Institution: University of Bath

Unit of Assessment: 16: Architecture, Built Environment and Planning

Title of case study: Clever Roofs: Innovative Methods to Cover Large Open Spaces

1. Summary of the impact

The Digital Architectonics group in the **Centre for Advanced Studies in Architecture** (CASA) in the Department of Architecture and Civil Engineering at the University of Bath has had continuous engagement with leading architectural and engineering practitioners since its foundation by the internationally renowned civil engineer Professor Sir Edmund Happold in the late 1970s. Its unorthodox digital methods have been fundamental to the recent establishment of *architectural geometry* as a new specialism in both professions. One feature of this work is the ability to addresses the common problem of how to cover large spaces (such as courtyards and stadium roofs) without relying on intermediate supports (such as columns). The novel structural analysis techniques developed at Bath have led to significant consultancy on major landmark buildings. In particular, the reductions in complexity, risk, and carbon footprint resulting from such an approach have led to a re-emergence of the timber gridshell as a cost-effective and spectacularly low-carbon building solution. The impact has thus been both economic and environmental.

2. Underpinning research

Staff involved: Sir Edmund (Ted) Happold (1976-1995: Professor), Michael Barnes (1995-2008: Professor), Paul Richens (2005-present: Professor), Richard Harris (2006-present: Professor); Drs Chris Williams (1976-present: Senior Lecturer), Deborah Greaves (2000-2008: Research Officer, Lecturer) and Paul Shepherd (2007-present: Research Fellow, Lecturer).

During the late 1990s Barnes extended his pioneering work on Dynamic Relaxation, a technique for the form-finding and analysis of cable and fabric structures (such as the Millennium Dome), to include compression and bending elements. This made possible the more accurate consideration of strut-and-tie (tensegrity) structures [1] and gridshells [2]. Through introducing analytical techniques to improve stability, the large deformations associated with these types of structures could be accurately modelled [3]. During this time, Williams was consulted by Buro Happold and Foster+Partners on work to develop the form of the British Museum Great Court roof (BMGC, opened in 2000), where he introduced two innovations to architectural geometry [4,5]. The first was the use of 'blended equations' to describe the shape of the roof. The second was in the way the structural grid was optimised using a modification of Dynamic Relaxation, leading to the efficient and beautiful spiral form seen today.

In 2000 Williams and Shepherd (then at Buro Happold) investigated the extension of Dynamic Relaxation to the design and construction of gridshells made from long, continuous members. They applied this work to the temporary cardboard gridshell by Shigeru Ban for the Japan Pavilion at the Hanover Expo 2000, which was built entirely of recyclable material. At the same time, these experimental algorithms were used to design the 2001 Weald and Downland Museum (Edward Cullinan, Buro Happold), the first permanent timber gridshell to be built since Mannheim. It is important to note that underpinning research and its impact on built structures have a symbiotic relationship in this case.

Two very important conferences on this group's research were convened in Bath in the early 2000s. *Widespan Roof Structures* (2000) [4] brought together researchers and the designers of many Millennium structures: the Dome, Eden Centre, BMGC, and the international stadiums at Cardiff and Wembley. The *Digital Tectonics* conference (2002) included architects Greg Lynn, Mark Burry, Bernard Cache, Lars Spuybroek, and engineers Mike Cook and Cecil Balmond. This marked the point where architects started to shed their technophobia and see digital technology as having a genuine creative potential, as well as feeding ideas back into research, and the resulting book is still in print [5]. Concerns over the lack of design guidance for the wind loading of fabric structures meant that many such building designs were overly conservative and inefficient. This led Williams to collaborate with Greaves and their PhD students on investigating fluid-fabric interaction. They looked for alternatives to conventional Computational Fluid Dynamics (CFD) techniques and in particular pioneered the application of a method of surface modelling used in computer graphics (Subdivision Surfaces) to the simulation of airflow around structures, especially important in cases where the shape of a building changes significantly in response to wind.

In 2007 and with industrial funding from Informatix of Japan, Richens and Shepherd investigated the use of the same Subdivision Surfaces to describe architectural form [6]. Current work is leveraging the various advantages that subdivision surfaces hold for analysis and optimisation over traditional CAD modelling tools, through software that promotes the simultaneous consideration of architectural and structural issues.

3. References to the research

[1] Adriaenssens, S. M. L. & Barnes, M. R., (2001), 'Tensegrity spline beam and grid shell structures', *Engineering Structures*, 23(1), pp.29-36, doi:10.1016/S0141-0296(00)00019-5.
[2] Harris, R., (2011), 'Design of timber gridded shell structures'. *Proc. ICE - Structures and Buildings*, 164(2), pp.105–116, doi:10.1680/stbu.9.00088.
[3] Barnes, M.R., (1999), 'Form finding and Analysis of Tension Structures by Dynamic Relaxation'. *International Journal of Space Structures*, 14(2), pp.89-104, doi:10.1260/0266351991494722.
[4] Williams, C.J.K., (2000), 'The definition of curved geometry for widespan structures', in Barnes, M. and Dickson, M. eds. *Widespan roof structures*, Thomas Telford, London, pp.41-49. ISBN 978-0727-728777.
[5] Williams, C.J.K., (2004), 'Design by algorithm', in Leach, N., Turnbull, D. and Williams, C.J.K. eds. *Digital Tectonics*, Wiley, Chichester, pp.78-85. ISBN 978-0470-857293.
[6] Shepherd, P. & Richens, P., (2012), 'The Case for Subdivision Surfaces in Building Design', *Journal of the Int. Assoc. for Shell and Spatial Structures*, 53(4), pp.237-245. ISSN 1028-365X. Shortlisted by IStructE, http://www.istructe.org/structuralawards/2013/the-shortlist.

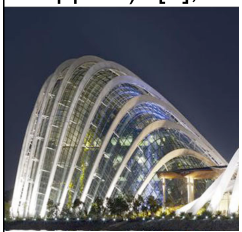
4. Details of the impact

The impact of this research lies in two principal areas, namely: the establishment of architectural geometry as a recognised professional specialism in both structural engineering and architectural practices; and a direct and substantial contribution to the design of a series of exemplary and influential buildings. This was made possible in many cases through a symbiotic relationship with Buro Happold (BH) initiated some 35 years ago by Ted Happold, then the Department's Professor of Engineering, and there has been close cooperation with BH ever since - in research, and just as importantly in its translation into challenging building projects. Whilst the Department has benefitted from the recruitment of expert BH staff with practical experience at all levels (including Harris and Shepherd), BH have in turn according to a Senior Partner enjoyed "**privileged access**" to our "**world-class research**". This has been **"a significant factor in the firm's international growth and success. The novel structural analysis techniques developed at Bath have led to significant consultancy on major landmark buildings.**" He also recognises "**the valuable role of Bath in training future researchers**" [7]. In this way we have contributed directly to the UK economy.

The impact on Foster's office of Bath's work on the BMGC roof was such that they immediately set about creating an in-house 'specialist modelling group' to develop their own expertise in using our research methods to inform the more geometrically complex of their projects. The Smithsonian Institution (2004-7) is the most obvious beneficiary, designed and engineered by the same team as the BMGC, and acknowledged on Foster's website (http://www.fosterandpartners.com/projects/smithsonian-institution/) as further developing the structural and environmental themes first explored in the BMGC. The idea of establishing a specialist geometry group has now been taken up by most leading architectural and civil engineering firms, for example Buro Happold SMART, Arup Advanced Geometry Unit (AGU), Ramboll Computational Design Group (RCD), Zaha Hadid Architects Computation and Design Group (CODE). In particular, SMART was set up by Shepherd to focus on applying Barnes' Dynamic Relaxation methods, and RCD is staffed entirely of Bath research graduates, showing how our innovations have changed the way the industry approaches the design of complex geometric buildings.

Indeed, according to the Director of Design at Ramboll UK, "**Since its inception [in 2011], the RCD team have partaken in a number of projects including Astana National Library (Kazakhstan), Tallinn Town Hall (Estonia), Kreod Pavilion (UK), Belvedere Sculpture (USA) and Trada Shell (UK), which would not have been possible without access to the digital architecture-focussed research of Chris Williams and Paul Shepherd**" [8].

The group has been involved in the design of other significant buildings. An early steel gridshell with which Williams and Barnes had involvement was the Singapore Esplanade Theatres (Michael Wilford, 1997-2002) that has been imitated by others during the REF period in Croatia (Dvorana Krešimira Ćosića), Abu Dhabi (Yas Marina Hotel), Taiwan (Kaohsiung Marine Gateway) and Frankfurt (Zeil Gridshell). Williams's research into novel analysis of forms was applied in 2006 to a further gridshell at Savill Garden (Glen Howells, Buro Happold) [9], where he and Harris (then Technical Director of Buro Happold, joining the Department in 2006) combined the blended-equation surface technique used at the British Museum with relaxation methods of grid-smoothing and analysis. Indeed Williams collaborated on the 2010 Gardens by the Bay gridshell (Wilkinson Eyre), which won the WAF World Building of the Year award in 2012. An independent project to build a GFRP gridshell by Douthe of the Universite Paris-Est specifically acknowledges use of the Barnes/Williams algorithms [10].



Williams has developed his Dynamic Relaxation methods further to produce gridshell roofs composed entirely of planar polygons. This is important for glass roofs since the cost of curved glass is prohibitively high. Williams applied this research as a consultant on the National Maritime Museum in Amsterdam (Ney+Partners, 2011), a project which won several architectural awards [11]. Williams provided consultancy for the design of the award-winning 2010 Aviva Stadium in Dublin, and supervised the PhD project that developed the architectural parametric design of the façade. A parallel role on the engineering side was played by Shepherd (initially at BH but then at Bath and jointly supervising the PhD student). The parametric methodology they developed allowed the structural and cladding models to adapt quickly to late changes in the overall geometry of the building, preventing the prohibitively expensive rework associated with traditional design. This was the first time that a single model embracing both structure and skin had been shared between architect and engineer [12].

A further example of research directly impacting on industry through a particular building is the 2012 Aarhus Botanical Garden Hothouse in Denmark. Research software based on subdivision surfaces developed by Shepherd was used (with architects C. F. Moller) to design and optimise the design-competition winning building completed in summer 2013, which was shortlisted for two IStructE Structural Awards [6].

The most striking buildings to benefit directly from the group's research into form-finding and analysis are undoubtedly the timber gridshells, which have about one-sixth the CO_2 cost of an equivalent steel structure. Prior to this research, expensive physical models and full-scale load tests had to be performed (as occurred at Mannheim) to give confidence in the design, and rectification of any problems at such a late stage was costly. The computational methods developed at Bath reduced this risk and have been important in a number of projects where the influence of our research is directly traceable in terms of knowledge transfer. These include Chiddingstone Castle (2007), the Savill Garden building (which won the IStructE Supreme Award in 2007 [9]), and, during the REF period, Scunthorpe Leisure Centre (2011). The last building was designed by BH's in-house SMART group (originally set up by Shepherd), which has employed many Bath graduate students and is currently sponsoring one of our EngDs.

Apart from direct involvement in consultancy, the Bath group has another major pathway by which its research impacts on industry and wider society, namely through education. Finding sufficiently skilled staff for such specialist modelling groups within consulting has been a challenge since they first started to appear on the back of the BMGC roof project. To help resolve this through CPD, Richens was among the founders of the Smart Geometry movement, which today runs annual intensive workshops around the world. Williams has been a tutor since the inaugural meeting in Cambridge (2003), and several research students have made substantial contributions as teachers at public workshops in New York (2007), Munich (2008), San Francisco (2009), Barcelona (2010), Copenhagen (2011), Troy (2012), as well as private ones in the offices of leading architects (such as HOK Sport, 2007; Ian Simpson Architects, 2008) and engineers (such as Whitby Bird, 2007; Atkins, 2012).

In 2009 Richens, Shepherd and Williams launched the Digital Architectonics MPhil Research programme at Bath, which gives architects and engineers in-depth exposure to the research methods developed by the group, and guides them in developing their own in practice. Students have been sponsored by several leading firms (BH, Arup, Ramboll, Schlaich Bergermann & Partners), taking approaches pioneered at Bath back into practice, as evidenced by their subsequent publications [13-15]. These training enterprises, and a steady flow of PhD and EngD students into the professions has been a major route of dissemination of the philosophy, methods and results of the group, and has had a significant role in establishing the new sub-discipline of architectural geometry. The breadth of influence is demonstrated by the firms which have employed our students since 2008: Arup (2), Buro Happold (2), Fosters (1), Schlaich Bergermann & Partners (1) and overseas universities (2). Indeed in 2011 in a scenario reminiscent of Fosters back in 2000, Ramboll set up a new Computational Design group, staffed entirely by postgraduate research engineers from the group, their first prize being for the demountable timber Kreod Pavilion (Chun Qing Li) which won Best Temporary Structure at the Surface Design Awards 2013.

5. Sources to corroborate the impact

Organisational Referees

[7] Buro Happold, Senior Partner & Chairman, personal letter.
[8] Ramboll, Director and Head of Ramboll Computational Design (RCD), personal letter.

Publications and Awards

[9] Harris, R., Haskins, S. & Roynon, J., (2008). 'The Savill Garden gridshell: design and construction', *The Structural Engineer*, 86(17), pp.27-34. http://www.istructe.org/journal/volumes/volume-86-(published-in-2008)/issues/issue-17/articles/the-savill-garden-gridshell-design-and-constructio.
Shortlisted for RIBA Stirling Prize and won IStructE Supreme Award for Structural Engineering Excellence, both in 2007, http://en.wikipedia.org/wiki/Savill_Building#Awards.

[10] Douthe, C., (2007) "Étude de structures élancées précontraintes en matériaux composites: application a la conception des gridshells". Doctoral Thesis. École Nationale des Ponts et Chaussées. Paris, pp.24. http://pastel.archives-ouvertes.fr/pastel-00003723/

[11] Adriaenssens, S., Ney, L., Bodarwe, E., & Williams, C., (2012), 'Finding the Form of an Irregular Meshed Steel and Glass Shell Based on Construction Constraints', *J. Archit. Eng.*, 18(3), pp.206–213. doi:10.1061/(ASCE)AE.1943-5568.0000074. Amsterdam Architecture Prize 2012 and Dutch National Steel Prize 2012 listed amongst others at http://www.ney.be/en/project_details/110.html.

[12] Shepherd, P., (2011), 'Aviva Stadium – the use of parametric modelling in structural design', *The Structural Engineer*, 89(3), pp.28-34. http://www.istructe.org/webtest/files/43/434a0326-f4e2-44a6-bc3f-3281be4947d4.pdf.
Many awards listed at http://www.avivastadium.ie/newsItem.aspx?id=81

[13] Georgiou, O., (2011), 'Interactive Structural Analysis', *Proc. 14th Int. Conf. on Computer Aided Architectural Design Futures*, Liege, pp.833-846, ISBN 9782874561429.

[14] Georgiou, O., Richens, P. & Shepherd, P., (2011), 'Performance Based Interactive Analysis', Design Modelling Symposium, Berlin, doi:10.1007/978-3-642-23435-4_14.

[15] Melville, S., Harding, J. & Lewis, H., (2013), 'TRADA Pavilion: Searching for Innovation and Elegance in Complex Forms Supported by Physical and Software Prototyping', *Proc. of the Prototyping Architecture International Conference*, The Building Centre, London, pp.277-289, ISBN 978-0-901919-17-5.