Section A

The fields in this section are mandatory.

Institution: Durham University

Unit of Assessment: 12, Engineering

Title of case study: Rail support systems: structural integrity of concrete sleepers and crossing bearers

Period when the underpinning research was undertaken: 2008 to date

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr William Coombs	Associate Professor	2011 to date
Professor Charles Augarde	Professor	2001 to date

Period when the claimed impact occurred: 2014 to date

Is this case study continued from a case study submitted in 2014? N

Section B

1. Summary of the impact

Computational stress analysis research at Durham University (DU) has led to fundamental changes to rail-bearer/sleeper fixing methods across the UK's National Rail network, and exposed structural integrity issues with methods that are used around the world (similar failures have been reported in Spain, Greece, and Iran). Collaboration with the UK's leading sleeper/bearer manufacturer has led to a widely used fastening method being abandoned, with an estimated cost saving of GBP100m per annum via reduced layout/junction replacements. The research has changed Network Rail and London Underground technical specifications, banning previously used fastening techniques, and provided a sound scientific basis for the next generation of resilient fastening methods.

2. Underpinning research

This Case Study is concerned with computational stress analysis of concrete sleepers/ crossing bearers that are used in the rail industry to support the running rails and how the stress distribution through the concrete members (and likelihood of fracture development) is influenced by the method used to attach the rail to the sleeper/bearer.

Computational solid mechanics has been a DU research strength for many years. Augarde was appointed as a DU Lecturer in 2001 and is currently a Professor of Civil Engineering in the Department of Engineering. Coombs was appointed as a Lecturer at DU in 2011 and is now an Associate Professor in Computational Mechanics. Coombs and Augarde are experts on robust, efficient and accurate stress analysis of pressure-dependent materials with a focus on civil, geotechnical and structure engineering applications. The quality of the research underpinning this case study is evidenced by publications (as explained below) in top journals [R1-R3] and associated open-source code [R4]. The key research tools that underpin this Case Study are a number of highly efficient numerical modelling codes that were developed from 2008 by Coombs and Augarde, and ultimately used to investigate rail-sleeper/bearer connection methods as described below.

The research that underpins this Case Study was on understanding the stress conditions, and likelihood of fracture, within concrete sleepers and crossing bearers that are used to support

the steel running-rails in railways around the world. The research was undertaken in collaboration with CEMEX, the UK's leading manufacturer of railway bearers and sleepers. The numerical models, specifically the finite element routines and associated material models that Coombs and Augarde developed at DU, can be traced to a paper at the 7th European Conference on Numerical Methods in Geotechnical Engineering [R4] which is being used by researchers across at least ten countries on four continents. The material failure analysis used during the research is underpinned by internationally leading journal papers: two in Computer Methods in Applied Mechanics and Engineering (top journal in Computational Mechanics [scimagojr.com]), on elasto-plasticity theory and the efficient implementation of constitutive algorithms [R2, R3] and one in the Journal of the Mechanics and Physics of Solids on predicting continuum complex stress paths and cyclic loading [R1]. These methods were used during eight separate phases of consultancy-based research, to analyse railway bearers and sleepers for CEMEX. The research concentrated on:
Analysing the stress distribution within the concrete sleepers/bearers subject to different loading/boundary conditions (pre-stress, rail traffic, partial support from ballast, ...).

1. Understanding how the stress distribution changes between different methods to attach the steel rail to the concrete member (glue/resin, plastic/steel inserts, …); and
2. Predicting when and where fractures are likely to develop (plus the orientation of the fractures) via advanced material failure analysis (appropriate failure criteria [R3] combined with acoustic tensor analysis).

The research conducted at DU has shown that plastic inserts and resin are soft relative to the surrounding concrete (10-40 times lower stiffness); they create local tensile stress concentrations (as shown in Figure 1) in the transverse direction that are exaggerated by high longitudinal pre-stressing [R5, R6]. It was also shown that these concentrations, along with destructive installation methods, have the potential to initiate longitudinal fractures in the concrete sleepers/bearers [R5,R6].

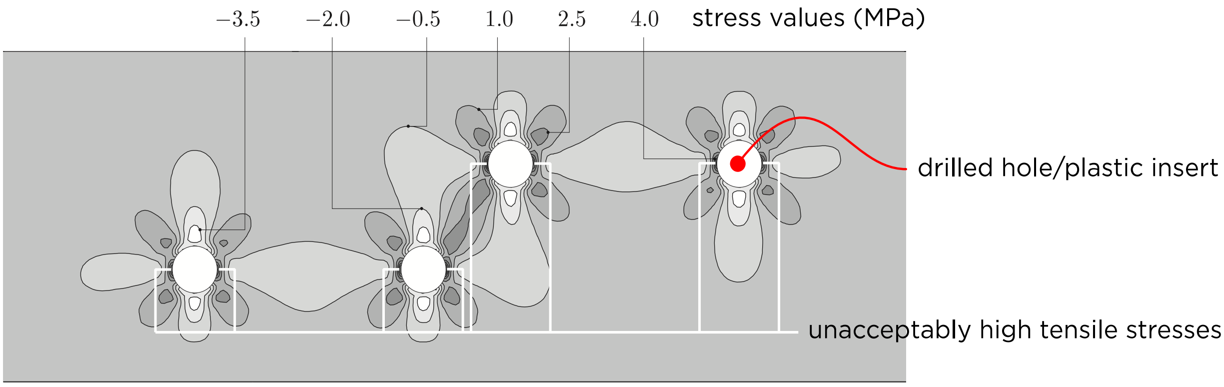

Figure 1: transverse normal stress distribution in a typical crossing bearer subject to pre-stressing: local stress distributions around the drilled holes & locations of high tensile stress.

This fundamental research led to the submission of an EPSRC grant under the Big Pitch call in ground and structural engineering (grant reference EP/M017494/1, 2015-2017, details below). Research relating to the use of different rail-sleeper/bearer fastening methods in the rail industry has been presented in 2016 at an International Conference on Railway Technology [R5] and, in 2017, published in an industry-facing article in The Journal of the Permanent Way Institution [R6].

3. References to the research

[R1] Coombs, W.M., Crouch, R.S. & Augarde, C.E. (2013). A unique Critical State two-surface hyperplasticity model for fine-grained particulate media. *Journal of the Mechanics and Physics of Solids* 61(1): 175-189, https://doi.org/10.1016/j.jmps.2012.08.002. Contextual information: 15 citations (Google Scholar), 10 citations (SciVal), 93rd percentile journal in Mechanical Engineering (Scopus).

[R2] Coombs, W.M., Crouch, R.S. & Augarde, C.E (2010). Reuleaux plasticity: analytical backward Euler stress integration and consistent tangent. *Computer Methods in Applied Mechanics and Engineering* 199(25-28): 1733-1743, https://doi.org/10.1016/j.cma.2010.01.017. Contextual information: 29 citations (Google Scholar), 21 citations (SciVal), #2 journal in Computational Mechanics (Scopus).

[R3] Coombs, W.M. & Crouch, R.S. (2011). Non-associated Reuleaux plasticity: analytical stress integration and consistent tangent for finite deformation mechanics. *Computer Methods in Applied Mechanics and Engineering* 200(9-12): 1021-1037, https://doi.org/10.1016/j.cma.2010.11.012. Contextual information: 26 citations (Google Scholar), 17 citations (SciVal) #2 journal in Computational Mechanics (Scopus).

[R4] Coombs, W.M., Crouch, R.S. & Augarde, C.E. (2010), 70-line 3D finite deformation elastoplastic finite-element code, in Benz, T. & Nordal, S. eds, 7th European Conference on Numerical Methods in Geotechnical Engineering (NUMGE). Trondheim, Norway, Taylor & Francis Group, Trondheim, 151-156, http://dro.dur.ac.uk/15418/. Contextual information: 18 citations (Google Scholar), 11 citations (SciVal), Field-Weighted Citation Impact of 1.99 (Scopus), code is in use by at least 25 research groups across ten countries (Brazil, China, Germany, India, Iran, Japan, Norway, Russia, UK and USA).

[R5] Coombs, W.M. (2016), On the use of Plastic Inserts in Prestressed Railway Components, in Pombo, J. eds, Railways 2016 - The Third International Conference on Railway Technology: Research, Development and Maintenance. Cagliari, Sardinia, Civil-Comp Press, Stirling, 330, http://doi:10.4203/ccp.110.238.

[R6] Coombs, W.M. & Ghaffari Motlagh, Y. (2017). Resilience of rail support systems: the use of plastic sockets. *The Journal of the Permanent Way Institution* 135(1): 10-14, http://dro.dur.ac.uk/20820/.

Research grant:
Title: *Resilient rail infrastructure: dissipation driven fracture analysis of concrete support systems*. Sponsor: Engineering and Physical Sciences Research Council (EPSRC), EP/M017494/1. Investigator(s): Coombs, W.M. (PI). Grant period: 1st May 2015 – 31st December 2017. Value: GBP188,326.

4. Details of the impact

The key impact of this research has been the fundamental redesign and deployment of rail-sleeper/bearer fixing methods in the UK. This change has been championed by the leading manufacturer, CEMEX, and reinforced by policy changes at both Network Rail and Transport for London.

Background

The UK's rail infrastructure currently supports 67bn passenger kilometres and 16bn tonne kilometres of freight each year. The freight transport alone contributes GBP1.7bn to the UK economy per annum. The sector has seen 40% and 60% increases in passengers and freight over the last 10 years, respectively, and it is expected that passenger numbers will double, and freight increase by 140% over the next 30 years [*Britain relies on rail*, Network Rail]. The vast majority of the 32,000km of rail infrastructure is supported by pre-stressed concrete sleepers (PCSs) and crossing bearers (CBs). These concrete members provide lateral restraint and vertical support to the running steel rails. The PCSs and CBs are in turn supported on three sides by track ballast. Since their introduction in the 1950s, PCSs have superseded traditional wooden sleepers in new track and Network Rail requires 1M PCSs/year (replacements and new track), with CEMEX currently meeting 60% of this demand [E1]. However, despite the reliance of the UK's rail network on these concrete structures, and the simplicity of their geometry, they are poorly understood in terms of their structural integrity and are the root cause of in-track failures. PCSs are attached to the running-rail through cast-in-place inclusions. Two types commonly used are: steel shoulders and threaded plastic inserts to allow bolting of components. CBs, of which CEMEX are the only UK manufacturer, are bespoke, with their configuration depending on the junction layout; shoulders are often installed through drill and glue/resin-in-place (*drill and fix*).

Impact on Industry Knowledge

Durham research has shown that the use of drill and fix can cause fractures that can lead to a loss of rail restraint due to failure of the concrete-shoulder fixity, significantly reducing the support system's designed 50-year service life [R5,6]. If this occurs, the only option is to replace the CB, with considerable cost implications (possessions, delays due to speed restrictions prior to replacement, loss of passenger confidence, see below for cost estimates). Precast concrete PCSs and CBs are used outside of the UK and such longitudinal fractures are reported in international literature – this is a worldwide concern – but without correct identification of the root pre-stressing cause. For example, similar failures have been reported in Spain, Greece, and Iran (doi:10.3390/ma12172731) but with a focus on fastening loads and temperature effects rather than the key issue of stress concentrations due to pre-stressing. This is evidenced by the statements in [E3]: *"In Europe the issue of cracking around rail fastenings is a cause of major concern. This work will be invaluable in helping others understand the problems encountered when placing compressible materials (such as plastic sockets) or drilling holes in prestressed concrete."*

The findings from the research have been confirmed by both in-track and in-storage observations by CEMEX, specifically: *"These findings have been confirmed by CEMEX - using plastic components and drilling does cause the concrete to crack during service."* [E1] The in-storage observations are of particular importance as they confirm that it is the combination of high pre-stress and the fastening methods that lead to fractures, not the rail traffic loading. The long-standing belief within the industry that longitudinal fractures were caused by traffic loading/impacts rather than the magnitude of the pre-stressing loads was challenged both during meetings with CEMEX and then Network Rail and by technical reports provided by Durham [E2]. Increased understanding of the issues raised by the research has caused an improved, evidenced-based understanding of the root causes of longitudinal fractures. This can be exemplified in changes in London Underground's Technical Specification T0404, 2016 [E4]: *"Where rail clip anchorages (shoulders) are incorporated in concrete sleepers and bearers by means of drilling and gluing, cracking can occur around the anchorage position, arising from the prestressing forces. Such cracking may be limited in extent but is undesirable as it may adversely affect the long-term integrity of the sleeper or bearer"*

Impact on manufacturing

CEMEX currently manufactures 60,000 linear metres (Lm) of crossing bearers per annum with the lengths of these bearers typically varying between 2.9m and 6m (approximately 13,000 bearers pa). The *drill and fix* process has been used on around 50% of manufactured bearers, starting six months after CEMEX established its bearer business in 1999. Therefore around 570,000Lm of bearer (or 126,000 bearers) have been produced using the *drill and fix* method. These bearers have been deployed in various layouts/junctions/crossings with an average of around 300Lm per layout (100 layouts using *drill and fix* pa) at a cost of around GBP1M per layout. If all the layouts using the *drill and fix* technique had to be replaced due to longitudinal cracking, the total cost would be in the region of GBP1.9bn. The numerical analysis conducted at Durham University has led CEMEX to abandon the *drill and fix* technique (see [E1]) and has been critical in the development of new resilient fastening methods. As stated by CEMEX [E1]: *"Since this time the numerical modelling expertise of Dr Coombs has been invaluable in assessing the fracture potential of new fastening methods, and other cast-in-place inclusions, prior to their deployment in our railway products. This has included a further four phases of FEA on products that will be deployed in both Network Rail and London Underground assets*." A CEMEX press release in 2016 also mentions Durham's input to design of concrete bearers on tight curves [E6].

Impact on policy

In addition to the manufacturing changes outlined above, the research findings from this Case Study have led to Network Rail changing the technical standard for sleepers and bearers, NR/L2/TRK/030, to no longer allow the *drill and fix* fastening method to be used (contact [E5] to verify). London Underground's technical specification T0404 for *Track: Concrete Sleepers and Bearers* issue A2 now includes Written Notice LU-WM-01405 on *Casting-in of rail clip anchorages (shoulders)* that states [E4]: *"This Written Notice prohibits rail clip anchorages from being formed by any method involving drilling into the concrete after casting." Clause 3.2.3 of the Technical specification has been revised to state: "Anchorages shall be secured by a method which does not involve drilling of the sleeper or bearer after casting."*

To summarise, Durham research has revealed the root cause of longitudinal cracking in concrete crossing bearers leading to a step change in practise both in the sole UK manufacturer and across the rail network. These changes led to improved consumer confidence and a significant reduction in maintenance work and associated costs.

5. Sources to corroborate the impact (indicative maximum of ten references)

[E1] Testimonial letter dated 9th December 2020 from UK Standards Manager (Prestress), CEMEX.

[E2] One of eight separate confidential reports as an example detailing the findings of the numerical analyses undertaken at Durham University and recommendations based on the interpretation of these results.

[E3] Testimonial letter dated 10th December 2014 from CEMEX briefly outlining the impact of the first four sets of analysis undertaken at Durham University.

[E4] London Underground Technical Specification T0404 for *Track: Concrete Sleepers and Bearers,* issue A2, including Written Notice LU-WN-01405, March 2016.

[E5] Principal Engineer (S&C) at Network Rail, key contact within Network Rail involved in changes to the technical standards related to sleepers and bearers.

[E6] CEMEX Press Release, https://www.cemex.co.uk/-/rail-solutions-get-curves-in-all-the-right-places-