Variety, relevance and significance

Loughborough's 3D Concrete Printing (3DCP) is capable of creating curved large-scale customised freeform structures.

Variety, relevance and significance

With over 250 industry partners currently supporting research and teaching activities in the School of Civil and Building Engineering at Loughborough University, there is plenty to report, as Chris Goodier, Jacqueline Glass, Alessandro Palmeri and Simon Austin describe.

The great strength of the School is its innovative, industry-relevant research and postgraduate training. The results of the last research assessment exercise in 2008 confirmed Loughborough as one of the country's leading research universities, being ranked fifth in the UK for built environment research and seventh for civil engineering. Research grant and contract income also currently stands at over £4.5 million per annum, supporting over 150 full-time research staff and students.

Innovative

One example is the School's Centre for Innovative and Collaborative Construction Engineering (CICE), an EPSRC-funded engineering doctorate centre, where the research engineers are supervised by Loughborough academics but work in industry on sector-related research problems.

Christian Christodoulou, based in Aecom, is one such research engineer who is nearing the end of his engineering doctorate on the durability of concrete structures and the corrosion of reinforcement, jointly supervised by Dr Chris Goodier and Professor Simon Austin, as well as Dr Gareth Glass from Concrete Preservation Technologies. This research investigated the long-term performance of some of the key corrosion management techniques through a programme of in-situ and laboratory testing focused on full-scale bridge structures (eg, the Birmingham Midland Links) in order to establish improvements for the corrosion management of steel-reinforced concrete structures. This brought together individual research themes of patch repair and incipient anodes[1], impressed current cathodic protection[2,3], galvanic and hybrid cathodic protection[4], as well as hydrophobic impregnations[5].

A recently completed engineering doctorate sponsored by Lafarge Tarmac has investigated the opportunities that self-compacting concrete (SCC) can offer the contractor on site, as reported previously in *Concrete*[6]. The research compared cost and time of conventional and SCC placement for slabs. Dave Rich, who carried out the study, and now works for Lafarge Tarmac, reports that "the data show how SCC significantly improves profitability because it removes the need to use inefficient, expensive, out-of-hours working."

Various aspects of precast concrete structures have been studied as part of Gary Robinson's engineering doctorate project, jointly supervised by Professor Austin and Dr Alessandro Palmeri and co-sponsored by Hanson Structherm. Three main streams of research have been pursued, namely:

1) design assisted by testing (DAT) procedure to allow a less conservative prediction for the ultimate buckling capacity of slender panels[7]

2) adoption of artificial lightweight aggregate (specifically, sintered fly ash) in the precast manufacture, with and without incorporation of steel fibres[8]

3) nonlinear push-down analyses to quantify the robustness of precast building structures[9].

The overarching theme of Robinson's doctoral studies has been the exploitation of contemporary material and fabrication technologies, as well as improved analytical and computational methods, for advancements in the precast concrete industry.

As part of an ongoing programme of research with Aggregate Industries, work has just started on a four-year engineering doctorate study of novel solutions for the building retrofit market. Initial evidence collected by Aaron Lang suggests that high-tech energy-efficiency measures are too complex to be operated by anyone other than

'techno-geeks', so passive measures, such as enhanced thermal mass, could be more likely to succeed and offer cost-effective energy savings on a broader scale.

International links

Loughborough has also recently hosted two researchers from the Universitat Politècnica de Catalunya (UPC), in Barcelona, Spain, who have been researching different areas of sprayed concrete. Luis Segura-Castillo has been investigating sprayed concrete bi-layer diaphragm walls, including experimental and numerical structural analysis, as well as the evolution of concrete-to-concrete bond strength at early ages[10]. Isaac Galobardes has been exploring design considerations for wet-mix sprayed concrete with set accelerating admixtures, together with new ways of applying the maturity (temperature) method for calculating the early-age strengths of sprayed concrete.

PhD student Thanh Nguyen, supervised by Dr Goodier and Professor Austin, and visiting from the National University of Civil Engineering (NUCE) in Hanoi, Vietnam, is investigating how to optimise the durability of fly ash-based geopolymer concrete, particularly with regard to the causes of reinforcement corrosion. He is working towards developing cement-free concrete with excellent durability properties such as porosity and permeability, and resistance to carbonation and chloride ingress. Close links have been formed with NUCE, with Dr Goodier recently chairing the international conference *Sustainable Built Environment for Now and the Future*, in Hanoi in March 2013[11].

Ruting Sun, from China, has been exploring the acoustic properties of cementitious materials as part of her PhD and investigating their potential for musical manufacture, supervised by Dr Goodier and Dr James Flint[12]. She aims to derive more fundamental knowledge regarding the acoustic properties of cementitious materials and to investigate the effect of the physical, mechanical (eg, compressive strength, density, elastic modulus, etc) and other properties (eg, shape, thickness, etc) of cementitious materials on the acoustic properties of the material. This work has potential implications for both the intelligent acoustic design of rooms and spaces, as well as more material-focused design of musical instruments.

Undergraduate research

Final-year BEng and MEng projects are also often heavily focused on materials research. Experimental investigations have been carried out on the mechanical behaviour and structural performance of 'rubcrete', ie, rubberised concrete where aggregates are partially replaced with rubber chips and crumbs.

Under the supervision of Dr Palmeri, three MEng dissertations have demonstrated that rubcrete can effectively change the mode of structural failure, with the material experiencing improved crack control, larger ultimate deformations and less brittle failure. For their joint work on the 'Mechanical characterisation of waste-tyre rubberised concrete', Thomas Godfrey and Steve Martin have won the first prize in the national poster judging held by the Institution of Structural Engineers for the 2011–2012 Undergraduate Research Grant. These experiments were also used to validate a novel imagery-based technique for measuring the field of strains and displacements during large-scale structural tests. David McCarthy, a second-year PhD student jointly supervised by Professor Jim Chandler and Dr Palmeri, is currently pursuing an extension of this technique to the case of dynamic loads, with potential applications for structural health monitoring[13].

(Photo: Nick Rawle Photography.)

Above: A key feature of research at Loughborough is close industry engagement; for example, debate at the last APRÈS responsible sourcing conference.

(Image: Google Earth.)

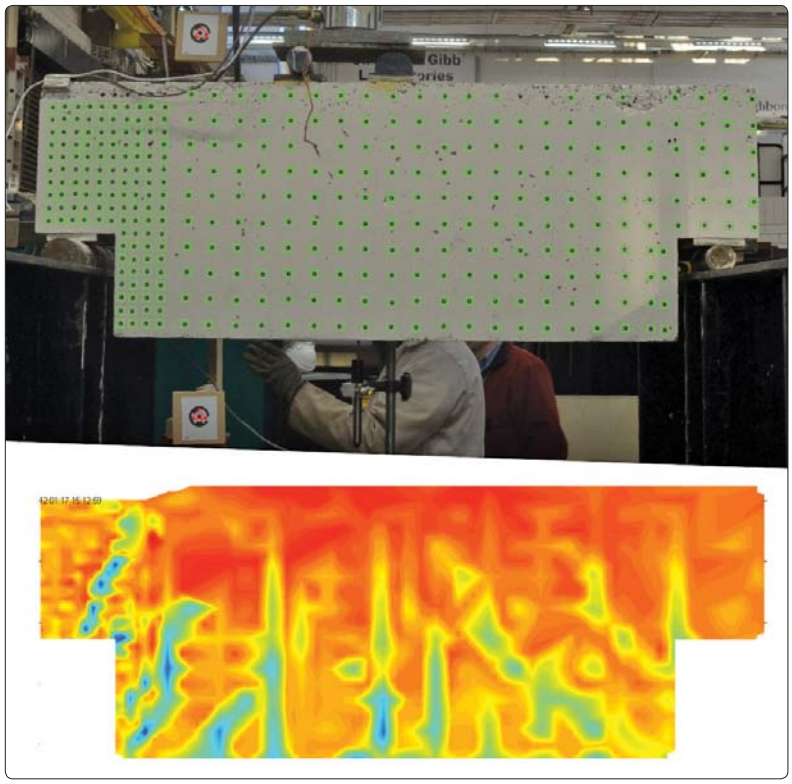
Above: Christian Christodoulou's Engineering doctorate work with Aecom and Concrete Preservation Technologies has included corrosion monitoring of the UK's famous M6/A38(M) 'spaghetti junction'.

From responsible to freeform

As well as more traditional laboratory-based concrete materials research, regular *Concrete* readers will already be aware that Professor Jacqui Glass's APRÈS project on responsible sourcing (RS) (*http://apres.lboro.ac.uk*) has been successful in bringing together over 150 organisations with an interest in demonstrating or procuring building materials against responsible sourcing criteria[14,15]. With version three of the framework Standard BES 6001[16] due out later in 2013, Glass and her team

have been reviewing previously issued RS certificates to offer insights on how materials have performed against the various clauses in the existing standards. A full paper analysing the results and comparing the concrete industry's performance with other materials is to be written with Responsible Solutions and BRE, which will contain important reading for all companies in the sector.

Last, but by no means least, Loughborough's 3D Concrete Printing (3DCP), a novel manufacturing method capable of creating large-scale freeform structures, has been attracting significant industry and media interest (*www.buildfreeform.com*). Starting with a 3D solid model, tool paths are generated through processing software, then an industrial robotic arm deposits the specially designed high-performance concrete precisely according to computer data, building the physical structure, layer by layer[17]. One application of 3DCP is the production of freeform curved customised façade panels, which are uneconomical to produce by traditional methods due to the high cost of individual moulds. Currently the FreeForm group is exploring the materials and methods for the application of reinforcement to the printed parts in an effort to create the technology for printing structural building components. Continuous yarns and technical textiles made of carbon- and alkali-resistant glass are being investigated, adapting the up and coming textile-reinforced concrete technology (TRC), with preliminary tests yielding very promising results.



Above: Experimental set-up and camera targets for one of the full-scale rubberised lintels tested within the structures and materials laboratory (top). Results of the digital image analysis and processing, showing presence of cracks in blue and concentration of compressive stress in red (bottom).

Concluding remarks

There is significant variety, relevance and significance to the current concrete-related research work within the School of Civil and Building Engineering at Loughborough University. We look forward to further continual collaboration with the concrete industry and we encourage interested readers to get in touch for more information, or for discussions regarding research and collaboration opportunities. ●

● Further information

Further information and staff contact details are available on the School's website: *http://www.lboro.ac.uk/departments/cv/index.html*. If your business is interested in benefiting from an engineering doctorate, please contact Dr Steve Yeomans or visit: *www.lboro.ac.uk/CICE*.

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