Institution: Kingston University		
Unit of Assessment: 12 - Engineering		
Title of case study: A Novel Wall System for Construction of Affordable Housing		
Period when the underpinning research was undertaken: 2009 – 2018		
Details of staff conducting the underpinning research from the submitting unit:		
Names:	**Roles:**	**Periods employed by submitting HEI:**
Ted Donchev	Associate Professor	Apr 2005 – present
Mukesh Limbachiya	Professor	Oct 2001 – present
David Wertheim	Professor	Jan 1999 – present
Homa Hadavinia	Associate Professor	Apr 2005 – present
Period when the claimed impact occurred: 2015 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The SIG I-House answers the UK housing market's need for newly, affordable homes. Donchev and Limbachiya demonstrated the value and opportunity of using lightweight concrete and thin-layer mortar in wall systems for offsite housing construction. Applying these findings, in collaboration with H+H Celcon and SIG Roofspace, led to the development of the SIG I-House system.

This system delivers watertight structures in 25% of the average construction time and at an average reduction of 56% of the cost for structural frames, whilst maintaining quality equal to traditional constructs. It has been used by developers such as Barratt Developments and Willmott Dixon, providing over 396 affordable, energy-efficient houses at 7 sites across England.

2. Underpinning research

The primary cause of the UK housing crisis is the lack of new houses being built. Additionally, many houses – both new-builds and older dwellings - are not affordable for first-time buyers. The need for solutions to this crisis has incentivised builders to develop innovative systems to quickly produce quality housing. Quick building, however, must not compromise structural integrity. Structural integrity relies upon the elements of the internal structure of a building (walls, floor, roof) withstanding the forces upon them. Conducting research focused on lightweight materials and the behaviour of wall systems, Donchev and Limbachiya have led to the design of a housing solution: an offsite method of construction which joins lightweight elements whilst maintaining structural integrity.

Modelling the properties and behaviours of lightweight materials

Early research by Donchev and Limbachiya proposed alternatives to steel for reinforcing concrete structures. They particularly focused on fibre reinforced polymers (FRP) and showed that they are extremely light yet possess high tensile strength **[R1]**. This is exhibited through high strength-to-weight and stiffness-to weight ratios which lead to reinforcement against tensile stress and compression. These properties are transferable to construction where such materials minimise compression forces within structures and demonstrate excellent resistance to tensile forces. To widen the applicability of FRP materials, they developed NDT (non-destructive testing) methods that identify surface and subsurface defects in these materials before industrial use. Their research modelled the response of FRP structures to low-velocity impact so that they could predict and prevent any negative effects. Their work - correlating results from models with experimental results from literature - demonstrated how to model stresses and tension on lightweight materials. They also showed how to develop tension fields which retain system stiffness and do not fracture. Finally, they provided guidelines and design procedures for modelling and simulations to reduce negative effects such as buckling and horizontal shifts **[R2]**.

Enhancing shear wall systems: lightweight and load bearing

FRP materials have been used in civil engineering, including strengthening structures, due to their high strength-to-weight and stiffness-to-weight ratios. They have the potential for innovative uses in construction because they can be easily transported to construction sites and within building projects. Donchev and Limbachiya turned their research to steel shear wall systems, which have been popular in high-rise construction in the USA and Japan as these thin, light-weight walls provide excellent earthquake resistance. A steel shear wall is a structural panel (also called a 'vertical element') which is designed to resist horizontal forces acting upon it. The researchers proposed a hybrid wall system may have even more beneficial properties and investigated the contribution of FRP materials to such a hybrid. They designed three specimens (scaled models), all with steel frames: one was made with a steel infill plate, the other two had hybrid steel/FRP infill plates (using different FRP materials). These three specimens were tested and then the frame repaired with additional FRP materials before being retested. The infill plate was simply replaced. The results compared the behaviour and failure modes of the three different models as well as the effects of retrofitting. Their testing methodology enabled precise measurement of load capacity, stiffness, and energy absorption. Their results showed that hybrid shear walls had superior load-bearing properties, and that their retrofitting technique increased ultimate load capacity by 11% more than that of the pristine specimens **[R3]**.
Later research compared the behaviour of shear walls using different infill plates. The protocol included testing five single-story specimens each with a different infill plate: one steel, two pure FRP materials, two steel/FRP hybrids. Noting that the weight of the structure is a crucial factor in the structural design of high-rise building, it was shown that the pure FRP and hybrid infill plates made a significant contribution to the average load and to the ultimate load capacity of the specimens. A comparison of stiffness also found that the hybrid specimens had the highest initial stiffness values. The hybrid specimens' results demonstrated the application of FRP-hybrid shear walls in future building projects **[R4]**.

Through conducting estimations of the technical characteristics of individual elements and panels, as well as the structural behaviour of whole structural wall systems, Donchev and Limbachiya demonstrated their expertise to compare the potential of different wall systems, specifically in multi-storey buildings.

3. References to the research

R1 – Kadhim, M., **Donchev, T**., Al-Mishhdani, S. and Al-Shaarbaf, I. (2009) Comparison between design codes and procedures for concrete beams with internal FRP reinforcement through innovation. *In:* **Limbachiya, Mukesh C.** and Kew, Hsein Y., (eds.) *Excellence in Concrete Construction through Innovation.* London, U.K. : Taylor & Francis. pp. 413 – 417. ISBN 9780415475921 DOI: 10.1201/9780203883440

R2 - Dogan, F., **Hadavinia, H**., **Donchev, T**. and Bhonge, P., (2012) Delamination of impacted composite structures by cohesive zone interface elements and tiebreak contact. *Central European Journal of Engineering*, 2(4), pp. 612 – 626. ISSN (print) 1896 – 1541. DOI: 10.2478/s13531-012-0018-0

R3 – Petkune, N., **Donchev, T., Hadavinia, H.**, **Limbachiya, M.** and **Wertheim, D.** (2016) Performance of pristine and retrofitted hybrid steel/fibre reinforced polymer composite shear walls. *Construction and Building Materials*, 117, pp 198 – 208. ISSN 0950-0618 DOI: 10.1016/j.conbuildmat.2016.05.013

R4 – Petkune, N., **Donchev, T**., **Hadavinia, H.**, **Wertheim, D.**, and **Limbachiya, M.** (2018) Comparison of the behaviour of steel, pure FRP and hybrid shear walls under seismic loading in aspect of stiffness degradation and energy absorption. *Construction and Building Materials*, 165, pp 621 – 630. DOI: 10.1016/j.conbuildmat.2017.12.013 REF2ID: 12-028-1584

4. Details of the impact

The findings of the research **[R1 – R4]**, the methodologies developed, and the expertise gained, led to the commission of a H+H Celcon (a manufacturer of lightweight, concrete structural elements, commonly called 'aircrete') report on the behaviour of one of their wall systems and a thin-layer mortar **[S1]**. This report is the basis of the SIG I-House, an innovative wall system which is providing affordable housing across England.

Donchev and Limbachiya modified and utilised the methodology developed in their investigations **[R1 – R4]** as they analysed the structural performance of nine types of full-scale H+H Celcon panels, both individually and as walls (joined panels). They varied influencing forces and factors to estimate structural behaviour through measurable characteristics such as flexibility, energy dissipation, and dynamic response. The report **[S1]** provided H+H Celcon with essential information on how aircrete and thin-joint systems could be used as a structural system for residential, multi-storey buildings.

Using this report, H+H and SIG Roofspace developed a structural design called the SIG-I House, which can be visualised **here**. This new system exhibits excellent construction characteristics: the lightweight aircrete elements can be loaded onto each other, using a single crane, to produce a stable structural frame, whilst the thin-joint mortar preserves the behaviour of the individual elements across the whole building.

The SIG-I House's storey-high panels of aircrete are manufactured offsite and delivered ready to be craned into place onto a bed of thin-join mortar, with the full system also featuring inner leaves of walls, floors, insulation, and roof trusses, and an offsite manufactured roof. This creates a watertight shell in one week, ready for follow-on, internal trades. The societal, economic, and environmental impact that the SIG-I House has had on construction efficiency, thereby meeting England's housing needs, can be summarised as follows.

Product Development: An Efficient and Environmentally Friendly System

The Technical Director at H+H commented on '*the excellent collaboration*' in which a '*modified tailor-made methodology for investigating the behaviour of unique wall system using materials and panels from H+H was agreed and developed*'. He continued by describing how the results and consequent analysis '*were the main factors allowing the development of SIG-I House'.* He concluded that '*the developed innovative housing system is helping to meet housing demand, allowing for fast and economic construction*' **[S2]**.

The flexibility and effectiveness offered by both the thin-joint system and the aircrete have led to several benefits:

- Faster construction: a two-storey home can be made air- and water-tight in 1 – 2 weeks rather than in the 8 weeks required for a traditionally constructed home **[S3]**.
- Sound insulation: filled elements meet UK Building Regulations Part E requirements on resisting the passage of sound, both within the house and to adjoining buildings.
- Thermal insulation: the wall system contributes superb 4 – 5 $m^3/hr/m^2$ air tightness, under half the regulatory limit, obtained by the low, 0.12 $m^3/hr/m^2$, air permeability Additionally, the block has a remarkably low thermal conductivity, 0.17 W/m^2K, and minimised thermal bridges allow for a heat loss reduction of 35% **[S4]**.
- Reduced CO_2 emissions: aircrete has three times less embedded CO_2 than conventional concrete (121 kg/m^3 compared to 318 kg/m^3) **[S5]**.
- Thin-layer mortar construction is a good flood resilience option, because by reducing the risk of water penetration it leads to water-excluding structures **[S5]**.

The SIG I-House system has received several accolades, including the Product Innovation award at the Barratt Developments' Supplier Excellence Awards, and both Best Building Fabric Product and the Best Product at the Housebuilder Awards in 2017 **[S6]**.
The system received BOPAS accreditation in October 2017, and in May 2020, the National House-Building Council accepted this new Modern Method of Construction (MMC), with NHBC's

Innovation Manager noting how these solutions meet the need of the housing supply in the UK and will '*help bring benefits and certainty to manufacturers, developers, and builders*' **[S6]**.

Housing Development: Fast and Affordable Quality

Since July 2016, over 500 SIG I-Houses have been built **[S6]**. The SIG I-House system reduces the average cost of a house's structural frame by 56%, from GBP25,000 to GBP11,000, producing savings of over GBP7 million for the sector. This system enables a structure to be made watertight six weeks faster than traditional methods, which supports the reduction of the overall house construction time by 35%. Further, offsite construction bypasses the considerable problems of the national bricklayer shortage and the construction bottleneck of the external brick façade **[S3, S7]**, allowing other trades to immediately get to work.
The lower price of the constructed dwellings, the significant reduction in CO_2 emissions, and the energy savings are valuable for buyers. The building system has been applied as part of Affordable Housing Schemes and, according to Barratt Developments in 2019 **[S3]**, used at 7 sites across England, including:

Bottesford, Nottinghamshire:
An early trial in 2015 by Barratt Homes built 41 new, energy-efficient homes with the SIG I-House system. The project demonstrated the speed of installation through maximum efficiency at the build stage, cost savings and workforce simplification compared to traditional construction, and improved hygiene and safety at work sites **[S8]**.

Banbury, Oxfordshire:
In 2016, Sajid Javid (then Secretary of State for Communities and Local Government) visited a Barratt Homes development in Banbury, Oxfordshire, where 88 SIG I-Houses were being built. He commented '*this innovative approach to housebuilding is a really exciting initiative which is significantly increasing the level and rate of construction, making home ownership possible for more and more people*' **[S9]**.

Bromsgrove, Worcestershire:
In 2016 – 2017, 164 houses were developed by Barratt Homes and David Wilson Homes at Norton Farm, Bromsgrove. The Bromsgrove District Housing Trust is using the majority of these houses to meet social housing needs and were '*really pleased with the speed of the units'. Oliver Novakovic, technical and innovation director of Barratt Homes, noted how the SIG I-House 'delivers an equivalent quality to traditional methods*' **[S7]**. Innovations such as the SIG I-House have contributed to the annual increases seen in Barratt's profitability, net assets, and working capital, and has contributed to Barratt's target of building a quarter of its homes through MMC by 2025.

Bristol, Somerset:
In 2018, in partnership with Homes England and Sovereign Housing Association, Galliford Try used the system extensively in a GBP90 million development of 346 new homes at Blackberry Hill. Representing the council, the Mayor of Bristol was delighted by the prospect of developing '*quality homes for people that they can afford to live in*'; whilst Kelly Hillman, a Senior Development Manager at Homes England said it was '*great to see … modern methods of construction which will improve construction efficacy, efficiency, and pace of delivery of new homes*'; and Jon Young, Managing Director of Partnerships West said that '*SIG I-House … is truly exciting, allowing us to build and deliver homes faster, construct more efficiently, and reduce transport and environmental costs*' **[S10, S11]**.

In 2019 – 2020, Willmott Dixon used the SIG I-House to build 50 homes at the Ashton Rise development for Bristol City Council, in a project valued at GBP21 million. The SIG I-House solution was combined with ground source heat pumps to produce '*a sustainable housing development*'. The Council Cabinet Member of Housing described how the project fulfilled the council's desire to '*build and bring together innovative design and energy efficiency*'. The heat

pumps achieve efficiency savings of 300 – 400%, remove a dependence on fossil fuels (gas), make lifetime carbon savings of 30 tonnes, and remove all local NOx emissions. The Managing Director for Willmott Dixon South West expressed his belief that '*these innovative developments will not only support the local community, but the local environment too*' **[S12]**.

5. Sources to corroborate the impact

S1 – Experimental Investigation Report for H+H

S2 – Letter of support from the Technical Director of H+H Celcon Ltd

S3 – Barratt Developments' Sustainability Case Study

S4 – SIG I-House Presentation, H+H Solutions Manager

S5 – Building a Sustainable Future, H+H

S6 – Collection of Awards and Accreditations

S7 – SIG I-House Norton Farm Case Study

S8 – Offsite Magazine, Issue 9, January 2018, p 6-7

S9 – EcoShowCase News Article, 2016

S10 – Evolve – Galliford Try's Employee Magazine, Autumn/Winter 2018, p 8

S11 – Galliford Try Blog Post

S12 – Architect Project News Release