

Impact case study (REF3b)

Institution: Oxford Brookes University
Unit of Assessment: 15 - General Engineering
Title of case study: Safer and more economical slender structures
<p>1. Summary of the impact (indicative maximum 100 words)</p> <p>Research, led by Oxford Brookes University's Dr Mike Godley and Dr Rob Beale, into the design and analysis of scaffold structures has enabled a better understanding of their behaviour, higher standards of safety and improved design. The Group produced technical guidance to the HSE and authored the design guide TG20:08 (2008); the basis for scaffold design in the UK. The Group contributed to new Euronorms for scaffolding and the UK design guide is compatible with these. Furthermore, the Group informed a pan- European design guide for storage racking systems (2000) that later transformed with little modification into EN 15512 (2009). This is now the basis for the design of all such storage racks across Europe.</p>
<p>2. Underpinning research (indicative maximum 500 words)</p> <p>Scaffold and storage rack structures are slender structures with semi rigid joints and splices and both exhibit looseness. Additionally, rack structures are sensitive to local buckling¹. The Group was amongst the first to demonstrate that traditional methods of design for access scaffolds, that assumed lift-height effective lengths, could produce unsafe scaffold structures. Such methods erroneously assumed that horizontal members (ledgers) acted as ties restraining deflections parallel to the facade². The true behaviour is that the restraint is only partial. Scaffold structures also require ties to the facade to give them their structural integrity. The Group demonstrated that the buckling behaviour of scaffolds is dependent on the pattern of such ties in addition to the degree of horizontal restraint provided by the ledgers. These results were confirmed by tests of full size scaffolds at BRE.</p> <p>For both scaffolding and storage racking systems the structural behaviour of the connection between beam and column has a crucial effect of performance³. Currently available software allows only a simplified linear model of the connection to be used, but work by Pabrakhan⁴ demonstrated ways of successfully introducing non-linear characteristics into the structural joint models.</p> <p>The configuration of access scaffolds is much less regular than that of storage structures, and was lightly regulated during the early days of the research. There was concern that safety levels might be compromised and premature failures might occur due to common errors in construction. With the support of the Health and Safety Executive (HSE) site surveys were made and some indication of the types of construction errors that occurred and their frequency was obtained. Reliability analyses of typical scaffold constructions were made to determine failure risks. It was discovered that these faults are usually caused by poor site supervision and practice and in 1997 HSE inspectors were issued with guidelines to ensure safer work.</p> <p>A major shortcoming of scaffold design is the lack of a thorough investigation into the effects of wind. To rectify this, Irtaza⁵ carried out extensive experimental work on wind tunnel models and a parallel computational fluid dynamics (CFD) study, to successfully identify the wind loads applied to scaffolds with and without sheeting and netting. He calibrated the CFD model against full scale tests made at Silsoe and derived pressure coefficients for scaffolds erected around a cubical building. A large data set derived from experimental work on models in a wind tunnel was deposited in the British Library for use by other researchers.</p> <p>Both scaffolds and storage racks have relatively short lives and there is therefore a reluctance to invest heavily in permanent column foundations. Temporary lightweight foundations are susceptible to failure due to the effects of lack of fixity, imperfections and column flexure. This problem was initially investigated by Feng¹ who designed a simple model of a base-plate which peeled off the substrate as column bending increased. Further work by Lau⁹ demonstrated the consequences of column flexure on flat ended column bases experimentally, confirming his theoretical predictions. The research is being extended into the reliability of scaffold structures⁶.</p>

3. References to the research (indicative maximum of six references)

1. Godley M H R, Beale R G and Feng X, 2000. "Analysis and Design of down-aisle pallet rack structures", *Computers and Structures*, Vol. 77, No. 4, 391-401. doi:10.1016/S0045-7949
 This paper presented the results of doctoral research by Ms Feng under the supervision of Dr Godley and Dr Beale into a single column non-linear model of pallet rack structures including imperfections which was shown to give results that were within 4% of full three-dimensional analyses. The model formed the basis of the state-of-the-art commercial program Palletsoft which designed storage structures to FEM10.2.02, 2000 and which had international sales. The program was able to design racks in significantly less time than the use of standard finite element programs enabling efficient and economical designs to be produced
Submitted to RAE2001, Oxford Brookes University, UoA33-Built Environment, RA2, MHR Godley, Output 4.
2. Godley M H R and Beale R G, 2001. "Analysis of large proprietary access scaffold structures", *Proc. Inst. Civil Eng. Structures and Buildings*, Vol. 146; Part 1, 31-40. doi:10.680/stub.2001.146.1131
 This paper presents bi-linear models of the non-linear elasto-plastic behaviour of scaffold connections and shows that the different moment-rotation curves for clockwise and anticlockwise rotation need to be considered in analyses. Finally it presents new two-dimensional models which accurately model the interconnection between elements in a full three-dimensional scaffold structure.
3. Ng A L Y, Beale R G and Godley M H R, 2009. "Methods of restraining progressive collapse in rack structures", *Engineering Structures*, Vol. 31, No. 7, 1460-1468. doi:10.1016/engstruct.2009.02.029
 This paper presents the results of doctoral research by Ms Ng under the supervision of Dr Godley and Dr Beale into the dynamic collapse of pallet racks under impact conditions. The research demonstrated an economical way of increasing the resistance of a rack to impacts by the insertion of restraining braces.
4. Prabhakaran, U, Beale R G and Godley M H R G, 2011. "Analysis of scaffolds with connections containing looseness", *Computers and Structures*, Vol. 89, No 21-22, 1944-1955. doi:10.1016/j.compstruc.2011.03.016
 Continuing the research into scaffolds the effects of looseness which is prevalent in all scaffold connections was investigated by Miss Prabhakaran under the supervision of Dr Godley and Dr Beale. The resulting new models developed in this paper have shown that the traditional way of dealing with looseness by applying an equivalent side load can lead to incorrect results.
Submitted to REF2014, Oxford Brookes University, UoA15-General Engineering, REF2, RG Beale, Output identifier 8533.
5. Irtaza, H, Beale R G and Godley M H R, 2012, "A wind tunnel investigation into the pressure distribution around sheet-clad scaffolds", *Journal of Wind Engineering & Industrial Aerodynamics*, Vol. 103, 86-95. doi:10.1016/j.jweia.2012.03.004
 The research into scaffolding was continued by Irtaza as part of a doctoral programme supervised by Dr Beale and Dr Godley. The paper extends the previous research which was primarily structural analysis into the determination of wind loads applied to access scaffolds. The study included a consideration of the porosity of the sheeting around the scaffold.
Submitted to REF2014, Oxford Brookes University, UoA15-General Engineering, REF2, MHR Godley, Output identifier 9123.
6. Andre, J, Beale R G and Baptista A M, 2013, "Recent advances and existing challenges in the design of bridge falsework systems", *Civil Engineering and Environmental Systems*, Vol. 30, Issue 2, 130-145. doi:10.1080/10286608.2012.733374
 The slender structures group have obtained funding from the Portuguese Research Council (FCT) for a doctoral student, Mr Andre, to investigate failures of bridge scaffold structures to extend the work into devising procedures for improving the safety of the structures. This

paper represents the preliminary results of the research.

4. Details of the impact (indicative maximum 750 words)

Research into the design and analysis of scaffold structures has enabled a better understanding of their behaviour, higher standards of safety and in improved design. The design guides TG20.05 and its revision TG20.08^{7,8} are extensively used throughout the UK and, together with the suggested revisions to testing procedures for scaffold connections, will enable proprietary scaffold systems to also be erected safely so that the number of scaffold collapses within the country will be reduced. As a consequence of the authors' involvement in the development of the Euronorms for access scaffolding, they are compatible with the Euronorms. Recently the group has attracted funding from the Portuguese government to extend the research into the reliability of bridge scaffolds, several of which have collapsed in the last few years in Portugal causing fatalities. The results of this research have been presented at conferences and in journal articles.

Although the research has been primarily applied to UK scaffolds it has also been referenced and used by scaffold designers in developing countries where Dr Beale through his research expertise has given seminars to Structural Engineers⁹ on causes of scaffold collapses and the improvements required for safe design (Hong Kong,2003 and 2008 and Malaysia,2007).

The earlier research for the HSE has led to scaffold contractors and users being made aware of the importance of tying and bracing on the behaviour of the systems and to the HSE Inspectors being given a set of strict guidelines to enforce when inspecting scaffolds. Test results on scaffold connections were used to help draw up the models used in producing the design guides referred above. The implication of looseness on scaffold designs has yet to make an impact but the work was only published in 2011 with recommendations for changes to the European scaffold codes.

The testing procedures developed for rack structure^{10,11,12} were used in developing the procedures for testing scaffold structures and as part of its consultancy programme the University has tested nearly every scaffold manufacturer/distributor in the UK to enable the manufacturers and designers to correctly determine their products' performances (income generated in excess of £400,000 over 15 years). During the period in question about 200 reports on structural testing of scaffolds and racking system components were completed.

Research-led consultancy work for Interserve UK¹³ resulted in new design tables for 'Kwickstage' scaffold structures being produced. These tables were immediately used by competitors supplying look-alikes although the university established that the alternative manufacturers' products could be 10% less safe¹³. Following this consultancy the group, with Interserve, developed a new economical scaffold structure (K2 system) requiring 20% less components and steel and being erectable in less than 50% of the time of its competitors.

The profits from the consultancy enabled several PhD students to be funded, many from developing countries. Some of these students have since gone on to become University lecturers in Malaysia⁹(2), Jordan¹⁴ (2) and India where they are using the knowledge gained in their research and disseminating it there. Other ex-PhD students have become leading designers and engineers working in the UK and the US.

The extensive research into pallet rack properties has led to the Euronorm BS EN15512¹⁵ being accepted. It requires racking manufacturers to take into account second order elastic effects in the stability of the racks so as to produce safer and more economic racks. Small reductions in the amount of material used in modern designs (typically from the new procedures) of around 15% can make a rack fully competitive in international marketplaces as material costs are around 85% of the total cost of an installed rack. Although there are only a limited number of UK pallet rack manufacturers the University has commercially tested the products of most of them. In addition a state-of-the-art computer program 'Palletsoft' written by the group and marketed by the University had international sales and is used in Australia and the UK to produce safe, economical designs efficiently and quickly.

Impact case study (REF3b)

The looseness effects on cross-aisle stability of pallet racks have been reported to the industry where they have caused some manufacturers to amend their procedures. Latest research has led to a very cost effective way of reducing the number of rack collapses under impact by fork lift trucks which is to insert additional plan bracing at the first level of the rack.

Insights from the research of Dr Godley and Dr Beale, at Oxford Brookes University, to better understand the analysis and design of slender structures has not only informed design guides and safety policy but also influenced construction standards in the UK and Europe with improved practice and safety measures for construction workers

5. Sources to corroborate the impact (indicative maximum of 10 references)

7. Corroborating contact 1. Managing Director, The National Access Scaffolding Confederation.
8. NASC TG20:08 :Technical Guidance on the use of BS EN 12811-1, 2008 (design code).
9. Corroborating contact 2. Head of Department of Civil Engineering, Curtin University, Sarawak Malaysia.
10. FEM 10.2.02, The Design of static Steel Pallet Racking, Section X of the Equipment et Proceeds de Stockage', 2000(design code).
11. Corroborating contact 3. Engineer, Harsco Infrastructure Ltd , (scaffolding and pallet rack structures).
12. Corroborating contact 4. Secretary General, FEM Racking and Shelving product Group (European Racking Federation).
13. Corroborating contact 5. Chief Engineer, Interserve Construction Limited (scaffold structures).
14. Assistant Professor, Department of Civil Engineering, Faculty of Engineering and Technology, University of Jordan (Contact details available from Oxford Brookes University Research & Business Development Office upon request)
15. BS EN 15512 'Steel static storage systems – adjustable pallet racking systems – Principles for structural design', 2009.(Euronorm)