Review Article

Hybrid Composites for Railway and Transportation Uses – A Review

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Abstract
The transportation industry with airways, road transportation, shipping, and railways is a huge market for composites both military and civil applications. The need for sustainable and lightweight solutions triggered the need for composite materials. There are many different approaches for composite materials design and manufacturing to optimize the properties in strength, acoustic, and many more like such as ballistic, thermal management, and so onetc. The use of various reinforcing elements for various resins created endless options for materials scientists and designers. Among a variety of possibilities, the use of hybrid reinforcement has been quite a new approach for the composites, which is analogous to composite to optimize the performance of the final properties, such as impact, ultimate tensile strength, modulus value, thermal properties, and other properties. In this review article, the future of the transportation sectors, the advantages of railway transportation in this area, and an overview of the railway and transportation industry are presented. Definitions of hybrid composites are made and examples of applications of hybrid composites used in the railway industry are shown. Studies and research in this field were examined and, in this perspective, the contribution of hybrid composites to future studies is stated.

Keywords: Transportation, Railway, Composites, Hybrid materials, Railway track designs

1 Introduction

The One of the most important building block of today's technological developments is material science. Light and durable composites can be produced by developing new material types, forms, and production techniques [1]. Composite materials are structures where at least two different materials come together and consist of two material forms [2]. One of these material forms is the matrix and the otheranother one is the reinforcement. These composite materials offering great potential for superior lightness compared to conventional materials, and composite materials result in stronger, more durable, and easy-to-clean materials, overall lower maintenance costs, and sustainable structures [3]. In addition to their mechanical properties, composite materials are preferred in applications where good acoustic damping and sound insulation are important [4]. Structural parts made from composite materials can have different reinforcement ratios, weave type, matrix and reinforcement configuration, and thicknesses depending on end-use applications. All these parameters can be optimized by changing them, so they have the design advantage [5]. Also, The widespread use of composites in transportation vehicle platforms ensures lower carbon emissions.

The use of lightweight and durable composites in transportation vehicles creates many opportunities [6]. Improvement in railways can be achieved especially by reducing the weight of wagons [7]. In addition, composite materials offer solutions for high-speed trains, such as durable rail systems, increasing useful load-carrying capacities, energy balance, and passenger comfort. One of the most important infrastructure elements of railway transportation is the sleepers [8]. Wood, concrete, and in some cases steel has been used to fabricate these sleepers in the past [9]. Wood has excellent dynamic load, electrical, and sound insulation properties [10]. In the 1880s, with the emergence of timber shortage and sensitivity to nature, steel was used, and with the increase in the cost of steel, concrete began to be used. Monoblock concrete sleeper was applied for the first time in 1943 [11]. The heavyweight of the concrete, the high transportation cost, the difficulty of transportation, and the need for expensive equipment for its installation have led to the search for alternatives [10]. The advantages of composite materials also offer important opportunities in this regard. This study review aims to show materials that are available for the railway industry and their opportunities.

2 Research Significance

The global greenhouse gas emission problem is growing day by day with the development of technology. Solving the emission problem has become the greatest concern lately for scientists. Transportation Industry industry is one of the biggest industries that contribute to global greenhouse emissions and the developing technology increases the requirement for cleaner solutions in transportation. Transportation Industry has many modes that serve people and freight. People need to get more conscious about the emission problems. We can solve the pollution issue by using fewer vehicles for transportation. Railway transportation has many opportunities to fill that gap about cleaner transportation and it is fully open for implementing new, better materials into the sector. Railway transportation has many advantages and one of the most popular is time reduction. Trains can transport at very high speed due to their special roads, which brings time advantages for everyone.

3 Transportation and Railway

The transportation sector has beaten the effects of the power generation industry in the last years. According to the literature, transportation will be the dominant sector for emission concerns in the future [12]. With that in mind, scientists have focused on solving transportation problems. Despite technological developments that can reduce greenhouse emissions, the main problem on this topic is people's preferences. Even if technology provides the lowest emissions with autonomous transportation, people's demands would have different criteria [13].

Transportation is a key to the modernization of our life, and it affects directly on economic, social sides of the Worldworld. Transportation has many challenges to overcome when compared to the other sectors. Improving fuel efficiency, Increasing increasing the alternative fueled vehicle usage (electric, fuel cell, etc.), and investing in clean public transportation are some of the challenges [12]. Thus, all the scientists have been studying the solution to these transportation sector concerns [14]. Generally, the transportation sector serves two main categories that are people and freight. Both groups have different requirements and characteristics in which implementing and operating [13]. People transportation involves road, railway, water, and air transportation. When considering freight transportation, pipeline transportation mode also needs to be concerned [13], [14].

Railway Industry industry might be a solution for efficient transportation according to the current requirements. It has a large carriage capacity in both people and freight sectors. Loads can take advantage from of travel time and costs by using rail transport at the same time. Even if rail transportation has some advantages, there are also competitors in the transportation sector. That is why the railway transportation need to be upgraded itself in travel time and capacity [15].

The history of the Railway railway industry is based on the 16th century. Firstly, they were found in mining areas in England and used for freight transportation by animal-powered wagons. This solution had been developed to prevent the formation of wheel channels and used since that time [16].

In the 18th century, metal rails and double-flanged wheels were developed and used in the railway industry for movement safety. Afterward, energy generation steam-machines were found, railways tried to implement these machines into their wagons. The first steam steam-powered locomotive was found in 1784 by Murdock, Watt's assistant. This development was followed by many other scientists with adding some improvements on it, such as Blenkisop's rack locomotive, Hedley's simple adherence locomotive, George Stephenson's first success in the construction of steam locomotives, and first commercial passenger service by Stockton and Darlington [16].

Prior studies in the literature have noted the importance of development in the Railway railway industry would solve transportation problems and brings a new competition area. Although, railway industry developments are focused on increasing transport speed and capacity. The main obstacle to these aims is finding the best material for providing all mechanical and economical requirements. Especially, the mechanic requirements are quite important lately. The high speeds can reach by decreasing the rolling resistance, using safe and strong materials in railways. These materials need to resist both dynamic and static loads. Furthermore, all these materials are generally operating under dirty and wet conditions. Rolling stock is designed to last for between 30 and 40 years, but it is often can be used for much longer. For example, infrastructure can survive for considerably more than 100 years. Their long service lives need well-structured designs and good material choices for preventing mechanical failures [17].

4 Hybrid Composites

Composite materials are structures that combine reinforcing materials added to the matrix materials [18]. When these, at least two, different materials come mix together, they exhibit distinctly different, mechanical, thermal, physical or chemical properties [19]. The combination of the components that makes up the composite materials from at least two similar or different materials is called hybrid composite structures [20]. In hybrid composites, the matrix structure or reinforcements may consist of at least two different or similar materials. Hybrid composites are formulated by incorporating a single reinforcement material into two similar or different matrix or using reinforcement of a particular matrix with more than one reinforcement material.

In composite materials, the matrix material can be polymer, ceramic, or metal, as well as hybrid composite structures can be formed in the case of a combination of these materials. At the same time, the combination of similar or different reinforcement materials through fiber, particle, or structure to a single matrix creates hybrid composites [21].

Hybrid composites affect the weight and design geometries of advanced structural components used in special applications [22]. Different material combinations are used to improve mechanical, chemical, thermal, and acoustic properties by creating various effects on both the interior and the interface.

The strength of hybrid composites, if fiber is used as reinforcement, depends on fiber properties, fiber length and diameter, fiber orientation, fiber aspect ratio, homogeneous distribution of fibers, matrix/fiber interface bonding, layers, and weaving type of fibers [23]. The orientation of the fibers used for reinforcement in composite materials and the weaving patterns significantly affect the mechanical properties. For this reason, fiber orientation and weaving patterns are critical when designing hybrid composites [24].

Nano-sized fillers are referred to as nanoparticles. By adding nanoparticles to the matrix material, its mechanical behavior can be changed without changing the total mass of the structure. It is possible to form hybrid composite structures with different nanoparticle reinforcements. It is also available in structures where particles and fibers are used together. Hybrid nanocomposites are obtained by adding nano-sized filler in addition to fiber-reinforced or nanoparticle-doped polymer matrix composites [25]. Surface areas of nano-sized materials are very large. Therefore, the inclusion of such substances in the structure affects the connection between the fiber and the matrix and allows the improvement of mechanical properties.

5 Railway Applications

From the early age of the railway industry, the system was designed as two parallel rails, which provide guidance of the locomotives or other rolling cars, and several blocks of lateral wood that connected with cross ties [26]. Conventional systems were usinguse the ballast or ballast + sub-ballast layers under the ties for better route layout maintenance, and transmission of train loads to the railway bed [16], [27]. Figure 1 shows

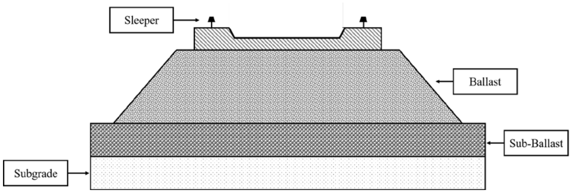

Figure 1: Conventional railway track design adapted from [28].

the structure of the conventional railway systems [28].

Ballast/sub-ballast degeneration and subgrade faults are the main concerns for railway tracks. With increasing contamination of small materials and changing excessive loads, these problems will occur. These problems can not be fixed easily, need higher costs and frequent maintenance [29]. In the last decades, design demands in the railway industry are increased rapidly, as in all industrial demands. These increasing demands are the results of the changing loads, technological developments, and volumes. In addition, the rise of environmental concerns brings sustainability term to consider while designing any concept [16], [28]. According to these demands, track systems are evolving and promising stiff, smooth, durable, and capable tracks for the future (Figure 2) [27], [28].

Railway industry has very high opportunities for creating new ideas like such as adopting new materials, improvement of vibration characteristics for more comfortable transport, and developing a safer way for speed applications.

The sleepers or ties are track structures that are responsible for distributing the load to the ballast. These structures are needed to resist all conditions (wearing and loading situations, enduring extreme weather conditions, etc.). Moreover, they are responsible for preventing both longitudinal and lateral track movements, keeping the correct line and level of the rails, therefore avoiding rail inclination, and helping the insulation of parallel rails [30], [31]. They can be different sizes or types of materials. However, the most common use is wood-based materials, they can also be made from reinforced concrete, steel, recycled plastic, a tropical hardwood, and composite ties. The goal for designing a new sleeper is mostly service life. Besides this goal, there are several goals like such as load-bearing capacity, and minimal defects [30].

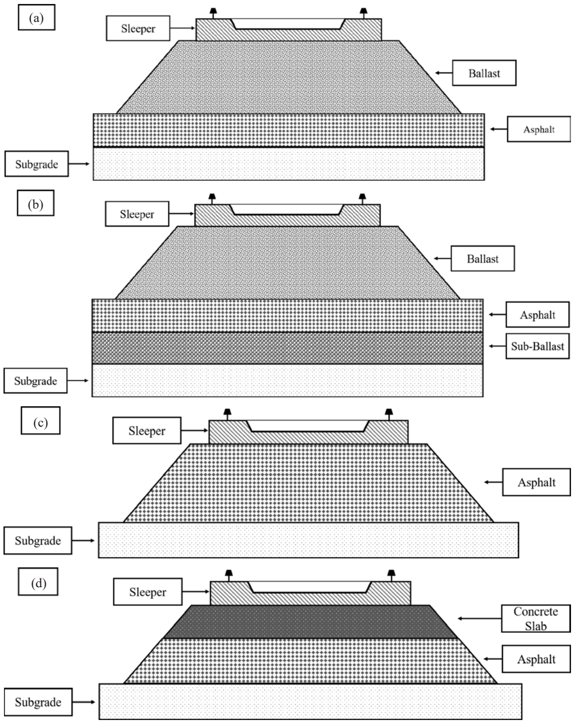

Figure 2: Railway track designsdesigns. (a) Asphalt-ballast combination (Asphalt used as sub-ballast), (b) Asphalt-ballast combination (Asphalt used as an intermediate layer), (c) Ballast-less combination (Complete asphalt track), (d) Ballast-less combination (Asphalt used as intermediate layer and concrete slab used for ballast layer) adapted from [28].

In literature, conventional sleepers have been tested and found as to be not satisfactory. With increasing demands materials are needed to be durable to the mechanical, biological, and chemical loads [11]. Wood-based sleepers are the most preferred materials from the beginning due to their adaptability. They can be suitable for all types of tracks and easily replaced while maintaining. Mechanical and biological resistance are the main problems with wood-based sleepers. They are often faced with rotting, splitting, and bug attacks (Figure 3) [32].

Steel sleepers are struggling with corrosion while operating in salty conditions and fatigue through dynamic loads [10], [33]. Besides these two materials, concrete materials provide a durable solution. Among the several types of railway sleeper applications, concrete-based sleeper usage is growing specifically in

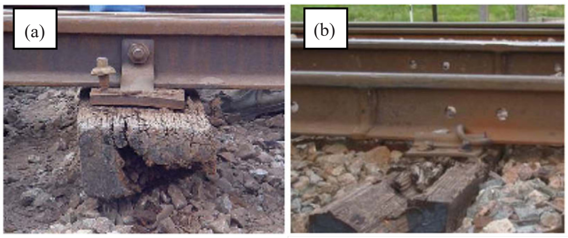

Figure 3: Wood-based sleeper failure types. (a) fungal decay failure, (b) splitting ends failure. Reprinted with permission [32].

high-speed applications. They are durable and provide high performance while they are decreasing lifetime costs. Prestressed concrete sleepers mostly preferred types of concrete-based sleepers. They have three main problems noted in the literature. Rail seat deterioration, flexural cracks from center connectors, and rail fastener failures. These failures cause maintenance every year [34]. However, it's to achieve good specifications, different important topics need to be considered while using concrete materials. They are natural resource consumption, energy consumption, and CO_2 emission values. The concrete provides good specifications, but the production of traditional concrete negatively reflects the aforementioned fields. Nowadays, there is an effort to change our transportation habits due to the requirement of emission reduction. In the case of concrete usage, researchers need to find a cleaner way to use this material. Structures made in this manner are sustainable. They are characterized by considering to limit the impact on the ecosystem of the world is limited as much as possible [35]. Besides, of the good specifications, they have good specifications that are heavy and have higher initial costs [36]. The latest findings showed that there is a high possibility to face impact load in sleepers up to 4–6 times higher than wheel loads. These loads can crack the sleeper and need immediate action for avoiding excessive maintenance. Concrete sleepers have disadvantages like these situations (Figure 4) [37], [38].

Lately, Composites composites are highly preferred materials due to their high strength-to-weight ratio, excellent resistance against corrosion, moisture, and insects, and thermal and electrical non-conductivity [30]. Concretes are one of the most using materials among all kinds of cement due to their low cost of production and availability. Another good specification

Figure 4: Crack in concrete sleeper. Adapted with permission [38].

is strength, and concrete has a very high compressive strength. The obstacles to using concrete for further application are low durability under different working loads, low anti-cracking performance, poor toughness, and low tensile strength. With the developing technology, researchers tried many times to compose traditional concrete with different materials, such as short fiber-reinforced materials mineral admixtures, and nanomaterials to give new specifications to it them [39].

One of the concrete examples is siliceous fly ash - concrete. This mixture can be used for improving mechanical properties (static and dynamic), rheological properties, reaching better fracture, corrosion, and temperature resistance, and also providing stronger properties to the abrasion and erosion effects. Szostak and Golewski show the positive effects of concrete - siliceous fly ash mixture and noted that the strength parameters can be reached by almost 4 times after 8 h [40]. Additionally, ground granulated blast furnace slag can be used as a binder for composite concrete with the addition of steel fibers in concrete mixes. Ground granulated blast furnace slag is a by-product of the manufacturing of pig iron. So, there is beneficial to use a material that has high strength, is resistant to several conditions, and has environmental advantages [34].

Strength is not only defining static loads. There are also dynamic loads that are also important for implementing new materials into the current designs and in some cases, dynamic loads can reach 4–6 times the static ones [41], [42]. These loads cause vibration in the design and it is directly related to lifecycle. Golewski noted that the harms of vibration can be reduced by suitable structure selection and good structure analysis. According to his study, reinforced concrete is one of the materials that provide all of the expected requirements and that is why we can see this material in constructions faced with dynamic loads [42].

Scientists are defending that the composite railway sleepers/ties can be an alternative for existing ones, and, they can bring many advantages to the industry. Ju *et al.* Studied on mechanical properties of municipal plastic waste-based particulate composites reinforced with coal ash and showed the possibility to use this material in railway sleepers [43]. Praveenkumara *et al.* has produced Areca/Sisal/Carbon fabric reinforced hybrid epoxy composites for railway interior applications by using a manual hand layup process. The study results are showing that the hybrid composite laminates can be used for seats, panels and secondary structures [44]. Ferdous *et al.* has developed three different concepts for composite sleepers and each of them brings different advantages. They perform a good mechanical property for replacing conventional ones. The latest studies show that composite sleepers will be viable in future solutions [45].

Composites are not only preferred in sleepers applications. They are comprehensive materials that can use in different parts of the railway industry. Some researchers had guessed these improvements of composite usages in the railway industry 20 years ago. According to Robinson's research, composites can be used in cab-ends, seats, internal fittings, and panels due to their high stiffness to weight expectations. Today, we can see many studies in composite usage as guessed by Robinson [46]. For example, with the development of high-speed trains, the railway industry is seeking a lighter material in its trains. Composites have been used widely in cab-ends due to their ease of production. Complex forms that can not be provided by metals can easily produce with composites [47]. On the other hand, crash energy management is one of the most important things of crash-worthy vehicles, especially like high-speed trains [48]. In literature, researches show that composite designs have been widely used because of their better collision energy absorption specifications [46]. One of the primer studies is InterCity 125 (Figure 5). This train was built from a sandwich structure consisting of laminated glass-reinforced fiber and polyurethane foam core [49].

Figure 5: InterCity train design. Reprinted with permission [50].

Figure 6: Complex design. Reprinted with permission [51].

Moreover, designs with better aerodynamical conditions have been created with the benefits of using sandwich structures without considering the complexity (Figure 6) [51].

The bogie is the one of the important sections of the rail industry. It is responsible for sustaining the weight of the body, controlling wheels due to the straight and curved tracks, and absorbing vibrations. Bogies are very heavy and Ttheir weight can be reach 1 or 2 t [52]. With the developing technology, lighter designs need to solve this weight problem as well [53]. The first known study in this area was published in 1983 by Guenich *et al.* They produced a bogie frame from glass fiber reinforced plastic. This gave an advantage from the weight side of the design and approximately %25 lighter design was produced. With the decreasing of the weight, they provide a better efficiency in the power requirements, energy consumption and the wear [54]. After this invention, there were many studies focused on the bogie parts. Jun-sun Goo and co-workers studied the structural integrity of glass fiber reinforced plastic-made bogie frame. They showed the effect of impact damage on the bogie frame [53]. Jeon *et al.* was studied the fatigue life and strength of the lightweight bogie design of an urban subway train [55]. The studies show that there is a trend in using composites in the rail industry.

6 Conclusions

The technical properties of materials such as wood, metals, which are currently used, do not meet requirements. The need for novel materials and designs with enhanced strength and optimized properties creates very novel processing methods and the use of many novel materials. Searching for new materials leads to new composite structures enhanced with nano materials and new generation fibers. Among all these materials, hybrid structures have been demonstrated in this review. Hybrid composites bring such an important opportunity for this sector, such as using concrete mixtures can be specifically used in highspeed railway areas. Special emphasis was shown for railway and transportation industries. Hybrid composites will bring a better feature to the railway sector thanks to their developing technical specifications. Furthermore, with the new developments in the circular economy, a cleaner world with the help of solutions like using recycled plastics or natural composites can help to pave the world for new hybrid systems. This is a very fruitful area for the composites world.

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