Proc Eng*. 2017;194:19-24.
8. Arifurrahman F, Budiman BA, Aziz M. On the lightweight structural design for electric road and railway vehicles using

fiber reinforced polymer composites – a review. *Int J Sustain Transp*. 2018;1(1):21-29.
9. Robinson M, Matsika E, Peng Q. Application of composites in rail vehicles. *ICCM Int Conf Compos Mater*. ICCM; 2017.
10. Rubino F, Nisticò A, Tucci F, Carlone P. Marine application of fiber reinforced composites: a review. *J Mar Sci Eng*. 2020;8(1):26.
11. Weitzenböck J, Hayman B, Hersvik G, et al. Application of composites in ships and offshore–a review and outlook. *Royal Institution of Naval Architects-International Conference on Marine and Offshore Composites*. Vol 1. Royal Institution; 2010.
12. Jagadeesh P, Puttegowda M, Oladijo OP, et al. A comprehensive review on polymer composites in railway applications. *Polym Compos*. 2022;43(3):1238-1251.
13. Kim JS, Yoon HJ, Shin KB. Design of a composite side beam for the railway bogie frame. *Mater Sci Forum*. 2010;654-656:2676-2679.
14. Kim JS, Lee WG, Kim IK. Manufacturing and testing of a GFRP composite bogie frame with straight side beam members. *J Mech Sci Technol*. 2013;27(9):2761-2767.
15. Fang Z, Tan X, Liu G, et al. A novel vibration energy harvesting system integrated with an inertial pendulum for zero-energy sensor applications in freight trains. *Appl Energy*. 2022;318:119197.
16. Geuenich W, Guenther C, Leo R. Fibre composite bogie has creep-controlled wheelsets. *Railw Gaz*. 1985;141(4):279.
17. Geuenich W, Guenther C, Leo R. Dynamics of fiber composite bogies with creep-controlled wheelsets. *Proceedings of IAVSD Symposium*. Vol 225. IAVSD; 1984.
18. Maurin L, Boussoir J, Rougeault S, et al. Fbg-based smart composite bogies for railway applications. *2002 15th Optical Fiber Sensors Conference Technical Digest*. IEEE; 2002:91.
19. Hou J, Jeronimidis G. A novel bogie design made of glass fibre reinforced plastic. *Mater Des*. 2012;37:1-7.
20. Nishimura T. *Japanese Railway Engineering*; 2016.
21. *Developing a Carbon Fibre Railway Bogie for Passenger Trains*. Accessed December, 2022. https://www.globalrailwayreview.com/article/102360/carbon-fibre-bogie-passenger-trains-irr/
22. *Lightweight Bogie Frame*. Accessed: March, 2023. https://cgrail.de/en/innovations/lightweight-bogie-frame/
23. Geuenich W, Gunther C, Leo R. The dynamics of fiber composite bogies with creep-controlled wheelsets. *Veh Syst Dyn*. 1983;12(1–3):134-140.
24. Kim JS, Yoon HJ, Lee WG. A study on comparisons of composite and conventional steel bogie frames. *J Mech Sci Technol*. 2016;30(12):5439-5446.
25. Kim JS, Yoon HJ. Structural behaviors of a gfrp composite bogie frame for urban subway trains under critical load conditions. *Proc Eng*. 2011;10:2375-2380.
26. Kim JS, Yoon HJ, Lee SH, Lee WG, Shin KB. Durability evaluation of the composite bogie frame under different shapes and loading conditions, Korea. *ICCM Int Conf Compos Mater*. ICCM; 2011.
27. Jeon KW, Shin KB, Kim JS. A study on fatigue life and strength of a gfrp composite bogie frame for urban subway trains. *Proc Eng*. 2011;2405:2405-2410.
28. Jeon KW, Shin KB, Kim JS. A study on evaluation of fatigue strength of a GFRP composite bogie frame for urban subway vehicles. *Adv Compos Mater*. 2013;22(4):213-225.
29. Kim MS, Kim JS, Kim SM. Design optimization of a bogie structure for a tradeoff between processing time and structureal propety. *ICCM Int Conf Compos Mater*. ICCM; 2015.
30. Goo JS, Kim JS, Shin KB. Evaluation of structural integrity after ballast-flying impact damage of a GFRP lightweight bogie frame for railway vehicles. *J Mech Sci Technol*. 2015;29(6):2349-2356.
31. Kim JS, Lee WG, Kim IK, Yoon HJ. Natural frequency evaluation of a lightweight GFRP composite bogie frame. *Int J Precis Eng Manuf*. 2015;16(1):105-111.
32. Yoon HJ, Kim JS, Song KY, Cho HW, Jung JY. Distributed strain monitoring of railway composite bogies using a Brillouin optical correlation domain analysis system. *Appl Sci*. 2018;8(10):1755.
33. Černý I. Evaluation of Interlaminar shear strength of longitudinal GRP railway bogie frames considering microstructure aspects. *Key Eng Mater*. 2014;577-578:521-524.
34. Chvojana J, Vaclavika J. Experimental methods for the grp bogie structure integrity assessment. *Proc Eng*. 2015;627:627-634.
35. Ma Q, Qin X, Gan X, Wang Y. Study on structural optimization of braid-and-lay integrated carbon fiber reinforced polymer for metro bogie. *Polym Compos*. 2023;44:6419-6439. doi:10.1002/pc.27568
36. Yao K, Yang Y, Li H, et al. Material characterization of a multi-cavity composite structure for the bogie frame of urban maglev train. *Compos B Eng*. 2016;99:277-287.
37. Tserpes K, Barroso-Caro A, Carraro PA, et al. A review on failure theories and simulation models for adhesive joints. *J Adhes*. 2022;98(12):1855-19151. https://doi.org/10.1080/00218464.2021.1941903
38. Cameselle-Molares A, Sarfaraz R, Shahverdi M, Keller T, Vassilopoulos AP. Fracture mechanics-based progressive damage modelling of adhesively bonded fibre-reinforced polymer joints. *Fatigue Fract Eng Mater Struct*. 2017;40(12):2183-2193.
39. Ševčík M, Shahverdi M, Hutař P, Vassilopoulos AP. Analytical modeling of mixed-mode bending behavior of asymmetric adhesively bonded pultruded GFRP joints. *Eng Fract Mech*. 2015;147:228-242.
40. Vassilopoulos A, Shahverdi M, Keller T. *Fatigue and Fracture of Adhesively-Bonded Composite Joints*. Elsevier; 2015.
41. Shahverdi M, Vassilopoulos AP, Keller T. Mixed-mode I/II fracture behavior of asymmetric adhesively-bonded pultruded composite joints. *Eng Fract Mech*. 2014;115:43-59.
42. Shahverdi M, Vassilopoulos AP, Keller T. Mixed-mode quasi-static failure criteria for adhesively-bonded pultruded GFRP joints. *Compos Part A Appl Sci Manuf*. 2014;59:45-56.
43. Shahverdi M, Vassilopoulos AP, Keller T. Mixed-mode fatigue failure criteria for adhesively-bonded pultruded GFRP joints. *Compos Part A Appl Sci Manuf*. 2013;54:46-55.
44. Shahverdi M, Vassilopoulos A. *Fatigue and Fracture of Adhesively-Bonded Composite Joints*. Elsevier; 2015.
45. Kim JH, Shin KB, Kim JS. Optimum design on suspension joint parts of GFRP composite bogie frame with H-shaped side beams for urban railway trains. *Int J Precis Eng Manuf*. 2012;13(1):71-76.
46. Lee WG, Kim JS, Yoon HJ. Strength evaluation of t-joint structures for the composite bogie frame under bending, Korea. *ICCM Int Conf Compos Mater*. ICCM; 2011.

47. Lee WG, Kim JS, Yoon HJ, Shin KB, Seo SI. Structural behavior evaluation of T-joints of the composite bogie frame under bending. *Int J Precis Eng Manuf*. 2013;14(1):129-135.
48. Liu B, Zhang Q, Li X, et al. Potential advantage of thin-ply on the composite bolster of a bogie for a high-speed electric multiple unit. *Polym Compos*. 2021;42(7):3404-3417.
49. Rizzo F, Cuomo S, Pinto F, Pucillo G, Meo M. Thermoplastic polyurethane composites for railway applications: experimental and numerical study of hybrid laminates with improved impact resistance. *J Thermoplast Compos Mater*. 2021;34(8):1009-1036.
50. Batchelor J. Use of fibre reinforced composites in modern railway vehicles. *Mater Des*. 1981;2(4):172-182.
51. Good T, Hannema G, Paradies R, Shahverdi M. Towards noise and weight reduction by application of frp wheelsets for freight cars. In: *19th International Wheelset Congress*, Venice, Italy; 2019.
52. Tang J, Zhou Z, Chen H, et al. Laminate design, optimization, and testing of an innovative carbon fiber-reinforced composite sandwich panel for high-speed train. *Polym Compos*. 2021;42(11):5811-5829.
53. Jagadeesh P, Puttegowda M, Girijappa YGT, Rangappa SM, Siengchin S. Carbon fiber reinforced areca/sisal hybrid composites for railway interior applications: mechanical and morphological properties. *Polym Compos*. 2022;43(1):160-172.
54. Brooks N. Schindler is on track with FRP trains. *Reinforced Plast*. 1995;11(39):28-32.
55. Perrella A. Hardcore-DuPont rolls out its first composite railcar. *Reinforced Plast*. 1995;11(39):48-50.
56. Kim JS, Lee SJ, Shin KB. Manufacturing and structural safety evaluation of a composite train carbody. *Compos Struct*. 2007;78(4):468-476.
57. Seo S, Kim J, Cho S. Development of a hybrid composite bodyshell for tilting trains. *Proc Inst Mech Eng Part F: J Rail Rapid Transit*. 2008;222(1):1-13.
58. Heller P, Korinek J, Triska L. Hybrid body of underground railway car: path towards reduced weight of rail vehicles. *MM Sci J*. 2015;2015:631-634.
59. Ulbricht A. Rail vehicle in CFRP-intensive design. *Lightweight Des Worldwide*. 2019;12(2):36-41.
60. Kim JS, Jeong J-C, Lee S-J. Numerical and experimental studies on the deformational behavior a composite train carbody of the Korean tilting train. *Compos Struct*. 2007;81(2):168-175.
61. Kim JS, Jeong J-C. Natural frequency evaluation of a composite train carbody with length of 23m. *Compos Sci Technol*. 2006;66(13):2272-2283.
62. Kim JS, Chung SK. A study on the low-velocity impact response of laminates for composite railway bodyshells. *Compos Struct*. 2007;77(4):484-492.
63. Jang BW, Park SO, Lee YG, Lee JR, Kim CG. Structural health monitoring based on strain distributions of a composite train carbody. *ICCM Int Conf Compos Mater*. ICCM; 2009.
64. Mozafari H, Khatami S, Molatefi H. Out of plane crushing and local stiffness determination of proposed foam filled sandwich panel for Korean tilting train eXpress – numerical study. *Mater Des*. 2015;66:400-411.
65. Tang J, Zhou Z, Chen H, Wang S, Gutiérrez A. Research on the lightweight design of GFRP fabric pultrusion panels for railway vehicle. *Compos Struct*. 2022;286:115221.
66. *3a Composites Mobility*. Accessed: July, 2023. https://3acompositesmobility.com/
67. Harte A, McNamara J, Roddy I. A multilevel approach to the optimisation of a composite light rail vehicle bodyshell. *Compos Struct*. 2004;63(3–4):447-453.
68. Kim J-S, Kim N-P, Han S-H. Optimal stiffness design of composite laminates for a train carbody by an expert system and enumeration method. *Compos Struct*. 2005;68(2):147-156.
69. Zinno A, Fusco E, Prota A, Manfredi G. Multiscale approach for the design of composite sandwich structures for train application. *Compos Struct*. 2010;92(9):2208-2219.
70. Hudson CW, Carruthers JJ, Robinson AM. Multiple objective optimisation of composite sandwich structures for rail vehicle floor panels. *Compos Struct*. 2010;92(9):2077-2082.
71. Cuartero J, Miravete A, Sanz R. Design and calculation of a railway car composite roof under concrete cube crash. *Int J Crashworthiness*. 2011;16(1):41-47.
72. Carruthers J, O'Neill C, Ingleton S, et al. The design and prototyping of a lightweight crashworthy rail vehicle driver's cab. *9th World Congress on Railway Research*. Newcastle University; 2011.
73. Wennberg D, Stichel S. Multi-functional design of a composite high-speed train body structure. *Struct Multidisc Optim*. 2014;50(3):475-488.
74. Grasso M, Gallone A, Genovese A, et al. Composite material design for rail vehicle innovative lightweight components. In: *Proc of the World Congress on Engineering Vol II WCE 2015*, London, UK; 2015.
75. Rothlisberger E. *History and Development of Wooden Sleeper*. Accessed: July, 2023. http://www.corbat-holding.ch/documents/showFile.asp
76. Taherinezhad J, Sofi M, Mendis P, Ngo T. A review of behaviour of Prestressed concrete sleepers. *Electron J Struct Eng*. 2013;13(1):1-16.
77. Raj A, Nagarajan P, Shashikala A. A review on the development of new materials for construction of prestressed concrete railway sleepers. *IOP Conf Ser Mater Sci Eng*. 2018;330:012129.
78. Zakeri J-A, Talebi R. Experimental investigation into the effect of steel sleeper vertical stiffeners on railway track lateral resistance. *Proc Inst Mech Eng Part F: J Rail Rapid Transit*. 2017;231(1):104-110.
79. Czyczuła W, Bogacz R. Mechanics of track structure with y-shaped steel sleepers in sharp curves. *Applied Mechanics and Materials*. Vol 9. Trans Tech Publ; 2008:71-88.
80. Ferdous W, Manalo A, Van Erp G, Aravinthan T, Kaewunruen S, Remennikov A. Composite railway sleepers – recent developments, challenges and future prospects. *Compos Struct*. 2015;134:158-168.
81. Xiao S, Lin H, Shi SQ, Cai L. Optimum processing parameters for wood-bamboo hybrid composite sleepers. *J Reinf Plast Compos*. 2014;33(21):2010-2018.
82. Soehardjo KA, Basuki A. Utilization of bagasse and coconut fibers waste as fillers of sandwich composite for bridge railway sleepers. *IOP Conf Ser Mater Sci Eng*. 2017;223:012036.
83. Santulli C. *Biomass, Biopolymer-Based Materials, and Bioenergy: Construction, Biomedical, and Other Industrial Applications*; 2019.

84. Manalo A, Aravinthan T, Karunasena W, Ticoalu A. A review of alternative materials for replacing existing timber sleepers. *Compos Struct*. 2010;92(3):603-611.
85. Koller G. FFU synthetic sleeper – projects in Europe. *Construct Build Mater*. 2015;92:43-50.
86. Arafat ME, Imam F. Suitability of recycled materials as a composite sleeper: a scoping review. *Mater Today: Proc*. 2022;65:1599-1607.
87. Sengsri P, Oliveira De Melo A, Kaewunruen S. Experimental and numerical investigation of vibration characteristics of fibre-reinforced foamed urethane composite beam. In: *Proceedings of the 4th World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium*, Prague, Czech Republic; 2019:17.
88. Sengsri P, Ngamkhanong C, de Melo ALO, Papaelias M, Kaewunruen S. Damage detection in fiber-reinforced foamed urethane composite railway bearers using acoustic emissions. *Inf Dent*. 2020;5(6):50.
89. Ferro E, Harkness J, Le Pen L. The influence of sleeper material characteristics on railway track behaviour: concrete vs composite sleeper. *Transp Geotech*. 2020;23:100348.
90. Kaewunruen S, Ngamkhanong C, Sengsri P, Ishida M. On hogging bending test specifications of railway composite sleepers and bearers. *Front Built Environ*. 2020;6:592014.
91. Kaewunruen S, Janeliukstis R, Ngamkhanong C. Dynamic properties of fibre reinforced foamed urethane composites in wet and dry conditions. *Mater Today: Proc*. 2020;29:7-10.
92. Liu J, Chen R, Liu Z, Liu G, Wang P, Wei X. Comparative analysis of resistance characteristics of composite sleeper and concrete sleeper in ballast bed. *Construct Build Mater*. 2021;300:124017.
93. Manalo A, Aravinthan T. Behavior of full-scale railway turnout sleepers from glue-laminated fiber composite Sandwich structures. *J Compos Constr*. 2012;16(6):724-736.
94. Ferdous MW, Khennane A, Kayali O. Hybrid frp-concrete railway sleeper. *Advanced Composites in Construction 2013, ACIC 2013 – Conference Proceedings*. ACIC; 2013:67.
95. Çeçen F, Aktaş B. Modal and harmonic response analysis of new CFRP laminate reinforced concrete railway sleepers. *Eng Fail Anal*. 2021;127:105471.
96. Ferdous W, Manalo A, Aravinthan T, Van Erp G. Properties of epoxy polymer concrete matrix: effect of resin-to-filler ratio and determination of optimal mix for composite railway sleepers. *Construct Build Mater*. 2016;124:287-300.
97. Yu P, Manalo A, Ferdous W, et al. Failure analysis and the effect of material properties on the screw pull-out behaviour of polymer composite sleeper materials. *Eng Fail Anal*. 2021;128:105577.
98. Shanour AS, Khalil AA, Riad HS, Bakry HM. Experimental and analytical investigations of innovative composite materials using GFRP and iron slag for railway sleepers. *J Eng Res Rep*. 2020;13(2):25-42.
99. Hiensch M, Burgelman N, Hoeding W, Linders M, Steenbergen M, Zoeteman A. Enhancing rail infra durability through freight bogie design. *Veh Syst Dyn*. 2018;56(10):1532-1551.
100. Burgoyne C, Balafas I. Why is FRP not a financial success. *Proc 8th Intl Conf on FRP Reinforcement for Reinforced Concrete Structures*. Univ. of Patras; 2007.
101. Kim D-H, Kim H-G, Kim H-S. Design optimization and manufacture of hybrid glass/carbon fiber reinforced composite bumper beam for automobile vehicle. *Compos Struct*. 2015;131:742-752.
102. Bhagwat P, Ramachandran M, Raichurkar P. Mechanical properties of hybrid glass/carbon fiber reinforced epoxy composites. *Mater Today: Proc*. 2017;4(8):7375-7380.
103. May D, Goergen C, Friedrich K. Multifunctionality of polymer composites based on recycled carbon fibers: a review. *Adv Ind Eng Polym Res*. 2021;4(2):70-81.
104. Scheier B, Schumann T, Meyer Zu Hörste M, Dittus H, Winter J. Wissenschaftliche Ansätze für einen energieoptimierten Eisenbahnbetrieb. *Eisenbahn Ingenieur Kalender*. 2014;2013:265.
105. E. DIN. Railway Applications-Fire Protection on Railway Vehicles-Part 2, 77.
106. Morgan AB. *Non-halogenated Flame Retardant Handbook*. John Wiley & Sons; 2021.
107. Häublein M, Demleitner M, Altstädt V. *Composite Materials*. Elsevier; 2021.
108. Onder A, Oneill C, Robinson M. Flying ballast resistance for composite materials in railway vehicle carbody shells. *Transp Res Proc*. 2016;595:595-604.
109. Sakly A, Laksimi A, Kebir H, Benmedakhen S. Experimental and modelling study of low velocity impacts on composite sandwich structures for railway applications. *Eng Fail Anal*. 2016;68:22-31.
110. Önder A, Robinson M. Harmonised method for impact resistance requirements of E-glass fibre/unsaturated polyester resin composite railway car bodies. *Thin-Walled Struct*. 2018;131:151-164.
111. Shah S, Karuppanan S, Megat-Yusoff P, Sajid Z. Impact resistance and damage tolerance of fiber reinforced composites: a review. *Compos Struct*. 2019;217:100-121.
112. Angioni S, Meo M, Foreman A. Impact damage resistance and damage suppression properties of shape memory alloys in hybrid composites—a review. *Smart Mater Struct*. 2010;20(1):013001.
113. Khalili S, Saeedi A. Dynamic response of laminated composite beam reinforced with shape memory alloy wires subjected to low velocity impact of multiple masses. *J Compos Mater*. 2018;52(8):1089-1101.
114. Wang X, Hu B, Feng Y, et al. Low velocity impact properties of 3D woven basalt/aramid hybrid composites. *Compos Sci Technol*. 2008;68(2):444-450.
115. Mouritz A. Review of z-pinned composite laminates. *Compos Part A Appl Sci Manuf*. 2007;38(12):2383-2397.
116. Francesconi L, Aymerich F. Effect of Z-pinning on the impact resistance of composite laminates with different layups. *Compos Part A Appl Sci Manuf*. 2018;114:136-148.
117. Çetin ME. The effect of carbon nanotubes modified polyurethane adhesive on the impact behavior of sandwich structures. *Polym Compos*. 2021;42(9):4353-4365.
118. Singh T, Sehgal S. Structural health monitoring of composite materials. *Arch Comput Methods Eng*. 2021;29:1997-2017.
119. Jensen JP, Skelton K. Wind turbine blade recycling: experiences, challenges and possibilities in a circular economy. *Renew Sustain Energy Rev*. 2018;97:165-176.

120. Fonte R, Xydis G. Wind turbine blade recycling: an evaluation of the European market potential for recycled composite materials. *J Environ Manage*. 2021;287:112269.
121. Frigione M, Lettieri M. Durability issues and challenges for material advancements in FRP employed in the construction industry. *Polymers*. 2018;10(3):247.
122. Balakrishnan VS, Seidlitz H. Potential repair techniques for automotive composites: a review. *Compos B Eng*. 2018;145: 28-38.
123. Mohammadi S, Yousefi M, Khazaei M. A review on composite patch repairs and the most important parameters affecting its efficiency and durability. *J Reinf Plast Compos*. 2021;40(1–2): 3-15.
124. Lluesma F, Arguedas A, Hoyas S, Sánchez A, Vicén J. Evacuated-tube, high-speed, autonomous maglev (hyperloop) transport system for long-distance travel: an overview. *IEEE Electrif Mag*. 2021;9(4):67-73.
125. Li SE, Park J-W, Lim J-W, Ahn C. Design and control of a passive magnetic levitation carrier system. *Int J Precis Eng Manuf*. 2015;16(4):693-700.

How to cite this article: Saeedi A, Motavalli M, Shahverdi M. Recent advancements in the applications of fiber-reinforced polymer structures in railway industry—A review. *Polym Compos*. 2024;45(1):77-97. doi:10.1002/pc.27817