SUMMARY

The crashworthiness of rail vehicles is an important design consideration, particularly for high capacity passenger vehicles. The unified European crashworthiness standard EN15227, released in 2008, brought together the existing research on best practice for crashworthiness design requirements combined with analysis of the most common and serious rail accidents in Europe. EN15227 sets standards for the passive safety design of rail vehicles as a last means of protection when active measures fail.

This paper outlines the design process that Bombardier Transportation utilises from the conceptual stage through to detail design for development of carshells that comply with the passive safety requirements of EN15227.

1. INTRODUCTION

European Standard EN15227 provides a framework that will reduce the consequence of collision events through the inclusion of elements within the rail vehicle design that improves the overall passive safety of the vehicle. EN15227 design requirements are intended to provide the last means of protection when all other active means of preventing a collision have failed. The requirements are compatible with the European Standard EN12663 covering the Structural Requirements of Rail Vehicle Bodies.

Bombardier Transportation crash experts were heavily involved and formed part of the working group in the development of the EN15227 standard. In recent years the design of the Adelaide 4000 class Electric Multiple Unit (EMU) and QNGR EMU has benefitted from this global experience and best practice in the area of vehicle structure and driver cab design and analysis.

Computational analysis is extensively used to simulate structural response to the EN15227 crash scenarios. The recent Bombardier approach to crash design for vehicles in the Australian market has been to ensure a robust cab crash structure that remains rigid through the crash event, and that regions designated as collapse zones are outside the carbody structure. This ensures safe areas for passengers and crew, and negates the need for full scale cab and intermediate end dynamic tests that were usually dictated by previous collapsible cab and intermediate end designs.

This paper describes the design process used by Bombardier in the development of a rail vehicle design compliant with EN15227. The focus is on a category C-1 vehicle design.

2. EN15227 DESIGN COLLISION SCENARIOS

EN15227 defines four design collision scenarios. These scenarios represent the most common collision risks that have been identified in the European rail environment that result in the most casualties. The collision parameters vary depending on the rail vehicle type, speed and operating environment. The four basic scenarios are:

1. A front end impact between two identical train units
2. A front end impact with a different type of rail vehicle
3. Train unit front end impact with a large road vehicle on a level crossing; and
4. Train unit impact into a low obstacle (e.g. car on a level crossing, animal, rubbish).

The standard recognises that it is impractical to design for all possible collision types and scenarios and instead defines a level of protection consistent with the most common collision risks. However, vehicles designed to satisfy the passive safety requirements for the four design scenarios listed above will have a higher level of crashworthiness and level of occupant protection in the event of a collision that varies from the nominal parameters.

3. EN15227 PASSIVE SAFETY REQUIREMENTS

EN15227 compliance is measured against five key passive safety principles:

- Reduce the risk of overriding;
- Absorb collision energy in a controlled manner;
- Maintain survival space and structural integrity of the occupied areas;
- Limit the deceleration; and
- Reduce the risk of derailment and limit the consequences of hitting a track obstruction

The quantitative measure against the passive safety requirements are listed in Table 1.

These passive safety requirements are satisfied by the vehicle Crash Energy Management System (CEMS).

<table>
<thead>
<tr>
<th>Passive Safety Requirement</th>
<th>Measure</th>
<th>Requirement</th>
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<tbody>
<tr>
<td>Carbody deceleration</td>
<td>Mean deceleration</td>
<td>Scenario 1 &lt; 5g</td>
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<tr>
<td></td>
<td></td>
<td>Scenario 2 &lt; 5g</td>
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<td></td>
<td></td>
<td>Scenario 3 &lt; 7.5g</td>
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<tr>
<td>Residual space preservation</td>
<td>Shortening of occupied space</td>
<td>&lt;50mm reduction in length over 5m</td>
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<tr>
<td></td>
<td></td>
<td>&lt;100mm at vehicle ends</td>
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<tr>
<td></td>
<td></td>
<td>&lt;30% reduction in vestibules</td>
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<tr>
<td></td>
<td></td>
<td>No infringement in driver’s survival space</td>
</tr>
<tr>
<td>Structural stability</td>
<td>Plastic strain in occupied areas</td>
<td>&lt;10% plastic strain</td>
</tr>
<tr>
<td>Derailment risk</td>
<td>Wheelset lift</td>
<td>&lt;75% of nominal flange height on at least one wheelset</td>
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<tr>
<td></td>
<td></td>
<td>&lt;100mm if anti-override device engaged</td>
</tr>
</tbody>
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Table 1: EN15227 Passive Safety Requirements

4. KEY ELEMENTS OF A CRASH ENERGY MANAGEMENT SYSTEM

A Crash Energy Management System (CEMS) typically includes a combination of fixed and energy absorbing elements that work together to manage the collision. Key elements of a Bombardier CEMS include:

- Auto-coupler;
- Intermediate or Inter-car Couplers;
- Anticlimbers integrated with Energy Absorbing Elements (Collision Tubes); and
- Cab Structure/Intercar Collision Posts

An example of the CEMS elements for the typical EMU are shown in Figure 1. A more detailed view of the leading end showing the Auto-Coupler and Collision Tubes is shown in Figure 2.

5. EN15227 DESIGN PROCESS

For Bombardier, the development of an EN15227 compliant design is generally a six stage process:

1. Develop Crash Concept
2. 1D Rigid Body Analysis
3. Hybrid 1D Rigid Body Analysis
4. Preliminary 3D System Analysis
5. Energy Absorbing Elements – Design and Verification
6. Final 3D System Analysis
Each of the six stages is discussed in more detail below.

5.1 Stage 1 - Develop Crash Concept

Consideration of the design requirements for an EN15227 compliant vehicle must start at the conceptual design stage. An integral part of this process is the development of a Crash Concept Document. The Crash Concept Document lists all of the elements of the Crash Energy Management System (CEMS) and defines how each element of the CEMS will be involved in satisfying the passive safety requirements for each design scenario.

An example of this process is listed below for the QNGR vehicle CEMS. The following points describe how the CEMS elements will operate for design scenario one, which for the QNGR vehicle, is a collision with an identical train unit at 36km/h.

- The initial impact will be at the Autocoupler heads (the GRP coupler cover is secondary structure).
- The engagement of the autocouplers expends the reversible gas hydraulic and irreversible deformation tubes.
- The Autocoupler then shears out with a small amount of free travel prior to the anticlimber engagement.
- The collision tubes are then engaged at their anticlimber interface and will travel rearwards absorbing the collision energy until all energy has been dissipated.
- At the same time the Intermediate Couplers have been activated and the reversible and irreversible elements are utilised.
- Closure of the first intercar is likely which will lead to engagement of the intercar anticlimbers.
- The Windscreen is pushed backwards until the overlap with the cab rail and the side support feature come into contact.

This stage of the design also requires consideration of other factors that will influence the layout and performance of the CEMS. These will have an influence on some fundamental design decisions at an early stage of the vehicle design. Some of the key considerations include:

- Vehicle movements including gauge and curving;
- Driver’s sight lines;
- Coupler height, length and low speed impact performance; and
- Vehicle overhang

These factors will be key considerations in the development of the vehicle structural layout, particularly the design of the cab frame and headstock. The concepts for number, size and position of the collision columns in the crash frame are developed at this point. An additional consideration is the type of cab frame. In the past Bombardier has developed cab structures that are designed to collapse and provide a level of energy absorption as part of the CEMS. EN15227 requires that a driver’s survival space is maintained either around or adjacent to the driving position. The addition of an energy absorbing structure can create difficulties in meeting the survival space requirements and for recent EMU designs for the Australian market, a rigid cab frame has been utilised.

The structural concept is modelled using a 3D drafting package. Once the geometric concept has been developed, the model is translated into a finite element model for preliminary static structural and fatigue analysis prior to further modelling as part of the crashworthiness design.

5.2 Stage 2 – 1D System Analysis

A 1D system analysis is used to determine the parameters for the energy absorbing components of the CEMS. The prediction of the 1D crash model analysis orients the design concept to determine the force/stroke requirement of the CEMS energy absorbing elements.

A parametric study is performed to find the optimum combinations of CEMS force and displacement whilst ensuring passenger deceleration limits are not exceeded. The analysis gives guidance on the following information:

- Optimum collapse forces for Auto and Intermediate end couplers;
- Optimum collapse forces for Collision Tubes; and
- The length of CEMS elements required to meet the deceleration limits

At a similar time, concept carbody static buckling analysis is performed to determine practical limits for carbody loading, which are translated to allowable limits for dynamically applied coupler and buffer loads. The differences between static and dynamic
buckling allowables can be large, depending on uniformity of carbody stiffness, intermediate end geometry, and capacity for dissipation of energy which is highly dependent on design and construction. In most cases, the analysis results are mostly conservative due to the carbody assumed as a rigid body. In reality, carbody elasticity does assist in absorbing a sizeable proportion of the energy during crash events.

The 1D model is developed using LS-Dyna as the solver and Altair HyperWorks for Pre and Post processing. At this stage of the design, the 1D model simulates design collision scenarios 1 and 2.

For the 1D System Analysis, the following input data are defined based on the vehicle conceptual design.

- Cab geometry (clearances between front CEMS elements)
- Auto-Coupler characteristics
- Collision tube characteristics
- Intercar clearances
- Intermediate coupler characteristics
- Mass of the cars (with EN15227 passenger mass and contingency included)
- Vehicle longitudinal stiffness
- Mass of bogies (different for motor and trailer bogies)
- Mass estimation of CEMS components

Current practice is to model each carshell in the train unit using 5 linear springs. The CEMS elements at the cab end and non-cab end are modeled in the first approach with linear springs, but non-linear springs can be used in case of heavy loading that causes end deformation. The cab model is linked to the node N1. Figure 3 maps the rigid element configuration for the leading car.

The linear springs are coupled with a damper to provide a linear translational damping between two nodes.

The front CEMS elements are linked to the representation of the cab. For the 1D study, the cab is represented as a planar rigid wall (Figure 4), though it can be replaced by a more representative 3D model for the Hybrid 1D System Analysis.

The mass of each carshell is applied based on the guidance provided in EN15227. The 50% seated passenger mass is included within the carshell mass, which is then spread over the nodes for each car.

The force and stroke parameters of the CEMS elements are modified to tune the system and achieve the best possible passive safety results. At this stage of the analysis, the primary design consideration is the vehicle deceleration results for each carshell. Various outputs are considered at this stage to ensure that the forces induced in each carshell will not exceed the nominal capacity of the carshell. An example of the results for a six-car trainset is shown below in Figure 5, Figure 6, Figure 7 and Figure 8.
The average deceleration in each car of the trainset is also calculated. An example of the filtered deceleration for the first vehicle in the six-car set is shown in Figure 9.

This result is then averaged to provide the deceleration measure used to assess the performance of the vehicle against the passive safety requirement. This result is shown in Figure 10.

In a rail collision scenario, the most significant forces are generally seen in the leading car. The first intercar connection also sees the greatest level of energy absorption (outside of the leading elements) which gradually reduces as the collision pulse travels along the length of the trainset. Therefore the peak forces and decelerations will be realised in the leading carshells. One of the challenges of the design process at this stage is to manage the load at the intercar connections and ensure that as much of the energy in the intercar connections is utilised while keeping the vehicle end loads and decelerations as low as possible. It can be seen from the previous figures how the collision pulse moves along the trainset and has significantly reduced by time it reaches the third carshell.

Once the parameters for the energy absorbing elements of the CEMS have been determined, the information is communicated to the sub-component suppliers to assist in the development of suitable options.

5.3 Stage 3 – Hybrid 1D System Analysis

The next stage is to expand the scope of the 1D model to provide a more detailed assessment of the performance of the cab structure. To facilitate this, the rigid wall used to model the cab at stage 2 is replaced with the finite element model of the cab structure. The cab structure has previously been verified for compliance with static structural and fatigue design requirements. The cab is modelled using 2D plate elements and a non-linear material curve. Inclusion of the cab structure allows design collision scenario 3 to be assessed.

Undertaking the Hybrid 3D System Analysis provides several benefits for the design process. It allows the leading end structure to be assessed against the passive safety requirements and determine if there will be a
potential loss in structural integrity that could affect the performance of the energy absorbing elements or result in the driver’s survival space being compromised. It also allows for more detailed assessment of the mounting interface for the leading end energy absorbing elements.

The Hybrid 1D model can be solved significantly faster than a full 3D non-linear carshell model and therefore allows design iterations to be developed and assessed quickly against the passive safety requirements.

The Hybrid 1D model is also utilised to assess the structural performance of the vehicle nosecone and windscreen assemblies. Modelling for design scenarios 1, 2 and 3 allows the movement of the windscreen to be tracked to ensure that overlap with the cab frame will be achieved thereby preventing the windscreen from collapsing into the driver’s cab and compromising the survival space of the driver.

The driver’s survival space is assessed by overlaying the structure from the non-linear analysis once equilibrium between the moving vehicle and impacted vehicle/obstacle has been achieved, with the undeformed structure. The survival space is plotted against the deformed structure to ensure that defined envelope has not been compromised.

Figure 11 to Figure 14 show the a Hybrid 1D assessment for design scenario 2.

5.4 Stage 4 – Preliminary 3D System Analysis

Once the design has progressed to a stage where the CEMS elements have been defined and the performance of the leading end under design scenarios 1, 2 and 3 satisfies the passive safety requirements, the remainder of the vehicle structure can be assessed. At the preliminary stage, this generally utilises a symmetrical half model of the carshell to reduce the analysis time. By this stage of the design, the carshell will have progressed to the point where a full linear-elastic FEM has been developed. The FEM is developed with element sizes and connections that are compatible with translation into the non-linear analysis.

The 3D carshell is imported into the 1D model to replace the leading carshell. Depending on the predicted performance of the first intercar connection, a portion of the second carshell is also modelled.

At this stage, the model is still constrained to only move in the longitudinal direction so the effects of vertical offset and the bogie suspension are not considered. Figure 15 and Figure 16 show the preliminary 3D model for design scenario 3 pre and post impact.
The analysis provides a good indication of the performance of the carshell and allows the designer to determine if the structural integrity of the occupied areas will be compromised. At this stage, the aim is to limit the peak plastic strain in the carshell to less than 10%. This will generally ensure that the chance of section collapse is minimised and that the passive safety requirements will be achieved at the detailed design stage. Figure 17 shows an example of the plastic strain results due to the design scenario 3 analysis.

5.5 Stage 5 – Validation of Energy Absorbing Elements

The performance of the energy absorbing elements of the CEMS is verified via both modelling and testing.

Generally, the validation process is undertaken by the element sub-supplier.

The testing generates characteristics for each element that are used in the final stage of the analysis. Figure 18 and Figure 19 show a collision tube pre and post test. The resultant test characteristic is plotted in Figure 20. This test characteristic is used directly in the final 3D system analysis.
5.6 Stage 6 – 3D System Analysis

The final stage of the EN15227 assessment of the carshell is to perform the final 3D System Analysis. The analysis uses the linear-elastic FEM which has been correlated against the results of a carshell-level static structural test as the basis for a 3D non-linear model. The analysis generally utilises the first and second carshells in the trainset in 3D with the remainder represented by the rigid 1D elements. At this stage of the design the vehicle mass balance has been refined to a stage that will be close to the final as-built vehicle.

The energy absorbing elements are modelled in more detail, utilising the characteristics of the validation tests. The model longitudinal constraint is removed and the vehicle bogies modelled in detail with the suspension characteristics included to provide a detailed estimate of the wheel lift during the collision events. Figure 21 shows the leading end of the 3D system analysis model including these elements. Figure 22 shows the second carshell with the intermediate couplers and bogies modelled.

Depending on the analysis hardware, solving the final 3D system can be time consuming therefore the designer should be confident of the results based on the preceding design stages.
Figure 25 to Figure 29 show the impact point for design scenario 1 at increasing stages during the collision scenario.

Figure 25: Design Scenario 1 at 0 ms

In Figure 26, the energy absorbing elements of the autocoupler have been expended and the couplers have sheared out prior to engagement of the anticlimbers.

Figure 26: Design Scenario 1 at 140 ms

In Figure 27, the anticlimber elements have engaged and the collision tubes have started to stroke.

Figure 27: Design Scenario 1 at 160 ms

In Figure 28, the energy absorbing stroke of the collision tubes has finished. Note that there is still capacity available in the tubes but the collision pulse has now transferred down the trainsets. Figure 28 also shows the effect of modelling the bogies and suspension elements as there is a noticeable dip at the impact point.

Figure 28: Design Scenario 1 at 350 ms

In Figure 29, the collision event has been completed and the impacting vehicles are at equilibrium.

Figure 29: Design Scenario 1 at 650 ms

From the final 3D analysis, the wheel lift can be measured to verify the derailment criteria. An example of this plot is shown in Figure 30.

Figure 30: Wheel Lift vs Time

6. OBSTACLE DEFLECTOR DESIGN

EN15227 design scenario 4 relates to impact with low lying obstacles at level crossings or on the track. This requires an Obstacle Deflector to be fitted to the leading end of the vehicle to control the impact and, if necessary, absorb the energy in this scenario.

The design loads are a combination of linear static and dynamic requirements. The static strength and stability of the Obstacle Deflector is analysed using linear-elastic FEM.

Recent Bombardier designs have utilised a collapsing element behind the obstacle deflector to provide controlled energy absorption in the event of a structural overload. These elements are designed to account for central and offset impacts. An example of the Obstacle Deflector mounting configuration is shown in Figure 31.
The performance of the Obstacle Deflector in the dynamic environment is modelled using the Hybrid 1D model. For this aspect of the design, the vehicle is kept stationary and an object with sufficient mass and velocity to overload the Obstacle Deflector is used to impact the deflector (Figure 32). By ensuring that the run time of the analysis is sufficiently long it can also verify that the obstacle will be deflected out of the path of the vehicle (Figure 33).

7. CONCLUSION

This paper described the approach to rail vehicle design for compliance with EN15227 undertaken by Bombardier Transportation for vehicles designed to operate in Australian environment.

By utilising a staged approach to the design process, Bombardier is able develop an effective and integrated Crash Energy Management System that complies with the passive safety requirements of the crashworthiness standard.