Validation Simulation of New Railway Rolling Stock Using the Finite Element Method

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1   ABSTRACT

Bombardier Transportation is the largest manufacturer of rail vehicles in the world. The current product portfolio includes a wide variety of vehicles from low speed 'people movers' through to high speed inter-city trains. Bombardier offers products in every sector of the passenger rail equipment market and therefore is required to meet a number of national and international crash safety requirements. These requirements range from simple static collapse loadcases to full collision events with other rail vehicles and obstacles. As part of the validation procedure for new designs, finite element (FE) models are produced to simulate new vehicle crash performance against targets set by these requirements.

The simulation of bolted and welded aluminium structures is particularly important for the Carbodies part of the business, since recent 'real life' crash cases have shown bolt failure and weld 'unzipping' as critical collapse modes for extruded aluminium carbody designs. The current technique used for modeling welded aluminium sections and particularly the heat affected zone (HAZ) is presented. Bolt failure modeling within large structures is also addressed and results are presented from calibration tests and simulations carried out to evaluate the failure behaviour of Huck Bolted connections.

This paper presents an overview of the current state of the art in the rail industry and describes, through various case studies, the approach that Bombardier Transportation uses for validation of new vehicles. These case studies also show novel aspects of new vehicle design, which increase safety and highlight the commitment of Bombardier Transportation to a 'design for crashworthiness' approach to new passenger vehicles.

2   INTRODUCTION

In the UK, new rail vehicles are required to meet a range of proof, fatigue and collapse loads before acceptance for use on the rail network. Additionally, in the latest release of the Railway Group Standard[1], specifying structural requirements, an alternative dynamic crash loadcase is defined. Recent customer specifications have also included a crashworthiness requirement, which in some cases exceeds that of the Group Standard.

It is for this reason and for the commitment of Bombardier Transportation to constantly improve the safety of its products, that design and analysis techniques used during the development of new vehicles are becoming more complex.

In the UK, aluminium is extensively used for the production of multiple unit vehicle bodyshells. These structures are constructed and assembled using welded and bolted joints. To fully characterise the crashworthiness of a vehicle a structural analyst must be able to simulate the behaviour of welded and bolted joints in aluminium under dynamic loading, since recent 'real life' collisions have shown these areas to be critical factors affecting structural integrity.

In this paper, the requirements for new vehicles are outlined along with the techniques employed during the design and development phase of a carbody. The process, from concept through to validation is presented with a specific focus on

analysis of crash performance including the strength and behaviour of critical joints in the carbody structure.

3   STRUCTURAL REQUIREMENTS FOR RAIL VEHICLES

When designing a new vehicle there are a number of requirements that need to be met before the design can be certified. These include static and dynamic loadcases for the full bodyshell of the vehicle. In the UK the Railway Group Standard defines these load cases, but similar requirements are specified for other world regions including the European and North American rail systems. For the purposes of this work, the legal requirements for the vehicle bodyshell will be discussed in terms of the UK Railway Group Standards.

Further to these requirements, customer specifications can include additional targets, relating to stiffness, strength, ride quality and crashworthiness.

3.1   Static Loadcases for UK Vehicles

The static loadcases detailed in the Railway Group Standard relate to all aspects of the bodyshell performance. These include longitudinal and vertical loads on the bodyshell, coupler and anticlimbers; longitudinal load on the obstacle deflector; jacking/lifting loads and vertical and transverse fatigue loadcases. (See Appendix A for a glossary of rail vehicle terminology.)

3.2   Crash Loadcases for UK Vehicles

The crash requirements for UK vehicles are defined in two sections of the Railway Group Standard. The first section details general requirements that specify that a vehicle, in the event of a collision, should collapse in a controlled manner, lateral forces should remain below the magnitude, which might lead to derailment, and risk of injury to occupants should be minimised. It also states that collision energy should first be absorbed by the ends of the vehicle and that the bodyshell should have a sufficiently high collapse load to react the crushing force of the vehicle ends.

The specific requirements for structural collapse relating to passenger vehicles are given as, either a quasi-static full-face crush, or a dynamic collapse performance, as well as an override crush. For most current UK vehicles in production, the quasi-static crush requirement is the one that has been met, since this can be relatively easily validated through testing of physical structures. Now though, through increase in computing power, greater understanding and reliability of dynamic simulation and improvements in analysis techniques, the alternative dynamic collapse performance of vehicles is being investigated.

The dynamic crash requirement states that, for multiple unit stock, 'energy absorption should be distributed between the vehicle ends in accordance with a theoretical simulation of a collision between similar trains at a closing speed of 60 km/h'. The requirement also specifies that, to limit the magnitude of the deceleration experienced by the passengers during the collision, the collapse force should not exceed 3000 kN, although short deviations from this load limit are allowable[2].

4   ALUMINIUM CARBODIES

Aluminium is a widely used material for the manufacture of rail vehicle bodyshells. It offers a number of advantages over steel, primarily weight saving and structural strength through design: a typical aluminium carbody could withstand end proof loads of approximately double that of a similar weight steel carbody.

4.1   Aluminium Grades Used in Current Vehicles

The current UK Electrostar and Turbostar vehicle carbodies are manufactured from 6005 aluminium alloys. The alloy is extruded as lengths of double skinned section and subsequently welded to form sections of the vehicle. Crashworthy cab and intermediate end structures are currently manufactured from carbon steel, although more ductile grades of aluminium, for example 5000 series have been used for this application and extrudable over aged 6000 series alloys, such as 6008 T7 are also becoming popular alternatives.

4.2   The 'Complete Knock Down' (CKD) Construction Method

The 'Complete Knock Down' construction method used for aluminium carbodies manufactured by Bombardier Transportation in the UK allows highly efficient vehicle assembly. Roof, bodyside and floor panels are extruded and welded to form the basic components of the vehicle. Equipment and trim are then fitted to the panels before the bodyshell is bolted together. Cab and intermediate end modules are also manufactured and fitted out before being supplied to the production line as bolt on items. An exploded view of the basic components of a CKD vehicle is shown in Figure 1.
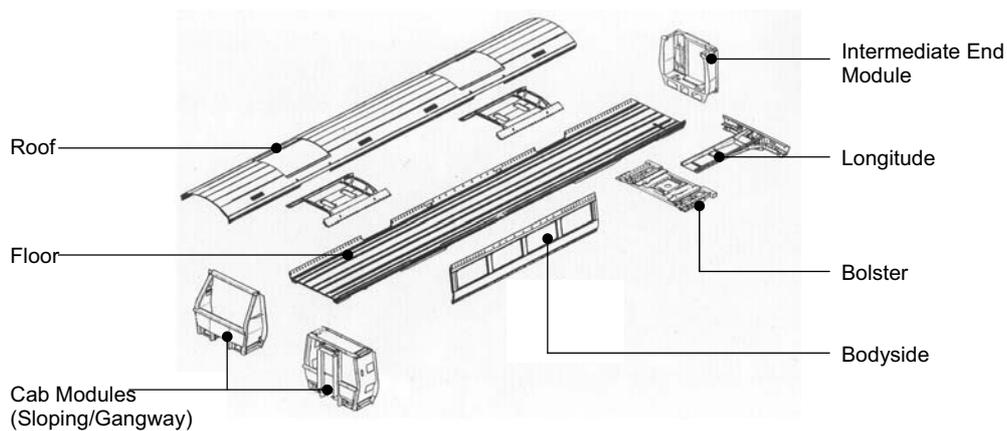

Fig 1   Components of a 'Complete Knock Down' (CKD) vehicle

Since the carbody plays an important part in the structural integrity and crashworthiness of a rail vehicle, this manufacturing method leads to a requirement for, not only an understanding of the mechanical behaviour of the parent metal, but also of the welded and bolted joints.

4.3   Joining Techniques

Various techniques are available for welding and bolting carbody structures to form a shell. Currently the most widely used welding techniques for rail applications are MIG, Twin Wire MIG and Friction Stir Welding (FSW). Each offers various performance and commercial advantages and comparative studies are being undertaken to evaluate these. For the purposes of this paper, only MIG welds will be evaluated, although the analysis techniques would be equally applicable to the other methods. Figure 2 shows a current vehicle floor structure post welding, prior to final assembly.

The bolted joints evaluated in this study are Huckbolt™ connections, since these are used for current vehicle manufacture, although other bolting methods are available and could be evaluated using a similar method. Figure 3 shows a typical bodyside/floor Huckbolt™ connection being assembled.

Fig 2   Current vehicle floor structure   Fig 3   Bodyside Huckbolted™ joint

5   DESIGN AND VALIDATION OF A NEW VEHICLE FOR UK OPERATION

Throughout the design and validation of a new vehicle, finite element analysis (FEA) techniques are employed. Both linear and non-linear static and non-linear dynamic analysis codes are used to evaluate the design against static loadcases and crash loadcases, respectively. The models used often appear similar for the static and dynamic work, although there are a number of differences. Often the areas where a static model needs to be refined, a dynamic crash model does not and vice versa. For example in the crash structures at the end of a carbody, a dynamic model would use a fine mesh, whereas this level of detail would in most cases not be necessary for a static loadcase.

Material models and failure criteria are also an area where the modelling techniques differ significantly. A static loadcase would require a basic material model calibrated using standard linear elastic material constants. A dynamic model, if being used to simulate plastic deformation and potential failure, needs a more complex non-linear material model, which describes both the elastic and post-yield behaviour of the material.

5.1   Static Loadcase Models

Static loadcase models are generated by creating layers of shell elements using a mid-surface geometry exported from the CAD model of the vehicle. Loads and boundary conditions are applied to represent each loadcase and a linear analysis is run for each. The von Mises stress contour results from these models are then used to evaluate the compliance of the vehicle with Railway Group Standards. Non-linear static analysis may also be conducted if structural behaviour beyond yield needs to be investigated.

In these models, bolts are represented using 1D beam elements. Bolt loads are taken from these beams and evaluated to assess whether the forces are within the limits at which bolt slip would occur. Stresses from parent metal and welds are evaluated using the British Standards BS8118[3] (aluminium) and BS7608[4] (steel), which give weld classifications and their corresponding allowable stress levels.

These methods have been used extensively and are widely accepted as suitable for the design and static validation of rail vehicles.

5.2   Crash Loadcase Models

The simulation of crash loadcases for rail vehicles is more complex, not only because of the size of the models and nature of the loading, but because the techniques available to the analyst for assessment of bolted and welded joints are less well documented than those for static cases. Also a more extensive and iterative approach to design is required for crash structures, so a larger number of geometries and potential solutions need to be evaluated.

This has lead to the development of a process for crash analysis, which starts with very simple 1D models representing a full train, right through to simulations of full vehicle crash scenarios.

Typically, for UK multiple unit vehicles, a four car set is simulated. Initially a 1D model is generated using a number of non-linear spring elements. These springs are calibrated to represent the crush behaviour of separate sections of the vehicle. Models of this type allow an analyst to define the 'ideal' crush behaviour for the crash structures and carbody, by running a number of simulations and assessing crush force, crush distance and deceleration in the passenger saloons against standard and customer specified requirements.

Figures 4 shows a schematic representation of a four car set and Figure 5 shows how each car is represented as spring elements. In Figure 5 the bogie spring is offset for clarity and is co-linear with the other springs in the actual model.
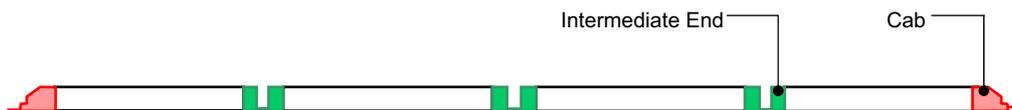

Fig 4   Schematic of a four car multiple unit rake showing energy absorbing zones
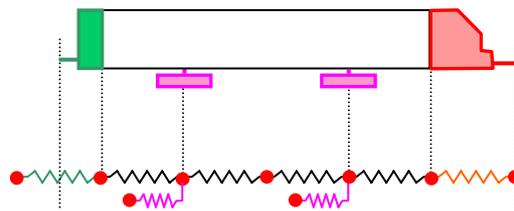
Fig 5   Spring element representation of cab end car for 1D analysis

Subsequent to the 1D modelling of a vehicle, crash structures are designed and developed and 3D shell element models are generated to validate each of the energy absorbing structures in isolation. Finally, when this has been completed a full, four car set, model is generated to validate the design. The mesh and model at this stage are often based on a refined version of the static analysis model for the vehicle, with the addition of the validated crash structure models.

Since the first car is often subjected to the highest loading and absorbs the most energy in a frontal collision, usually only this car is modelled fully. The crash structures of subsequent cars are modelled, but it is not usually necessary to model the full carbody, unless a high collision energy scenario is being investigated. For the trailing cars, the intermediate ends are connected with rigid elements, which are given density properties to provide the correct mass, see Figure 6. This technique allows an accurate representation of the vehicle to be analysed, without the need for prohibitively large models. (A single car model can often contain over 250,000 elements.)
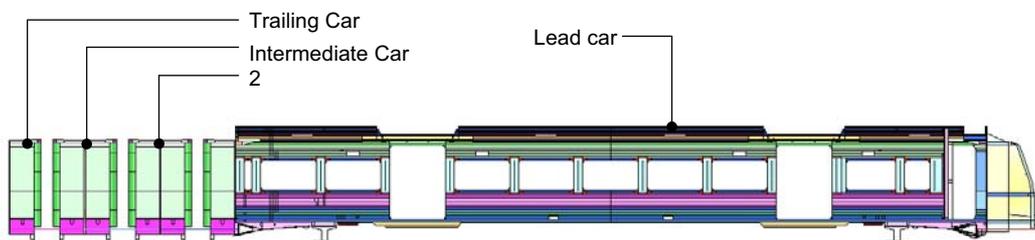

Fig 6   3D analysis model with 'simplified' intermediate and trailing cars

In the case of the Railway Group Standard crash scenario, of a head on collision between two identical vehicles at a relative speed of 60 km/h, this type of model is sufficient to validate a new design. For this case, a half model (with a longitudinal plane of symmetry) would be simulated impacting with a 'rigid wall' at 30 km/h, taking into account the two planes of symmetry in the scenario.

In evaluating the results from a dynamic simulation, visual inspection of the displaced shape, plastic strain and the reaction load at the rigid wall can be used to ascertain whether a vehicle has met the requirement or not. It is also important though to consider the joints in the carbody to assess whether failure has occurred in the passenger saloon areas due to the loads associated with crushing the cab and intermediate end crash structures.

5.3   Dynamic Simulation of Welded Aluminium Joints

To assess failure in the welded aluminium joints in the carbody, a modelling technique which accounts for the difference in properties between the parent metal and weld metal needs to be employed. Since the carbody structure is large compared to the size of the weld, it is impractical to model the weld zone in detail, with a highly refined mesh.

The modelling method employed for a welded extrusion is detailed in Figure 7. The heat affected zone (HAZ), which has reduced strength compared to the parent metal, is located around the weld. The corresponding FE mesh is also shown. It can be seen that the mesh, due to both its density and the use of shell elements to model a complex 3D weld, is not a perfect representation of the physical structure, although it is accurate enough to determine likely failure in the weld region.
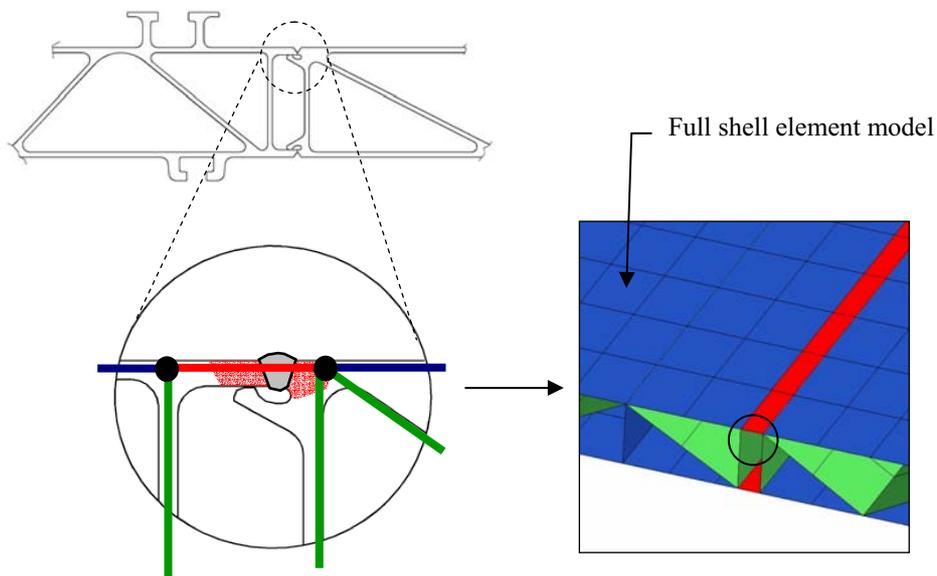

Full shell element model

Fig 7   Section showing geometry, weld location and structure 'as modelled'

Typical material properties assigned to the parent aluminium and the HAZ are shown in Figure 8. The HAZ is calibrated to yield at a significantly reduced stress and to fail at a lower plastic strain than the parent metal. The HAZ properties are calibrated from a tensile test on a specimen taken from the HAZ of a welded aluminium plate.

Parent metal failure strain, which results in element elimination from the model, is set at 0.3 plastic strain. The failure strain of the HAZ is usually calibrated at 0.1 plastic strain, although when assessing the results from a simulation, plastic strains of greater than 0.05 in welded regions are considered to be potential areas of crack initiation and failure.
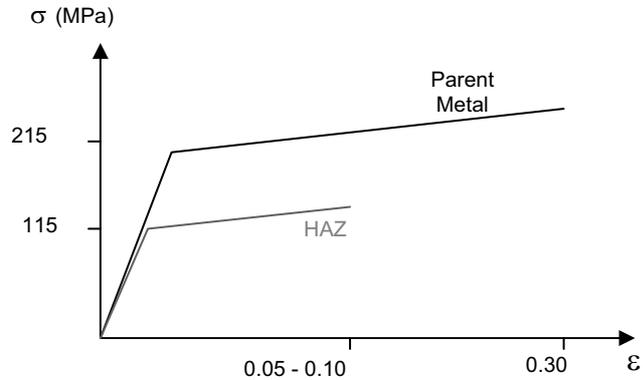
σ (MPa)

Parent
Metal

215

115   HAZ

0.05 - 0.10   0.30   ε

Fig 8   Parent metal and Heat Affected Zone (HAZ) material model curves

5.4   Dynamic Simulation of Bolted Aluminium Joints

Modelling of bolted joints is more complex than welds, since a number of deformation and failure modes can occur. Potentially a Huckbolt™ could fail in shear, tension or tearing through the parent metal. Bolt slip can also occur, where load is redistributed through the joint to other bolts, without catastrophic failure. Therefore, to accurately model a bolted joint, taking into account these modes, a very complex model would be required. Like the welded regions discussed previously, due to the nature of the models, it is impractical to produce a highly refined mesh for each bolted area.

The method used for large crash models connects two bolted plates by a 'spotweld', see Figure 9. This type of constraint allows shear and tensile load data to be assessed throughout the simulation and compared against failure data for the bolts used in the structure. The spotweld can be calibrated to fail the connection between the shells at both a load limit in shear and tension as well as a plastic strain limit in the shells adjacent to the nodes, which are connected. This calibration captures the three main failure modes of a Huckbolted™ joint, although it does not account for bolt slip and load redistribution. The spotweld technique is therefore a conservative approach to simulation of bolt failure.
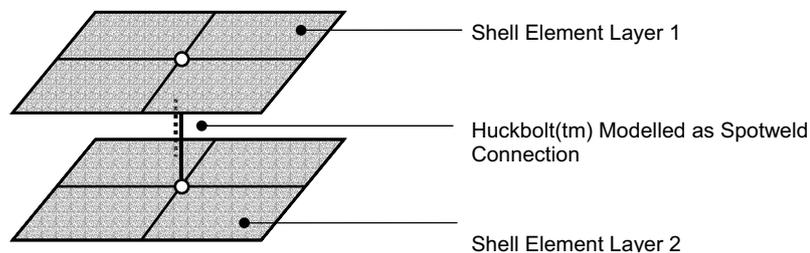
Shell Element Layer 1

Huckbolt(tm) Modelled as Spotweld
Connection

Shell Element Layer 2

Fig 9   Schematic of spotwelded shells representing Huckbolt™ connection

the carbody. Figure 12 shows that, in this case, the largest plastic strain is found in the bodyside weld nearest the front of the leading car. In this location, localised strain in the weld HAZ is 0.03. This is well below the level at which failure would be expect to occur.
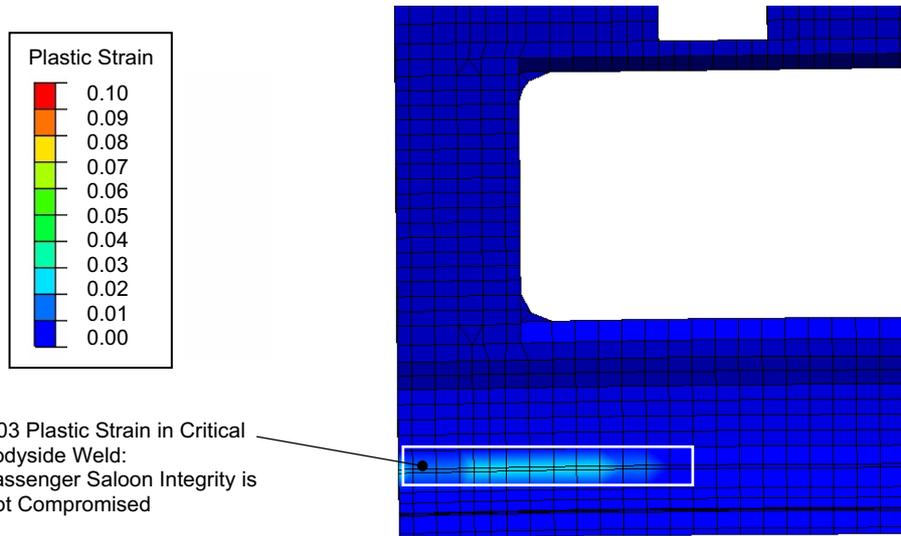

Fig 12 Plastic strain in bodyside weld located at front end of leading car

The two basic calibration tests for spotweld bolt models are shown in Figure 10. These give the shear and tensile failure load data required as input for the FEA model.
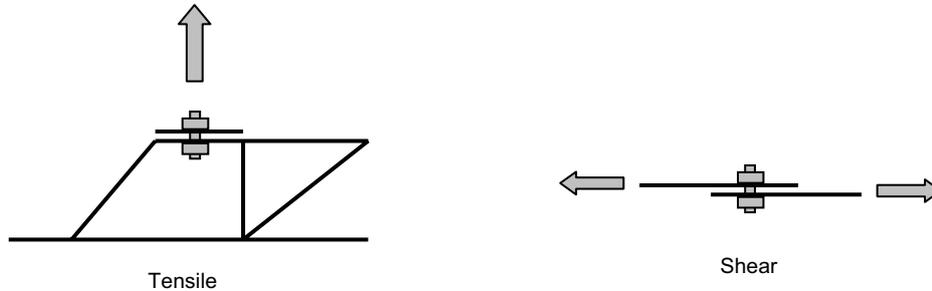

Tensile

Shear

Fig 10 Tensile and shear test configurations for Huckbolt™ failure load calibration

6   TYPICAL RESULTS FROM DYNAMIC SIMULATION

The final validation 3D analysis model for a multiple unit shows how these simulation techniques can be used to produce a fully validated crashworthy rail vehicle. A typical four car set has been simulated colliding with an identical vehicle at 60 km/h closing speed, as defined by the Railway Group Standard.

The displaced shape of the multiple unit four car set after the collision, shown in Figure 11, demonstrates that all crash energy, in this case 6.5 MJ, is absorbed in the cab and intermediate end zones, leaving the passenger saloon intact and preserving survival space.
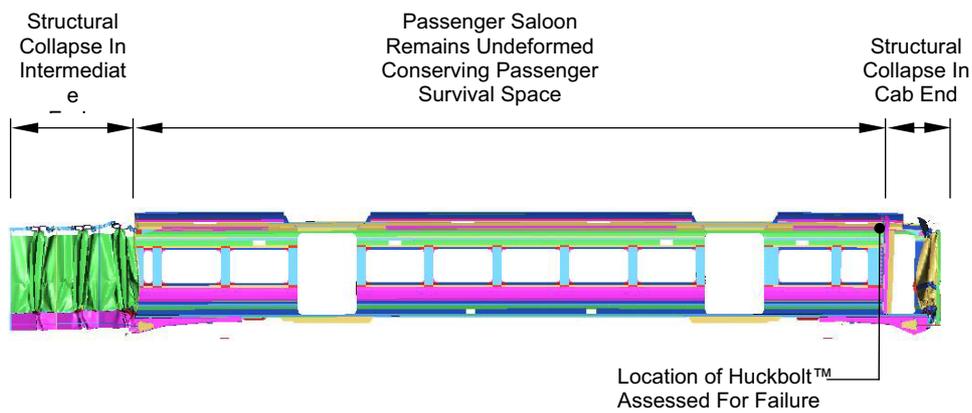

Structural Collapse In Intermediate

Passenger Saloon Remains Undeformed Conserving Passenger Survival Space

Structural Collapse In Cab End

Location of Huckbolt™ Assessed For Failure

Fig 11 Multiple unit post 60 km/h closing speed collision - Displaced shape

To confirm that the carbody is not structurally compromised during the collision, post-processing assessment of welds and bolts is undertaken. Contour plots of weld regions showing plastic strain are used to assess the likelihood of crack formation in

Assessment of the bolted joints in the vehicle also suggests that failure is unlikely to occur. Figure 13 shows a tensile load time history for the upper bodyside bolt nearest the front of the vehicle (see location on Figure 11). Throughout the crash event the load in this bolt remains below a predetermined failure level, calibrated from experimental test. Further bolt load/time histories were also analysed to confirm that bolted joints remained within allowable limits.
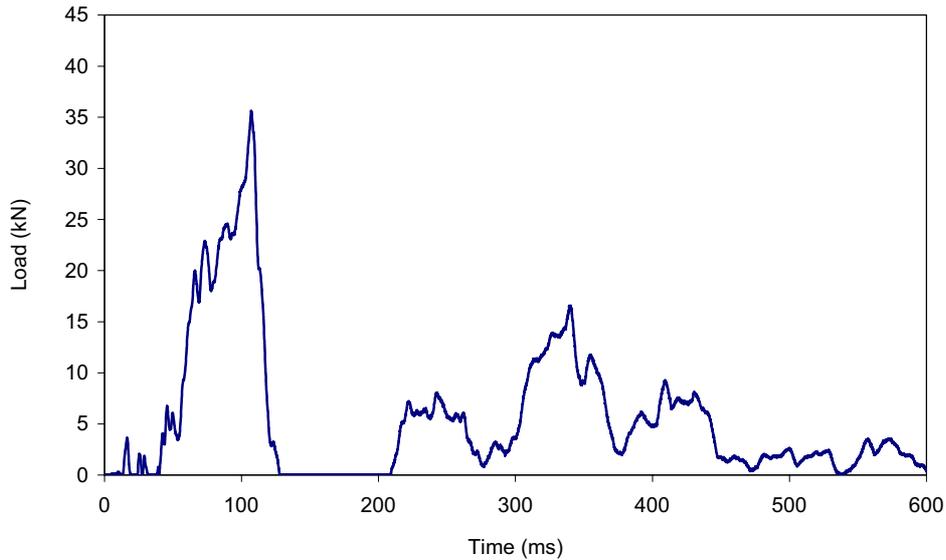

Fig 13   Load/time history for bodyside spotweld, representing Huckbolt™ connection

7   CONCLUSION

The structural requirements for new UK rail vehicles have been presented. The method used to design an aluminium bodied multiple unit rail vehicle to meet these is described in detail. Particularly the structural analysis and simulation work performed to validate an aluminium vehicle against current crashworthiness requirements.

A method for modelling welded and bolted joints in aluminium has been used to confirm that the integrity of the joints in the carbody is not compromised during a 60 km/h collision with a similar vehicle.

LS DYNA is the company standard crash analysis tool that is used by Bombardier. This helps to ensure that we comply with current group standards, and continue to push the crash design envelope of our future vehicles, and maintain our competitive edge in today's safety driven commercial environment.

8   REFERENCES

1.   Railway Group Standard GM/RT2100, Issue 3, October 2000

2.   Railway Group Guidance Note GM/GN2560, Issue 1, October 2000

3.   British Standard BS8118 Structural Use of Aluminium, Part 1. Code of Practice for Design, 1991

4.   British Standard BS7608 Code of Practice for Fatigue Design and Assessment of Steel Structures, 1993

9   APPENDIX - GLOSSARY OF RAIL VEHICLE TERMINOLOGY

Anticlimber - device mounted on ends of vehicle to prevent one car riding over another in a collision.
Bogie - wheel and suspension assembly (can include integrated motor or engine).
Bolster - reinforced structure to which bogie is connected.
Cab end - an end module of a rail vehicle with a driver's cab area.
Cantrail - structural beam running along carbody at the connection between the roof and bodyside.
Car - single rail vehicle.
Carbody - the structural bodyshell of a rail vehicle.
Huckbolt™ - steel locking bolt used in vehicle assembly.
Intermediate end - an end module without a driver's cab area.
Longitude - reinforced member under vehicle floor, running from bolster to coupler.
Obstacle deflector - device mounted on cab end to clear objects from the track and minimise derailment risk.
Set - collection of cars making up a multiple unit.
Solebar - structural beam running along carbody at the connection between the floor and bodyside.