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A review on utilization of textile composites in transportation towards sustainability

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Abstract. Transportation industry is rapidly developing owing to its size and importance which affects on various aspects of life. It includes all the transport means that facilitate mobility of people or goods either by air, land or sea like aircrafts, automobiles, ships, trains, etc. The utilization of textiles in this industry is increasing as a result of moving towards achieving sustainability and enhancing performance, comfort and safety. Through substituting heavier materials with textiles of high performance specifications and textile reinforced composites to reduce weight, fuel consumption and CO₂ emissions. Composite materials can fulfil the demands for sustainability in the transportation sector through using renewable, recycled and lightweight materials, considering the requirements of each category of transport vehicles. Textiles used in reinforcing composites are diverse including fibers, yarns or fabric preforms such as woven, nonwoven, knitted, braided which varies from 2D to complex 3D structures. This paper presents a brief review on the utilization of textiles in reinforcing composites for various transportation applications to achieve sustainability. Also, discussing the influence of textiles structural parameters like fiber material properties, fabric production technique and construction on their mechanical behaviour. Focusing on researches findings in this area and highlighting some prospects for further developments domestically.

1. Introduction

Transportation industry is rapidly developing owing to its importance, as it plays an essential role in the development of global economy. It facilitates mobility requirements of people and goods either by air, land or sea, enabling access to trade, social interactions, education, health care, etc. Transport vehicles include automobiles, aircrafts, motorcycles, ships, trains, etc. Several aspects needed to be developed in this industry to achieve sustainability including vehicles materials performance, structure and design. Sustainability requires consideration of human, economic and environmental factors, providing basic demands with equality between generations, reducing negative impacts on environment and consumption of non-renewable resources, and reuses/recycles its components [1-3]. Europe Union's End-of-Life Vehicle had demonstrated that from 1st January 2015, 95% by weight of vehicle had to be reused/recovered and 85% by weight needs to be recyclable. Recovery involves materials incineration to recover energy, while recycling comprises material processing to be reused. Various issues should be considered in designing vehicles like material properties, costs, durability, ease of vehicles dismantling, recycling and ensuring that their components don't contain harmful substances. Textiles utilization in transportation construction is increasing as a result of moving towards achieving sustainability, enhancing comfort and performance and safety. It is estimated that the textiles consumed in an average car will rise from 20kg in the year 2000 to reach 35kg in 2020. Through using textiles of high performance specifications and textile reinforced composites in various applications like seats, headliners, door and side panels, trunk liners, thermal and sound insulation, etc. Their performance is highly depending on fiber properties, fabric structures, production techniques and the finishing processes applied during manufacturing [4, 5].



The key drivers for sustainability development in transportation industry are promoting weight reduction, lowering gas emissions, fuel consumption and recyclability. Transportation activities are a main source of Greenhouse Gases (GHG) such as CO₂ & NO₂. Their emissions caused severe health problems, premature deaths, and environmental issues like climate change and global warming. Increased awareness about these concerns leads to focus on using electric vehicles and biofuels. Weight reduction is driven by the need to comply with EU legislation to reduce emissions (from <130g CO₂/km in 2015 to <95g CO₂/km by 2021). Every 1 kg saved on vehicle's weight reduces about 20 kg CO₂. Also, weight reduction could be enhanced by optimizing vehicle design and materials replacement, since metals accounts about (30-65%) of weight. Safety is a vital issue, since passenger carriage requires consideration of safety standards especially fire retardancy and crashworthiness [1,6-8].

2. Composite materials

Composite materials could fulfil the demands of sustainability. They are preferred for construction of transport vehicles, assisting in producing high energy-efficient, lightweight and durable vehicles without affecting on their performance. Composites are offering superior properties compared to metals like high strength to weight ratios, high flexural and impact strengths, corrosion and weather resistance, durability, dimensional stability, design flexibility and aesthetics. Composites have anisotropic properties in which the fibers can be tailored in a specific orientation (0°, +/-45° or 90°) to provide the best mechanical properties in loads direction. Composites could be produced in the form of a "Lamina" which is one individual ply or as a "Laminate" consists of many plies of fibers stacked with different orientations to attain the desired stiffness and thickness [5,9,10]. Polymer matrix composites; Thermosets and Thermoplastics are widely used in composites applications in the transport sector. Thermoset resins exhibit high temperature resistance, solvents and corrosives resistance, tailored elasticity, excellent finishing and adhesion and low costs, although their recycling remains a challenge. Common types are polyester, epoxy, vinyl ester, phenol, etc. Thermoplastic resins advantages comprising stiffness, high temperature tolerance and recyclability. Common types are polyethylene, polypropylene, polyamide, etc. Generally, carbon, glass and kevlar are the dominant reinforcing fibers used in automobiles, aerospace and marine applications. Carbon fiber characterized by high strength, low density, although its main drawbacks are high cost and brittleness. Glass fibers have very good thermal insulation and electrical properties; however they have low modulus and high density. Kevlar fibers are characterized by their high strength, heat resistant, high energy absorption, providing quality and reliability that are vital for aerospace applications. Even though, production of these fibers causes environmental hazards besides their high costs, which increased the interest for using more sustainable materials like biocomposites [5, 9,11].

Biocomposites combines using natural fibers such as flax, hemp, sisal, bamboo, jute, kenaf, etc for reinforcement with polymer matrices either from renewable or non-renewable resources. They offer numerous advantages like biodegradability, low density, high specific strength, reduced dermal and respiratory irritation, low cost, better insulation, ecofriendly, etc. Green composites are bio-based resins derived from renewable resources such as starch, sugar, vegetable oils and soy oil reinforced using natural fibers. Polylactic acid (PLA) is the common type used [12-14]. A major concern regarding using natural fibers is their poor compatibility with polymeric matrices, because of their hydrophilic nature and the hydrophobic nature of polymer matrices, which result in non-uniform distribution of fibers in the matrix. Also, fibers interchangeable growth conditions leads to irregularities in their mechanical properties. So, chemical treatments are applied to reduce water absorption, increase fibers consistency and enhancing fiber/matrix interfacial bonding. Biocomposites are used in transport vehicles interior and non-structural components. Exterior components in automobiles such as bumpers are usually produced using glass fiber composites. They could be made of mixed natural and man made fibers reinforced composites, which shown to have similar or better mechanical properties [5,9, 12,13 ,15]. Composites manufacturing processes are; open molding techniques including spray lay-up, hand lay-up, filament winding, sheet molding compound, pultrusion and closed molding techniques like resin transfer molding, injection molding, compression molding, etc. Joining different materials structures presents challenges, so reliable techniques are needed to join composites to metals, and composites to other types of composites like adhesive bonding which are commonly used for multi-material vehicle bodies [5,12,16].

4. Textile preforms used in reinforcing composite materials

The versatility of textile composites contributed in achieving sustainability. Textiles preforms are differing significantly in terms of fibers orientations and entanglement, manufacturing processes and fabric structures. Unidirectional fibrous preforms comprise rovings or yarns that can be utilized directly in composites using filament winding and pultrusion techniques. 2D preforms are generally manufactured using weaving process. 3D textiles characterized by their interlacing yarns in the longitudinal, cross and vertical directions. 3D composites

have enhanced out-of-plane properties that allow optimizing design, high delamination resistance and better mechanical properties in all directions. They are used in aerospace applications such as wing panels, landing gear, rocket nozzles, etc. Also used for automobiles and defense applications. Generally, woven and nonwovens are extensively used in transportation construction in the form sandwich structures, which considered as essential structural materials because of their high skin/core debonding resistance, bending stiffness, lightweight, enhanced insulation and damping characteristics [11,15,17,18].

4.1. Characteristics of Textile preforms

Woven fabric is a continuous preform characterized by its higher intralaminar and interlaminar strength and damage resistance. Common types are; plain fabric that exhibits good stability, and shear deformation resistance, characterized by high crimp due to the highly interlaced and tightest weaves. Twill fabric is characterized by forming diagonal lines on its surface, its reduced crimp leads to better mechanical properties compared to plain fabrics. Satin fabric is flexible, presents minimum interlacing, reduced shear deformation resistance, high tensile and flexural strengths that allows their effective utilization in aerospace applications [17-19]. Nonwoven fabric is a web of directionally or randomly orientated fibres bonded either by chemical, thermal, or mechanical means. It offers good strength, flexibility, lightweight, besides its z-directional properties that reduces delamination problems. Cross-ply nonwovens of fibers with different orientations are offering better uniformity of composites [17,19]. Nonwoven needle punched mats produced using natural fibers are extensively used in various interior components of vehicles. Knitting is a looser and flexible fabric produced either by weft knitting or warp knitting processes. It offers high out-of-plane properties and energy absorption capabilities that contribute to their good impact and delamination resistance. Knitted fabrics enabled manufacturing of complex shaped products for automobiles and aircrafts such as jet engine vanes, T-shaped connectors, car wheel wells, aerospace fairings, etc. Braiding is a technique where yarns are interlacing each other to produce tubes, narrow flat strips or 3D solid structures. Braids show reduced in-plane properties due to the yarn path relative to the axial direction. Braided preforms characterized by their durability, strength, reliability and structural integrity. They have been utilized in various automotive and aircrafts applications such as airframe spars, F-section fuselage frames, tail shafts, etc. Stitching process was developed to join single or multilayered textile preforms to overcome low delamination resistance and in-plane shear properties of composites. It provides advantages like strength, impact resistance, improving interlaminar fracture toughness, reducing weight and costs. High performance stitching threads are made from glass, carbon or Kevlar fibers. Several developments in stitching machines were driven by the aerospace industry. NASA and Boeing have designed a 28 m long stitching machine to produce aircraft wing components with a reduction 25% in weight and 20% in costs compared to corresponding aluminium parts. Also, 3D stitching robot was used to produce textile preforms in the shape of the rear pressure bulkhead of Airbus A380 to improve its strength and weight, as well decrease handling and lay-up times [11,17].

5. Textile composites applications in transportation sectors towards sustainability

5.1. Automotives industry

The early usage of biocomposites in automotive industry in 1940s, when Henry Ford proposed the first car body using hemp, sisal and wheat straw fibers for reinforcement and soya oil to produce phenolic resin [6,7]. Through the last decades, automotive industry continues in developing its composites products and specifications to meet markets requirements. It is estimated that automotive composites market to reach \$4.3 Bn in 2017 from \$2.8 Bn in 2011, signifying annual growth rate 7% [5,20]. Automotive industry used glass fiber composites that offered lightweight benefits up to 25% and up to 40% with using carbon reinforced composites compared to other metallic materials [9,10]. A 10% weight reduction in vehicle weight leads to improving fuel efficiency by (4-8%) or increasing battery range of electric vehicle up to 10% [2,13,16]. As in BMW i3 all-electric vehicle body constructed from aluminium and carbon reinforced composites, makes it (30-50%) lighter and improves driving characteristics (acceleration, braking, cornering, etc). Moreover lightweighting in heavy-duty vehicles leads to increase their freight capacity. Also in military vehicles, assist in improving their performance, survivability and ability to support operations [16,21]. Biocomposites are recently utilized in some of the worlds most revered vehicles brands. Mercedes- E-class door panels was made from sisal needle punched nonwoven in epoxy matrix. Mercedes-Benz Travego travel coach equipped with a (polyester/flax) reinforced composite engine encapsulations. Abaca (banana) fiber reinforcement was used in the spare wheel pan covers of Mercedes A-Class (W169). Wood fibers was used in 2006 Mercedes S-class front door linings and driver's seat back rest, while flax fibers was used in parcel shelves and trunk covers [7, 13]. Toyota used natural reinforced composites made of PLA matrix produced from sugar cane and sweet potato, reinforced with kenaf fibers in the spare tire cover of the RAUM 2003 model. Mitsubishi motors with Fiat SPA produced interior vehicle

components using bamboo fibers and polybutylene succinate (PBS) bio- resin, and floor mats made from PLA and nylon fibers . Ford F-150 wire harness manufactured using composites reinforced with rice hulls. Kenaf fibers were employed in reinforcing the interior door panels reducing weight by 25%. Ford and Heinz company collaborated to investigate using tomato fiber in wiring brackets and storage of 2014 vehicles .Since 1990s, natural fiber composites were used in BMW 3, 5, and 7 series in the interior door linings and paneling. Lately, biocomposites were used in BMW structural parts like bumpers, fender liners, shields and suspension system components [7,13,14]. Automotive composites recycling is a complex process, including disassembly, debonding and separating parts from the vehicle. Also it is difficult to extract individual materials from composites with maintaining their original characteristics [5,6].The existing recycling processes include thermoplastics melting to separate them, pyrolysis to extract high value carbon fibers from thermosets, and incineration to recover the energy contained in composite materials. Also, some composite materials can be shredded to be used as filling materials for other applications [2,5].

5.2. Aerospace industry

Aerospace sector had a series of changes with respect of composites utilization in production of civilian aircrafts, helicopters, military jets, etc. Textile composites exhibit high strength-to-weight ratios up to 20%, reduced fuel consumption and emissions, enhancing aerodynamic efficiency, lowering production costs, fatigue and fire resistance, low dielectric loss in radar transparency, etc. Composites main applications including instrument panels, fuselage skin panels, propellers, fuselage fairing panels and in interiors like luggage compartments, cargo liners, sidewalls, ceilings, floors, galleys, etc . Glass fibers are used in small passenger aircraft parts, highly loaded parts, while aramid fibers are used in fairings, unloaded bearing parts and radomes. Carbon fibers are used in all types of components, satellites, antenna dishes, missiles and primary structural parts. For most ceilings and walls, interior sandwich panels are used with Nomex honeycomb core faced with skin plies of glass/phenolic prepreg, and glass/epoxy or carbon/epoxy composites used for floor panels [8,22-24].Composites have been used in aerospace industry since 1950s, where glass fiber composites used in manufacturing Boeing 707 accounted 2% of its structure .Each developed generation of Boeing aircrafts had an increasing percentage of composites in its structure, see figure 1. It is more fuel efficient and had a small environmental footprint . Recently, the highest composites percentage was presented in Boeing 787 Dreamliner, accounted about 50% of its primary structure which increased its service life and reduced maintenance costs, figure 2. Its major structural elements fabricated using carbon/epoxy laminates like fuselage sections, wing box and stabilizer boxes. Secondary structures such as rudder, elevators winglets and nacelle cowlings fabricated using carbon sandwich composites, while glass/epoxy laminates were used for wing fairings, stabilizers, radome and wing-to-fuselage fairings [22,25-28]. Airbus A350 XWB and A380 aircrafts widebody platforms composites reduced assembly costs, enhance damping engine noise/vibration, cabin atmosphere less conducive to dehydration, longer design life [29].

Military aircrafts are widely using composites to meet high performance requirements, improve speed and maneuverability. For example; Advanced Tactical Fighter (ATF) utilized composites about 50% by weight which reduced drag, low radar observability and increased temperature resistance. Advanced Technology Bomber (B-2) employed composites enhanced its stealth qualities. Composites usage is suitable for the extreme vibratory environment that helicopters operation creates, offering improved aerodynamic geometry and tuning, good damage tolerance and low costs. Boeing undertook an experimental program in which 11,000 metal parts were replaced by 1500 composite ones. Producibility and maintenance considerations improved along with overall structural reliability. Unmanned aerial vehicles (UAVs) such as Global Hawk has nacelle, radomes, rear empennage, stabilizers and wing/body fairings constructed from carbon fiber and glass fiber reinforced composites . Composites structures are usually constructed of different ply layers, so internal damages like delamination and cracks could be occurred between layers. Due to the strict requirements on safety and reliability in aircrafts various techniques are used to detect any invisible fault such as Non-destructive inspection (NDI) testing, embedded sensors and self-sensing material systems, etc. Structural health monitoring (SHM) becomes more integrated especially in multifunctional composites through using carbon nanotubes in composites to provide integrated damage sensing capability and enhance mechanical reinforcement [11 ,27,30].As indicated also from the study applied on notional Boeing 747-400 and 757-200, Airbus A320, and Embraer E145 airframes using carbon nanotube composites replacing aluminium counterparts. They exhibit high strength and toughness, low weight and high corrosion resistant [31]. Recently, there is a highly shift towards utilizing Green Composites in aircrafts interiors. Flax/epoxy prepregs showed 35% lighter than carbon/epoxy prepregs. Flax fabrics were treated with flame retardants and used to produce (flax/epoxy) sandwich composites for cabin sidewall panel of Boeing 737. Boeing Company is particularly involved in recycling all aircraft composites,

separating composites from other materials and recovering good quality fibers to be re-introduced as a materials source in aircrafts manufacturing. Airbus demonstrated In December 2014, that recycled carbon fiber was used in a full-scale interior sidewall panel [23,28,32].

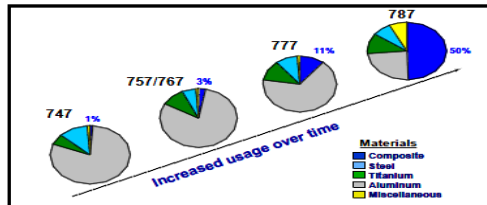


Figure 1. The usage of composites overtime in Boeing aircrafts [26].

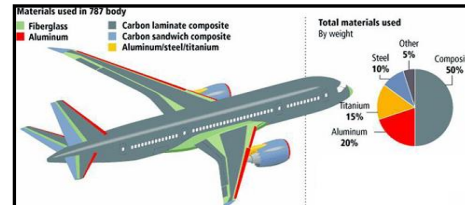


Figure 2. Usage of composites in Boeing 787 Dreamliner structure [22].

5.3. Marine industry

Textile composites are extensively utilized as lightweight construction solutions for marine applications, including power boats, yachts, fast ferries, passenger ships, naval vessels, submarines and submersibles. Racing yachts are using composites more in order to sail with maximum speed, resist waves impacts and other elements in marine environments [33,34]. Advances in materials, fabrication techniques and design tools have widened the areas of marine composites applications. They are used for superstructures, mast systems, bulkheads, decks, watertight doors, propellers, propulsion shafts in addition to internal equipment such as engine parts, heat exchangers, machinery foundation, valves, pumps, pipes, ducts, etc. Also, their high acoustic transparency resulted in employment in ships sonar domes and submarines sonar domes. Composites usage in marine industry was initially driven by need for weight reduction, durability and high corrosion resistance to overcome problems occurred with using steel and aluminum alloys and the environmental degradation caused by wood. During the 1960s, glass reinforced composites were used in marine industry for both leisure and commercial sectors. Also in naval vessels to provide low radar signature for stealth operations and have low electro-magnetic signature that reduces the probability of detonating magnetic sea-mines. Global market for boat composites industry is expected to reach \$1.2 bn in 2018 from \$954 million in 2013 with 4% annual growth rate [35-38]. Over 95% of maritime crafts are fabricated with glass reinforced polyester composites, using woven glass fabric and/or chopped strand mat layers in their reinforcement. Also glass reinforced vinyl ester composites are used in marine crafts, offshore platforms, racing yachts and power-boats. Carbon reinforced epoxy composites are usually used in boat hulls with honeycomb or foam core, frames, keels, masts, shafting. They have good absorption to electromagnetic waves, giving good stealth properties. Recently, new composites including using carbon nanotubes and epoxy mixtures to produce small naval vessel [33,34,36,38,39].

Composite structures thickness is usually between (10-150 mm), so issues like joint construction and impact damage tolerance should be concerned. Implementation of Structural Health Monitoring systems using fiber optic sensors, such as (Bragg grating sensors) in ship composite joints can considerably improve the reliability of these structures, reduce weight as well maintenance costs, maximize performance and efficiency [37]. Lately, biocomposites were employed in marine industries combined with low environmental impact. Flax fibers were utilized in reinforcement of the first racing boat prototype "Araldite" incorporated up to 50% of flax fiber in epoxy matrix to prevent water absorption. Moreover, flax fibers promoted higher vibration adsorption with respect to Kevlar or glass fibers. Flax and a bio resin EcoComp® UV-L have been used to make eco-friendly marine products such as kayaks and canoes [40]. Basalt fiber is optimally suited for marine applications due to its superior physical and mechanical properties, as well its eco-friendly nature. Sailing yacht hull and deck prototype were fabricated from sandwich construction with skins of Fipofix UD basalt composite laminated to balsa wood core [41]. Additionally, driven by recyclability objectives, a sailboat prototype with a hull and bridge made from Elium® resin thermoplastic acrylic resin reinforced with carbon fiber. The resin mechanical properties are similar to epoxy resins. At end-of-life parts can be ground and reused to manufacture new parts [42].

6. Conclusion

Sustainability has gained serious interest for transportation industry development. Textile composites are very promising, especially with the continuous development in textile performs technologies and incorporation of new materials and innovations, which contributed significantly in achieving sustainability in the transport sector.

On the domestic side, transportation industry has developed considerably over years. Egypt considered one of the largest car-producing markets in Africa. The industry had grown exponentially with the production of components and assemblies of cars, buses and trucks. Also, manufacturing and assembling of aircrafts components had improved, particularly for defense applications, as well in Marine industry, high performance boats and luxury yachts are produced. Future prospects comprise exploring utilization of high-tech developed textile products in reinforcing high performance applications. More employment of biocomposites through making use of the available and effective natural fibers, agriculture wastes, and recycled textile products in various vehicles components. Further, increasing coordination between science and industry is needed to establish a strong connection to strengthen the industry and promoting competitiveness in global markets.

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