Review Article

Role of Polymer Composites in Railway Sector: An Overview

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Abstract
The composite materials, which have a high strength-to-weight ratio, are preferred for designing complex and light structures in various industries. Especially in the railway sector, the composites with lightweight property and flexibility in designs cause an increment in fuel efficiency and cost-effectiveness on overall rail vehicle developments. The fiber-reinforced polymer (FRP) composites meet the above requirements and are used in the production of rail components, such as bogie frames, floor materials, sleepers, switches, crossings, and other internal parts. These FRPs are good replacements for existing metal-based components interns of durability, high stiffness, and corrosion resistance. This review gives an overview of polymer composite's role in the railway sector for various applications and outlines the previous research works done on railway vehicles using FRP composites. This review will be beneficial for researchers to overcome all challenges in the railway sector and promotes new developments.

Keywords: Polymer composites, FRP composites, Lightweight, Sleepers, Carriage structures

1 Introduction

Composite materials can also be referred to as composition material or shortened to composite, which is a combination of two or more materials of similar or dissimilar properties combined at a macroscopic level. The composites consist of mainly two phases, they are reinforcement phase and matrix phase. The matrix phase shows an adhesive nature between two or more fibers, also acts as a load transfer medium between them. Whereas the reinforcement phase increases the mechanical properties and overall performance of the resin systems. Based on the matrix material, the composites are classified as metal matrix composites, polymer matrix composites, and ceramic matrix composites. In the polymer matrix composite domain, fiber-reinforced polymer composites are popular due to their potential characteristics [1]–[5]. The addition of two or more reinforcements in a single matrix (hybridization) improves the overall performance of the resultant composite, especially with mechanical properties. Hybrid composite materials are used in many engineering applications for their versatile properties like lightweight, low cost, ease of structure development, high strength, and strength to weight ratio [6]–[8]. The fiber-reinforced polymer (FRP) composites are being utilized by the designers to deliver intelligent and innovative solutions to the infrastructure and vehicle industries to overcome the ever-growing issues. The combination of high-stiffness, high-strength structural fibers along with lower cost, environmentally resistant, and light-weight polymers result in better durability and mechanical properties than the individual constituents. In these composites, the continuous or discontinuous fibers are preferred as reinforcements, and thermoplastic or thermosetting matrices are used as a binding material [9], [10]. The earliest FRP-based composites are found to exist during world war-II that is used by petrochemical industries. The high strength materials, such as glass, boron, and carbon fibers were commercialized in industries to overcome the challenges during 1960–1970 because of low density, high strength, and stiffness [11], [12]. These factors are taken advantage of in recent years for various industries like automotive, aerospace, railway, and construction sectors. Additionally, these FRP composites possess the ease of tolerability, good formability, higher specific strength, and specific modulus, also potential lightweight alternatives to traditional concrete and metal materials [13]. These alternative FRPs promotes easy process with high components production speed, and it causes economic benefit through the processing cost reduction. The demand in industries for corrosion-free materials is fulfilled by these FRP composites in place of ferrous and non-ferrous materials [14], [15]. Economically, the FRP composites contribute to greenhouse emissions reduction by reducing fuel consumption when used in transport vehicle body applications. Currently, FRP composites recycling is a big debate in the composite industry, and sustainable, renewable materials industry. These results in an economic impact of the FRP wastes obtained from the utilization and production of FRP materials. These FRP wastes have economic value in energy recovery. The recycling of FRP's adds up the advantages to the composite industry through the reduction of overall processing cost during the synthesis of polymers. The recycling of FRPs was done through a thermal process called conventional pyrolysis, since it gives excellent recycled quality, high energy saving, and economically preferred process. Despite the challenges with the application of recycled FRP composites, due to the strength issues not being highly validated in large-scale structures applications; it is still an enabling technology in some other products and can be harnessed [16], [17].

The lightweights and flexibility of FRP composites play an important role in railway industries for designing complex streamline structures for the reduction of air resistance/pressure and drag force while the rail vehicle passes through the tunnels [18]. The requirement of advanced technologies and luxuries in the railway vehicle causes a 35% increment in overall weight including bazaar requirements and more safety constraints. The adoption of AC equipment and more entertainment devices in railway vehicles make it heavier and consume more energy for transportation [19], [20]. Furthermore, stiffer, and resistant rail vehicle compartments are required to manage the developed stresses. Hence, all these things affect directly and indirectly the railway vehicle economy through higher energy consumption, CO_2 emissions, high manufacturing cost, and high track wear. So that the railway transportation system needs to be changed by adopting the latest technologies with suitable lightweight FRP materials to gain economic benefits and potentiality in the rail vehicle transportation system [21], [22].

In previous years and decades, researchers are tried to incorporate these FRP composites for various railway applications. Goo *et al.* [23] suggested the glass/epoxy composites for rail vehicle bogie frame applications and evaluated the structural integrity of these composites. The tested results show that very less effect was found on structural integrity by the impact force, where the force was induced by the prepared bogie frame through the ballast flying. Khalil [24] prepared novel polymer composites using iron slag, E-glass, polyester, polyethylene, and styrene materials for railway sleeper application. This composite was subjected to mechanical tests, and it reveals that the composite meets the requirement of international standards applicable for railway sleepers. Heller *et al.* [25] fabricated sidewall and ceiling panels of the rail vehicles using GFRP composites. Usage of these composites shows the overall weight reduction by 20% in the manufactured parts as compared to parts fabricated using stainless steel materials. So, this review gives an overview of FRP composites usage in railway industries for various potential applications.

2 Brief on Railway Vehicles

At first, the glass FRP composite materials were applied in the railway sector for the manufacturing of components like seats, baggage places, toilet features, etc. in the year 1950s. The reasons for employing these composites are good performance, power efficiency, and reduction of harshness, vibration, and noise aspects. These composite structures were applied for the trains, such as Bimodal tram (Korea), Tilting Train express (TTX), and Automatic Guided Transit (AGT) [26], [27]. The Tokaido Shinkansen line was the first high-speed train introduced in 1964 with a speed of above 200 km/h, followed by 300 km/h high-speed train TGVA-A in 1989. With the huge number of technologies and efforts, Korea has developed the KTX-II train with the capability of running up to 400 km/h speed in 2007. These vehicles are helpful to the passengers while reaching their destinations quickly. Along with that, these vehicles were subjected to aerodynamic shockwave naturally on the way through the tunnels. At the entry of the tunnel, the compressive waves hit the nose profile of the vehicle and propagate over the entire body; hence the high-speed vehicle should be capable of withstanding high stress against the compressive waves [28], [29]. These critical issues are possible to resolve using suitable composite technologies with materials. The railway vehicle's complex nose profile is effectively produced using composites fabrication. Some of the advantages of using these composites are cost efficiency, quick fabrication of nose profiles, and ease of manufacturing than the sheet metal process. The reduction of impact resistance and drag force is also possible using the composite's streamlined shape. The utilization of FRP composites adds up the advantages, while designing and production of complex structures and nose profiles with mechanical parts [30], [31]. In the United Kingdom, the carbon fiber reinforced materials were utilized in CAFIBO and British rails for the manufacturing of bogie frames and axles. The composites made of carbon and glass fibers with epoxy and phenolic resins were utilized in Monorail for the car body applications in USA and Florida. In the USA, it was also developed a Monorail using E-glass/epoxy composites with aramid core for windows, doors, sidewalls, body shell, and door equipment. The Metropolitan train developed by Denmark utilizes glass and carbon fiber reinforced polyester composites for carriage body shell applications. The Combino trains manufactured in the Netherlands contain glass fiber reinforced polymer composites as sidewalls, underframes and vehicle front ends. The German manufacturers developed a CG rail utilizing carbon fiber reinforced composites with a length of 22 m and 25 mm thickness for rail car body structure fabrication [32], [33].

3 FRP Components in the Railway Sector

The lower weight of FRP composites contributes to the production of interior and exterior parts of the railway vehicle. The previous research works done on the railway vehicles components production using FRP composites are tabulated in Table 1. The balancing and sustainability of overall weight were controlled by the bogie frame, and it also reduces the track wear by balancing the overall weight. This bogie frame supports twisting, static and dynamic loads with its weight approximately 20% of the overall bogie weight. The usage of steel-based materials in bogie frames causes more weight and it undergoes corrosion when exposed to the environment. Hence, there is a requirement of lightweight and corrosion-free materials for the manufacturing of railway bogie frames instead of steel-based materials [34]. Hou and Jeronimidis [35] developed glass fiber reinforced epoxy composites for rail bogie frame application and the performance was analyzed using finite element analysis under various loading conditions. The stresses developed when subjected to torsional and longitudinal loads are very small and are high in vertical loads. These stress levels are satisfactory for bogie application. Chvojana and Vaclavika [36] manufactured cost-effective bogie upper and lower bogie frames using GRP material and evaluated the structural integrity of these frames. The results of the sweep, drop, and track profile tests show an optimal performance and good structural integrity behavior when subjected to the above tests. Yao *et al.* [37] conducted a static, weight prospect and FEM evaluation of fiberglass reinforced casting block for bogie applications. The fabricated composites possess weight reduction by 30.9% than aluminum-based materials. The evaluated test results give a clear picture about satisfying basic load-bearing requirements for bogie frames applications in urban railways.

Table 1: Previous research works done on railway components production

Polymer Composites	Railway Components	Research Outcomes	Ref.
GEP 224 glass/epoxy, Quadaxial glass fiber/epoxy	Bogie frame application	The developed composite achieves safer in-plane and out-of-plane material properties and fatigue limits. This similar outcome was observed in both experimental and numerical studies conducted for these composites	[42]
Graphite/epoxy	Railway carriage structures	The composite specimens were exposed to aging environments and the results show that the composites exposed to aging possesses lower mechanical properties and decreases further with increasing aging time	[43]
Glass/epoxy	Side beam for railway bogie frame	The composites exhibit higher stiffness and structural integrity under static loading conditions of 182 KN and 140 KN. The radiograph test was conducted for internal damages analysis and it was found that the damages are less in the fabricated composites	[44]
Fiber-reinforced foamed urethane (FFU) composites	Composite beams in railway crossings and switches	The dynamic young's modulus value is higher for FFU composites at the initial bending mode resonant frequency and reduced for a further second and third mode of bending. The damages in FFU composite reduce dynamic model parameter and damage severity	[45]
Carbon fiber/epoxy	Railcar body application	The highest tensile strength of 2.21 GPa was obtained for CF/epoxy composite with curing temperature and duration of 1180 C and 24 h respectively. These model values are in good agreement with the actual and predicted values. The CF/epoxy composite was deformed at a top peak load of 17 KN at room temperature	[46]
Carbon nanofibers (CNFs)/thermoplastic polyurethane (TPU)	Steering pads in railway vehicles	The prototype pad model was developed with 85 wt% TPU and 15 wt% CNFs. The increment of applied loads between 0–3500 pounds results in the decrement of steady-state resistance. Above 3500 pounds of load has no significant effect on steady-state resistance	[47]
E-glass/polyester	Rail car bodies	These composites were subjected to cost-effective and practical approach to check the feasibility of composites for certain applications. The results are in good agreement with the standards	[48]

As per the railway networks survey, there are approximately 3 billion sleepers are being utilized around the world, and most of them are made using timber materials. These timber materials have undergone mechanical, biological, and thermal degradation under environmental impact. This easy failure mechanism is difficult in railway sleepers when manufactured by using FRP composites. Manalo and Aravinthan [38] developed a glue-laminated glass fiber reinforced sandwich structure and evaluated the structural behavior for railway sleeper application. The results reveal that the structure possesses higher strength and stiffness values that meet the standards for sleeper application. The better performance with optimal mechanical properties is obtained in comparison to existing sleepers. Soehardjo and Basuki [39] created a railway sleeper model using a composite sandwich structure made of glass fiber, epoxy, bagasse or coconut filler, and polyurethane adhesive. This model was subjected to compressive, flexural, and tensile tests to check the technical feasibility of these composites. The maximal tensile, flexural and compressive strengths obtained were 3324 kg/cm^2, 3227 kg/cm^2, and 3208 kg/cm^2 respectively. Hence, these composites meet techno-economic aspects and are suitable for turnout sleeper application. Xiao *et al.* [40] investigated the optimal parameters for the manufacturing of wood/bamboo hybrid polymer composites with phenol-formaldehyde resin for railway sleeper applications. The optimal materials conditions i.e. 0.65 min/mm of hot-pressing time, 0.8 g/cm^3 of target density, 15.5% of resin content, and 1700 °C hot temperature gives 70.08 MPa of modulus of rupture value and gives elasticity, thickness swelling, and internal bonding behavior more than the required standard for sleeper application. Çeçen and Aktaş [41] developed carbon fiber reinforced concrete sleepers and studied the modal, harmonic analysis of these composites. This composite was employed for the static positive moment test and the result shows a good static strength suitable for the high-speed track. The damping properties are positive, and it increases the life span of the developed railway sleeper. The non-prestressed process also increases the component life span and reduces the overall maintenance of the resultant sleeper composites.

The carbon emissions and fuel efficiency were improved by utilizing lightweight materials in the railway vehicle carriage structures. Irikovich *et al.* [49] developed a goods train flooring polymer composites using glass fibers calico with epoxy resin materials. The polymer composites with glass fillers as reinforcement possess more ductility, lightweights, and strong values. The coarse calico/glass fiber composite possesses an average strength value of 100 MPa and this is suggested for railway flooring applications. The usage of this calico material adds up environmental and economic aspects to the composite development. Jeon *et al.* [50] evaluated the dynamic and mechanical properties of carbon fiber reinforced composites (CFCs) for the low noise railway slab application. These composites were subjected to oxygen plasma treatment, and this enhances the adhesion between carbon fibers and epoxy. The 12 mm carbon fiber length and 2 wt% reinforcement give a maximal mechanical and dynamic property. The maximal damping values and flexural strength were obtained were 0.0194 and 25.12 MPa, respectively.

4 Conclusions

The utilizations of FRP polymer composites in the railway sector to produce various components were discussed in this review article. The fiber composite possesses many advantages, including light-weightiness, consuming fewer amounts of energy, higher durability, and stiffness value as compared to steel-based materials. While designing the properties of FRP composites, the arrangement/orientation of fiber in the load direction was also considered. However, the high strength of the composite can be found when the orientation of fiber was parallel to the direction of imposed loading. In the railway sector, the application of these FRPs improves fuel efficiency, reduces the overall weight, and changes the aerodynamic characteristics of the rail vehicle. The high-speed trains can be overcome by aerodynamic resistance; it is possible through the development of a complex streamline nose profile using FRP composites. The traditional timber sleepers are being replaced by FRP composites due to the easy degradation of timber materials under environmental conditions. The railway sleepers made of fiber composite have minimal maintenance cost and long service lifetime. The glass fiber/epoxy composite was commonly preferred in the manufacturing of rail components, such as railway carriage structures, sleepers, bogie frames, switches, and other internal parts. The high corrosion and high-cost steel, iron-based alloy materials are replaced by FRP composites in the railway sector. Hence, the usage of FRP composites gives potential outcomes in all manners for the railway vehicle especially in terms of cost-effectiveness. Also, further research works are needed to increase the applicability of FRPs and to boom the confidence in the railway sector.

References

[1] P. Jagadeesh, M. Puttegowda, S. M. Rangappa, and S. Siengchin, "A review on extraction, chemical treatment, characterization of natural fibers and its composites for potential applications," *Polymer Composites*, vol. 42, no.12, pp. 6239–6264, Sep. 2021.

[2] D. K. Rajak, D. D. Pagar, R. Kumar, and C. Pruncu, "Recent progress of reinforcement materials: A comprehensive overview of composite materials," *Journal of Materials Research and Technology*, vol. 8, no. 6, pp. 6354–6374, Nov. 2019.

[3] P. Jagadeesh, M. Puttegowda, Y. G. T. Girijappa, S. M. Rangappa, M. K. Gupta, and S. Siengchin, "Mechanical, electrical and thermal behaviour of additively manufactured thermoplastic composites for high performance applications," in *Additive and Subtractive Manufacturing of Composites*, S. M. Rangappa, M. K. Gupta, S. Siengchin, and Q. Song, Eds., Singapore: Springer, 2021, pp. 167–199.

[4] K. N. Bharath, P. Madhu, T. Y. Gowda, A. Verma, S. M. Rangappa, and S. Siengchin, "Mechanical and chemical properties evaluation of sheep wool fiber–reinforced vinylester and polyester composites," *Materials Performance and Characterization*, vol. 10, no. 1, pp. 99–109, Mar. 2021.

[5] S. Rastogi, A. Verma, and V. K. Singh, "Experimental response of nonwoven waste cellulose fabric-reinforced epoxy composites for high toughness and coating applications," *Materials Performance and Characterization*, vol. 9, no. 1, pp. 151–172, Apr. 2021.

[6] S. Jothibasu, S. Mohanamurugan, R. Vijay, D. L. Singaravelu, A. Vinod, and S. M. Rangappa,

"Investigation on the mechanical behavior of areca sheath fibers/jute fibers/glass fabrics reinforced hybrid composite for light weight applications," *Journal of Industrial Textiles*, vol. 49, no. 8, pp. 1036–1060, Mar. 2020.
[7] A. Vinod, J. Tengsuthiwat, Y. Gowda, R. Vijay, S. M. Rangappa, S. Siengchin, and H. N. Dhakal, "Jute/Hemp bio-epoxy hybrid bio-composites: Influence of stacking sequence on adhesion of fiber-matrix," *International Journal of Adhesion and Adhesives*, vol. 113, Mar. 2022, Art. no. 103050,
[8] K. N. Bharath, P. Madhu, T. G. Gowda, A. Verma, S. M. Rangappa, and S. Siengchin, "A novel approach for development of printed circuit board from biofiber based composites," *Polymer* Composites, vol. 41, no. 11, pp. 4550–4558, Nov. 2020.
[9] M. Z. Naser, R. A. Hawileh, and J. A. Abdalla, "Fiber-reinforced polymer composites in strengthening reinforced concrete structures: A critical review," *Engineering Structures*, vol. 198, Nov. 2019, Art. no. 109542.
[10] X. Tang and X. Yan, "A review on the damping properties of fiber reinforced polymer composites," *Journal of Industrial Textiles*, vol. 49, no. 6, pp. 693–721, Jan. 2020.
[11] P. Jagadeesh, Y. G. T. Girijappa, M. Puttegowda, S. M. Rangappa, and S. Siengchin, "Effect of natural filler materials on fiber reinforced hybrid polymer composites: An overview," *Journal of Natural Fibers*, Dec. 2020, doi: 10.1080/15440478.2020.1854145.
[12] J. Praveenkumara, P. Madhu, T. G. Yashas Gowda, S. M. Rangappa, and S. Siengchin, "A comprehensive review on the effect of synthetic filler materials on fiber-reinforced hybrid polymer composites," *Journal of Industrial Textiles*, Apr. 2021, doi: 10.1080/00405000.2021.1920151.
[13] C. E. Bakis, L. C. Bank, V. Brown, E. Cosenza, J. F. Davalos, J. J. Lesko, and T. C. Triantafillou, "Fiber-reinforced polymer composites for construction-State-of-the-art review," *Journal of Composites for Construction*, vol. 6, no. 2, pp. 73–87, May 2002.
[14] S. S. Choobbor, R. A. Hawileh, A. Abu-Obeidah, and J. A. Abdalla, "Performance of hybrid carbon and basalt FRP sheets in strengthening concrete beams in flexure," *Composite Structures*, vol. 227, Nov. 2019, Art. no. 111337.
[15] P. Jagadeesh, M. Puttegowda, S. M. Rangappa, and S. Siengchin, "Influence of nanofillers on biodegradable composites: A comprehensive review," *Polymer Composites*, vol. 42, no. 11, pp. 5691–5711, Sep. 2021.
[16] S. Gharde and B. Kandasubramanian, "Mechanothermal and chemical recycling methodologies for the fibre reinforced plastic (FRP)," *Environmental Technology & Innovation*, vol. 14, May 2019, Art. no. 100311.
[17] J. Zhang, V. S. Chevali, H. Wang, and C. H. Wang, "Current status of carbon fibre and carbon fibre composites recycling," *Composites Part B: Engineering*, vol. 193, Jul. 2020, Art. no. 108053.
[18] P. Jagadeesh, V. S. Ningappa, M. Puttegowda, Y. G. Girijappa, S. M. Rangappa, M. R. Khan, I. Khan, and S. Siengchin, "Pongamia pinnata shell powder filled sisal/kevlar hybrid composites: Physicomechanical and morphological characteristics," *Polymer Composites*, vol. 42, no. 9, pp. 4434–4447, Sep. 2021.
[19] S. S. Ding, Q. Li, A. Q. Tian, J. Du, and J. L. Liu, "Aerodynamic design on high-speed trains," *Acta Mechanica Sinica*, vol. 32, no. 2, pp. 215–232, Apr. 2016.
[20] A. Manalo and T. Aravinthan, "Behavior of full-scale railway turnout sleepers from glue-laminated fiber composite sandwich structures," *Journal of Composites for Construction*, vol. 16, no. 6, pp. 724–736, December 2012.
[21] P. J. Mistry, M. S. Johnson, and U. I. K. Galappaththi, "Selection and ranking of rail vehicle components for optimal lightweighting using composite materials," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 235, no. 3, pp. 390–402, Mar. 2021.
[22] M. Robinson, J. Carruthers, C. O'Neill, S. Ingleton, and M. Grasso, "Transport of DE-LIGHT: The design and prototyping of a lightweight crashworthy rail vehicle driver's cab," *Procedia Social and Behavioral Sciences*, vol. 48, pp. 672–681, Jan. 2012.
[23] J. S. Goo, J. S. Kim, and K. B. Shin, "Evaluation of structural integrity after ballast-flying impact damage of a GFRP lightweight bogie frame for

railway vehicles," *Journal of Mechanical Science and Technology*, vol. 29, no. 6, pp. 2349–2356, Jun. 2015.

[24] A. A. Khalil, "Mechanical testing of innovated composite polymer material for using in manufacture of railway sleepers," *Journal of Polymers and the Environment*, vol. 26, no.1, pp. 263–274, Jan. 2018.

[25] P. Heller, J. Korinek, and L. Triska, "Hybrid body of underground railway car: Path towards reduced weight of rail vehicles," *MM Science Journal*, pp. 631–634, Oct. 2015.

[26] Y. C. Ku, H. I. Park, M. H. Kwak, and D. H. Lee, "Multi-objective optimization of high-speed train nose shape using the vehicle modeling function," in *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, 2010, doi: 10.2514/6.2010-1501.

[27] J. Lee and J. Kim, "Approximate optimization of high-speed train nose shape for reducing micropressure wave," *Structural and Multidisciplinary Optimization*, vol. 35, no. 1, pp. 79–87, Jan. 2008.

[28] A. Zinno, E. Fusco, A. Prota, and G. Manfredi, "Multiscale approach for the design of composite sandwich structures for train application," *Composite Structures*, vol. 92, no. 9, pp. 2208–2219, Aug. 2010.

[29] J. S. Kim, S. J. Lee, and K. B. Shin, "Manufacturing and structural safety evaluation of a composite train carbody," *Composite Structures*, vol. 78, no. 4, pp. 468–476, Jun. 2007.

[30] C. Zhu, J. Li, F. Ji, X. Yi, C. Rudd, and X. Liu, "Sandwich structure composite with expandable graphite filled or coated: Evaluation of flame retardancy and mechanical performances," *Open Journal of Safety Science and Technology*, vol. 9, no. 1, pp. 7–21, Jan. 2019.

[31] S. Alotaibi, M. Quddus, C. Morton, and M. Imprialou, "Transport investment, railway accessibility and their dynamic impacts on regional economic growth," *Research in Transportation Business & Management*, Sep. 2021, Art. no. 100702, doi: 10.1016/j.rtbm.2021.100702.

[32] S. Xiao, H. Lin, S. Q. Shi, and L. Cai, "Optimum processing parameters for wood-bamboo hybrid composite sleepers," *Journal of Reinforced Plastics and Composites*, vol. 33, no. 21, pp. 2010–2018, Nov. 2014.

[33] K. A. Soehardjo and A. Basuki, "Utilization of bagasse and coconut fibers waste as fillers of sandwich composite for bridge railway sleepers," in *IOP Conference Series: Materials Science and Engineering*, vol. 223, no. 1, Jul. 2017, Art. no. 012036.

[34] K. W. Jeon, K. B. Shin, and J. S. Kim, "A study on evaluation of fatigue strength of a GFRP composite bogie frame for urban subway vehicles," *Advanced Composite Materials*, vol. 22, no. 4, pp. 213–225, Aug. 2013.

[35] J. Hou and G. Jeronimidis, "A novel bogie design made of glass fibre reinforced plastic," *Materials & Design*, vol. 37, pp. 1–7, May 2012.

[36] J. Chvojana and J. Vaclavika, "Experimental methods for the GRP bogie structure integrity assessment," *Procedia Engineering*, vol. 114, pp. 627–634, Jan. 2015.

[37] K. Yao, Y. Yang, H. Li, X. Liu, H. Lei, H. Fan, and D. Fang, "Material characterization of a multi-cavity composite structure for the bogie frame of urban maglev train," *Composites Part B: Engineering*, vol. 99, pp. 277–287, Aug. 2016.

[38] A. Manalo and T. Aravinthan, "Behavior of full-scale railway turnout sleepers from glue-laminated fiber composite sandwich structures," *Journal of Composites for Construction*, vol. 16, no. 6, pp. 724–736, Dec. 2012.

[39] V. A. Gerard and M. Mckay, "Recent Australian developments in fibre composite railway sleepers," *Electronic Journal of Structural Engineering*, vol. 13, no. 1, pp. 62–66, Jan. 2013.

[40] E. A. Silva, D. Pokropski, R. You, and S. Kaewunruen, "Comparison of structural design methods for railway composites and plastic sleepers and bearers," *Australian Journal of Structural Engineering*, vol. 18, no. 3, pp. 160–177, Jul. 2017.

[41] F. Çeçen and B. Aktaş, "Modal and harmonic response analysis of new CFRP laminate reinforced concrete railway sleepers," *Engineering Failure Analysis*, vol. 127, Sep. 2021, Art. no. 105471.

[42] J. S. Kim and H. J. Yoon, "Structural behaviors of a GFRP composite bogie frame for urban subway trains under critical load conditions," *Procedia Engineering*, vol. 10, pp. 2375–2380, Jan. 2011.

[43] K. B. Shin and S. H. Hahn, "Evaluation of the structural integrity of hybrid railway carriage structures including the ageing effects of composite materials," *Composite Structures*, vol. 68, no. 2, pp. 129–137, Apr. 2005.

[44] J. S. Kim, H. J. Yoon, and K. B. Shin, "Design of a composite side beam for the railway bogie frame," in *Materials Science Forum*, pp. 2676–2679, 2010.

[45] P. Sengsri, C. Ngamkhanong, A. L. O. de Melo, and S. Kaewunruen, "Experimental and numerical investigations into dynamic modal parameters of fiber-reinforced foamed urethane composite beams in railway switches and crossings," *Vibration*, vol. 3, no. 3, pp. 174–188, Sep. 2020.

[46] I. A. Daniyan, K. Mpofu, A. O. Adeodu, and O. Adesina, "Development of carbon fibre reinforced polymer matrix composites and optimization of the process parameters for railcar applications," *Materials Today: Proceedings*, vol. 38, pp. 628–634, Jan. 2021.

[47] A. A. Villarreal, C. Tarawneh, M. Ontiveros, J. Aranda, and R. Jones, "Prototyping a conductive polymer steering pad for rail freight service," in *ASME/IEEE Joint Rail Conference*, 2019, doi: 10.1115/JRC2019-1286.

[48] A. Önder and M. Robinson, "Harmonised method for impact resistance requirements of E-glass fibre/unsaturated polyester resin composite railway car bodies," *Thin-Walled Structures*, vol. 131, pp. 151–164, Oct. 2018.

[49] Z. O. Irikovich, R. R. Vyacheslavovich, and W. Mahmod, "Development of new polymer composite materials for the flooring of rail carriage," *International Journal of Engineering & Technology*, vol. 9, no. 2, pp. 378–381, 2020.

[50] E. B. Jeon, S. Ahn, I. G. Lee, H. I. Koh, J. Park, and H. S. Kim, "Investigation of mechanical/dynamic properties of carbon fiber reinforced polymer concrete for low noise railway slab," *Composite Structures*, vol. 134, pp. 27–35, Dec. 2015.