Use of Composite Materials in Railway Applications

Emigiano Campus¹, Bernard Roure²
¹ALSTOM Transport, La Rochelle, France, ²SNCF Direction du Matériel Centre d'Ingénierie du Matériel (CIM), Le Mans, France

1. PREAMBLE

Development in the field of railways goes in particular through decreasing the weight of rolling stock vehicles. Such needs are expressed in the field of very high speed transport - where weight reduction will result in higher speed, higher transport capacities and/or enhanced passenger comfort whilst keeping a good energy balance - as well as in the field of urban and sub-urban rolling stock, where weight reduction results in enhanced acceleration and hence, in increased capacity in terms of passenger flow/hour. Technical Interoperability Specifications limit the weight per axle to 17 tons for speed above 250 km/h: this is one of the main constraints for articulated trains.

Currently, composite materials are rarely used for structural elements of rolling stock vehicles. Studies undertaken in the middle of the nineties have allowed the industry to acquire competence in the field of composite materials. The progress achieved with regard to such materials in addition to the "multi-material" approach (composite materials, steel, aluminium) will allow the need for weight lightening to be satisfied at competitive costs.

Railway crafts have always been strongly related to metallurgy crafts. As far as rolling stock vehicle structures are concerned, the definition of needs is often based on characteristic features of metallurgical work.

The current evolution in the field of railway rolling stock requires that railbound vehicles be made lighter in the short term, by turning towards techniques based on modularity and the use of composite materials for the structures.

2. PRESENTATION OF THE "MULTI-MATERIAL INTERMEDIATE COACH"

In collaboration with the SNCF, ALSTOM have developed the concept for a "Multi-Material Intermediate Coach" prototype, with its central and end parts being made of composite materials, in order to validate potential weight gain of such a structure, with the mechanical performances maintained and at identical costs.

First of all, the feasibility and interest of such a change in technology with a view to improving the performance/weight ratio - whilst complying with economical constraints and constraints inherent to passenger transportation in general: safety, ride quality, reliability and maintainability – must be demonstrated,

Unlike the current state of art, the Multi-Material Intermediate Coach project is not initially oriented towards a given type of material (for instance, high-performance composite materials). The Multi-Material Intermediate Coach project does not start with prejudices; it will associate composite materials as well as metal materials on the basis of a "multi-process" approach.

Compared to work realised to date, a maximum degree of modularity of the vehicles was striven for, in order to enable the largest possible customisation, according to the various Customers' requirements.
This is achieved through global processes including experimental, analytical and digital methods at a time for the test result interpretation, to be applied to multi-material and multi-process structures.

The studies deal with bi-directional fatigue behaviour of thick multi-material structures in railway environment, taking particular account of aspects such as ballast-impact, climatic and chemical conditions, fire-behaviour, etc.

By definition, the Multi-Material Intermediate Coach uses metal and non-metal materials, which means that all aspects relating to the assembly of such materials must be studied. The analysis of interlinks in combination with hybrid structures was therefore an essential part of the work.

Validation of predictive calculation methods was carried out on test pieces, but also on structures.

Investigations were led by searching better integration of functions, which will result in reductions in weight and costs of body shells: weight gain of at least 1 ton with equivalent mechanical performance.

Industrial reproducibility at a cost level that would be compatible with the current and future situation of the railway vehicle market, the capability of producing pre-equipped sub-assemblies (mechanical and electrical equipment, interior arrangements, finishing, etc.) that would then be able to be assembled very quickly to form the final coach are investigated into, whilst bearing maintainability requirements in mind.

**Presentation of the concept**

Technical and economical studies lead to using the right material in the right place. Materials and design of the structure shall comply with:

a) Mechanical functions (constraints in static and dynamic service conditions as per standard EN 12663),

b) Fire-behaviour constraints,

c) Electrical functions,

d) Comfort and ride-quality functions,

e) Impact-resistance functions,

f) Repair requirements

Amongst these functions, certain are specific to railway applications and were in-depth analysed (for instance, current return, drop of catenary, impact-resistance).

**Basical structure design**

This project started in October 2000 with a preliminary analysis. After having made an initial design study, we are now in a position to give a complete definition of trailers and their main sub-assemblies.

There are 6 main sub-assemblies:

- A steel floor,
- Two multi-material sidewalls (symmetrical to the Y = 0 plane)
- One multi-material "carrying end"
- One multi-material "supported end"
- One steel roof.

Within the scope of the Multi-Material Intermediate Coach concept, investigations have been made – individually for each sub-assembly – into the opportunity of pre-equipping these elements with their trimmings before they are integrated into the trailer.
Side walls

The side walls are made up of 3 types of parts:
   a) end modules: monolithic carbon epoxy laminate
   b) repeat modules in RTM: HR multi-axial dry-fabric
   c) external skins: monolithic hybrid carbon/glass laminate

The composite-material side wall has a particular feature: the triangulation of posts. The side wall is made up of modules incorporating the triangulation; the assembly is riveted and laminated. The modules enhance the mechanical behaviour of the side wall thanks to reinforced stiffness, which enables reduction of both weight and width of the window piers. Sensitive areas at the window corners are thus eliminated and the bonding areas of exterior skin are enlarged. The modules may be placed indifferently along the side wall. The exterior skin makes up the link between all modules.
The ends

The carrying end and the supported end are essential elements in terms of safety. They are made of monolithic carbon epoxy laminate.

The structures are calculated so that:

a) at no time during their life cycle, they are subjected to deformation or propagating damage, in particular under the effect of exceptionally high stress,

b) no fatigue failure of materials occur within the structures, for thirty-five years of service life,

c) The eigenfrequencies are uncoupled from the operational frequencies.

Carbody assembly

Underframe / side wall connection (steel / composite materials)

Roof/side wall connection (steel / composite materials)

Carbody ends with the tube: in this case, two materials of different natures (underframe in steel, sidewalls in composite material and roof in steel) are connected together.

Assembly is made by means of rivets or bolts. Resin is used to recover the tolerance dispersion.

It would also have been possible to envisage metallic inserts in the carbody ends for attachment of the metal parts. Such inserts would have to be specifically designed: they are embedded in the laminate (mechanically integral with the laminated structure) and have threaded ends to enable attachment to the structure by traditional bolting. This solution was not chosen, for reasons of fatigue resistance of the inserts.

3. COMPOSITE MATERIALS

Given the requirements of the specification, in particular requirements in terms of “mechanical strength, fatigue, safety, dimensional stability, life time, economical aspects”, the choice of basic resin is “epoxy”.

Materials that comply with the specifications
- fibre glass – epoxy resin: less light-weight solution (density: 1.8 to 2.0)
- carbon fibres – epoxy resin: most expensive but most lightweight solution (density: 1.6)
- fibre glass – polyester resin: less expensive but less effective solution

The main difference lies in the higher rigidity of carbon fibre – intrinsically at least 3 times more rigid than fibre glass.

Description of conceivable technologies

There are many possible variations to a process methodology. The detailed descriptions below may not list all possibilities offered by these techniques, but at least they take stock of those that are applicable to manufacturing.

Drape forming

This manufacturing procedure, sometimes called "autoclave drape forming", consists in placing pieces of pre-cut prepreg fabric on a model or mould and in polymerizing the structure in a specific curing cycle, most of the times in an autoclave. The type of fabric, the orientation of the fibres, the number of pieces of fabric (or plies) and the pre-cutting dimensions are defined by the Engineering and Design Office.

The main interest in this procedure lies in that the fibres can be placed in the direction of the stress that the part will be subjected to, and that perfect prepreg semi-finished products with a very precise fibre content can be produced. However, the procedure requires a great deal of manpower and a long time for implementation.

Drape forming automation

Manual intervention can be limited to manipulation of the plies exclusively, that is, cutting the plies using an automatic process ((hyperbaric water jet for instance), automatic control of correct position of plies in the mould as they are placed (by visual control), and change from one work station to another by conveyor belt.

The application of the above procedures are notable improvements to the basic process and can reduce the costs, provided that the manufacturing series are sufficiently large.

Contact moulding

This is one of the oldest procedures used for manufacture of composite-material parts. It consists in successively impregnating several layers of fibres with thermosetting resin, giving it the required shape by means of a mould.

To start with the process, a mould release agent is applied. There are two main types: wax and film.

Resin Transfer Moulding (RTM) and "infusion"

This designation is used for technologies the common principle of which is to place fibre laps in a mould and to add resin, either under pressure or under vacuum.

Amongst the industrial applications, there are parts of any industrial sector and any geometry, from single-block floating pontoons of 10 m in length produced in some hours, to automobile car bodies manufactured in some minutes, at the rate of 300 to 500 per day.

By comparing the different technologies in their standard conditions as per the state of art, in decreasing order of mechanical characteristics, we state the following:
- by prepreg drape forming: regular fibre rate, quite high (in the order of 60%),
- by RTM: fibre rate regular and mean (< 40%),
- by contact moulding: fibre rate quite low (20 to 30%), impregnation quality and characteristics less good and depending on the laminating operator's skill.

This decreasing order is in particular related to the fact that mechanical characteristics are directly proportional to the fibre rate, and they are more significant if the fibres are equally taut (because they all withstand the mechanical stress at the same time).

**Material prices**

The purchase price of basic constituents (dry fibres and resin) is, of course, much lower than that of preimpregnated fibres.

The ratio between the "prepreg with regulated fibre rate" price and the "separate constituents" price is at least 2 to 3 in most cases.

**Validation**

Alstom and the SNCF have jointly been leading a validation campaign for materials and assembly techniques over the last 5 years.

Please find below some of the conclusions relative to these investigations.

**Suitability for Repair**

There is little difference in terms of suitability for repair for the various processes. The following stock may be taken:

- small repair actions: scoring or superficial damage (not damage to fibres!) due to light and localized impacts. In such cases, the difference between the processes will not be relevant. The repair will consist in adding resin and sanding after hardening. This is also valuable for through-going but very localized damage (a hole of only some millimetres, for instance).

- Mean repair: more serious damage where the first layers of fibres are damaged over several centimetres. In this case, the differences between the processes become evident. The repair actions will mandatorily be made by hand and consequently, the mechanical characteristics obtained will not be the same as those of a machine rolled laminate. So if a structure was designed and dimensioned taking account of the characteristics of machine-rolled laminate, further repair seems difficult, except if an "extra thickness" in the repaired area is accepted. Except this particular feature for rolled laminate, repair is less difficult using the other processes, as the characteristics of the laminate added for repair are close or even identical to those of the basic laminate (case of contact moulding, for instance).

- Significant repair: through-going damage over a large area (several centimetres). The differences between the processes become still more evident. It would be difficult to give the same characteristics to a machine rolled structure, except with an excessive thickness in this area, which can be achieved from the inner side. It will however be possible to restore the moulded structure by contact moulding and, with greater care, with the draped structure (note: Air France have a special workshop for repair of carbon-epoxy draped aerofoils for the Airbus. The damages are sometimes rather significant, especially when caused by lightning).

- Heavy damage: an element that is seriously damaged over several meters (even if it is bonded) may be removed and replaced using the drape forming, RTM, infusion and contact moulding
process. However, machine rolled structures must be entirely replaced.

**Impact-resistance**

Intrinsically, composites based on carbon fibres are more fragile than those based on glass fibre. However, the design (dampening structures for instance) is essential for the behaviour.

Behaviour of composites to hail impacts is very good: the hailstones rebound without leaving scuffs, unlike on metal sheets.

Ballistic protection often uses the Kevlar fibre (for bullet-proof vests, military helicopter cockpits, military helmets, etc.). The multimaterial design also allows for improvement of behaviour by inserting hard and resilient layers, which will deviate the projectile.

**Fire-resistance**

When submitted to fire, a composite material structure (epoxy or polyester) will char without melting, i.e. the walls will lose their thickness – more or less quickly, according to the fire intensity – until they sag, like tree trunks in a burning forest. The structure will not sag by melting down as a steel framework would.

Unlike a metal structure, the material will not propagate the fire heat by thermal conductivity either.

However, the composite material burns, on the contrary to metal, more or less depending on its makeup and presence of specific fire-retardant products. Its combustion also generates toxic gases, which is the reason for classification being used in railway construction. It takes account of two aspects: M for combustibility and F for smoke toxicity.

The required classifications are the following (for information: no polymer obtains grade M0):
- for the roof: \( \leq M1F4 \)
- for side walls: \( \leq M1F4 \), possibly M2F3 – to be decided case per case
- for floors: \( \leq M2F3 \)
- for air-conditioning ducts: \( \leq M1F1 \) (most difficult classification for polymer).

**Electrical conductivity:**

Carbon fibre is slightly conductive and allows a certain degree of electromagnetic screening to be achieved. It is also possible to incorporate a copper-wire fabric into the moulding or to apply a paint containing silver.

The most efficient screening is by metallization (aluminium, for reasons of weight). The composite materials can be metallized in different ways: electroplating (after application of a conductive coat), vacuum (for small and mean parts – this procedure is currently developing but remains restrained to parts that are likely to enter a vacuum chamber), zinc projection (granular surface appearance and limited to zinc) or by bonding of an aluminized film.

**Sound and vibration isolation**

The specifications for vibration and dynamic comfort are part of the mechanical dynamic design studies; they take account, in particular, of the modulus of elasticity and density of the material, together with the geometrical structure.

Usually, sound insulation is most efficient with flexible polyurethane foam, but the geometrical design is almost as important as the nature of the used material.
Environment-resistance and maintenance

The carbodies are exposed to inclement weather conditions and to temperatures ranging from –25 to +35°C, with a service life of at least 30, often 40 years. This is not a relevant issue if the materials chosen are epoxy resin or polyester resin with anticorrosion features, whatever the nature of the fibres, carbon or glass.

The "maintenance" aspect is not a relevant issue either (please refer to the preceding section dealing with the differences with regard to "repair").

4. ECONOMIC EVALUATION

This is essential, but difficult to achieve given the possible disparity of design (prototypes/series).

The customers strongly tend to refuse extra costs for manufacturing even though these are compensated by economic gains in commercial service and for maintenance.

In the majority of cases, this economical topic is the determining factor for the decision to use - or not use - composite materials.

Within the scope of investigations, the following basic elements have been validated:

   a) Basic technology: the prepreg drape forming may be completed by an RTM-type technology;
   b) With a view to reducing the labour costs, the development (already initiated during investigations) of multiaxial prepreg must be continued;
   c) With a view to reducing the material costs, investigation into low-cost carbon must be continued;
   d) With a view to reducing the manufacturing labour costs, a certain number of work stations must be automated.

5. CONCLUSION

For the time being, composite materials essentially have entered the sector of non-load carrying parts or semi-strain parts. In the sector of structural parts, the development has been longer, and investigations are continued by the construction of a natural-scale structure which will soon be set into service.

For ALSTOM, the stakes

are of economical, technical but also strategic nature. In fact, facing the more and more "aggressive" competition, this innovative project shall allow us to keep our technical advantages.

The manufacturer is embarking on modularity techniques and on use of new materials, in order to customise the rolling stock vehicles according to the various Customers' requirements.

The initial stakes – mastering the construction of a structure in composite materials – will therefore be completed by the stakes of definition ("mastering the specifications"), manufacture ("mastering the characteristics of constituent parts") and characterization of composite-material connections ("mastering the assembly methods").

The following step should therefore be the observation of the concept in service conditions.

The economic analysis shall be global and is to consider not only the manufacturing costs, but also the costs induced for commercial service and maintenance (Life cycle Cost) – "mastering of costs".
For SNCF, the stakes

- are of technical nature on the one hand, as they have to draw up clear specifications and therefore must master any new technique. They must be able to accept new technology and to foresee the behaviour, in service conditions, of the future rolling stock proposed by the manufacturers, whilst always keeping the target in mind: enhancement of performances. The SNCF cannot commit themselves to accepting a new concept if they do not know the behaviour in service-conditions and the effects on commercial operation and maintenance of rolling stock vehicles.

– are of economical nature on the other hand, as the rolling stock vehicles must be maintained for 40 years and maintenance costs must be reduced. The SNCF master and know all maintenance aspects for their current rolling stock vehicles, from the industrial as well as from the economic point of view.