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SLIPPING AND CLIMBING?

Projects using cranes that climb within the core while slipforming continues

TESTING CONCRETE

Alkali–silica reaction: widespread but manageable

CONSTRUCTING CURZON VIADUCT

The challenge of large-scale temporary works for HS2 project

WORLD FIRST: 3D PRINTING FOR CONCRETE BEAMS SHOWCASED IN PILOT FOOTBRIDGE

3D concrete printing, historically used mainly to construct walls for houses, has now been used for the first time for a completely new and innovative application – printing the concrete permanent formwork for single-span beams for large-scale construction. Andy Coward and Sarah Blake of minimass report.

Figure 1 – COBOD BOD2 3D printer printing the bridge beams.

3D printing is used to precisely place the minimum quantity of concrete required by the design; using less material through design optimisation is considered one of the best ways to reduce embodied carbon in construction.

Until recently, there have been two significant hurdles for 3D construction printing, which have meant it has only been used for compression-only structures such as walls. First, only a high-cement mortar could be used, containing no aggregates. To comply with the Eurocodes for concrete, aggregates are required. Second, historically it's been difficult to incorporate reinforcement into 3D-printed concrete structures.

These two problems have been overcome by fabricating an innovative new type of beam – the minimass beam – using a COBOD BOD2 printer, operated by Harcourt Technologies Ltd. The perimeter is printed to create a permanent load-bearing structural formwork (Figure 1), with zero waste as no plywood/steel formwork is required and only the concrete required is used. The printer can use any mix of concrete required for the design – typically a C40/50 code-compliant strength-class to BS 8500[1], which includes aggregates of 6–10mm. This is crucial as it reduces the cement content of the mix, enabling this 3D-printed concrete to be similar in carbon content to traditional poured concretes. The concrete can be sourced from any ready-mixed concrete supplier, so the supply chain already exists. Standard mild steel reinforcement cages can then be positioned inside the printed permanent formwork and then any suitable mix of concrete is poured into the cavity, which can include low-carbon options.

> "The bridge... provides an embodied carbon of 30% and a supply cost saving of 40% vs traditional steel or concrete footbridge designs."

Post-tensioning steel cables are used in tension along the base of the beams, with anchors at either end. These allow the beams to take extra load. At the end of the manufacturing process, the cables are inserted and stressed for the first time to put the concrete into compression, tighten everything up and allow the beam to be moved around. The beams can be lifted, transported and installed seven days after printing. Once a beam is in position and the loads applied, value proposition

example 9m beam, office loading	minimass (reinforced)	minimass (unreinforced)	concrete	steel	glulam
lead time (days)	7	7	28	90	-
embodied carbon (kg)*	875	640	2,020	1,780	630
total mass (kg)	2,950	2,870	9,200	1,125	2,250
supply cost (£)**	2,700	2,500	4,200	3,400	10,400

*Note: This is one example beam – savings in each case will differ. *Using ICE DB v3.0 and Arup recommended glulam factors; ** Estimate includes supply, fire protection & delivery. Cost comparison provided by Core 5 (London-based quantity surveyor), based on London prices from January 2023; using low-carbon material choices going forward would drive minimass further towards net-zero carbon.*

ABOVE:
Figure 2 – carbon, cost and lead-time comparison of minimass vs concrete, steel and glulam options – for an example 9m beam with office loading.

a second stressing is carried out to take out the deflection caused by the load.

The technology allows any geometry to rapidly be produced for no additional cost with minimal labour, providing mass customisation. This means huge savings in material quantities compared with traditional concrete or steel beam manufacture, which results in significant reductions in both embodied carbon and cost. Carbon emissions are reduced by up to 70% and supply cost by up to 35%, for equivalent performance, length and depth (Figure 2).

Compression and tension elements are separated in the beams – a bit like a hybrid concrete and steel truss. The aim is to use the right material, in the right place, for the right purpose – concrete in compression and steel in tension (Figure 3). Both the design of these beams and their additive manufacturing process are patented in the UK and these patents are being extended to cover Europe, the US, Canada and Australia.

PILOT DEMONSTRATION FOOTBRIDGE

minimass, a Buckinghamshire-based start-up, recently completed its first pilot project at the Norfolk site of Constructionarium, a not-for-profit educational centre providing immersive experiential learning to students and professionals in the built environment sector. This is a 10.8m-long showcase footbridge, funded mainly by an Innovate UK Net Zero pre-commercialisation grant. This is the first Eurocode-compliant structure to be made using 3D-printed formwork for concrete beams. It includes two minimass beams, Scottish glulam timber decking from the company Ecosystem and timber parapets, demonstrating the ideal combination of 3D-printed formwork for concrete beams and timber to create a highly functional low-carbon hybrid solution (Figure 5).

The bridge (excluding foundations and prelims) provides an embodied carbon of 30% and a supply cost saving of 40% vs traditional steel or concrete footbridge designs.

As the bridge is a world-first demonstrator project, the beams are fully instrumented to gather data on strain and temperature using fibre-optic sensors provided by infrastructure monitoring specialist Epsimon. Material uncertainty occurs in the early

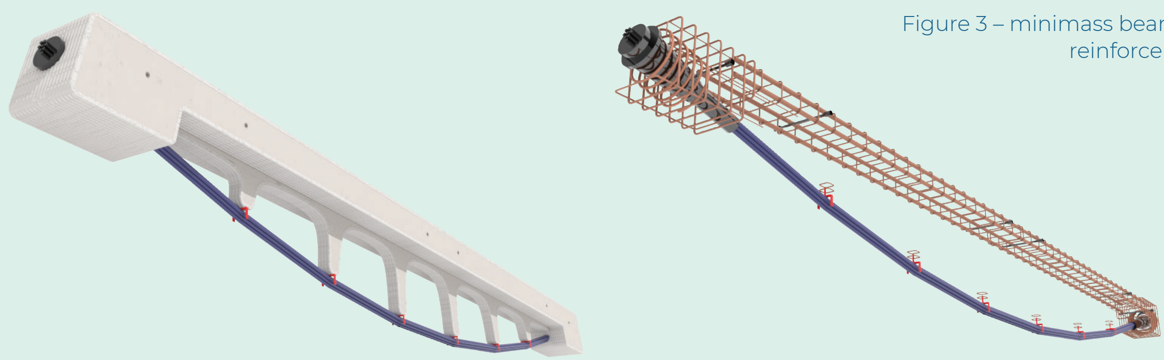

Figure 3 – minimass beam and steel reinforcement cage.

life of a structure, mostly due to the unknowns regarding the sequence of construction. The testing will be carried out for six months to observe the period of greatest uncertainty. At this point, the majority of material strength gain and creep effects will have occurred, enabling extrapolation of the long-term future performance of the full design life with a high degree of confidence.

Constructionarium offers 17 iconic civil and structural engineering projects, along with net-zero and construction-related skills training. Once testing is complete, the bridge will be donated to Constructionarium; it has been designed to be easily disassembled and rebuilt to allow it to join the centre's project roster. This will help educate the next generation of industry professionals on sustainable and innovative concrete construction solutions.

The project also gives the industry tangible proof of concept of the technical performance, procurement process, warranties and insurance, as well as the low-carbon and low-cost credentials of these beams.

GOING FORWARDS

Beyond simple beams, patents are pending for further minimass structural elements, including continuous beams, frames and floor slabs. Ultimately, the company aims to provide a complete kit of parts for large buildings and bridges, and to open its own UK manufacturing facility. Beyond bridges, the beams are applicable for a range of applications in which spans are at least 6m, including commercial, industrial, educational, retail and temporary structures.

3D printing is an enabling technology for these beams, given most projects involve bespoke designs in terms of loading and span. However, they can also be precast if there are sufficient identical elements required, eg, for an out-of-town car park. C

ABOVE:
Figure 4 – pilot footbridge at Constructionarium.

BELOW:
Figure 5 – minimass display beam.

INSET, ABOVE LEFT:
Figure 6 – the founding team and visitors on the demonstration bridge at Constructionarium.