Crashworthiness of rail vehicles

Dr George Kotsikos

NewRail – Centre for Railway Research
Crashworthiness of rail vehicles

Dr George Kotsikos

NewRail – Centre for Railway Research
“Railways owe their existence to the horse and high speed rail travel has been made possible by the development of the internal combustion engine and the aeroplane”

(Source unknown)
Rail vehicle design

Early 1900s… ...to today
Rail vehicle design - Overview
Early carriages were simple constructions made predominantly of wood on which simple axle system was mounted.

By 1900 the “bogie” coach was introduced, a concept still in use today.

The carriage body was still made of wood but with steel underframe. Until the advent of the "monocoque" steel coaches of the 1970s, this underframe was separate from the body.

In monocoque construction, the structure of the coach is integrated as a complete unit, all the strength being built into the body with no separate underframe.
For many years steel has been the preferred material for rail vehicle construction.

Good ductility and weld strength makes steel a good choice for crashworthy designs.

Steel rail vehicle bodies tend to buckle before failure.

Crash repair can be easily facilitated (especially for modular steel designs).
In recent years a drive for energy efficient, lightweight rail vehicles has seen the introduction of aluminium in rail vehicle construction.

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (kg/m³)</th>
<th>YS (N/mm²)</th>
<th>UTS (N/mm²)</th>
<th>Young’s modulus (GN/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>7800</td>
<td>275</td>
<td>430</td>
<td>200</td>
</tr>
<tr>
<td>Aluminium (eg 6005)</td>
<td>2700</td>
<td>225</td>
<td>270</td>
<td>70</td>
</tr>
</tbody>
</table>
Rail vehicle design

Aluminium has been in use in the rail industry for many years making its first appearance in rail freight cars in 1931.

Influenced by aircraft design aluminium makes first appearance in passenger rail car design in the US circa 1935.

Precursors of modern high speed trains making use of lightweight materials and aerodynamics.
In the 50s and 60s some aluminium skinned rail coaches were built by BR in the UK.

The first aluminium monocoque bodyshells were designed in the 70s for the APT in the UK and the TGV in France.

Greatest application in the UK has been the London Underground stock
The successful use of aluminium in rail body construction has been made possible by the emergence over the past 15-20 years of extrusion technologies for large profiles.

Availability of closed cell extrusions provided designers with lightweight and stiff sections that could easily be welded together to construct strong double skinned bodysells.

Extruded sections are particularly suited for automated welding allowing the manufacture of structures with exceptional dimensional accuracy (far better than with steel fabrications) at relatively low cost.
Hollow aluminium extruded profiles are stronger structurally than steel single-skin bodies, and thus exhibit superior collapse strength performance against compression loads in the direction of the rails.

Superior impact resistance also introduces “rigid body” behaviour upon impact, which raises the requirement for impact energy absorbing zones (crumple zones).

Although the rigid body behaviour was understood for closed cell aluminium extrusions, the knowledge did not extend to their welded joints.
Crashworthiness
Crashworthiness

Legislative European Crash Scenarios – EN 15227

- Like to like impact at 36 km/h
- Like to like impact at 36 km/h with 40 mm Vertical Offset
- Impact at 110 km/h with a level crossing obstacle
- Impact at 36 km/h with 80 tonne truck
- Impact with a small obstacle like a car
The Ladbroke Grove Accident

5th October 1999, 21 fatalities and 400 injured
The Ladbroke Grove accident

‘…the aluminium extrusions had fractured along the weld lines and that there was a lack of plastic deformation (…) the structure appeared to have failed along the welds rather than deforming in a controlled manner’

The Right Honourable Lord Cullen

The catastrophic failure of welds in this manner is a phenomenon known as ‘weld-unzipping’.
Weld Unzipping

Weld unzipping caused by dynamic ductile tearing of the weld metal or heat affected zone.

The process is controlled by:
- Speed of crack propagation
- Geometry of applied stresses/crack trajectory
- Plastic deformation at crack tip

Material factors which are important
- Composition
- Impurities
- Microstructure (fine grained better than large grained)
- Defects

Since welding changes microstructure and mechanical properties and can introduce defects, the process can be critical in localising failure.
Steel welds can be produced with strength equal, higher or lower than the parent metal by selection of appropriate filler wires without any post weld treatments.

The high strength of various aluminium alloys has been achieved through a range of specialist heat treatments.

Aluminium alloys are therefore sensitive to heat input introduced by the fusion welding processes.

Proof strength of 6005A HAZ ~ 50% parent pate
In the following slides the presentation describes the approach taken to:

- Understand the problem of joint failure (weld unzipping)
- Improve the performance of welded joints in crash scenarios
- Provide modelling tools to simulate the behaviour of rail vehicles during collisions

The approach followed here is also applicable to assessing the crash response of any future materials and their joints to be used in rail vehicle construction and adopts the following methodology:

- Material characterisation at the fundamental level
- Material characterisation at the component level
- Component dynamic response modelling and validation
- Vehicle collision modelling
Fracture assessment of aluminium alloy welds
This section describes work undertaken to understand the dynamic fracture process of the weld region in aluminium welded joints aiming to:

- Improve the performance of welded aluminium joints under dynamic loads
- Improve modelling capabilities for developing crashworthy rail vehicle designs

The alloy investigated was the heat treatable 6005T6 (Al-Mg-Si) used predominantly in rail vehicle construction in Europe.

Automated MIG welding is the preferred method for joining of extruded sections in the rail industry.
Materials & Experimental Procedure

- 6005T6 aluminium extrusions (3mm sheet thickness) were MIG welded with two types of filler wire:
  - Al-Si (4043) filler wire.
  - Al-Mg (5356) filler wire.
- Detailed mechanical property characterisation of
  - the parent metal (PM),
  - weld metal (WM) and
  - the heat affected zone (HAZ) was carried out
- Fracture mechanics parameters determined:
  - J-integral static & dynamic, energy dissipation rate (D), tearing resistance index (T), CTOD
Mechanical property characterisation

- Use Al-Mg filler produces welds with improved mechanical properties over Al-Si filler
- Hardness variation across the weld is similar

<table>
<thead>
<tr>
<th>Material</th>
<th>Charpy impact energy (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parent plate</td>
<td>0.73</td>
</tr>
<tr>
<td>Weld – (Al-Si filler)</td>
<td>0.32</td>
</tr>
<tr>
<td>Weld – (Al-Mg filler)</td>
<td>0.56</td>
</tr>
</tbody>
</table>
Fracture mechanics tests

- Static and dynamic J-R curves were obtained through SENB tests for the parent material and weld region.
Fracture mechanics tests

Al-Si (WM)

Al-Mg (WM)

Al-Si (FB)

Al-Mg (FB)
Fracture Mechanics Tests

- CCT samples were also used for the fracture mechanics analysis which was based on the energy dissipation rate (EDR) approach. The EDR is defined as:

\[ D = \frac{dU_p}{Bda} \]

- Where \( dU_p \) is the increase in dissipated energy for crack growth, \( da \), and \( B \) is the specimen thickness.

- It is a simple extension of the Griffith energy balance to include plasticity. The test procedure is identical to the J-integral test.
Fracture Mechanics Tests

● Advantages of EDR
  - A major advantage of the EDR approach is that it does not need an increase in toughness with crack growth to explain stable tearing.
  - Increase in tearing resistance with crack growth sometimes occurs due to shear lip development but in thin sheets where fully slant fracture develops after only a few mm of crack advance this explanation is not available.

● Disadvantages of EDR
  - The major disadvantage of the EDR approach is that it is geometry dependent. Nevertheless, it provides a useful comparative tool to obtain structural tearing instability predictions through small specimens.
Fracture Mechanics tests

- Quasi-static fracture mechanics tests using a modified SENB specimen design were also performed. The analysis used the EDR approach and the results were similar to the ones obtained for CCT specimens.

- The tests provided information such as critical CTOA and were intended to aid with numerical modelling of tearing process in the welded aluminium extrusions.

- The crack path in most tests with starter crack in WM deviated within a few millimetres of growth and propagated along WM/HAZ interface.
Fracture Mechanics Tests

- **Al-Mg filler**
  - $D = 1170 \text{ kJ/m}^2$
  - $T = 0.03$

- **Al-Si filler**
  - $D = 350 \text{ kJ/m}^2$
  - $T = 0.011$
Influence of weld undermatch

- What matters when a collision takes place is whether the structure spreads the impact energy or concentrates it in a specific region (the weld in this case).

- The heat inputs introduced by the fusion welding processes subject aluminium alloys to a localised solution treatment reducing the mechanical properties (significantly in some cases) at the weld region.

- The input (impact) energy in a structure with a strength undermatch, may channel all this energy to the weld region. This will have to be taken up by the energy dissipation rate which implies extensive crack growth.

- It could be argued that the “weld unzipping” that has been observed in recent train collisions is not only a result of the fracture properties of the weld but also the strength undermatching at the welded joints.
Solutions approach
Solutions approach

- Joint flaws
  - design
  - welding

- Reducing the heat input
  - Laser MIG
  - FSW

- Altering weld geometry by thickening plating at the weld region
Full scale impact tests
Dynamic tear tests on full scale welded extrusions were carried out at Bombardier Transportation’s facility in Crespin – France.

The impact tester is fully instrumented and provides a trace of the impact load and the energy absorbed.
Full scale component impact tests

- Air cannon
- Projectile clamped to rigid base
- Lever arm
- Welded Al extrusion

Diagram details:
- Lever arm
- Welded Al extrusion
- Projectile
- Air cannon
- Clamped to rigid base
Full scale component impact tests

- In excess of 200 samples were prepared and tested.
- Samples were prepared with MIG, FSW, Laser MIG techniques.
- All samples above were tested with different levels of plate thickening near the weld zone (x1.2 to x2) and with and without initiator slots.
- Impact tests of full scale sections showed that thickening of the plate at the weld region by a factor of approximately 1.6:
  - moves failure initiation away from the weld region and into the parent material (with no initiator present),
  - more than doubles the energy absorbed by the weld (when initiator is present).
- Further thickening of the section reverts to unstable fracture.
Friction stir welded samples

No thickening

Thickening by 1.4

Thickening by 1.6
Laser MIG welds

No thickening

Thickening by 1.4

Thickening by 1.6
MIG welds

No thickening

Thickening by 1.4

Thickening by 1.6
Collision simulation
Modelling weld fracture

- The information obtained from the experimental test programme was used to develop FEA models of the weld failures under dynamic loads.

- Code used LS-DYNA

- Failure criteria used:
  - Maximum strain failure model
  - Gurson Tvergaard model
Max strain failure model

- Linear plasticity model with maximum strain failure criteria
  - failure condition is based on the accumulated plastic strain in the structure, according to the following relationship:

  \[
  \varepsilon_{\text{eff}}^P = \int_0^t \left( \frac{2}{3} \varepsilon_{ij}^P \dot{\varepsilon}_{ij}^P \right)^{1/2} \, \text{d}t \leq \varepsilon_f^P
  \]

  where \( \varepsilon_{\text{eff}}^P \) the effective plastic strain and \( \varepsilon_f^P \) the plastic strain to failure in a uniaxial tensile test.
The Gurson – Tvergaard model uses a state variable plasticity law, in which the void volume fraction is an explicit state variable and the yield stress is taken to be a function of the volume fraction of voids in the material.

\[ \Phi = \left( \frac{\sigma_e}{\sigma_y} \right)^2 + 2f^* q_1 \cosh \left( \frac{3q_2 \sigma_H}{2\sigma_e} \right) - 1 - (q_1 f^*)^2 = 0 \]

- where \( \sigma_e \) is the von Mises equivalent stress, \( \sigma_y \) is the yield stress, \( \sigma_H \) is the hydrostatic stress component, \( f^* \) the effective void volume fraction, defined as:

\[ f^* = \begin{cases} f & \text{if } f \leq f_c \\ f_c + \left( \frac{1}{q_1} - f_c \right)(f - f_c)/(f_E - f_c) & \text{if } f > f_c \end{cases} \]

- \( q_1 \) and \( q_2 \) constant material parameters, \( f_c \) the critical void volume fraction, \( f_E \) the damage parameter corresponding to the void volume fraction at failure.

This yield function contains both the stress triaxiality and void volume fraction, which are the two major factors in the dimpled rupture.
Modelling of CTOA test

- Simulation of the SENB tearing test was carried out to assess the accuracy of the two failure models used in the FE analysis.
Modelling of tearing test – Max strain

Contours of Effective Plastic Strain
max ipt. value
min=0, at elem# 1
max=0, at elem# 1

Fringe Levels
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
Modelling of tearing test – Gurson - Tvergaard
Modelling of tearing test
Simulation of a rail vehicle collision

- FE model of a class 165DMU as that involved in the Ladbroke Grove accident in the UK was created.
- The model simulates a collision at 20m/s (72km/h) on a solid flat surface.
- The simulation is repeated with the introduction of the new joint design and thickening of the weld region by a factor of ~1.6.
Train collision simulation – Max strain
Train collision simulation – Max Strain
Train collision simulation – Max Strain
(x1.6 weld thickening)
Train collision simulation – Max Strain
(x1.6 weld thickening)
Train collision simulation – Gurson (x1.6 weld thickening)
Train collision simulation – Gurson (x1.6 weld thickening)
Conclusions

- Welded joints produced with an Al-Mg filler wire show a clear improvement on the dynamic fracture behaviour over those produced with an Al-Si filler.

- Weld undermatching appears to be the most influential factor in preserving the structural integrity of a rail vehicle during a collision.

- Localised thickening of the weld region by a factor of 1.6 changes the failure mode from weld unzipping to buckling.

- Attention to joint geometry, to avoid crack initiation promoting features and partial penetration welds.

- The output from this work has been a contribution to the following standards:
  - EN 15085 "Railway applications - Welding of railway vehicles and components" and
  - EN 15227, the draft standard for Crashworthiness Design of Rail Vehicle Bodies
Thank you
Contact details:

**George Kotsikos**

NewRail – Centre for Rail Research
Newcastle University
Stephenson Building
Newcastle upon Tyne, NE1 7RU
Tel: +44 (0)191 222 5821
Email: [george.kotsikos@ncl.ac.uk](mailto:george.kotsikos@ncl.ac.uk)