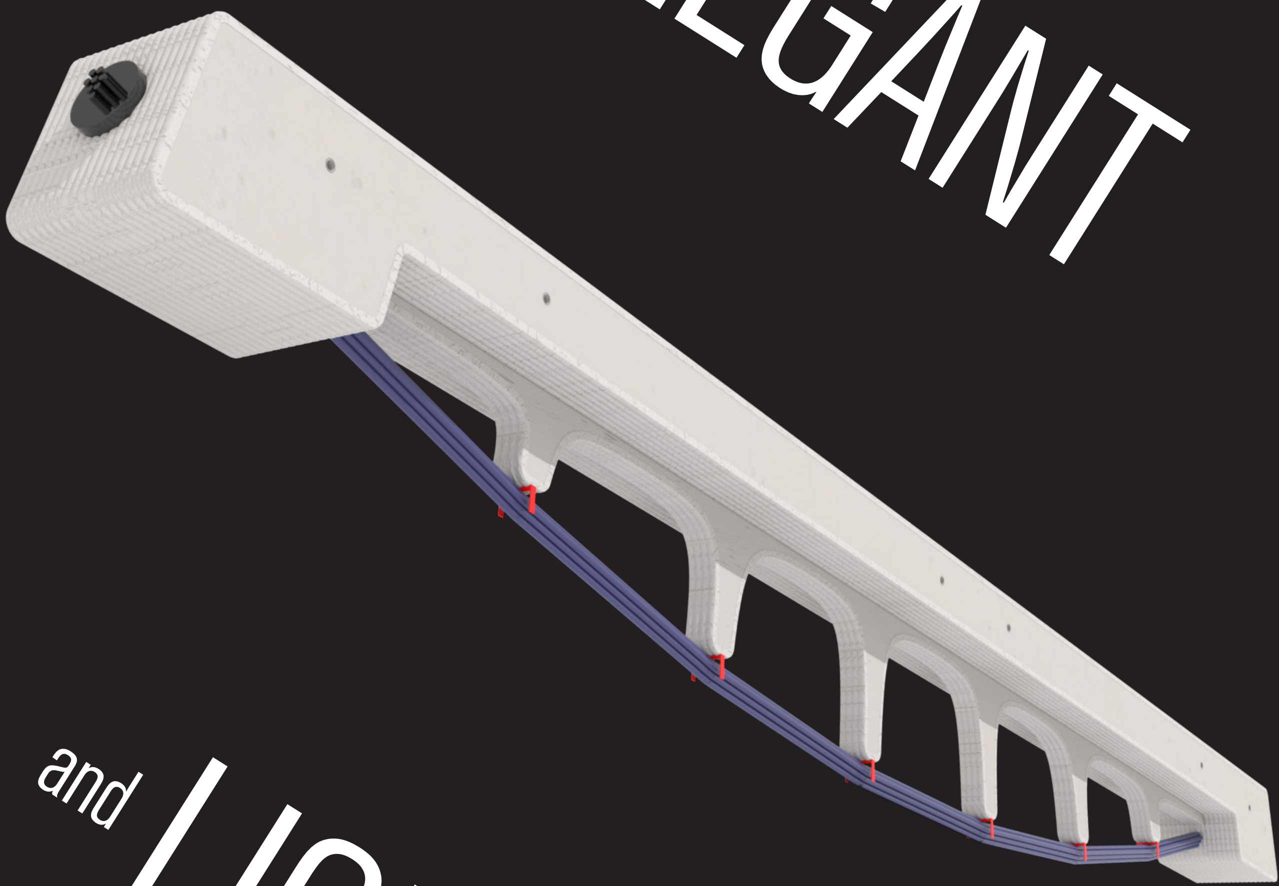
minimass™

an introduction to 3D printed concrete elements for buildings and bridges

can concrete be ELEGANT



and LIGHTWEIGHT?

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About minimass

minimass is the name of a range of new structural elements made using 3D printed concrete, developed by Net Zero Projects Limited (NZP), based in UK. The aim of minimass is to drive down both the cost and the carbon footprint of concrete structures, by using design optimisation and digital manufacturing techniques. The minimass approach strictly follows Eurocode or US code requirements.

For more information about minimass, refer to the website at http://minimass.net

There are two families of minimass element: (1) post-tensioned AND reinforced; (2) reinforced (no post-tensioning). In both cases, the elements are designed with poured concrete and conventional mild steel reinforcement, following all the requirements of Eurocode 2 or ACI 318. The choice between using post-tensioning, or not, is dependent on the use case and the span and load on the structure.

A minimass element is defined by the manufacturing method, which uses 3D printed concrete to create a permanent structural formwork, into which reinforcement and post-tensioning strands are placed, with the resulting form being filled with poured concrete. Extremely efficient designs are possible due to the flexibility of geometry derived from the 3D printing process. Very lightweight shapes can be made, with reduced labour costs and zero wasted materials. This is the economic and sustainable choice, with these methods of construction promising to be the future of large-format precast concrete construction.

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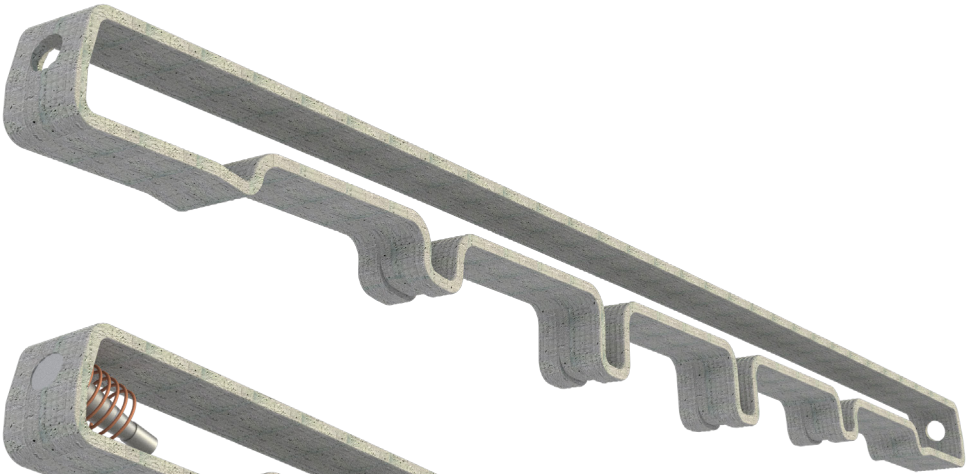
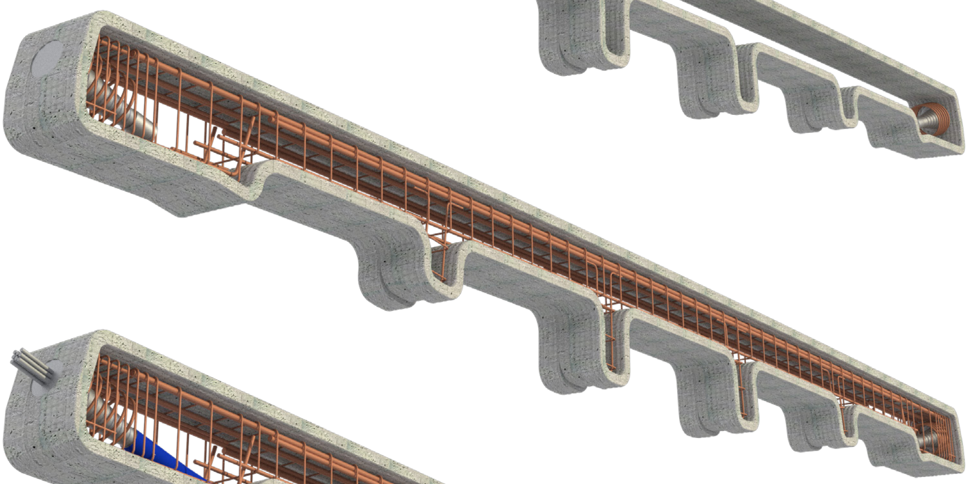
Introducing the principle of the post-tensioned beam type:

step 1: 3D print the shape

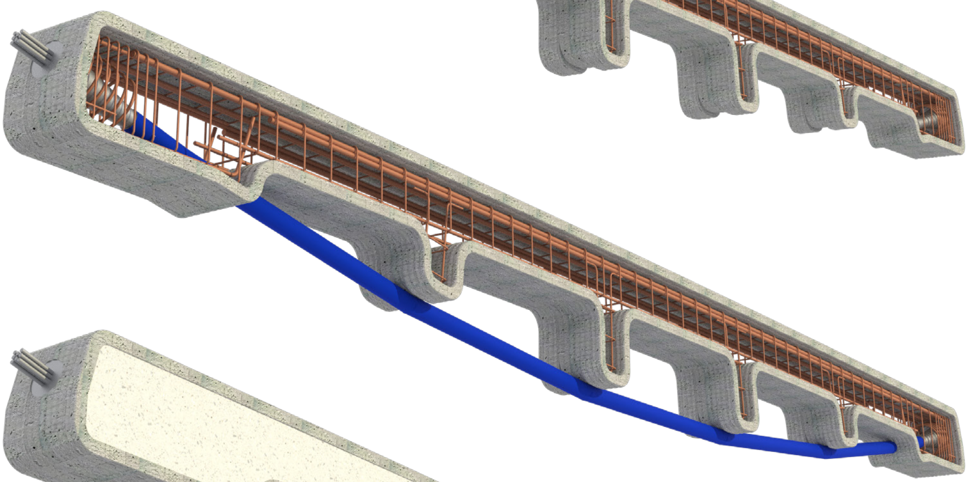


step 2: place the PT anchors

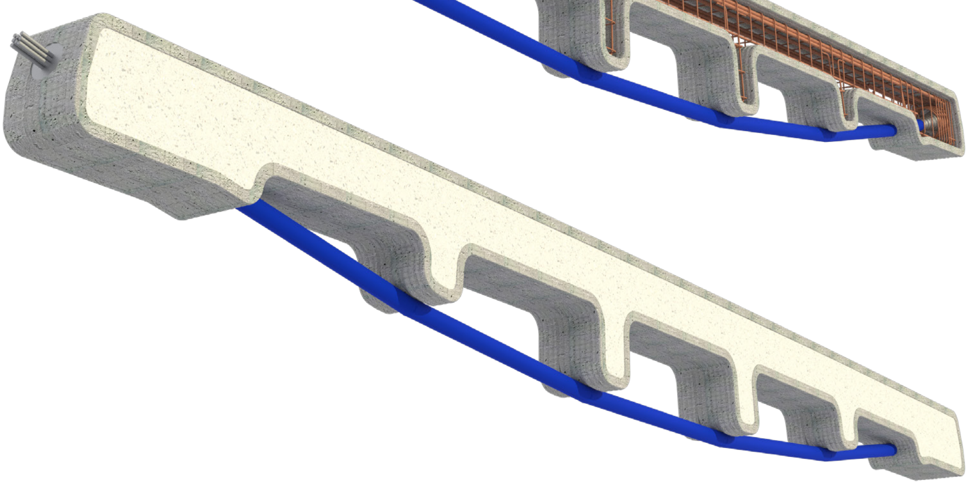
step 3: place the mild steel reinforcement



step 4: place the PT strands and duct



step 5: pour the concrete and tension the PT strands



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3D printed beam characteristics

Manufacture

The elements are typically manufactured off-site, in factory conditions. However, it is possible to take the equipment to the construction site to set up a small minimass factory next to the planned construction. This approach removes all transport limits on weight, length and transport emissions. Each element goes through a 7-day manufacturing cycle:

1. Day 1: 3D printing of the perimeter of the element
2. Day 1: Cutting of any openings, addition of any inserts
3. Day 2: Placement of reinforcement cage
4. Day 2: Pouring of infill concrete
5. Day 7: Initial stressing of the cables
6. Day 7: Ready for transport or placement on site.

load testing our pilot footbridge in UK

demonstrating the printing of the perimeter

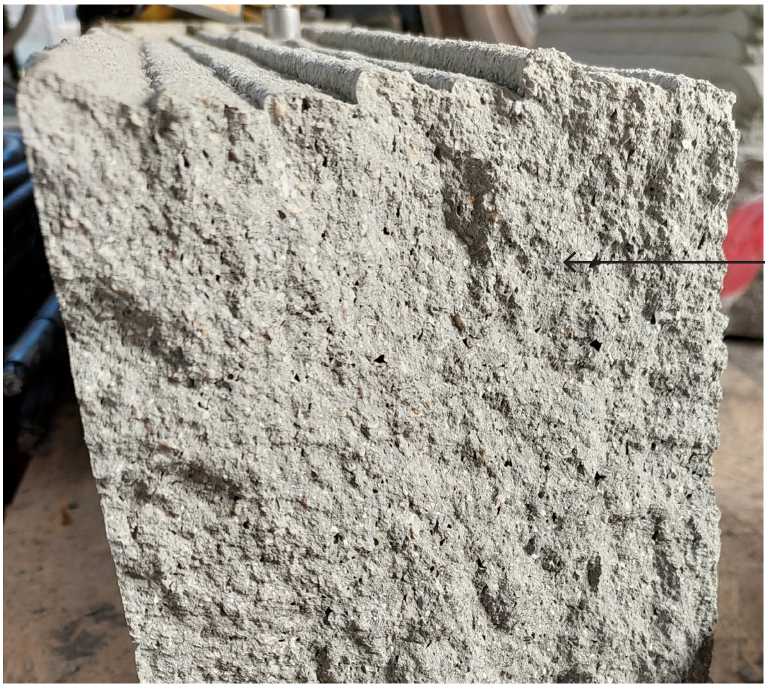
reinforcement within the printed perimeter

conventional concrete poured within the permanent formwork

Texture, feel and finish

3D printed concrete gives a layered finish and not a formed or cast finish. That gives the beam surface a texture which speaks of the manufacturing technique. However, from a structural point of view, the layering process is such that a bond forms between the layers, preventing de-lamination or the occurrence of layers within the solid material.

layering on a physical prototype.



no visible layering within the printed concrete section

homogeneous concrete texture despite the layering process.

fire test set-up at Efectis, Belfast, showing full integrity at 2hrs fire duration

Fire

Fire resistance is an important consideration for these types of beams, with post-tensioning below the main body of the concrete and the use of 3D printed concrete itself. Fire testing has been carried out on an example beam (full details can be supplied), showing that the 3D printed concrete behaves in the same way as traditional poured concrete.

We take a fire-engineering approach and evaluate the fire resistance requirements on a project-by-project basis. For post-tensioning elements, with exposed PT strands, there are two options for fire resistance. The first option is to apply a protective covering to the duct, as is commonly used in cable-stayed construction for bridges. The second option is to leave the duct exposed and to design the structure to be stable in the event of a fire, with the removal of the PT strand. In the latter case, the mild steel reinforcement provides the residual capacity to support the loads or provide the tie forces.

However, if neither of those approaches are applicable, it is possible to use the type (2) approach, whereby the

example fire test beam after 132 mins at 1100 deg. C - minimal signs of damage, no spalling or cracking in the 3D printed concrete

elements are not post-tensioned. In this case, the full strength capacity is provided by the reinforced concrete in at room temperature and during a fire scenario.

A full set of fire tests is planned for the design option whereby the exposed PT ducts are wrapped with fire protection material. However, to make sure that the underlying behaviour of the system was well understood, a fire test was carried out on the unprotected beam arrangement. The purpose was to demonstrate that the behaviour of the 3D printed concrete was the same as standard poured concrete and to show the transition in load from the PT strand into the reinforced concrete part.

The test used a 2m long beam placed in a furnace for 132mins at up to 1100 degrees C. The aim of the test was to demonstrate the ability of the beam to transition the load from the steel cables, into the concrete such that the cables can be sacrificed during the fire scenario whilst still maintaining the required strength capacity. The test was successful and a full fire test report can be provided on request. The exposed steel cables were sacrificed but the load-carrying capacity of the beam was maintained by the reinforced concrete part. The test was carried out by one of the leading test agencies in UK, Efectis UK & Ireland, in their Belfast test laboratory.

Strength testing

A series of physical prototypes have been built and tested.

The first set of prototypes was designed using unreinforced, 3D printed concrete, to test the principle and performance of the beam at the extreme case of having no tension reinforcement in the concrete itself. Three 6m long test beams were built and loaded to destruction at the Structures Lab of the Danish Technical University, Copenhagen. Full details of the testing can be provided on request, with the resulting academic paper having been published by the technical journal of the Institution of Structural Engineers, "STRUCTURES".

test set-up for 6m long DTU test beams of type MM-01

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3D printed concrete beams as optimised load carrying structural elements – The Minimass beam

Andy Coward [a,*], Jesper Harrild Sørensen [b]

[a] Founder Net Zero Projects Limited, Director Net Zero Projects ApS, United Kingdom
[b] Technical University of Denmark, Denmark

refer to the above technical paper for further details of the first round of physical testing

A second set of physical tests were carried out at the Structures Lab of the University of Cambridge, as part of a testing programme funded by a grant from Innovate UK. This set of tests was planned to demonstrate the performance of the reinforced and post-tensioned behaviour of the design. These tests showed the robust methodology of the minimass design, showing the reserves of strength and redundancy within the concrete cross-sections.

photo taken at 265kN compression force, similar to SLS load level for this design. No damage, minimal cracking.

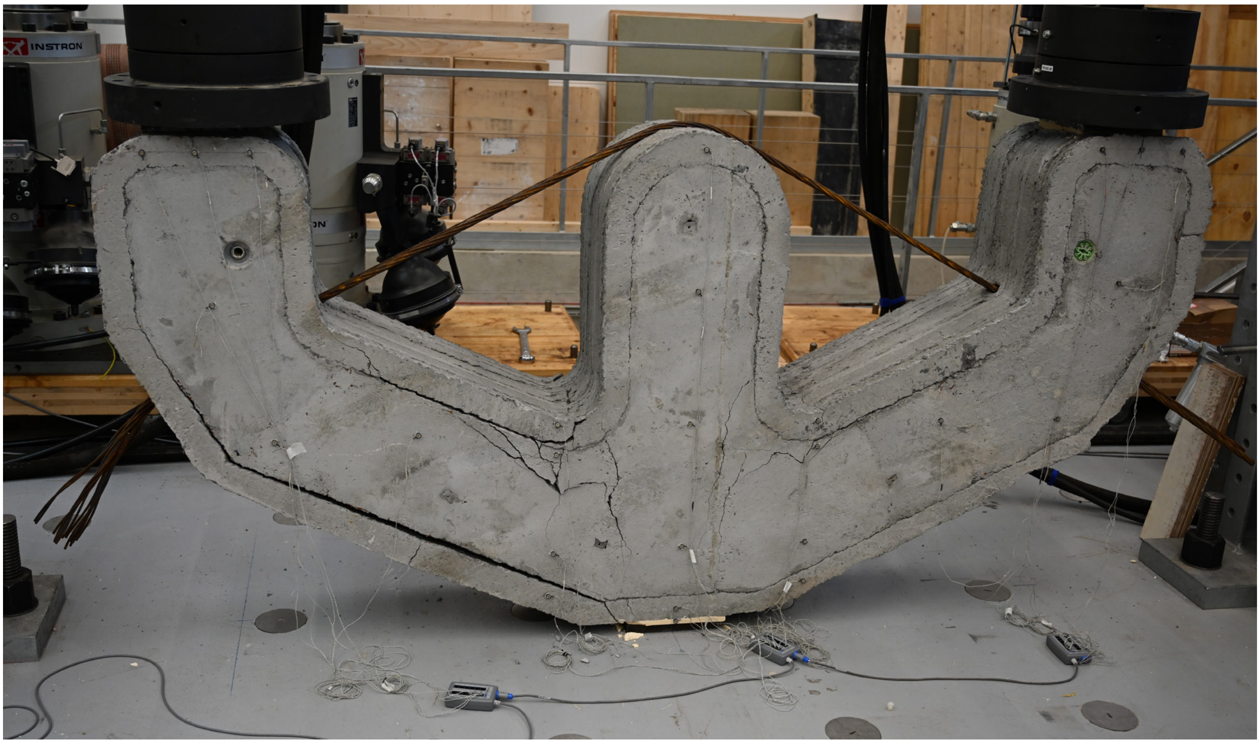
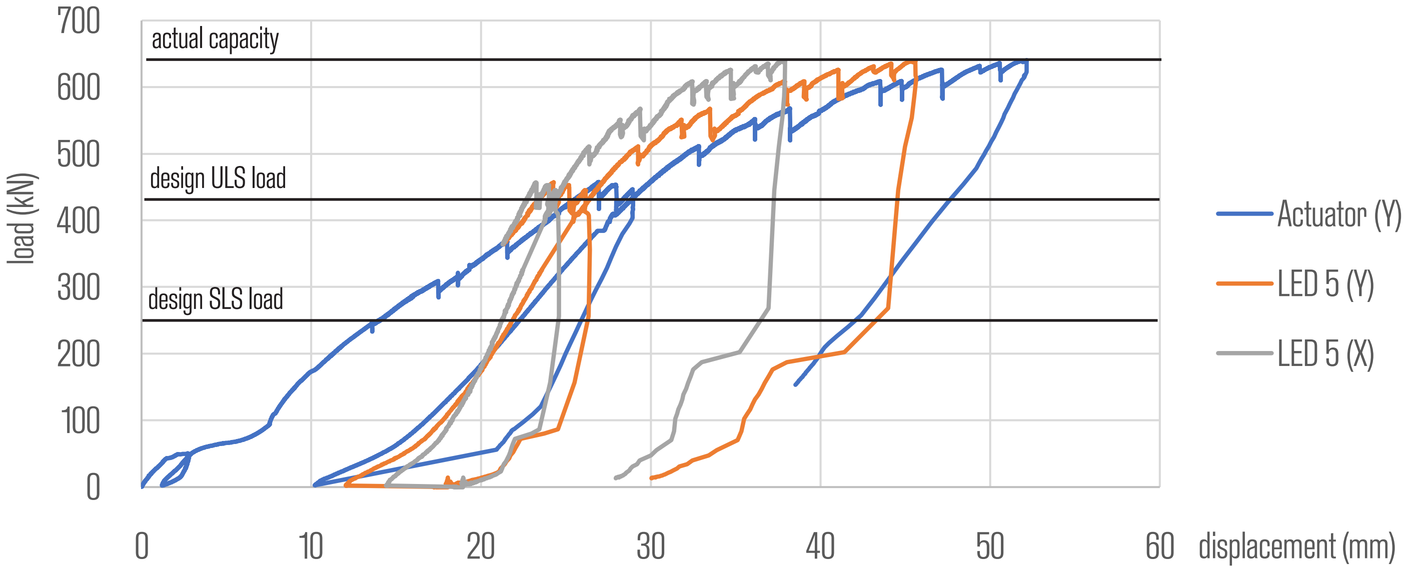


photo taken after the test, once the ULS capacity was deemed to have been reached, showing cracking



example test specimen load vs displacement plot

These tests show three very important features:

1. reinforced concrete minimass structures behave the same way as traditional reinforced concrete structures;
2. standard design codes (e.g. Eurocode or ACI) can be used to design minimass structures;
3. redundancy and ductile behaviour are both part of the minimass design approach.

Currently, minimass designs use the full cross-section width, including the 3DCP, for serviceability considerations such as stiffness, cracking and deflection. This is because the testing has shown that delamination between the 3DCP layers and the poured concrete, in the absence of reinforcement crossing the joint, does not occur at service level stresses. However, at ULS design levels, the strength capacity is based on the reinforced cross-section dimension only, ignoring the width and thickness of the 3DCP. This is because some tests did show delamination across the joint at higher stress levels.

Future designs will be developed that include reinforcement that crosses the interface between the printed and the poured concrete, which will ensure that delamination cannot occur and the full cross-section width can be used for ULS design capacity checks.

Case studies and design examples

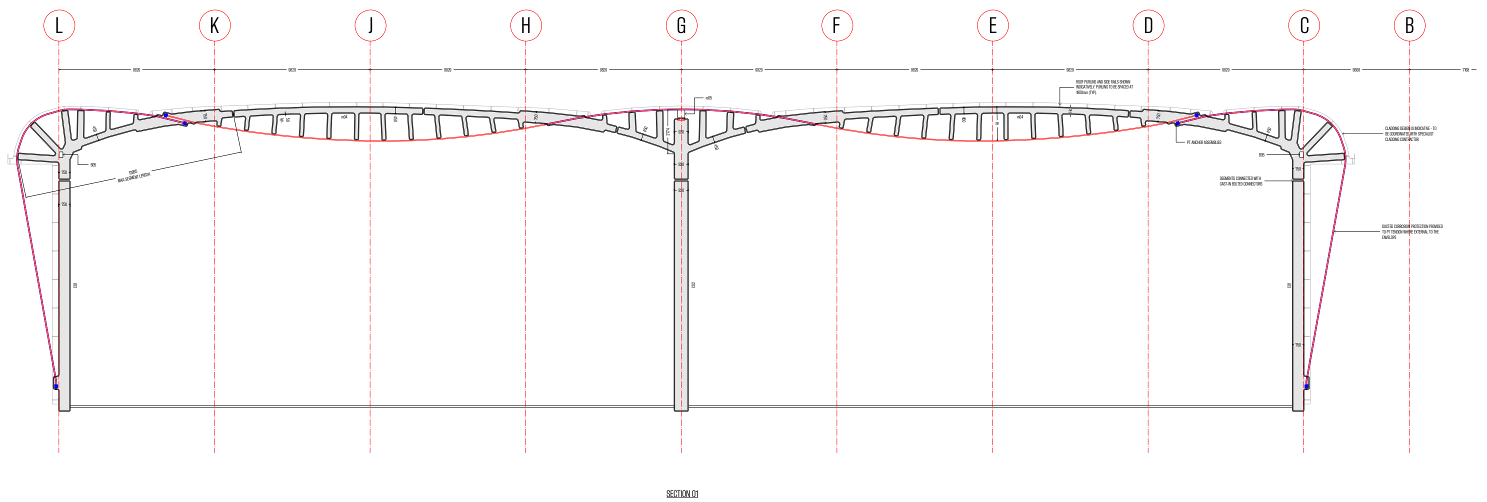
minimass is ideal for use in both buildings and bridges. The first sectors of the market that we are focusing on are:

1. industrial buildings, such as logistics warehouse or data centres;
2. short and medium span footbridges, up to 36m in span.

Industrial buildings

This design approach for industrial buildings depends on the fire requirements of the end user. Working with a large European contractor, we have developed two approaches which compete directly with the traditional methods of construction.

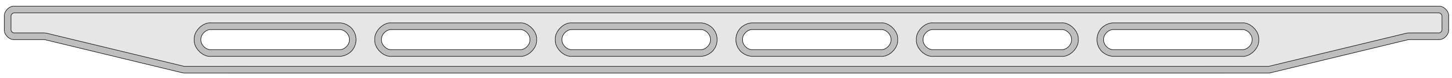
First, long-span portal frames, competing with the long-span steel warehouse structures, which are particularly common in UK. An example minimass portal frame elevation is here:



typical multi-bay minimass portal frame design elevation

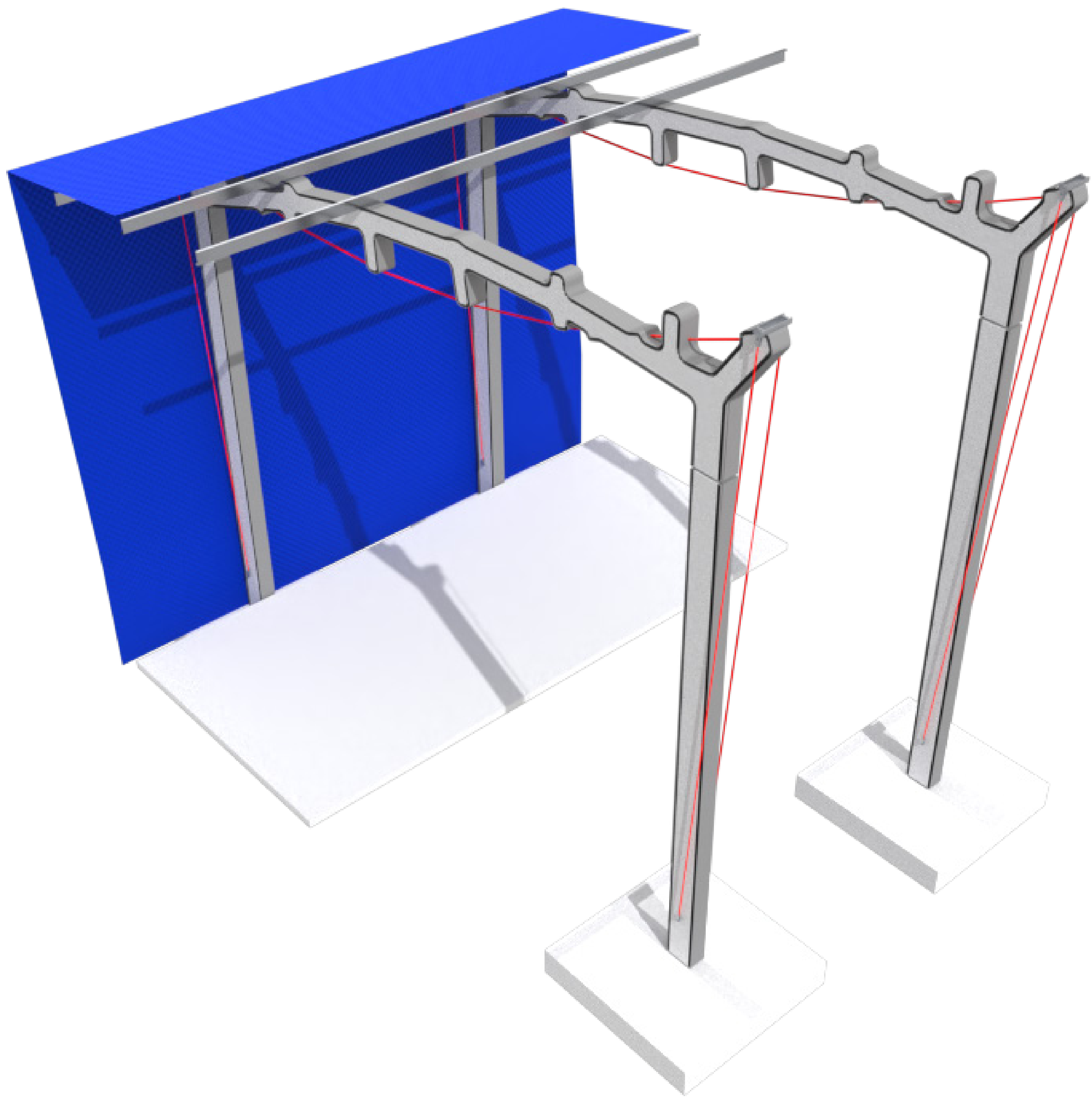
This is a 40m span, multi-bay portal frame with a 16m eaves height. For a cost-equal structure (compared with steel), the embodied carbon is reduced by 39% and the effective construction schedule is reduced by 2 weeks, leading to financial savings for both the client and the contractor.

Below is an alternative approach which does not use post-tensioning but is applicable for flat floor structures with service penetrations (e.g. for air or electrical cables). This demonstrates the flexibility of the minimass approach - enabling highly optimised geometrically sculptural solutions for long spans, or very efficient prefabricated elements for integrated structure and MEP designs.



example design for a minimass castellated floor beam with service openings

The limit for minimass is the imagination of the designer, with many different arrangements possible. The image below shows an alternative for a short-span warehouse structure, with sharp eaves and conventional cladding.



short span portal frame structure, with sharp eaves corners

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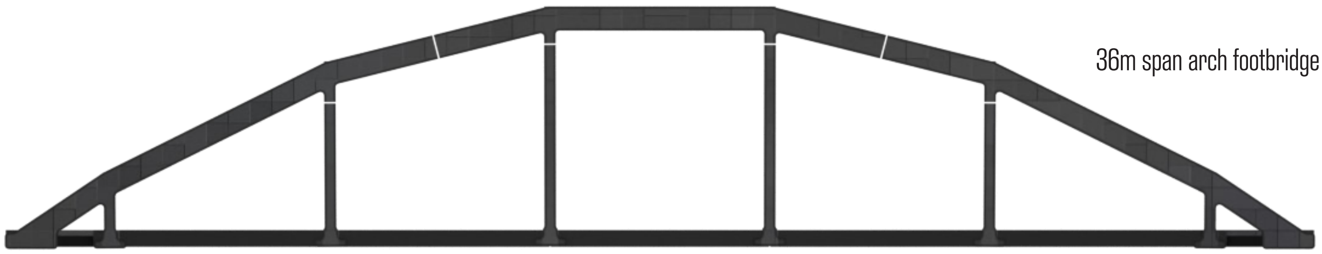
Bridges

Both single and multi-span bridges have been designed over the past 5 years but the primary use case is for short-span (up to 36m) foot and cycle bridges. A road bridge was designed for construction Ukraine but that project has not yet been constructed.

Below is a range of different design approaches for minimass bridges, using both post-tensioned and reinforced concrete structures.

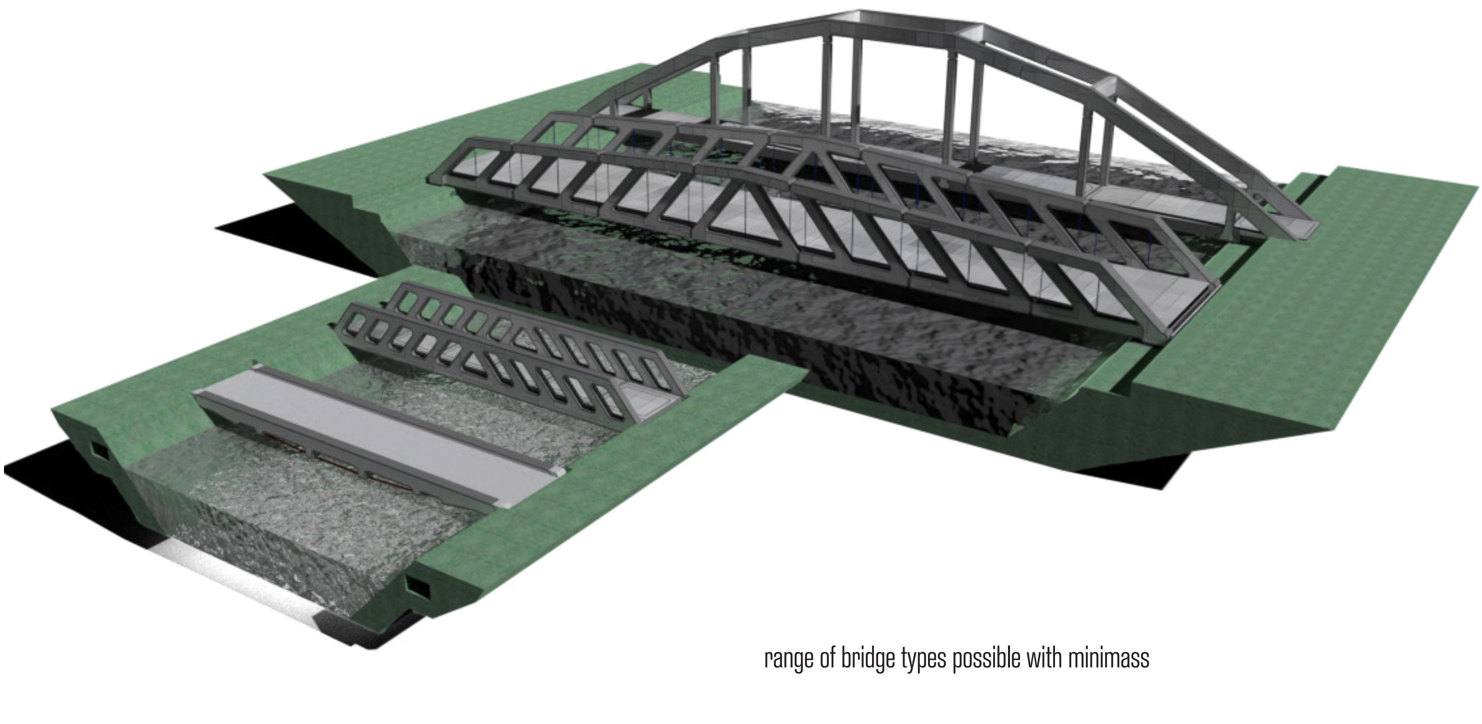


36m span arch footbridge

30m construction traffic site access bridge

14m modular reinforced concrete footbridge

14m bespoke post-tensioned footbridge



range of bridge types possible with minimass

world-first minimass™ pilot footbridge

This first-of-a-kind footbridge, built in September 2024 at the Norfolk site of Constructionarium, was funded predominantly by an Innovate UK Net Zero pre-commercialisation grant. This project gives the construction industry the tangible proof that minimass™ is a viable alternative to traditional concrete or steel structural beams in terms of technical performance and procurement process, and far surpasses these options on carbon and cost credentials.

It includes:

- two 10.8m long minimass™ beams;
- ready-mix concrete and real aggregates;
- Scottish glulam timber decks, by Ecosystems Tech;
- timber parapets.

Manufacturing of the minimass™ beams:

- printed by HTL Ltd, using a COBOD BOD2 3D printer;
- steel reinforcement positioned inside;
- concrete poured into the cavity;
- post-tension steel cables inserted and stressed.

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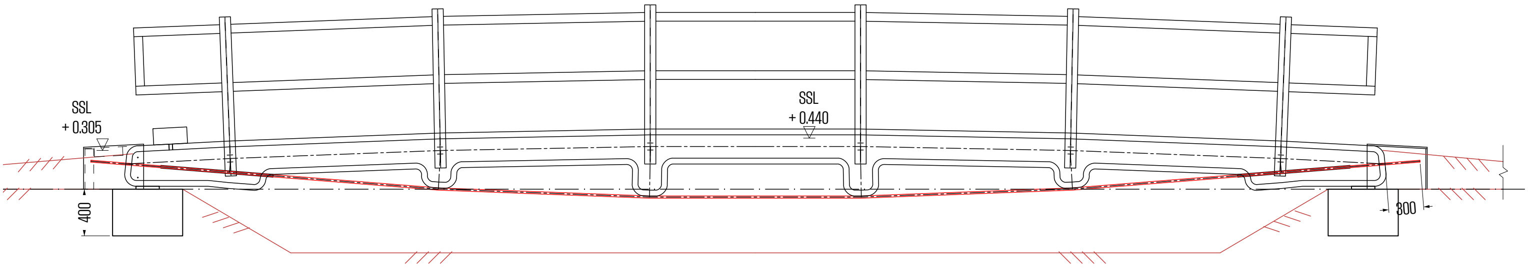
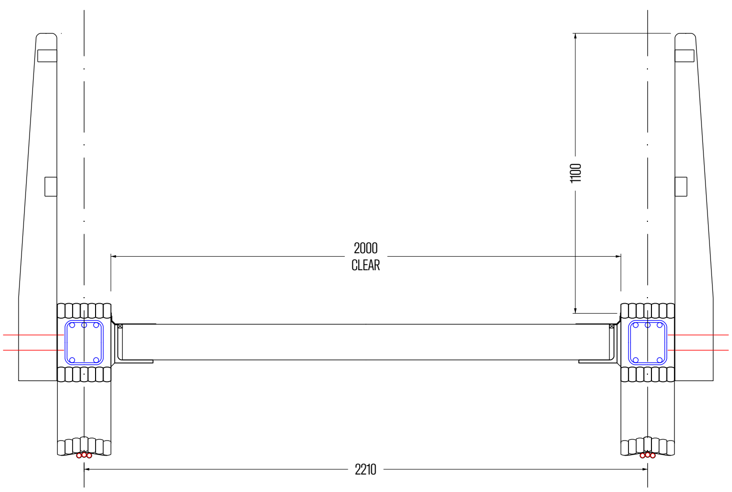


savings vs traditional concrete or steel equivalents:

- the minimass™ beams provide a 50% saving in embodied carbon
- overall, the bridge provides a total project embodied carbon reduction of 30%
- the cost saving for this bridge compared to a typical steel bridge design was estimated as 40%.



FOOTBRIDGE: TYPICAL SECTION





















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