

THE RESEARCH REQUIREMENTS OF THE TRANSPORT SECTORS TO FACILITATE AN INCREASED USAGE OF COMPOSITE MATERIALS

Part III: The Composite Material Research Requirements of the Rail Industry

Prepared by NewRail
June 2004

Supported by the European Commission under Contract G4RT-CT-2001-05054

www.compositn.net



CONTENTS

Summary	3
Introduction	4
The COMPOSIT Thematic Network	4
The Scope of this Report	4
Current Applications of Composites in Rail Vehicles	5
Technical Issues Associated with the Use of Composites in Rail Vehicles	6
Repair	6
Design and Structural Simulation	6
Crashworthiness	7
Manufacturing	7
Lightweighting	7
Joining	8
Recycling	9
Modelling	9
Fire Safety	10
New Material Concepts	10
Future Research Priorities for Composites in Rail Vehicles	11
Primary Research Priorities	11
Secondary Research Priorities	12
Other Recommendations (Non-Research Led)	12
Centres of Excellence for Composites in Rail Vehicles	13
Future Opportunities for Composites in Rail Vehicles	14
ERRAC's Strategic Rail Research Agenda	14
Potential New Structural Applications	14
Conclusions	15
Glossary	15

For more information, please contact:

Joe Carruthers
NewRail – Newcastle Centre for Railway &
Transport Research
School of Mechanical & Systems
Engineering
University of Newcastle upon Tyne
Stephenson Building
Claremont Road
Newcastle upon Tyne
NE1 7RU
UK

Tel: +44 1246 418635
Fax: +44 191 222 8600
joe.carruthers@ncl.ac.uk



SUMMARY

Composite materials, such as fibre reinforced plastics and sandwich panels, have considerable potential for use in the next generation of transport structures. They are lightweight, durable, and readily moulded to shape. However, there are also additional complexities associated with the use of composites, particularly in terms of design and manufacture. These complexities, together with issues of cost, are currently limiting their adoption by the transport sectors.

Throughout 2002 and 2003, the COMPOSIT thematic network on "The Future Use of Composites in Transport" organised a series of workshops on ten of the critical issues associated with the use of composite materials in the aerospace, automotive and

rail industries. These ten issues were repair, design and structural simulation, crashworthiness, manufacturing, lightweighting, joining, recycling, modelling, fire safety, and new material concepts. As an output from each workshop, priorities for future research activity to meet the needs of the transport sectors were identified.

This report presents the findings of COMPOSIT in terms of the rail industry. Key recommendations for future research priorities include:

- The development of better prediction methodologies for non-linear behaviour, long-term behaviour, damage mechanisms / failure modes, and behaviour at elevated strain rates.

- The development of more cost-effective manufacturing technologies.
- The development of life cycle analysis models to quantify the financial and environmental benefits of lightweight composites.
- The development of better tools for the specification of joints.
- The development of new fire safe resin systems that provide good all-round performance.

Further information on COMPOSIT can be found at www.compositn.net.

INTRODUCTION

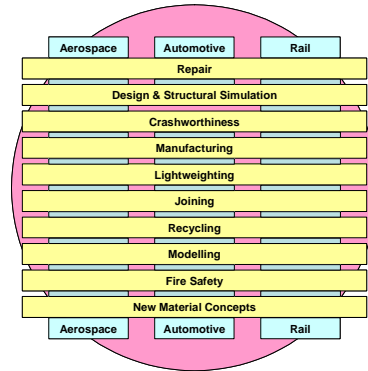
This report summarises the findings of the COMPOSIT thematic network on “The Future Use of Composites in Transport” in relation to the railway sector.

The COMPOSIT Thematic Network

The aim of the COMPOSIT thematic network was to bring together researchers, designers, manufacturers and end-users of composite materials across the aerospace, automotive and rail industries. This was achieved through a series of ten workshops that were held throughout 2002 and 2003. Each workshop addressed a specific theme or issue relating to the use of composites in transport by providing a forum for comparison, collaboration and cross-fertilisation between the different sectors. The intention was to encourage knowledge transfer and promote best practice in the use of composites within the transport system.

As an output from each workshop, issues of common interest were highlighted and future research needs were identified and prioritised. Centres of excellence that could act as focal points to address these research needs were also identified. In this way, research “clusters” were developed for each workshop theme, thus providing a roadmap for future research direction. The full details of the clusters can be found at www.compositn.net.

The COMPOSIT consortium was headed by four partners, each representing one of the industrial sectors with a vested interest in the project: NewRail for the rail industry, EADS Deutschland for the aerospace industry, Centro Ricerche Fiat for the automotive industry, and SICOMP for the composites industry. Six additional members provided further specialist technical input: D’Appolonia, IKV, INEGI and the Universities of Leuven, Newcastle and Zaragoza.



Summary of the COMPOSIT thematic network - research clusters have been developed for each of the ten horizontal workshop themes

In identifying and ultimately addressing the composite material research needs of the transport sectors, it is anticipated that the legacy of COMPOSIT will be:

- New and improved concepts for composite material transport applications, leading to an increased usage of composites and better vehicle solutions.
- Improved competitiveness for the composites industry by reducing development costs and time-to-market for new transportation products.
- The creation of an infrastructure for sustainable inter-industry co-operation.

The Scope of this Report

This report summarises the findings of the COMPOSIT thematic network in relation to the railway sector. It focuses upon the use of composite materials in rail vehicles. Infrastructure applications are not considered here. The report provides an overview of the applications in which composite materials are currently employed. It then considers the various technical issues associated with the use of composites in rail vehicles as identified by the research clusters. These issues provide the basis for a list of future research

priorities. Furthermore, centres of excellence capable of leading this future activity are identified. Finally, assuming that the research deficiencies can be addressed, potential future applications for composites within rail vehicles are suggested.



This report constitutes Part III of the collated published output from the COMPOSIT thematic network. The companion volumes are:

- Part I: The Composite Material Research Requirements of the Aerospace Industry.
- Part II: The Composite Material Research Requirements of the Automotive Industry.

CURRENT APPLICATIONS OF COMPOSITES IN RAIL VEHICLES

Material and Process Selection

Today, the single biggest factor influencing the specification of composite materials for rail vehicle applications is probably initial component cost. This usually means that it is cheaper to mould a part with a complex shape in composites than it is to fabricate it from metals. Alternatively, the tooling costs associated with the required production volumes might favour composite processing over other material and manufacturing options. Perhaps surprisingly, the wider perceived benefits of composites, such as lightweighting, crashworthiness, durability and even life-cycle costing, are often secondary considerations.

The implication of this situation for composite material selection in the rail industry is that low cost fibres, resins and cores are normally specified. This means typically:

- Polyester, vinylester, phenolic or modified acrylic liquid resin systems.
- Glass fibres in a variety of forms, including chopped strand mats, continuous filament mats, unidirectional rovings, woven fabrics, and multi-axial non-crimped.
- Polymer foam, aluminium honeycomb, or balsa wood cores.

The selection of specific raw materials from the above list will normally be influenced by cost, processing considerations (resin viscosity, fibre permeability, cure cycle, etc.) and the structural requirements of the part. Furthermore, rail vehicle components must often meet stringent fire, smoke and toxicity requirements and this can affect the choice of resin and foam system. Fire retardant fillers (such as aluminium hydroxide) may be added to the resin to improve fire performance.

The selection of the manufacturing process for a composite component will normally depend upon the nature of part and the required production volumes. For example:

- Hand lay-up for very low production volumes (less than 100 parts per year).
- Vacuum infusion (VI) for low-medium production volumes (less than 500 parts per year). VI is well suited to large parts (greater than 1 m) with intermediate fibre content (less than 35% by volume).
- Resin transfer moulding (RTM) for medium production volumes (less than 30,000 parts per year). RTM is particularly suitable for small-medium sized parts (less than 2 m) with high fibre content (30 – 55% by volume).



Vacuum infusion of a rail vehicle roof structure (courtesy of Bombardier Transportation)

Current Applications

There are two main applications for which composites are routinely employed at present:

- Rail vehicle cabs.
- Interior components, such as seats and panelling.

In both of these cases, composites are primarily specified because they can be used to produce cost-effective, lightweight components of relatively complex geometries.

The aerodynamic profiles demanded by modern high speed train cabs are easily moulded from composite sandwich

structures. Similarly, the medium volume batch production runs typical of interior components such as seats are ideally suited to composite processes such as RTM.



Composite high speed train cab produced by VI (courtesy of Alcan Airex Composites)

However, outside of these limited application areas, there has been no significant adoption of composites by the rail industry. This report, based on the findings of the COMPOSIT workshops, will highlight the main reasons why this should be the case.



Composite rail seat produced by RTM (courtesy of Ashland Composite Polymers)

TECHNICAL ISSUES ASSOCIATED WITH THE USE OF COMPOSITES IN RAIL VEHICLES

The COMPOSIT thematic network focussed on ten key issues relating to the use of composites in transport. During the course of the project, a workshop was dedicated to each of these ten issues. Leading international experts in the relevant fields were invited to present and participate at the workshops. Here, the findings are presented in terms of their relation to the rail industry.

Repair

The use of composite materials for truly structural applications in rail vehicles is currently not common. Consequently, composite repair is not a major concern of the rail industry at present. As a current issue, it is certainly much less critical to the rail industry than it is to the aerospace industry where structural composites are routinely employed.

Composite rail vehicle interior fittings (seats, panels, etc.) are generally very robust and damage tolerant. The vast majority of damage is cosmetic (scratches, dents, graffiti, etc.). Should a repair of a composite interior part be deemed necessary, it can usually be undertaken with filler and paint. Seriously damaged interior components tend to be replaced rather than repaired.

The most common causes of damage to exterior components such as cabs and decorative mouldings are: (i) localised impacts with trackside debris, and (ii) more extensive structural collapse due to collisions. With respect to the former, cabs for high speed trains are generally designed to be damage tolerant to localised impacts.

Two concerns regarding composite repair practices in the rail industry were highlighted at the COMPOSIT workshop. Firstly, because composite rail vehicle parts are rarely structural and hence not safety-critical, there is a general lack of routine damage inspection. Normally, only when composite damage is obvious and serious is remedial action taken. Visual inspection for damage is usually the only method

employed. Minor damage can often remain undetected for long periods of time and hence has the potential to deteriorate further through environmental degradation (moisture ingress, etc.).

The second concern relates to an apparent lack of standardised composite repair procedures within the rail industry. This suggests that there is potential for variation in the quality of repairs. At present, the single biggest factor influencing repair quality is likely to be the skills and experience of the person undertaking the repair.

Finally, if the use of composites for structural rail vehicle parts is to become more widespread in the future, then a more comprehensive and rigorous approach to damage inspection, detection and repair will be required.



A composite high speed train cab undergoing structural repair

Design and Structural Simulation

If rail vehicle structures are to be realised in composites, a designer will require:

- Knowledge and understanding of the structural requirements.
- Access to appropriate design and simulation tools.

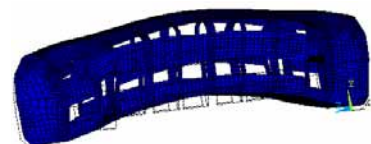
In terms of the structural requirements, rail vehicles must typically satisfy a range load cases including applied static proof loads,

fatigue loads, structural collapse (crashworthiness) and jacking / lifting loads. The stiffness of the structure (i.e. the modal response) also needs to be considered.

Having established the requirements, the designer is then faced with the challenge of developing the structure in composites. However, a current major obstacle is that whilst accurate steel and aluminium material models are readily available for use with finite element analysis (FEA) software, composite material models are generally much less well developed. Whilst the elastic FEA of composite structures (e.g. response to proof loads) can often be performed satisfactorily using linear material models, non-linear behaviour (e.g. structural collapse) is considerably more problematic. For example, during the recent development of a composite rail vehicle roof structure, the formulation of a full non-linear finite element simulation required 35 calibration tests and 15 weeks of development and validation. The developer estimated that the same model in steel or aluminium would take just one day to implement.

Another area of concern relates to the long-term properties of composites. Designers, manufacturers and end-users all need to be confident that composite structures will have adequate service lives. Presently, there is a lack of reliable prediction methodologies for estimating the long-term behaviour of composite systems.

Overall, the increased complexity and time associated with the design and simulation of composite structures is a major barrier to their more widespread adoption in railway applications



Finite element analysis of a composite double-deck bodyshell (courtesy of D'Appolonia)

Crashworthiness

It is known that composites can be designed to provide higher mass specific energy absorption capabilities than metals. The controlled brittle failure of fibre reinforced plastics provides very efficient energy absorption mechanisms. Consequently, composite vehicle structures ought to be capable of dissipating more of the kinetic energy associated with a collision than a conventional metallic design.

Whilst niche sectors within the automotive and aerospace industries successfully exploit the crashworthiness properties of composites, there has been little significant uptake in the rail industry to date. This is largely due to the difficulty in accurately and cost-effectively predicting the crash performance of composite structures. Experimental crashworthiness development, particularly at full-scale, is very costly. It requires the use of highly specialised test facilities and the structure being evaluated inevitably suffers extensive damage (i.e. it can only be tested once). For this reason, numerical simulation using non-linear FEA has become the mechanism by which the majority of routine crashworthiness development is undertaken.

With metallic vehicle structures, such an approach is employed with a reasonable level of confidence. The crashworthiness properties of a vehicle can be optimised "virtually" using computer simulation and then verified with a minimum of experimental testing.

With composites, the confidence in employing finite element techniques to simulate crash performance is much lower. It is doubtful as to whether the representation of composite failure within existing commercially available finite element codes is sufficiently comprehensive. Other concerns include the availability of reliable material property data for input to the analyses (particularly relating to elevated strain rates), and the solution times that are required for fully-featured models that attempt to capture the wide range of composite damage mechanisms.

Consequently, it is currently quite common for composite rail vehicle cabs (which might weigh upwards of 500 kg) to be deliberately neglected in rail vehicle crashworthiness analyses simply because of the difficulties in accurately modelling them. Instead, only the metallic components of the body structure are considered.

In summary, the lack of reliable methods for cost-effectively predicting the crashworthiness properties of composites is inhibiting the exploitation of their considerable potential as materials with inherently high energy absorptions.



Compression testing of an energy cell component from a prototype all-composite structural cab design

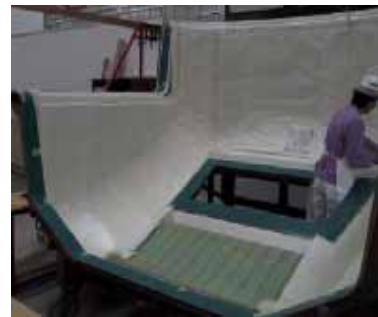
Manufacturing

As described on page 5, a variety of different processing techniques are employed for the manufacture of composite rail vehicle parts. Process selection is typically driven by the material and geometric design of the component and the required production volumes. Techniques such as hand lay-up, vacuum infusion (VI) and resin transfer moulding (RTM) are all routinely employed and have a proven track record.

However, the initial cost of composite components remains a barrier to their more widespread adoption by the rail industry. Current manufacturing costs are a contributing factor to this. Therefore, any technologies that improve the overall efficiency and cost-effectiveness of

composite processing would be of benefit to the industry. The goal should be composite products that are the same cost, or even cheaper, than equivalent metallic designs.

Another processing issue that was highlighted at the COMPOSIT manufacturing workshop relates to resins with particulate additives. Fillers such as aluminium hydroxide are often introduced to polyester or modified acrylic resin systems to improve their fire performance. Highly-filled systems can become difficult to process via VI or RTM, and further work is needed to fully understand their characteristics.



Lay-up of a composite rail vehicle cab (courtesy of Alcan Airex Composites)

Lightweighting

The availability of lighter vehicles would benefit the rail industry two key ways:

- Lighter vehicles would yield capacity increases, either by providing increased payload (e.g. the full-utilisation of double-deck capacity without exceeding axle load limits), or by reducing the detrimental effect of an increased service (longer trains or more frequent trains) on the existing railway infrastructure.
- Lighter vehicles would reduce running costs (i.e. energy consumption) over the life of the vehicle.

However, it is clear that these two potential benefits of composites, which are widely known even to non-composite specialists, have not been sufficiently strong drivers for the more widespread adoption of composites for structural rail applications. This is in marked contrast to the aerospace industry, which has seen an evolutionary growth in the use of composites for primary structures over the last twenty years.

This situation can be largely explained by the differing approaches of the two industries to procurement and operating costs.

Commercial aircraft are financed on a life-cycle basis. Operators have a very clear understanding and appreciation of the cost benefits of saving each kilogram of weight (perhaps of the order of €100/kg). In this way, the substitution of metallic parts with lighter composite alternatives can be justified.

Procurement in the rail industry is currently dominated by initial costs. Furthermore, the operating cost benefits of lightweighting are perceived to be much lower (probably closer to €10/kg). In this framework, it becomes much more difficult to justify a switch to composites.

Prototype composite rail vehicle structures have been shown to offer weight savings of around 20% over equivalent aluminium designs. However, unless the rail industry embraces the principles of life-cycle costing more extensively than at present, the initial cost of composite structures must be equivalent to, or even cheaper than, metallic alternatives if they are to be considered a viable option. The wider issues and uncertainties surrounding composites, as outlined elsewhere in this report, only exacerbate this situation.



A prototype composite double-deck coach section, providing a 20% weight saving over aluminium (courtesy of Fibrocom)

Joining

If the use of composites is to become more widespread in the rail industry, then this is likely to happen in an evolutionary fashion. Rather than an industry-wide transition from predominantly metallic to predominantly composite vehicles over a period of just a few years, a more realistic scenario is a gradual component-by-component switch over successive generations of vehicles. This is the approach that has been adopted by the aerospace industry over recent decades. It allows design and manufacturing engineers to gain confidence in composite technologies in a controlled, managed way.

The results of such an approach are hybrid vehicles containing significant proportions of both composite and metallic materials. Joining, and in particular the joining of dissimilar materials, therefore becomes a critical technology. Specific issues that will need to be addressed include:

- Selection of the most effective joining technique for a given application. How does one identify the most appropriate joining technology and joint design for a

certain set of requirements? Both adhesive bonding and mechanical fastening, or a combination of the two, are suitable for the joining of thermosetting composites and metals. Joint selection and design tools are required to allow engineers to specify joint configurations and simulate their performance.

- Improved understanding of joints between dissimilar materials. When two different materials are joined together (e.g. composites and metals) there are additional issues that need to be considered. These include ensuring that the two bonding surfaces are properly prepared and accommodating any discrepancies in the coefficient of thermal expansion between the two materials.
- Information and education regarding the use of adhesives. New adhesive technologies are being continually developed and, with proper design and implementation, it is now possible to produce adhesive joints with exceptional performance. However, to many, adhesives are still regarded as a "black art" that should not be trusted. Design engineers need to be provided with the necessary information and education to allow them to specify adhesives with confidence.
- The need for efficient and effective non-destructive testing procedures for the assessment of bonded joints in composite and hybrid structures.

The foreseeable advantages of fully exploiting modern joining technologies for all-composite, hybrid composite-metallic, and even all-metallic parts in rail vehicles can be summarised as follows:

- Design advantages. The freedom of design enabled by the joining of different materials can facilitate increased levels of optimisation. In other words, rather than accepting the compromises associated

with designing in predominantly a single material, hybrid designs allow the most effective material to be specified for each component, or sub-component, within a vehicle design.

- Manufacturing advantages. New primer-less, non-sagging, fast curing adhesives, as well as the potential to widen geometrical tolerances through the gap-filling abilities of adhesives, lend themselves to the automation of bonding processes and the reduction of cycle times.
- Durability advantages. Adhesives are not affected by corrosion in the same way as mechanical fasteners. They also provide effective sealing and have excellent fatigue properties. However, the real impact of these characteristics needs to be assessed through life-cycle evaluations.



A hybrid bolted-bonded T-joint between the external cover and bracket of a composite sandwich coupler door for the Italian ETR 460/470/480 high speed train (courtesy of Sistema Compositi and the University of Rome)

Recycling

Similarly to the issue of repair, the recycling of composite materials in the rail industry is not currently a primary concern. This is because:

- Composite materials are not extensively used at present (in contrast to the aerospace industry).
- Rail vehicles are not produced in high volumes and service lives are long, so

the potential for generating materials that need to be recycled is low (in contrast to the automotive industry).

- There is no impending legislative requirement to recycle materials (in contrast to the automotive industry).

However, again as with the issue of repair, if the use of composites is to become more widespread in the rail industry in the future, then recycling will need to be addressed at some stage. Furthermore, as a transport mode, rail has strong environmental credentials in terms of energy efficiency, emissions, capacity and land-use. These are advantages to be exploited, and a lack of effective recycling strategies would be at odds with this position.

From the COMPOSIT workshop on recycling, it appears that the single biggest issue relating to the recycling of composite materials is the lack of feasible end-use applications for recycled materials. A re-use as a filler is not enough as the processed material cannot compete price-wise with virgin fillers. It is therefore necessary to develop products in which the specific properties of recycled materials are exploited (e.g. their mechanical properties or processability).

Other issues relating to the recycling of composites that would be worthy of further study and development include design for recycling (e.g. dismantling, identification of materials, etc.), the integration of recycling technologies within the current waste management system (e.g. collection, transportation, sorting, processing, etc.), new recycling technologies (e.g. pyrolysis, gasification, hydrolysis, etc.), and the further development of easily recyclable material systems (e.g. natural fibre composites).

Finally, as a technical issue, the recycling of composites is largely generic to the aerospace, automotive, rail and composites industries. All would benefit from improved solutions, and consideration should be given to the effective pooling of resources in this area.

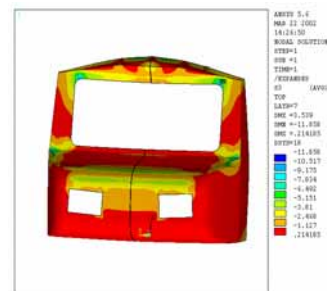


Glass fibres recovered using a fluidised bed process (courtesy of the University of Nottingham)

Modelling

In terms of the issues surrounding the modelling of composites, there is little to add to the discussion already presented in the sections on "Design and Structural Simulation" and "Crashworthiness". If composites are to be as routinely specified as metals, then rail vehicle analysts need to be provided with the necessary tools, the majority of which are presently under-developed. In particular, analysts need:

- Accurate, reliable and efficient composite material models that can be used to predict failure, damage propagation, fatigue life, non-linear stiffness properties, and processing characteristics.
- Comprehensive, integrated, material property databases.



Finite element analysis of a composite rail vehicle cab (courtesy of D'Appolonia)

Fire Safety

In comparison to other modes of transport, the rail industry has some of the most stringent fire requirements. Although there are many mechanisms by which a fire can start (crashes, technical failure, negligence, arson, etc.), the consequences of intense heat, thick black smoke and toxic fumes are uniformly deadly.

The thermosetting polymer resins on which the majority of rail vehicle composites are based are organic and hence burn. Therefore, when specifying composites for rail vehicle applications, fire regulations often dictate essential pre-requisites that have a significant influence on material selection, design and manufacturing. This is because composite materials with excellent fire characteristics tend to be compromised in other aspects of their performance, such as their mechanical properties, processability and/or surface finish. The relatively poor (in comparison to metals) fire performance of composites is perceived to be one of the major barriers to their more widespread adoption by the rail industry.

The assessment of the response of composite materials to fire is traditionally split into the areas of "fire reaction" and "fire resistance".

Fire reaction assesses the ability of a material to resist the start-up and progress of a fire, as well as the threat posed to human health by the quantity and toxicity of the fire effluents. Up until now, one of the major difficulties in this area has been the lack of harmonised standards. In effect, each country in Europe has its own railway fire and smoke regulations and the standards vary from country to country. As a result, there are currently thirty-five different fire test methods being employed across Europe to specify materials for use in railway rolling stock. To address this situation, a new harmonised European fire standard, EN 45545 - "Fire Protection on Railway Vehicles", has been prepared and is expected to be in its final form and available for public comment in early 2004. In terms of the future of composite materials in the rail

industry, it is essential that this new standard should be:

- Performance-based (i.e. not prescriptive in terms of material selection).
- Able to accurately and consistently characterise the behaviour of materials to a range of fire scenarios.
- Practical, in the sense that it doesn't require overly extensive and costly testing.
- A tool for the research and development of fire safe composite structures, not a barrier.

In terms of the reaction of specific composite material systems to fire, there is no universal solution at present. Halogenated resins appear to have little future in the rail industry because of their poor smoke and toxicity performance. Phenolic resins are probably the most widely specified fire safe composite system in rail vehicles, but their mechanical performance is relatively poor, there are concerns over their emissions of toxic carbon monoxide, and they tend not to provide high class surface finishes. Filled polyester and modified acrylic resin systems have good smoke, toxicity and surface finish properties, but they are more difficult to process. Clearly there is scope for the development of new fire safe composite resin systems with better all-round properties.

Fire resistance represents the ability to maintain structural integrity (i.e. survival space) in the event of a fire. At the COMPOSIT workshop on fire safety, there was a general opinion that the use of careful design, in conjunction with adequate fire protection solutions (e.g. material "barrier" technologies), can ensure that structural composite applications perform as well as equivalent metallic structures for a given fire scenario.

Overall, technologies that would assist in the development of the next generation of fire safe composite structures include new

material developments, the development of reliable low cost fire test protocols, the development of guidelines for fire safe design, and the modelling and simulation of the response of composite materials to fire.



Fire safe composite interior components (moulded with aluminium hydroxide-filled polyester resin) for the Electrostar trains (UK) (courtesy of DSM Composite Resins)

New Material Concepts

Although there is still much to be done in terms of fully exploiting existing composite technologies within the rail industry, there is still the need for new material concepts to push the boundaries of what can be achieved. For the rail industry, the principal drivers for new composite material technologies should be cost reduction, easy manufacturing, lightweighting, improved fire performance, improved energy absorption capability, increased functionality, and recyclability. If composites are to find increased usage within rail vehicles, then the next generation of materials need to address these issues. Some examples of promising emerging technologies from the COMPOSIT "New Material Concepts" workshop include:

- Nanocomposites, including carbon nanotubes (CNTs) and nanoparticles. These materials are currently at the forefront of research into new composite technologies. CNTs can be thought of as flat arrays of carbon atoms (graphite sheets) rolled up to form a cylindrical nanostructure (with diameters within the nanometre scale). They show exceptional strength and stiffness properties (of the order of GPa and TPa

respectively). Their main application within composites would be as fillers for polymer resins. A small percentage of carefully dispersed CNTs can significantly enhance a resin's mechanical properties, as well as serving a wide range of multifunctional tasks, (e.g. improved fire performance or enhanced electrical / thermal properties). However, much more research and development is required in this area, especially in terms of the affordable bulk production of nanotubes, as well as their handling and processability. Hence, at the moment, there is little to suggest that such materials are going to find feasible and affordable applications within rail vehicle structures in the short or medium term.

- Three-dimensional tailored textile preforms. Traditional textile technologies such as weaving, braiding, knitting and stitching are now being applied to composite reinforcements. They allow the fast, automatic, low cost production of near-net-shaped fibre preforms with high functionality and high levels of optimisation. Such technologies are particularly well suited to medium volume closed moulding processes such as RTM. Typical applications might include, for example, rail vehicle seats.
- Bio-based composites. In recent years, significant progress has been made in the development of genetically engineered bio-based polymers (processed from plant oils) and natural

fibres (processed from plants and poultry). Renewable resources, abundant domestic production, and the potential for biodegradation or recycling make these new technologies particularly interesting for many composite applications.

- New processes for continuously produced honeycomb cores. Manufacturing technologies such as the patented ThermHex and TorHex folding concepts have high potential for enabling the fast, automated production of low cost structural cores for sandwich panels. In terms of the rail industry, this could open-up new applications for lightweight, cost effective sandwich components.

FUTURE RESEARCH PRIORITIES FOR COMPOSITES IN RAIL VEHICLES

In the previous section, some of the key technical issues associated with the use of composites in rail vehicles were reviewed. Here, we build upon this information to identify the key knowledge gaps arising from this study. By focussing future research and development efforts upon the priorities listed in this section, the potential for increasing the level of composite usage within rail vehicle applications will be maximised.

The research requirements are prioritised in terms of "primary" (essential) and "secondary" (desirable or longer term). Non-research led recommendations (e.g. relating to various aspects of industry standardisation) are also presented.

Primary Research Priorities

- Techniques that allow a non-linear structural analysis of a composite part to

be performed as quickly as a steel or aluminium equivalent.

- Prediction methodologies for estimating the long-term behaviour of composite systems.
- Improved understanding of composite material damage mechanisms and failure modes, and the integration of this understanding within commercial finite element analysis software.
- Improved understanding of the behaviour of composites at elevated strain rates. This might produce an additional requirement for the development and standardisation of new test procedures for characterising composites under dynamic loading.
- Manufacturing technologies that improve the overall efficiency and cost-effectiveness of composite processing.

For example, (i) improved process simulation for better optimisation, (ii) online monitoring / control technologies for improved process consistency, (iii) technologies for more cost-effective sandwich panel manufacture, and (iv) the application of advanced preform technologies to reduce lay-up times.

- The development of comprehensive and accurate life-cycle analysis models for the use of lightweight composite materials in the rail industry to quantify their environmental and financial benefits.
- Improved understanding and the availability of tools for (i) the selection of joining technologies, and (ii) the design and simulation of joints. It is essential that these tools should accommodate joints between dissimilar materials (e.g. composite – metal hybrid structures) to

support the evolutionary adoption of composites by the rail industry.

- New fire safe resin systems that provide good all-round performance in terms of fire, smoke and toxicity, processability, mechanical properties, and surface finish.

Secondary Research Priorities

- The development of highly compatible multi-purpose repair materials (particularly resins) with long shelf lives. These would help to optimise the variety of materials employed for composite repair. It would also facilitate the standardisation of repair procedures, thus reducing the risk of low quality repairs.
- The development of new raw materials, textile architectures and structural concepts for further improving the energy absorption properties of composites.
- Improved understanding of the processing and properties of resin systems that have been highly filled with particulate additives such as aluminium hydroxide to meet stringent fire requirements.
- Efficient and effective non-destructive testing procedures for the assessment of bonded joints in composite and hybrid structures.
- The development of end-use applications for recycled composite materials.
- The development of low cost fire test protocols to assist the research and development of new fire safe composites.
- The development of guidelines for designing fire safe rail vehicle structures that fully exploit the available technologies (resins, fillers, "barrier" materials etc.) to give optimised fire reaction and fire resistance properties.

Other Recommendations (Non-Research Led)

- The standardisation of procedures for the inspection, detection and repair of damaged composite parts.
- The standardisation of materials, and the availability of material parameters for design. This would reduce the requirement for extensive material property data generation as part of the design process. The properties of steel and aluminium are widely available. The properties of composites are not. This is always going to be a barrier to composite design.
- The provision of the necessary information and education to allow engineers to specify adhesives with confidence.
- The development and introduction of international, harmonised, practical, accurate and reliable standards for determining the fire safety of composite materials for use in rail vehicles.

CENTRES OF EXCELLENCE FOR COMPOSITES IN RAIL VEHICLES

As well as establishing the composite material research priorities for the transport sectors, another of COMPOSIT's remits was to identify centres of excellence capable of leading this future activity. All of the organisations listed here are considered to be leading European experts in the various aspects relating to the application of composites in rail vehicles. They have been identified through their participation in the COMPOSIT thematic network. The list of organisations is not intended to be all-encompassing. It should however provide a useful starting point when establishing collaborative research teams or consortia to address the research priorities.

Centre of Excellence	Competencies									
	Repair	Design & Structural Simulation	Crashworthiness	Manufacturing	Lightweighting	Joining	Recycling	Modelling	Fire Safety	New Material Concepts
Alstom Transport		•	•		•			•		
AEA Technology Rail	•								•	
Alcan Airex Composites		•		•						
Ashland Composite Polymers				•						•
Bombardier Transportation		•	•		•	•	•	•	•	
Borden Chemical				•					•	
D'Appolonia		•						•		
DSM Composite Resins				•			•		•	
EADS						•				
Engineering Systems International (ESI)		•	•					•		
Fibrocom				•						
FiReCo									•	
Halmatic	•			•	•				•	
Institut für Kunststoffverarbeitung (IKV) – Institute of Plastics Processing		•		•				•		
Institut für Verbundwerkstoffe GmbH										•
Katholieke Universiteit Leuven										•
NewRail – Newcastle Centre for Railway & Transport Research		•	•					•	•	
QinetiQ	•									
Reichold Global Composites				•					•	
SICOMP				•			•	•		
Sistema Compositi				•		•				
Stena Fragmentering							•			
Technical University of Hamburg-Harburg										•
TWI						•				
University of Delaware										•
University of Nottingham							•			
University of Rome						•				
Vantico						•				
Warrington Fire Research Centre									•	

FUTURE OPPORTUNITIES FOR COMPOSITES IN RAIL VEHICLES

Having discussed the technical issues associated with the use of composite materials in rail vehicles, this section briefly examines the future opportunities assuming that the identified research deficiencies can be addressed. How can composite materials contribute to the future of Europe's railways?

ERRAC's Strategic Rail Research Agenda

The European Rail Research Advisory Council (ERRAC) is an advisory body to the European Union (EU) representing Member States, the railway manufacturing and supply industries, rail operators, infrastructure managers, users, academia, environmental and urban planning organisations, and the EU. Its primary mission is to establish and carry forward a Strategic Rail Research Agenda (SRRA) that influences all stakeholders in the planning of research programmes, particularly at a national and EU level. The SRRA provides an outlook for innovations in the railway industry to meet the demands of Europe's citizens over the next twenty years. It focuses on five thematic areas: (i) interoperability, (ii) intelligent mobility, (iii) global rail safety and security, (iv) the environment, and (v) innovative materials and production methods.

Composite materials are particularly well placed to contribute directly to the "innovative materials and production" thematic area. They could also address aspects of "global rail safety and security" (in terms of their crashworthiness properties) and "the environment" (reduced emissions and energy consumption through lightweighting).

An additional challenge facing the rail industry is the implementation of the SRRA whilst simultaneously fulfilling the European Railway Business Scenario 2020. This anticipates the rail mode capturing twice the passenger and freight market share, and three times the passenger and freight market volume compared with the year 2000 levels. Lightweight materials technologies,

such as composites, could play an important role in achieving these capacity increases. Lighter vehicles would permit the full exploitation of the capacity advantages of double-deck trains within axle load constraints. Alternatively, lighter vehicles would allow longer trains or more frequent trains to run on the existing infrastructure without accelerating damage to track.



A prototype lightweight composite double-deck coach section (courtesy of Fibrocom)

Potential New Structural Applications

In recent years, prototype composite structures and components have been developed for a range of fully structural rail vehicle applications. These include cabs, bodysells, bogies and wheel sets. For most such cases, the technical feasibility of producing the composite prototype was well demonstrated. It has been the associated issues of part cost, the required manufacturing investment, and a lack of customer confidence over ongoing fitness for purpose that have limited their introduction to the market.

The implementation of the recommendations for future research activity outlined earlier in this report would be a significant contribution

towards overcoming these current barriers. For example:

- Improved design tools would reduce the development costs of composite structures and components, and would provide increased confidence over their fitness for purpose. They would also help to reduce part costs by allowing the development of optimised structures that eliminate excessive levels of over-engineering.
- More efficient and cost-effective manufacturing technologies would also help to reduce part costs.
- A better understanding of issues such as repair, crashworthiness, joining, recycling and fire safety would provide increased confidence in the functionality of composite structures and components for designers, manufacturers, operators and end-users.

If future research, development and demonstration efforts are able to adequately address the key concerns of industry in this way, then the routine application of fully structural composite cabs, bodysells, and bogies in the medium-long term does not seem wholly unreasonable.

CONCLUSIONS

Composite materials are already routinely employed by the rail industry, albeit mainly in limited, semi-structural, non-safety critical applications. If composites are to be used more widely, then three key conditions need to be fulfilled:

- Design and manufacturing engineers need to be able to employ composite technologies as routinely as traditional materials, i.e. appropriate tools need to be made available.
- The rail industry needs to be confident that composite structures will function in a predictable manner, over the life of a vehicle, without compromising safety.

- Composites need to be cost-competitive with metals within the framework of the rail industry's normal costing practices.

In terms of the first two points, this report has identified a number of key technical areas in which further research and development is required. If progress could be made towards addressing these issues, then the rail industry would be in a better position to routinely evaluate composite technologies as an alternative to metals. Of course, this wouldn't guarantee that composites would actually be specified, but it would at least allow a fair comparison.

The third point, that of cost, is critical. If initial component cost is a strong influence on material and product selection within the

rail industry, then composites need to be no more expensive than equivalent metals, and preferably cheaper. A greater emphasis on life-cycle costing would undoubtedly benefit composites given their potential for lightweighting, and the composites industry should be preaching this message.

Finally, the European Rail Research Advisory Council (ERRAC) has established some challenging targets for 2020, particularly with respect to increases in passenger and freight volumes. If these targets are to be met within the framework of the existing rail system, then it is likely that new vehicle technologies will have to be adopted. If the issues highlighted in this report could be addressed, then composites would be well placed in this respect.

GLOSSARY OF COMPOSITE MATERIALS

Chopped strand mat (CSM) – A randomly distributed layer of short fibre strands bound together chemically or mechanically.

Composite material - A material that combines two or more physically different constituents, each of which largely retains its original structure and identity.

Continuous filament mat – Filaments (typically glass) of indefinite length forming a layer of randomly distributed fibres bound together chemically or mechanically.

Core - In sandwich structures, the central low density component to which inner and outer skins are attached. Foams, honeycombs and balsa wood are all used.

Cure - To irreversibly change the molecular structure and physical properties of a thermosetting resin by chemical reaction using heat, pressure and/or catalysts.

Fibre reinforced plastic (FRP) - A composite material that consists of a polymer matrix containing reinforcing fibres.

Glass fibre - An individual strand of glass typically of 9-24 µm in diameter.

Honeycomb - A lightweight cellular structure made from either metallic sheet materials or non-metallic materials (e.g. resin-impregnated paper or woven fabric) and formed into a nest of hexagonal cells.

Matrix - The material in which the fibre reinforcements of a composite system are embedded. Thermoplastic and thermoset resin systems, as well as metals and ceramics, can be used.

Non-crimped fabric - A textile structure produced by the consolidation of continuous rovings or yarns without weaving. This is typically achieved by mechanical means (e.g. stitching) or with a polymeric binder.

Preform - A pre-shaped dry fibre reinforcement for insertion in a mould.

Resin transfer moulding (RTM) - A composite manufacturing process in which a catalysed resin is pumped into a two-sided, matched mould in which a dry fibre preform has been placed.

Roving - A collection of parallel, non-twisted, continuous fibre strands.

Sandwich structure - A composite material composed of a lightweight core material to which two relatively thin, dense, high-strength functional or decorative laminate skins have been adhered.

Vacuum infusion – A composite manufacturing process in which a vacuum draws resin into a one-sided mould. A cover, either rigid or flexible, is placed over the top to form a vacuum-tight seal.

