OPPORTUNITIES FOR THE USE OF COMPOSITE MATERIALS IN RAIL APPLICATIONS – A CASE STUDY

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ABSTRACT

Lightweighting is an increasing focus in the rail industry and attention is turning to the application of composite beams to satisfy demands. Patented technology Axontex™, developed by Axon Automotive Ltd for the automotive sector, moves away from traditional high-waste composite solutions and offers a potential alternative to metal components currently used in the rail sector. It offers a new way of designing car bodies and bogies with flexibility in the dimensions and properties of the beam along its length, width and height, supporting end-users' needs. This paper reviews the opportunities for the use of composite materials in rail, and includes a specific discussion around the use of braided Axontex™ beams, and their applicability to rail structural members. The quasi-static behaviour of the beams reveals advantages and benefits in using composites, with an improvement in specific stiffness of over 50 % compared to steel, whilst the environmental aging and fatigue testing needs further investigation.

1 INTRODUCTION

The rail industry is facing unprecedented pressure to deliver an integrated, cost-effective and efficient transport system for both passengers and freight. In order to meet these demands, there are a number of recently-launched initiatives at national and international level. In the UK, a 30-year Rail Technology Strategy was launched in 2012 [RTS 2012] which has been matched by a response in the academic community [AARTS 2013] [1]. Lightweight rail vehicles present major advantages and help address the *4 C's* of the RTS. These are *reduced carbon emissions* via lightweighting and lower fuel consumptions in part, an *increased capacity* via reduced braking distances and faster accelerations, an *improved customer experience* through novel, modular, technologically advanced railcars and finally, *lower costs*, through a combination of intelligent deployment of materials in the design phase and smart, multifunctional operating. As such, rolling stock is one of the target challenges, highlighting a need for trains that are lightweight and efficient whilst not compromising on safety, performance or comfort. This could in part be enabled through new materials and innovative designs. The possible options for mass reduction by material substitution include, but are not restricted to: bodyshell, windows, exterior attachments, bogies, passenger interior seats, drivers cab interior and cabinets, external doors and couplers.

The rail industry is not alone in facing significant challenges to improve efficiency. The aerospace sector is at the forefront in the use of innovative materials to create lightweight structures offering step-changes in performance e.g. the use of carbon fibre reinforced polymer (CFRP) composite airframes in the Boeing Dreamliner [2, 3]. Similarly, the automotive sector is experiencing extreme pressure in the form of legislation on emissions and safety. Part of the response from the automotive industry has been to move towards lightweight vehicle bodies which exploit materials using an 'intelligent deployment' approach. Modern high-volume vehicles employ 'the right materials in the right place' strategies, creating multi-material bodies but, critically, at costs that are relevant to the market.

A thorough literature review of materials in rail applications is presented by Winnett *et al*. [4] in their assessment of the rail industry for a Very Light Rail (VLR) vehicle, weighing less than one tonne per linear meter. The VLR project consortium is committed to developing and building an affordable low carbon, lightweight rail vehicle to facilitate low-cost connectively of regional and rural areas. As in the automotive sector, steel is the dominant material for rail applications. However, in recent years, alternative materials and topological optimisations have been implemented to reduce vehicle weights. Non-structural components present obvious target structures as their requirements are less stringent. Aluminium has been already widely used in high-speed passenger trains alongside associated developments in joining technologies. As an example, Friction Stir Welds of 30 m length were developed for the high speed China trains [5]. Examples exist also of the implementation of aluminium in freight wagons [6], and passenger metro, intercity [6] and regional [7] passenger trains.

In the automotive sector, significant research and development is under way to utilise fibre reinforced polymers (FRPs) in structural applications achieving substantial (30-50 %) reductions in mass compared to steel. BMW have launched the first medium-volume 'fully-composite' vehicle, the i3. The vehicle is a multi-material solution, where the body-in-white is constructed of carbon fibre, whilst the electric power pack and crash structure uses aluminium. In the rail sector, the use of FRPs has been limited to specific applications. For example, non-structural composite body panels are seen in the High Speed Train (HST) Intercity 125, operational since 1977 in the UK [4, 8]. The Korean Tilting Train Express, built in 2007, uses CFRP sandwich structures with an aluminium honeycomb core [9], which reduces the vehicle mass by 3.9 tonnes. Studies [10] also show applications where the weight, part number and cost of CFRP cabs could also be reduced.

Uptake in specific applications only is partly due to the conservative nature of the rail sector and due to questions about the capability of the new material and design to withstand the demanding environment of rolling stock. In particular, among the significant barriers to the uptake of composites are the very high shock acceleration of rolling stock structures (of the order of 20g at bogie level and 5g above the bogie), the significant fatigue loads, the demanding environmental conditions (extreme temperatures, water, impact, fire and toxicity regulations, etc.) and the significantly long body lifetimes of approximately 40 years.

Composite materials are also known to have been applied to bogie design and manufacture. Glass fibre reinforced polymer (GFRP) composites have been used to lightweight certain bogie frames by up to one tonne [11], although it is worth noting some bogies already weigh less than one tonne [11]. In addition to their lightweight and anisotropic properties, they present other advantageous properties such as high energy absorptivity, fatigue tolerance, intrinsic damping qualities, and a higher natural frequency. As such, a GFRP sandwich structure including ribs, chords and a foam core, offers a solution which combines the primary suspension with the frame [12]. While GFRP leaf springs offer component lightweighting of up to 75 % [13], CFRP leaf springs spanning the bogie negate the necessity for a frame, as demonstrated by the Kawasaki efWING for a 40 % total bogie weight reduction [14]. In terms of life cycle analysis of composites in the automotive sector, recent work in the Warwick group has shown the difficulties in producing cost effective carbon fibre solutions. The cost is high at the fibre *production phase* particularly, and the life cycles of the structures are not always high enough to recuperate those costs through the lower operational costs of the lighter structures in the *usage phase* [15]. However, in rail applications where vehicles life times and *usage phase* are up to four times that of automotive, there is a clear cost benefit to the use of intelligently designed and manufactured composite structures.

An opportunity has been identified to use a cost-effective composite beam structure to help address the need for lightweighting rail rolling stock. It specifically focuses on ensuring that the beam structures are capable of withstanding the demanding environments experienced by structural materials in rolling stock applications. This paper focuses on the case-study of Axontex™ technology braided composite beams, and their applicability to structural components in rail, where metallic materials currently dominate.

2 GENERAL SPECIFICATIONS - AXONTEX™ TECHNOLOGY

The patented composite beam technology, Axontex™, developed by Axon Automotive Ltd moves away from traditional high-waste composite solutions and is an alternative to metal components currently used in the rail sector. It offers a new way of designing car bodies and bogies and flexibility in the dimensions of the beam along its length, width and height, supporting end-users' needs. The patented process produces a carbon fibre composite beam that fails progressively in crash to absorb very large amounts of energy per kg. Figure 1 shows the breakdown of the manufacturing stages. The fibres are braided into cylindrical socks, filled with low density closed cell foam which expands under the vacuum resin transfer moulding (V-RTM) process. The cross section of one of the beam designs, highlighting the cell structure and design can be seen in Figure 2. The shape and size of the foam determines the ultimate shape and size of the beams, as well as the fibre alignment.

Figure 1: Axontex™ patented manufacturing process

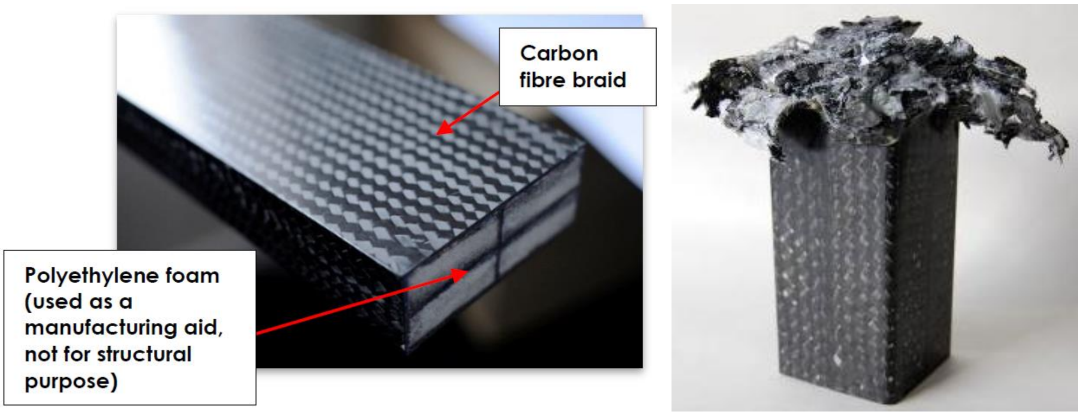

Figure 2: Axontex™ technology beam cross-section and under longitudinal crash load

Axontex™ beams can be designed to give extremely light automotive structures whilst still achieving crash performance significantly better than hollow beams. A crash structure can be seen in Figure 2. The Axontex™ process has a similar cost compared to the fabrication of aluminium structures, for an improved performance. The cost of the beams is significantly decreased by reducing the amount of waste per beam to less than 2 %, when FRPs typically produce 30 % waste. Additionally, cost savings are made in the reduced tooling required for this process. The process was designed specifically for space-frame structures, it provides maximum design scope from one frame where multiple engine and body options are easily accommodated. It forms the core technology for Far Platform Chassis (FPC) [16] presented in Figure 3.

Figure 3: Far Platform Chassis (FPC), car structure prototype, made from Axontex™ (space frame)

Using both glass fibre and carbon fibre braids, as well as a urethane-acrylate matrix material, the beams studied as part of this project are undergoing a full experimental and finite element (FE) investigation. This includes, but is not limited to, quasi-static, dynamic (impact) and fatigue tests of the strength and stiffness performance of the beams. These are subjected to environmental, accelerated ageing (hot/cold, humidity, salt) and ballast resistance pre-conditioning (localised impact damage from stones). The long-lifetime of the beams is also evaluated. At the time of writing this paper, all quasi-static testing has been completed, with results presented as follows. Fatigue and long-life environmental testing requires further investigation.

3 METHODOLOGY

3.1 Material selection

Four types of materials were tested: Axontex™ Carbon Fibre (CF) beams, Axontex™ Glass Fibre (GF) beams, Pultruded Glass Fibre (GF) beams and Steel beams. As steel is the material being replaced in the railcars, it is used as the benchmark and normalisation point throughout the study. The pultruded GF beams were also selected as they are a readily available composite structure, with a manufacturing process that has known advantages and flaws, and present a valid comparative for the study.

Axontex™ is a patented technology using vacuum resin transfer moulding (V-RTM), and details of the provenance of the braid, foam and resin are presented in Table 1. The pultruded GF beams were purchased from Excel composites; the steel beams were welded stainless steel grade 304.

Table 1: Axontex™ details for braid, foam and resin

Axontex™ Carbon Braid	Fibre Manufacturer	Toray
	Fibre Tow/ K value	12K
	Fibre angle	25 degrees nominal
Axontex™ Glass Braid	Type	E-glass fibre
	Linear density	1200 TEX (gr/km)
	Sizing	15D micron
Axontex™ Foam	Manufacturer	Zotefoam
	Grade	Low density closed cell foam
	Density	60 kg/m3
Axontex™ Resin	Manufacturer	Scott Bader
	Type	CRESTAPOL® 1250L

3.2 Quasi-static testing

All tests presented in this paper were performed quasi-statically on a Universal Tensile Testing machine, Instron 5800R using a 100 kN load-cell. The tests were run at a rate of 2 mm/min, cross-head displacement. Testing was run using a four-point bend fixture, as large amounts of localised crushing on all samples were evident from the initial three-point bend fixture and tests.

The support span for both fixtures was 400 mm, and loading span for the four-point bending was 200 mm. Three repeats of each tests were carried out. Table 2 identifies the tests carried out. All samples were 500 mm in length, 60 x 60 mm in cross section. The variations in wall thickness is captured in Table 2.

Table 2: Summary of tested samples (three repeats of each)

Fixture	Identification	Sample dimensions
Four-point bend	Axontex™ CF	1.5 mm wall thickness (±0.1), '+' cross section as seen in Figure 2
	Axontex™ GF	2.5 mm wall thickness (±0.1), '+' cross section as seen in Figure 2
	Pultruded GF	4.2 mm wall thickness (±0.3)
	Steel	1.9 mm wall thickness (±0.1)

4 RESULTS AND DISCUSSION

Results from the tests generate standard load extension diagrams. These are analysed to capture the elastic stiffness behaviour as well as to note early onset plasticity under the impactors and localised crushing. The localised crushing evident was lesser in the testing achieved using the four-point bend fixture compared to the three-point bend fixture. Using standard elastic beam theory equations, Young's modulus E is calculated from the experimental data. It is further standardised to express specific bending stiffness using the stiffness criterion developed by Ludke [17]. Ludke, BMW Body Design specialist, identified four areas for critical consideration in automotive optimisations: structural dynamics, static stiffness, crashworthiness, weight optimisation. He developed a lightweight design material criterion for bending stiffness $\sqrt[3]{E/\rho}$ [18] where E is Young's modulus and ρ is the density of the material. The relative merits of using this criterion as a comparative as opposed to the load-extension diagrams or calculated Young's modulus values are discussed at length in [18]. Figure 4 presents the specific stiffness performance of the four-point bend samples tested, normalised to the behaviour of steel. The divergences in results are seen to be small (>3 %), giving confidence in the nature of the results.

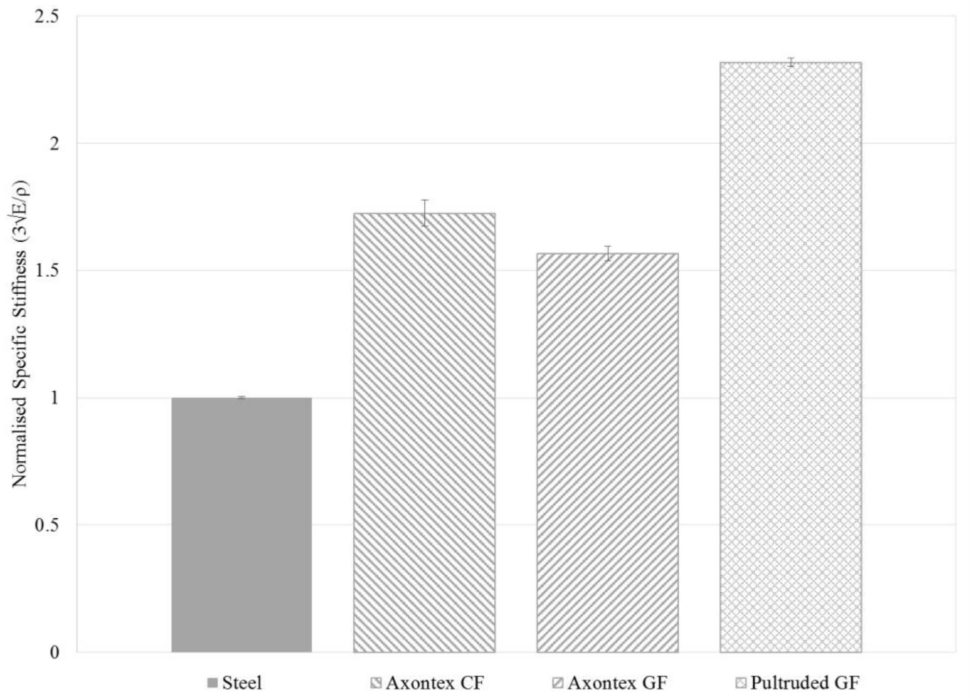

Figure 4: Normalised specific stiffness of the four-point bend samples

It can be seen from Figure 4 that all the composite beams present a significant improvement in behaviour when compared to the steel. The Axontex™ CF beams additionally outperform their GF counterparts, however it can be noted that the pultruded GF beams present the best performance. The Axontex™ CF beams show a 76 % improvement on the steel, the Axontex™ GF beams show a 56 % improvement on the steel, and finally the pultruded GF beams present a 130 % improvement on the steel performance. This performance peak in the pultruded GF beams is attributed to the directionality of the fibres, loading in tension and compression along the outer faces of the beams during the tests. This indicates *exciting potential* in the braided composite technology, where the fibre orientation can be intelligently manipulated to create structures with varying properties along the length, tailored to their specific uses.

At time of writing, these samples are undergoing rigorous environmental aging and fatigue testing to determine their performances in the harsh environments encountered in rail.

5 CONCLUSIONS

In conclusion, the key challenges to the rail industry have been identified, known in the UK as the four Cs i.e. reduced Carbon, increased Capacity, improved Customer experience and lower Costs. Light-weight beam structures open up the possibility of reduced-mass rolling stock with benefits including reduced emissions, improved acceleration and reduced rail wear. The potential benefits are significant, 65 % of a typical urban rail vehicle mass can be attributed to both the body and bogie structures. If lightweighting seen in the rail industry can be similar to that achieved in the automotive industry by the use of FRP (30-50 %) then there are significant potential impacts of the work. Current Axontex™ frames in volume production are projected at a cost in line with an aluminium space frame of equivalent mechanical properties. Quasi-static results have shown promising performances from the Axontex™ beams. An improvement in specific stiffness of over 50 % compared to benchmark steel structures shows the potential in these braided structures. Using braiding as the manufacturing process enables a manipulation of the fibre directionality over the length of the structures, tailoring the fabrication process to the specific desired output. The multifunctional nature and adaptable design of the beams highlights the high-impact that the manufacturing process is destined to have on structural components in the industry. Through its comprehensive testing, the project helps investigate a radical improvement in the application of composite beams for novel markets in the UK. The project verifies that a low-waste and affordable composite beam can sustain extreme conditions and therefore be a new disruptive solution for the rail industry.

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