Leroy Gardner

Within the next five years, structural steel designers will be making greater use of advanced design methods and 3D printing to achieve more efficient structures and reduce embodied carbon, believes Leroy Gardner. Helena Russell finds out more.

When a full-scale 3D-printed steel footbridge **(Figure 1)** was unveiled in the city centre of Amsterdam in 2021, the world's media took note. It was a significant step towards acceptance of this technology in the construction sector. But despite rolling news coverage of the space-age structure, Professor Leroy Gardner of Imperial College London predicts the real gains will come from much more modest applications.

Gardner's research specialism is structural steel and he agrees that there is a high level of interest worldwide in printed steel technology – both in the construction industry and in other sectors where potential applications abound, such as medical, aeronautical and shipbuilding.

Accidental academic

The fact that Gardner's professional life has been spent entirely in academia – albeit with strong links to practice – still gives him pause for thought. It was not a path that he made a conscious decision to follow. His interest in engineering was initially sparked by his father, a practising production engineer with a passion for making.

'My upbringing was quite practical and I worked with my father at weekends – we built a kit car together in the garage over the period of a year,' Gardner smiles. Meanwhile, he gravitated towards engineering when his favourite subjects at school, maths and physics, turned out to be 'the right ones' for such a career.

Even the choice of civil engineering was not immediately obvious, he adds. 'I could just as well have chosen mechanical engineering or physics!' But he already had an interest in structures and applied to study civil engineering at Southampton University.

'I enjoyed the course, but when I got to the end, I wanted to learn more,' he says. Structural steel design had been his favourite subject at degree level, so he applied to study for an MSc at Imperial with the intention of moving on to a 'proper job' afterwards.

Further research had not occurred to him until his tutor asked if he was interested in a PhD in stainless steel structures. It was an exciting time in this field and marked Gardner's introduction to the novel materials for which his expertise is now recognised worldwide.

Advances in stainless steel

Use of stainless steel in construction was relatively rare at that time; manufacturers were keen to support research that would enable them to gain a greater understanding of how and in what way it could be used, whether the design guidance could be enhanced or improved and so on.

'The main reason to use stainless steel is its corrosion resistance; the main reason not to use it is its cost,' Gardner summarises. 'Using it properly so that you get the most out of it, and connecting it properly are the key challenges.'

Gardner developed a new design process, named the continuous strength method, for use with stainless steel – the main novelty being that it was strain-based rather than strength-based. 'Stainless steel has a rounded stress–strain curve compared with normal steel, which has a sharply defined yield point. That lent itself to a new design approach which I developed, using numerical modelling and lab testing to get the data I needed,' he explains. There was no standard for stainless steel design at that time, although there were a few in development; now, almost every region has its own international standard, and the design method that came from Gardner's work forms part of them.

Introducing a more relevant design method had an obvious impact. 'With an expensive material like stainless steel, if you can reduce the material requirement by 20%, then it is more viable,' he says.

Joy of teaching

Gardner's ongoing quest for a 'proper' job was once again derailed by circumstances. In the second year of his doctorate he was invited to lecture MSc students in structural engineering at London South Bank University. He initially welcomed the opportunity as a chance to earn some extra cash, but found the work unexpectedly fulfilling.

'I had to spend some time developing lectures, then I taught part-time students one evening a week for 15 weeks

CAREER MILESTONES

1995–98	Civil engineering degree at Southampton University
1998–99	MSc in Structural Steel Design at Imperial College London
1999–2002	PhD research at Imperial College London
2002	Appointed Lecturer in Structural Engineering at Imperial College London
2012	Appointed Professor of Structural Engineering at Imperial College London Bergermann & Partner, Stuttgart
2014	Founding Editor-in-Chief of IStructE *Structures* journal
2017	Awarded IABSE early career prize 'in recognition of his outstanding contributions to structural engineering in the areas of structural steel research, code development and teaching'
2020	Elected Fellow of the Royal Academy of Engineering
2021	Awarded ASCE Shortridge Hardesty Prize 'for cumulative efforts and outstanding achievements in the advancement of knowledge in the areas of thin-walled steel structures, tubular structures, stainless steel structures, connections, and extreme load effects'

in the second and third years of my PhD,' Gardner says. 'I really enjoyed it, much to my surprise! I got satisfaction from teaching people, knowing that they were listening, taking things in and understanding it. In order to teach things, you have to really understand them yourself, so it was helpful in reinforcing the fundamentals for me.'

Gardner believes this work experience was an important factor in Imperial offering him a role as lecturer in structural engineering in 2002 once his PhD was complete – and gave him the confidence to accept. Over the subsequent years, he progressed to senior lecturer then reader, being appointed professor of structural engineering in 2012 at the age of 36 – the youngest age at which anyone had reached this level in the department.

Industry links

While his career so far has been within academia, Gardner is a keen advocate for establishing strong links between research teams and industry. His involvement in the IStructE Research Panel – which he chaired for 12 years – is evidence of this. 'A lot of what we do is to try to demonstrate the benefit of research in practice and highlight how it can be applied successfully in the real world. We introduced a new funding scheme that required applicants to have both an industry partner and a research partner, to bring the two sides together.'

Gardner's involvement with the IStructE and interest in bridging the gap between academia and industry also saw him accept an invitation to become the founding Editor-in-Chief of a research journal the IStructE launched in 2014. Under Gardner's lead, *Structures* has since grown rapidly to become highly regarded in the international structural/civil engineering field, receiving thousands of manuscripts each year.

Gardner will also chair the task group producing the IStructE manual to accompany the second generation of Eurocode 3 on the design of steel structures.

Research advances

At Imperial, Gardner's first research students – of more than 60 he has supervised so far – continued the work he'd started in stainless steel. Subsequently, he branched out into new materials such as high-strength steel and 3D printing, and further development of design by advanced analysis.

> "GARDNER LED THE TESTING AND SAFETY VERIFICATION OF THE MX3D PRINTED STEEL FOOTBRIDGE THAT WAS IN PUBLIC USE IN AMSTERDAM

Design by advanced analysis exploits tools such as finite-element analysis (FEA) to design structures in a one-step process rather than the conventional two-step approach which involves a relatively simple analysis to determine the internal forces and moments, followed by design checks on the individual elements.

'In advanced analysis, covering both geometric and material non-linearities, all of the key structural phenomena – buckling, yielding and so on – can be captured in a single step. But the input is the critical bit – to make sure that you have a safe design – and that's the bit we've been working on,' Gardner explains.

'We have developed material models for hot-rolled steel, cold-formed steel and stainless steel that are now in the new Eurocode 3 Part 1.14 *Design assisted by finite element analysis*. These models are an analytical description of the stress–strain curves and are needed to model the material response in this method; information about imperfections, residual stresses and reliability, as well as the continuous strength method, are also given in the new code.'

3D printing

Design codes and guidelines can be dry subjects with a limited audience, but Gardner is also an expert in a subject that has a much wider appeal – printed steel or wire arc additive manufacturing (WAAM). This uses traditional welding

↑**FIGURE 1:** As the MX3D bridge was open to the public, it had to be safe, so was tested beyond its ultimate limit state design requirement technology in conjunction with a robotic arm and a digital model to create a structure layer by layer.

Gardner led the testing and safety verification of the MX3D printed steel footbridge that was in public use in Amsterdam until last year. He says that while the footbridge might have raised the profile of this technology, the most exciting opportunities will come from much more modest applications.

'The Amsterdam MX3D bridge is still regarded as the biggest and best demonstrator of this technology in construction,' Gardner says. As a 4.5t structure made of printed stainless steel and open to the public, it had to be safe, so it was tested beyond its ultimate limit state design requirement.

'What we've been doing since is exploring the response of more optimised WAAM structures to try and understand the material behaviour more deeply. We are looking at the consistency of the material performance, the link between how you do your printing and what the final characteristics of the product are – so we can identify the best applications,' adds Gardner. 'It's definitely not the case that we are going to be printing all of our buildings and bridges in the future, but we might be printing key bits of them. Where you have got more intricate details, for example, such as connections, there's obviously the potential for optimisation' **(Figure 2)**.

Another area where WAAM could be used sooner rather than later, is strengthening of existing structures and also strengthening/augmenting new steelwork **(Figure 3)**. 'I-sections are great, but they are constant along their length and loading demands rarely match that,' Gardner explains. 'We've shown that supplementing members by adding material at the relevant points offers significant gains in capacity for relatively little extra material.

'These two areas – connections and strengthening – are where 3D printing is going to make the most sense in the short term.'

Hybrid elements

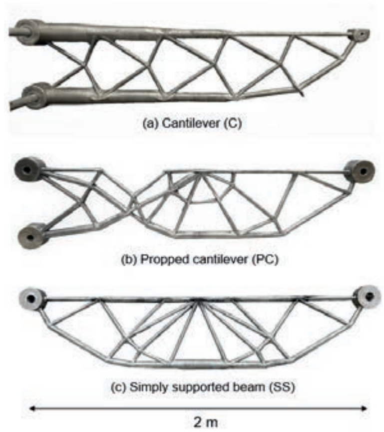
Lab experiments at Imperial are providing increasing evidence of good sound mechanical performance both for printed elements and 'hybrid' elements where printed steel is added. Small quantities of extra material offer 'exceptional' gains in capacity and that translates directly to a saving in embodied carbon, Gardner says.

'To produce one kilogram of printed steel is twice as carbon intensive as one kilogram of normal steel,' Gardner says. 'Using the hybrid approach, with the material added in a targeted way, we've found that the additional printed elements can be 10 times as efficient as the underlying steel, far outweighing the higher per-kilogram carbon intensity!'

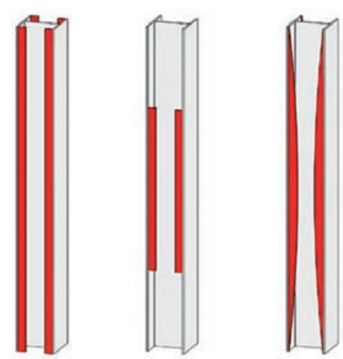
He is working with steel fabricator Severfield on this; the company already produces large steel structures and wants to know how to make them more efficient while using less steel. Gardner believes this is achievable in just a few years' time.

'There's not much more we need to overcome to have the first hybrid example in practice. We need exemplars and we need guidance.'

One benefit of the WAAM process is that fabricators are very familiar with it – the feedstock material, the machines, how to prepare the surfaces and so on. Grades can even be combined, with high-strength steel 'printed' onto a normal steel member, for example – something that Imperial has just begun to investigate.



↗FIGURE 2: 3D printing will allow greater optimisation of structural elements once a fuller understanding of material behaviour is developed



↗FIGURE 3: Strengthening of existing structures or new steelwork in relevant areas is another area in which 3D printing is likely to be applied

> **"ADDITIONAL ELEMENTS CAN BE 10 TIMES AS EFFICIENT AS THE UNDERLYING STEEL**

Printing connections is more challenging. 'The only practical way we can design these is by FEA. Maybe we will develop standardised connections – still with optimised geometry, etc. – for joining standard section sizes,' he suggests.

One of the biggest challenges is the consistency in material properties and its potential for defects. 'Anyone dealing with welds will know that defects are part of the game – you can't have zero defects but you do need to inspect your material, and show that it has a low enough level of defects that they won't affect the structural performance.' A lot of work is being done on defect detection, Gardner acknowledges; not just how to detect them but how to do it in a sufficiently automated way to keep the process practical and viable.

Nonetheless, he sees great potential for WAAM and points out how things have changed in a decade: 'The MX3D bridge was a gamechanger – even 10 years ago it would have been considered impossible. But the real impact will be seen when this technology is used in every building, and for every connection.'

Recent research publications

→| Gardner L. (2023) 'Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook', *Structures*, 47, pp. 2178–2193; https://doi.org/10.1016/j.istruc.2022.12.039

→| Gardner L., Yun X. and Walport F. (2023) 'The Continuous Strength Method – Review and outlook', *Eng. Struct.*, 275, 114924; https://doi.org/10.1016/j.engstruct.2022.114924

→| Gardner L., Li J., Meng X, Huang C. and Kyvelou P. (2024) 'I-section steel columns strengthened by wire arc additive manufacturing – concept and experiments', *Eng. Struct.*, 306, 117763; https://doi.org/10.1016/j.engstruct.2024.117763

→| Meng X. and Gardner L. (2025) 'Hybrid construction featuring wire arc additive manufacturing: review, concepts, challenges and opportunities', *Eng. Struct.*, 326, 119337; https://doi.org/10.1016/j.engstruct.2024.119337