Institution: University of Nottingham

Unit of Assessment: 15 General Engineering

Title of case study: A Novel Method of Composite Design for Structural Engineering

1. Summary of the impact

University of Nottingham research into a composite design for steel beams and floor slabs has resulted in environmental and economic benefits and an important change in the construction industry. The work has reduced the weight of beams and the overall tonnage of buildings, enabled easier installation and improved structural strength. More than 40 projects, with a total combined floor area in excess of 380,000m^2, have used the technology since 2008, and the method's market share has been estimated at up to 60%. The breakthrough has facilitated partnerships between steel frame designers and precast flooring manufacturers, with the value to the latter alone put at more than £5M.

2. Underpinning research

There are two methods of fabricating reinforced concrete. The first is to pour the concrete into forms at the building site – in situ concrete. The second is to manufacture components elsewhere and bring them to the site for assembly – precast concrete.

The design of structural steel beams in buildings such as offices, car-parks, grandstands and so on can be carried out compositely with an in situ concrete floor slab that sits on a beam. Compression in the slab is transferred into opposing tension in the beam by a metal connector welded or bolted to the beam's top, increasing bending capacity by up to 50%. This type of design has been common since the 1970s.

However, precast concrete hollow-core units (HCU) (see Figure 1) are used as floor slabs in a large proportion of construction projects. These have no mechanical or reinforced connectors, presenting engineers with the problem of having to justify transferring forces between separate structural components. Research by the University of Nottingham (UoN) has provided the first technical information and experimental verification to prove HCU can offer at least the same composite strength, stiffness and ductility found in in situ slabs.

Between 1994 and 1996, Dr Kim Elliott (Associate Professor at UoN between 1987 and 2010) carried out research using HCU in precast concrete buildings, including semi-rigid connections in precast structures with HCU and floor plate action using HCU. In all cases, composite action was assured by bonding small quantities of reinforcing bars into the voided ends of the HCU. The next step was to extend this work to composite action between HCU and steel beams, as shown in Figures 1 and 2.

Fig. 1. Precast concrete hollow core slab placed onto steel beams.

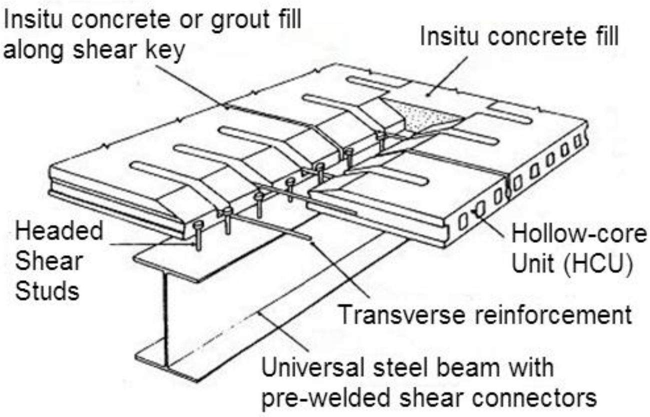

Fig. 2. Structural mechanism between HCU and steel beams, adapted from [2.1].

The research developed analytical models and design procedures to quantify the transfer of force through the key parameters shown in Figure 2: depth of HCU and steel beam, shear key joints, in situ infill, headed stud and transverse reinforcement. A feasibility study identified that the region of interaction was controlled by several material and geometric parameters. Each interface had to be proven both individually [2.1, 2.2] and collectively [2.3].

With technical and product support from a number of firms, testing on individual components [2.1, 2.2] and full-scale 6m-span beams with 150mm-deep HCU [2.3] was complemented by finite element (FE) work [2.4]. The results showed increased bending capacity of 40% to 100% and mid-span deflections a third of those without composite action [2.3, 2.5]. This allowed some 30% savings in the weight of the beam or enabled spans to be increased by between 20% and 40%. Small adjustments to the key parameters produced behaviour very similar to that of in situ slabs.

The success of analytical and FE models in predicting structural behaviour allowed a parametric study to extend the range of beam size, HCU depth and the gap and strength of infill to a series of design graphs and procedures for practising engineers [2.4, 2.5]. The research was subsequently incorporated in the Steel Construction Institute's (SCI) publications from 2003 to 2007 [see 4.5].

3. References to the research

Publications *(Items marked with an asterisk indicate 3 most significant papers)*:

2.1 *Lam, D., Elliott, K.S. and Nethercot, D.A., 1998, Push Off Tests on Shear Studs With Hollow-Cored Floor Slabs, *The Structural Engineer*, Vol. 76, No. 9, 167-174. Pdf available on request
2.2 Lam, D., Elliott, K.S. and Nethercot, D.A., 1995, Interaction Between Hollow Cored Floor Slabs and Structural Steelwork, *Proceedings of ICSAS '95, 3rd International Conference on Steel and Aluminium Structures, Istanbul, 24-26 May 1995 WOS:A1995BD44D00059*
2.3 *Lam, D., Elliott, K.S. and Nethercot, D.A., 2000, Experiments on Composite Steel Beams with Precast Concrete Hollow Core Floor Slabs, *Proceedings of the Institute of Civil Engineers, Structures and Building*, Vol. 140, 127-138 DOI: 10.1680/stbu.2000.140.2.127
2.4 Lam, D., Elliott, K.S. and Nethercot, D.A., 2000, Parametric Study on Composite Steel Beams with Precast Concrete Hollow Cored Floors, *Journal of Constructional Steel Research*, 54, 283-304 DOI: 10.1016/S0143-974X(99)00049-8
2.5 *Lam, D., Elliott, K.S. and Nethercot, D.A., 2000, Designing Composite Steel Beams with Precast Concrete Hollow-Core Slabs, *Proceedings of the Institute of Civil Engineers, Structures and Building*, Vol. 140, 139-149 DOI: 10.1680/stbu.2000.140.2.139

Grants:

EPSRC: Hollow Core Floor Slabs in Steel Framed Buildings, Grant No. GR/K17279, November 1994 to October 1996, (PI Elliott), £34,067
EPSRC: Semi-Rigid Connections in Precast Concrete Structures, Grant No. GR/K17286/01, November 1994 to April 1996, (PI Elliott), £34,205

4. Details of the impact

Three types of impact have resulted from UoN's new composite design: environmental, through a significant reduction in steel usage; economic, in terms of competitive advantage and sales; and change in industry practice, through the bringing together of the steel frame and concrete flooring sectors. Each of these has continued throughout the impact period.

A number of benefits have arisen from the new design, including easier installation and reduced floor-to-floor heights, but the key advantage for the structural engineering industry is the significant tonnage saving compared to non-composite solutions. For example, for typical office loading and spans, if a 150mm-deep HCU acts compositely with a 457mm-deep steel beam there is a 75% increase in strength and a 130% increase in stiffness (the attribute that controls beam deflections).

UK-based Bison Manufacturing, a leading specialist in the precast concrete industry and a key collaborator during UoN's research, is among the companies to have made extensive use of this benefit, which it expresses in the summary below (Figure 3). The figures here show a 55% reduction in beam weight and a 17% saving in tonnage in a particular building.

Composite Steel Frame Vs. Non-Composite Steel

	Composite	Non-Composite	Saving (T)
Steel Tonnage	192 Tonnes	232 Tonnes	17%
Typical Internal Beam Size	203x203x46 UC	457x191x67 UB	31%
Typical Internal Beam Weight	46kg/m	103kg/m *	55%

** Denotes inclusion for shelf angles to reduce construction depth*

BISON

Fig. 3. Bison composite design tonnage saving [4.1]

The cost and effort in providing the shear stud and additional reinforcement are small. Furthermore, these components are also employed by design engineers as part of the horizontal floor diaphragm and to safeguard against progressive collapse, so in certain cases they might be specified for such reasons alone – in which instances the composite action is effectively provided for free.

Adoption of the method in completed projects since 2008 has been extensive. A survey carried out by UoN [4.2] indicates at least 45 projects, with a total combined floor area of more than 380,000m^2, have used the new composite design. Table 1 summarises the survey's findings. Projects identified include 13 car-parks, 16 supermarkets/shopping centres, five schools and seven offices (including Airbus's HQ in Bristol). In addition to the companies listed below, Millbank Ltd, BHC Scotland and Tekla Structures have confirmed their regular use of the technique [4.2].

Company Name	No. of example projects identified	Area using composite design (m^2)	% uptake of composite design	Estimated Value (£)
Hollow Core Manufacturers				
Creagh Concrete [4.2]	6	126,305	50%	£3.9M
Bison (4.3]	N/a	N/a	65%	N/a
Acheson Glover Precast [4.2]	10	57,400	N/a	£1.8M
Steel Beam Manufacturers / Contractors				
Caunton Engineering [4.2]	13	101,423	30%	N/a
Tata Steel [4.2]	5	16,960	N/a	N/a
Fabsec [4.2]	9	85,200	N/a	N/a
Atlas Ward [4.2]	2	N/a	N/a	N/a
Total	**45**	**387,288**	**30-65%**	N/a

Table 1. Survey results - uptake of composite design since January 2008 [4.2].
N/a – Manufacturer/Contractor unable or unwilling (due to commercial confidentiality) to provide information.

Companies such as Bison, Creagh Concrete Ltd, of Ireland, and Caunton Engineering, another UK specialist, have estimated the percentage uptake of the design to be between 30% and 65% – and nearer 100% for certain building types, such as multi-storey car-parks. Daniel Westgate, Bison's Technical Sales Manager, says: "It's fair to say that most steelwork contractors would adopt composite steel beam design when they're tendering for a design-and-build project. Severfield Rowen, William Hare, Billington, Elland Steel, Conder Allslade, Hambelton and Atlas Ward are just a few from a list of many that have worked with Bison on schemes where composite steel beams have been adopted" [4.3]. Eunan O'Donnell, Creagh's estimator, says: "Over a 12-month period we would expect to sell in the region of 600,000m^2 of hollow-core planks in the UK. Of that, typically, we would expect in the region of 300,000m^2 to 350,000m^2 – 50%+ – to be composite beam design" [4.4].

Industry practice has also changed, with the composite design forging partnerships between steel frame designers/fabricators and precast concrete flooring contractors. The material savings and other benefits, including reduced construction depths, make the combination of these companies a commercially viable alternative to other forms of construction. The value to precast flooring manufacturers alone has been estimated to be in excess of £5M (Table 1).

Underpinning the impact has been the incorporation of the design into commercially available software (e.g. CSC) and the take-up of the research in the Steel Construction Institute's (SCI) publications [4.5]**.** CSC, a software developer specialising in providing technical support to structural engineers, has incorporated the composite design in their *Fastrak Building Designer* suite and has sold more than 3,000 *Fastrak* licences, with 2,000 sold internationally [4.6].

5. Sources to corroborate the impact

4.1 'Composite Construction' presentation (slide 21) by Daniel Westgate, now Technical Sales Manager, Bison Concrete Products Ltd.
4.2 Survey details available on request from UoN. Survey carried out between August 2012 and April 2013. Companies surveyed included leading HCU manufacturers (e.g. Bison, Creagh Concrete, Acheson Glover Precast and Millbank) and steel frame suppliers and contractors (e.g. Caunton, Fabsec, Westok, Bourne Construction, Atlas Ward Structures, BHC, Tata Steel).
4.3 Daniel Westgate, Technical Sales Manager, Bison Manufacturing Ltd (Email dated 12th September 2012)
4.4 Eunan O'Donnell, Creagh Concrete Ltd (Email dated 13th September 2012)
4.5 Steel Construction Institute: Design of Composite Beams with Precast Concrete Slabs, SCI Publication P287, 2003; Design of Asymmetrical Slimflor Beams with Precast Concrete Slabs, SCI Publication P342, 2006; Steel Construction Institute, Precast Concrete Floors in Steel Framed Buildings, SCI Publication P351, 2007
4.6 Richard Dobson, Technical Director, CSC (UK) Ltd (Telephone conversation)