ABSTRACT

This paper presents an overview of manufacturing, static/dynamic test and validation work carried out on composite rail vehicle structures. Two case studies, detailing the development and experimental validation of a composite bodied people mover and a foam core composite roof for a regional train are presented, demonstrating new and novel applications of composite materials within the rail industry. Particular reference is made to the static and dynamic performance of these structures. It is concluded that composite materials offer a viable alternative to traditional steel and aluminium components on a wide range of rail vehicles, in terms of both performance and cost.

1. INTRODUCTION

The use of composite materials in semi-structural railway applications is widely accepted. Composites offer a number of advantages for low to medium volume production over metallic alternatives, primarily component cost, reduced weight and reduced manufacturing investment. Examples of some current applications include cab fairings on a wide range of vehicles and body structures for light rail applications, see Figure 1.

Figure 1. Regional train with non-structural composite cab fairing and composite bodied monorail vehicle

This paper presents the design and development of two composite rail structures and the results of physical testing. Results are compared to simulations performed during the design and development phases. The first structure is a carbody for a light rail vehicle, which was extensively modelled and tested to validate the design. The second structure is a composite roof for an aluminium bodied regional train. The whole vehicle bodyshell was proof tested to certify the strength of the structure and sections of the roof were dynamically tested to validate numerical modelling techniques for the composite.

These case studies are typical of the approach taken during the pre-production phases of a rail project, since all new vehicles are required to meet a range of customer specified and legislative structural requirements before certification for passenger use. These requirements are often dependent on the type of vehicle and the country of operation, although they usually include a range of static loadcases, a dynamic stiffness requirement and various crashworthiness targets. In the UK, minimum requirements are detailed by the Railway Group Standards and similarly for the whole of Europe by the EN12663 standard (Working Group CEN256/WG2). To fully validate a new vehicle against these standards, it is therefore usually necessary to perform a range of numerical simulations and physical tests.
2. CASE STUDY 1: DEVELOPMENT AND TEST OF A COMPOSITE BODYSHELL AUTOMATED PEOPLE MOVER

The APM (Automated People Mover) under consideration is designed for automated guideway transit systems. It is approximately 12 metres long, and can carry 100 passengers at speeds of up to 80km/h. The vehicle is supported on rubber-wheeled axles, steerable from central guidance on a dedicated track.

The carbody consists of a steel chassis, incorporating attachments for the suspension and underframe equipment, supporting an all-composite bodyshell, as shown in Figure 2. The carbody is constructed from six separate glass-reinforced plastic mouldings; bonded and bolted together, forming one integrated load-bearing structure designed to meet the specified strength and stiffness requirements. The composite panels in the vehicle were manufactured using SCRIMP (Siemens Composite Resin Infusion Process). The reinforcing fibre selected was E-glass, with a vinyl-ester matrix material, laminated over a balsa core.

Figure 2. Composite bodyshell people mover with steel underframe

A summary of the structural loadcases that the vehicle is required to meet are given in Table 1. These loadcases are typical of the requirements for new vehicles and include static fatigue and proof loads and a dynamic carbody stiffness. All of the loadcases were simulated using the implicit finite element (FE) analysis technique and comparison was made with results from physical testing. The results from loadcases 3 and 11 are presented along with the corresponding test results.

<table>
<thead>
<tr>
<th>Loadcase</th>
<th>Description</th>
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<tbody>
<tr>
<td>1</td>
<td>1.0g x tare mass vertical</td>
</tr>
<tr>
<td>2</td>
<td>Longitudinal compression on the coupler</td>
</tr>
<tr>
<td>3</td>
<td>1.0g x fully laden mass vertical</td>
</tr>
<tr>
<td>4</td>
<td>Vertical force acting downwards on 152mm x 102mm area of roof</td>
</tr>
<tr>
<td>5</td>
<td>0.3g x tare mass acting laterally</td>
</tr>
<tr>
<td>6</td>
<td>0.3g x normal passenger mass acting laterally</td>
</tr>
<tr>
<td>7</td>
<td>Lateral wind pressure</td>
</tr>
<tr>
<td>8</td>
<td>Combined 1.0g longitudinal load and 1.0g x tare mass vertical</td>
</tr>
<tr>
<td>9</td>
<td>Combined 1.0g longitudinal load and 1.0g x fully laden mass vertical</td>
</tr>
<tr>
<td>10</td>
<td>2g x tare mass vertical jacking load</td>
</tr>
<tr>
<td>11</td>
<td>Dynamic stiffness - 1st vertical frequency &gt; 7.5 Hz</td>
</tr>
</tbody>
</table>

Table 1. Loadcases for design of APM carbody

For the simulation of the composite material behaviour, laminated material properties were derived using classical laminate theory. This approach combines the elastic properties of the resin and fibre to give an overall material behaviour, which can be input as material model parameters in the FE code. Since the analysis was required to predict behaviour up to proof load, non-linear damaging behaviour was not considered for this work. Composite material failure criteria were used to confirm that the multiaxial stress states in the composite shell were within 'safe' limits.
2.1 CASE STUDY 1: LOADCASE 3 (1.0g x FULLY LADEN MASS VERTICAL)

For the fully laden vertical loadcase a pre-production vehicle, similar to that shown in Figure 3, was tested. The bodyshell was supported rigidly at the axles and a distributed load was applied internally to the floor. Vertical deflection of the underframe was measured at various points along the length of the vehicle. During test, there was a measurable variation in the deflection when comparing the left and right hand side of the vehicle. This was due to the non-symmetrical equipment mounted to the underframe, marginally affecting the bodyshell stiffness. The deflection was therefore averaged to give a centreline deflection, which could be compared to simulation results.

The FE model was generated from a mid surface CAD model and was meshed using shell elements. Shell elements are ideally suited to the simulation of laminated composite materials as they can efficiently capture the behaviour of relatively thin structures. A quarter model with symmetry boundary conditions along both the longitudinal and lateral plane was used for computational efficiency. This model was also used for the analysis of the modal response of the vehicle and the other proof and fatigue loadcases.

Figure 4 shows the displacement of the bodyshell along the length of the vehicle, compared against the results of simulation. It can be seen from this figure, that during test, the bodyshell displacement was limited to a maximum of approximately 7 mm which is within the target stiffness. The structure itself exhibited no permanent deformation and joints remained intact in all areas.

Comparison of the test result with the calculated displacement from the FE model shows good agreement. Simulation results are within 1.1% based on the average test deflections along the structure. The FE model therefore accurately represents the structural performance of both the steel and composite components, which validates the model and gives confidence in the levels of calculated stress and strain in the carbody structure.

Subsequent simulation results for the remaining static loadcases showed that the vehicle structure was compliant with the legislative requirements and those detailed in the vehicle technical specification.

Figure 4: Vertical loadcase underframe deflection

2.2 CASE STUDY 1: LOADCASE 11 (DYNAMIC STIFFNESS)

A dynamic test was carried out on the prototype vehicle while running on the test track, to evaluate the natural frequency of the sprung carbody. This test used an accelerometer mounted on the vehicle body structure to determine the first vertical bending natural frequency. This type of assessment is used to evaluate the ‘passenger comfort’ of a vehicle as well as giving a qualitative measure of the stiffness of the sprung carbody. The FE model developed for simulation of the static loadcases was also analysed in the free-free condition to determine its 1st vertical bending frequency. This result was compared to the experimentally obtained value.

Figure 4 shows the frequency response of the vehicle during test and the analytical result. The contour plot from the FE simulation shows the displaced shape of the vehicle and is used to confirm that the analysis is capturing the 1st vertical bending frequency and not higher order modes, or resonances in localised areas of the structure.
Both experiment and simulation show that the vehicle meets the specified target of >7.5 Hz. The predicted natural frequency is within 3% of the measured frequency and, like the vertical loadcase, confirms that the model is an accurate representation of the vehicle as manufactured.

2.3 CASE STUDY 1: CONCLUSION

This case study has given an overview of the typical structural requirements for a vehicle and the approach to validation and test of new designs. In the case of this vehicle, the use of a composite material as an integral part of the structure, lead to a requirement for thorough validation through test and the generation of complex models for the glass reinforced plastic components in the design. The FE technique employed, when compared to experimental results, has been shown to be accurate to within acceptable limits for various loadcases, including static and dynamic (modal) situations.

3. CASE STUDY 2: DEVELOPMENT AND TEST OF A REGIONAL TRAIN COMPOSITE ROOF STRUCTURE

In this case study, a composite roof structure for a regional rail vehicle will be discussed. This component is a prototype part, designed to evaluate the potential of such structures to replace more conventional steel or aluminium designs. The vehicle that the roof is designed for is currently constructed using a modular assembly technique known as Complete Knock Down (CKD). This involves manufacturing large components or structures prior to final assembly and then subsequently combining these modules to produce a finished structure, see Figure 6.
The CKD technique allows development of novel technologies for specific components or modules without the need to fully redesign a vehicle. Using this approach, a new material or design can be validated in a low risk environment and then subsequently developed for new vehicle programmes.

Figure 7 shows a CAD model of the composite roof structure, which was developed to replace the existing aluminium extruded design. A certain amount of optimisation of the structure through part integration and modification of the existing design was possible, although, on a new vehicle, the potential for further improvement is greatly increased.

The structure is manufactured using a resin infusion process, similar to that used in the people mover case study. Aligned glass fibres were predominantly used for the reinforcement, although in areas of high stress, unidirectional carbon fibre was included in the layup to increase stiffness and strength. A foam core material was chosen, rather than balsa, for economic reasons, due to the size of the component (approximately 21 m in length). The choice of foam as a core material also allowed improvements in the performance of the structure and the ability to form more complex shapes.

The vehicle is a specific design for the UK market and therefore must conform to local legislation before acceptance. The structural requirements for multiple unit vehicles such as this are detailed in the UK Railway Group Standards[1]. These standards include a range of proof loadcases, similar to those for the people mover, as well as crashworthiness requirements. The vehicle is also expected to meet ride quality and bodyshell stiffness targets, measurable by the modal response of the structure.

The crashworthiness targets are of particular interest when investigating the behaviour of composites, since their energy absorption characteristics can offer improved performance over metallic structures. In the UK, regulations covering the performance of rail vehicles specify that energy absorption should be managed in specific modules and that the passenger tube should remain intact in low to medium speed collisions. Recently though, customer requirements and the response to initiatives to improve performance of rail vehicles, have led to the investigation of high speed collision scenarios. In these scenarios it is important that the behaviour of the bodyshell can be modelled accurately, so that predictions relating to these requirements are fully validated. It is for this reason that sections of the composite roof were tested dynamically and complex material models were developed to simulate the behaviour of the component.

3.1 CASE STUDY 2: DYNAMIC TESTING AND MODEL VALIDATION

Due to the physical size of the roof, only a section of the structure was tested. A particular geometry, including part of the aluminium extrusion was chosen, as the test needed to capture the behaviour of the composite structure and that of the bond between the roof and the rest of the vehicle body. Part of the extrusion was cut away to allow the roof structure to be tested without the result being dominated by the ‘end on’ crush performance of the aluminium. The test specimen was impacted with a 1500 kg sled with an initial velocity of 9 m/s. The sled was decelerated at the end of the test using two steel crush tubes, to absorb the remaining kinetic energy. The specimen, pre and post test is shown in Figure 8.
The deceleration of the sled during the test was measured to evaluate the performance of the specimen. High-speed video footage was also taken so that the failure mode during impact could be investigated. The primary failure mode in the roof was delamination and failure in the bond between the composite and the foam core. There was also a significant amount of damage developed in the composite and some failure in the bond between the composite structure and the aluminium.

To use the result from the test to evaluate how a composite roof structure would perform in a high energy collision scenario involving a full vehicle, a finite element model was developed. The test specimen was modelled using solid elements for the foam core and predominantly shell elements for the composite and aluminium, see Figure 9.

![Figure 9: Section of composite roof dynamic test specimen model](image)

The bonds between the composite and the foam core and the roof structure and the aluminium body extrusions were modelled using contact interfaces, with criteria calibrated to fail the bond at predetermined load levels. The composite and foam core both used material models calibrated from coupon test data. Figure 10 shows two of the calibration curves for the composite in tension and compression including subsequent simulations to validate the material models. The aluminium parts of the specimen were modelled using a standard elastic-plastic material.

![Figure 10: Example material model calibration curves and validation simulation results](image)

The simulation of the composite roof section dynamic impact was run with identical boundary conditions to the experiment and results were correlated against results from the test. Figure 11 shows the comparison between the deceleration of the impact sled from test and simulation. It can be seen that the rigorously developed model accurately captures the complex behaviour of the roof component.
3.2 CASE STUDY 2: CONCLUSION

Composite moulding and adhesive bonding technologies have been established to produce a 21 m long train roof incorporating multiple curvature. Significantly fewer parts were used in the composite roof compared to the existing aluminium roof. When compared with the current optimised structure, the first prototype assembled roof showed a measurable weight saving. Improvements in production techniques and design could increase these savings significantly, proving that the technology is economically viable.

The roof structure has been manufactured and fully tested using a range of proof loadcases and sections of the roof have also been tested dynamically. The results have been used to validate a material model, which can now be implemented in larger simulations to fully evaluate the performance of the component when installed in a full vehicle.

4. ACKNOWLEDGEMENTS

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5. REFERENCES