Institution: Newcastle University

Unit of Assessment: 12 Aeronautical, Mechanical, Chemical and Manufacturing Engineering

Title of case study: The development of new standards for aluminium rail vehicle welding and crashworthiness

1. Summary of the impact

The Cullen Report into the Ladbroke Grove rail crash attributed the catastrophic failures of the rail vehicles to “weld unzipping” (brittle fast fracture). Research carried out at Newcastle University into the fabrication and design of aluminium rail vehicles has informed two new European standards: EN 15085 "Railway applications - Welding of railway vehicles and components" and EN 15227, “Crashworthiness requirements for railway vehicle bodies”. These two standards have been developed to ensure that the “weld unzipping” failure cannot re-occur in a rail crash. The two standards were formally adopted throughout the EU in 2008, and are mandatory for all aluminium rail vehicles used across Europe.

2. Underpinning research

The research was stimulated by the publication, in 2000, of the Cullen Report into the 1999 Ladbroke Grove rail crash, in which catastrophic failures of the rail vehicles resulted in loss of life and serious injury. The failure of the rail vehicles was attributed to “weld unzipping” (brittle fast fracture). Until the Ladbroke Grove accident weld unzipping was associated with the pipeline industry (where it was encountered in failures of pressurised longitudinally welded steel pipelines), and had not been considered a significant safety concern within the railway industry.

Mark Robinson, then at Sheffield University, applied, with partners, for EC funding to look into this issue and with the ALJOIN project (G1 in the list in section 3, co-ordinated by D’Appollonia in Italy) began to research the crashworthiness of aluminium joints in 2002. This project was initiated with Sheffield University as a partner, but when Robinson moved to Newcastle in 2004 the project moved with him and Newcastle University replaced Sheffield University as a partner. The work carried out at Sheffield prior to the move was directed at testing existing rail vehicle joint designs.

At Newcastle, Kotsikos (who was already a Research Associate at Newcastle, and did not transfer from Sheffield) started to work with Robinson on the ALJOIN project, and it was at Newcastle that the significant engineering and materials science research was undertaken, with Kotsikos the lead researcher. The research work carried out at Newcastle involved a fundamental appraisal of the dynamic fracture response of aluminium welds, and was the first time that a detailed investigation of this type of material performance had been carried out in the UK for the transportation industry. The research undertaken first established the factors that promoted the weld unzipping behaviour in extruded aluminium welded sections, most significantly the high loading rate involved in a collision, the chemical composition of the microstructure at the weld region, and the inherent undermatching problem in heat treatable aluminium fusion welds (where the yield strength of the weld is lower than that of the base material). Having identified the underlying problems methods of improving the dynamic fracture response of the Metal Inert Gas (MIG) welding process (normally used by industry) were researched, as well as examining alternative welding processes, such as Friction Stir welding (FSW), Laser Beam welding (LBW) and adhesive bonding (AB). The research demonstrated that none of the joining techniques investigated would eliminate weld unzipping although small improvements could be made through the use of an alternative welding consumable to the one normally used by the industry for MIG welding.

The focus of the research then concentrated on the design of the joint region by investigating geometries that would facilitate the dissipation of the impact energy over the whole structure, rather than it being confined to the joint region as a result of the localised weakening of the material strength resulting from the fusion welding process. Finite element analysis (FEA) modelling, supported by experimental fracture mechanics, and validated through large scale impact tests, resulted in the development of an optimised joint design that was able to eliminate weld unzipping failures. The FEA models created reproduced remarkably closely the failures that occurred at the Ladbroke Grove accident, giving confidence in the modelling approach developed during the project and demonstrating the significant improvement in crashworthiness of the same vehicles if the type of joint designs developed in the project were implemented.

Recognising the importance of the outcomes of the ALJOIN project, the Railway Safety & Standards Board commissioned ALJOIN plus (G2, with Kotsikos as PI), to provide the necessary information to create a benchmark for welded joints in aluminium rail vehicles against which improvements in joint design could be measured.

The main research findings from ALJOIN and ALJOIN plus were reported in publications P1 and P2 (listed in section 3), and the quality of the science was recognised through P1 receiving two prizes: the "2008 Safety in Engineering Award" from the IMechE and the "2009 Sir Alfred Rosling Bennett /Charles S Lake Award" from the Railway Division of the IMechE.

The key researchers at Newcastle for this research have been:

- **Kotsikos**: Research Associate, 1997-2005; Principal Research Associate 2005 to date.
- **Robinson**: Professor of Rail Systems, 2004 to date.

3. References to the research

Publications:

P1. G. Kotsikos, M. Robinson, D. Zangani, & J. Roberts.Investigation of the weld unzipping failure mode during collisions of welded aluminium rail vehicles. Journal of Rail and Rapid Transit – Proceedings of the IMechE - Part F, Volume 222, Number 1, 2008.
***Key output**: this paper is the major research output from the work, and was awarded the "2008 Safety in Engineering Award" by the IMechE and the "2009 Sir Alfred Rosling Bennett /Charles S Lake Award" by the Railway Division of the IMechE.*

P2. G. Kotsikos, Benchmarking weld performance in aluminium joints (ALJOIN PLUS), Rail Safety and Standards Programme Research Report, 2006. Available at http://www.rssb.co.uk/SiteCollectionDocuments/pdf/reports/research/T520_rpt_final.pdf.

Grants:

G1. M Robinson, ALJOIN (Crashworthiness of joints in aluminium rail vehicles), EC FP5 Project G3RD-CT-2002-00829, August 2002 to July 2005 (started at Sheffield University in August 2002, transferred to Newcastle University in March 2004). Sheffield funding: €159,536; Newcastle funding: €260,330.

G2. G Kotsikos, ALJOIN plus (Benchmarking weld performance in aluminium joints). Project T520, Railway Safety & Standards Board, August 2006 to August 2007, £60,000.

4. Details of the impact

The importance of the results of the research work undertaken at Newcastle University as part of the research projects were recognised by the industry partners (Bombardier Transportation, Alcan) and the UK Rail Safety and Standards Board. These organisations (and in particular Bombardier Transportation, who had collaborated in the work and co-authored publication P1) informed the standardisation organisations of the project results. As a result of these activities the output from this work was incorporated into two European standards (S1 and S2 as listed in section 5), both adopted across Europe in 2008:

- EN 15085 Railway applications - Welding of railway vehicles and components (in particular Part 3, Annex H).
- EN 15227 Crashworthiness requirements for railway vehicle bodies.

One of the elements of the research output that facilitated the uptake of the project results was the fact that the joint redesign solution provided to prevent weld unzipping did not affect normal operations and manufacturing processes to a significant degree and therefore the market uptake was almost immediate. The main recommendations involved the use of an alternative filler wire, Al-Mg, that proved to provide a microstructure more resistant to tearing, instead of the Al-Si normally used by the industry, and also a localised thickening of the extrusion cross section at the joint to compensate for the strength loss arising from the heat input from the welding process. The latter joint design feature was the result of an optimisation process as excessive thickening of the cross section resulted in promoting weld unzipping. These two standards have been mandatory for railway vehicles since April 2008, and remain in force now.

The former Head of Crash Safety at Bombardier has confirmed in a letter to the University that the standards were developed on the basis of the research carried out at Newcastle, making two key statements (S3):

- *The R&D work carried out at Newcastle University was of excellent quality and its significance was recognised at an early stage in the project by our Legislation and Standards Group which is heavily involved in the development of Rail Standards in Europe. The manner in which the work was carried out was in line with one of the Bombardier key objectives of "Flawless execution".*
- *Importantly these standards would not have been introduced without the recommendations and underlying scientific work carried out at Newcastle University.*

All European rail vehicle manufacturers have to comply with the standards in order to market their products, and all worldwide manufacturers wishing to sell aluminium rail vehicles in Europe have to ensure that the vehicles comply with the standards. The European annual rolling stock market is worth in excess of £10 billion (S4), and most new build unpowered rolling stock is aluminium rail vehicles.

The former Head of Crash Safety at Bombardier also notes (S3) that EN 15227 is now being embedded into a Technical Specification for Interoperability. The European Interoperability Directive (2008/57/EC) sets out a number of essential requirements to be met for interoperability in the European rail system, which include safety, reliability and availability, health, environmental protection and technical compatibility along with others specific to certain sub-systems. The Directive also requires the production of mandatory Technical Specifications for Interoperability (TSIs) which define the technical standards required to satisfy those essential requirements. TSIs in essence set out the expected performance levels of the European railway system, and so standard will be a benchmark for new product development in aluminium rail vehicles for the European market.

The Head of R&D of the Rail Safety and Standards Board has noted that the research has (S5):

"made a significant impact on the safety of aluminium rail vehicles in Europe and beyond."

The motivation for the original research was to improve passenger safety, which it is difficult to quantify. Thankfully, there has not been a crash which replicated the conditions of the Ladbroke Grove incident. However, we can note that since the introduction of the standards there have been no reported instances of weld unzipping failures within the European rail system.

5. Sources to corroborate the impact

S1. EN 15085 Railway applications - Welding of railway vehicles and components. First published as a British Standard in 2007, adopted across Europe in 2008, revised in 2011.

S2. EN 15227 Crashworthiness requirements for railway vehicle bodies. Published 2008, revised in 2011.

S3. Letter from Head of Safety, Bombardier Transportation, involved in the ALJOIN project and in recommending the work to the standards agencies.

S4. Renner and Gardner, Global Competitiveness in the Rail and Transit Industry, Worldwatch Institute, 2012. Available at www.worldwatch.org/system/files/GlobalCompetitiveness-Rail.pdf.

S5. Letter from Head of R&D, Rail Safety and Standards Board (RSSB). The RSSB funded the ALJOIN+ project and was involved in recommending the work to standards agencies.