Printing Where It Matters: Hybrid Steel Design

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Rethinking How We Build in Steel

Metal 3D printing offers freedom of form and robotic automation but remains slower and more costly than established methods such as hot-rolling or cold-forming. *So, what if we only 3D-printed the hard bits?*

This idea led to the development of hybrid nodes, where wire arc additive manufacturing (WAAM) is applied only at critical junctions, with geometry shaped by topology optimisation. The concept was proven through experiment and scaled to a world-first 10-metre hybrid 3D truss, designed through layout and size optimisation and soon to be tested at Imperial College London.

Why Hybrid

Recent demonstrators such as the MX3D bridge and the Imperial-Shimizu garden bridge showcased WAAM's potential for complex, large-scale steel structures. Yet their reliance on fully printed components exposed a key challenge: WAAM alone cannot compete with conventional steelwork in cost, productivity, or scalability, restricting its use in mainstream construction.

Our work takes a hybrid approach – using conventional fabrication for primary members and WAAM only where geometric complexity or performance gains justify it. This combines WAAM's design freedom and automation with the speed and economy of standard steelwork.

Structural connections are the ideal starting point – intricate, labour-intensive, and critical to performance. Selective WAAM enables optimised, near-net-shape nodes that improve efficiency while reducing manual fabrication.

This project demonstrates how optimisation-informed hybrid construction can deliver greater efficiency, automation, and design freedom, moving metal 3D printing from one-off demonstrations toward scalable, everyday structural practice.

MX3D bridge

Imperial-Shimizu garden bridge

When Structure Finds Its Form

Though the final geometry recalls the branching of tree roots, it wasn't inspired by nature – it emerged from structural optimisation, following the same logic of force that shapes roots in the ground.

Material is placed only where it contributes most, creating geometry that is both efficient and expressive. The design establishes alternative load paths, redirecting force from the weaker chord face into the sidewalls and engaging more of the sidewall in bending to enhance resistance.

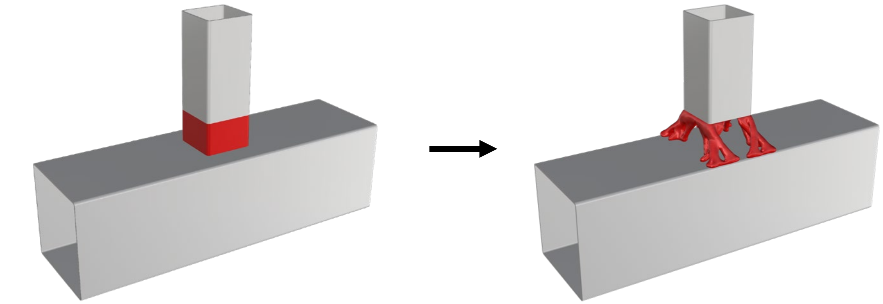
Topology-optimised hybrid node resembling the branching form of a tree root

Designing by Optimisation

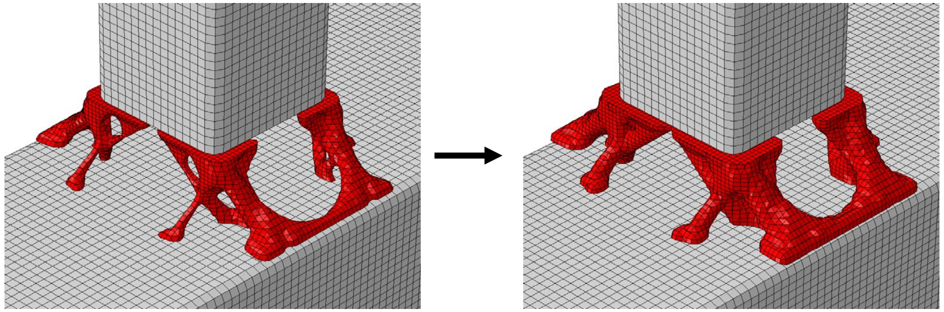
Topology optimisation was carried out using the TOSCA module in ABAQUS, following the SIMP (Solid Isotropic Material with Penalisation) method. The design domain was defined at the brace-to-chord junction, aiming to minimise strain energy within a fixed material volume.

The resulting geometries were evaluated through geometrically and materially nonlinear analysis with imperfections (GMNIA) to capture second-order effects and realistic material behaviour, confirming the structural benefits of the optimised designs.

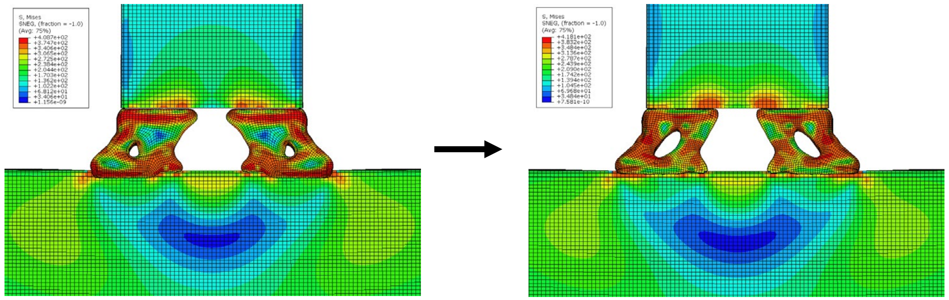
Some fine features were too small to print. To preserve the optimised geometry while ensuring printability, the solid models were converted into shell forms by expanding the iso-surface (see figure), creating hollow components with practical wall thicknesses of 2.5-6.5 mm. Subsequent stress-based refinements removed low-stress regions, reducing material use while maintaining the nodes' stiffness and strength.



Topology optimisation of a hybrid node from its benchmark



Solid-to-shell conversion by expanding the iso-surface

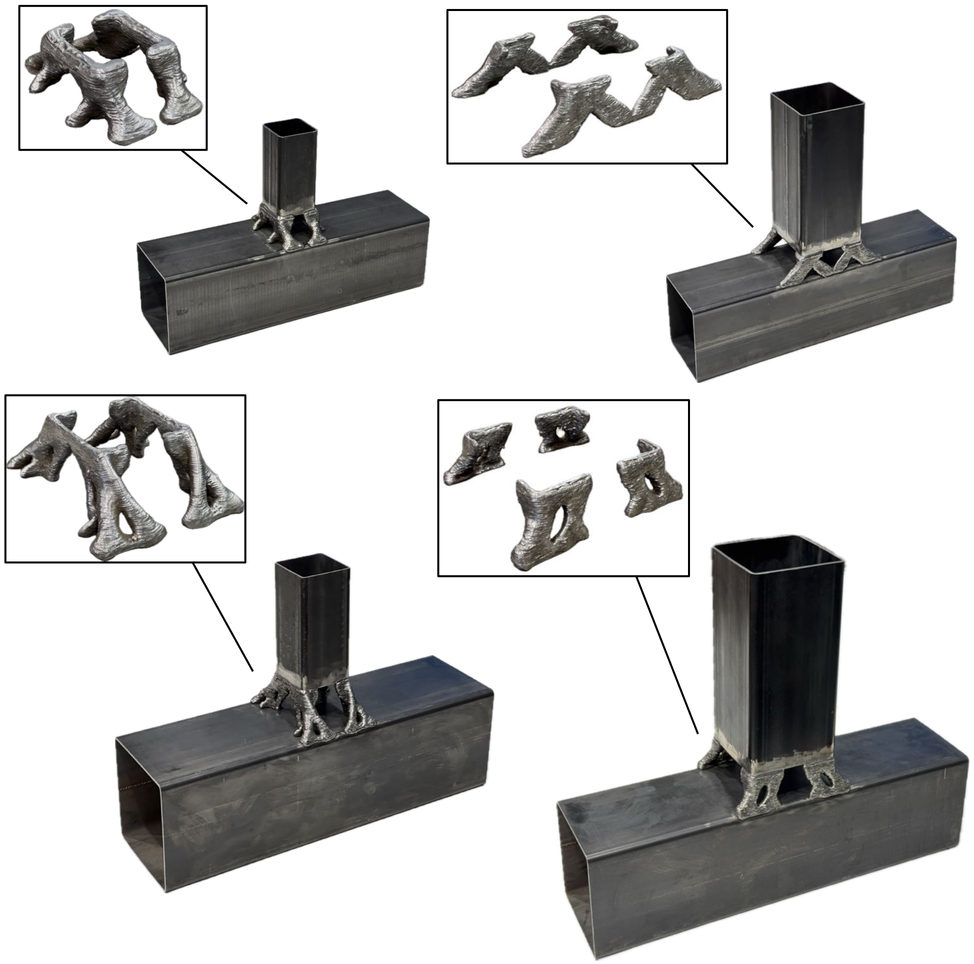


Post-optimisation refinement to remove low-stress regions

Printing the Hard Bits

Seven hybrid node specimens in four configurations were fabricated to assess improvements over benchmarks. Two brace-to-chord width ratios produced distinct failure modes: chord face failure for the narrower brace and combined chord face-sidewall failure for the wider one. Chord widths ranged from 200 mm to 300 mm to explore benefits across plates of different slenderness.

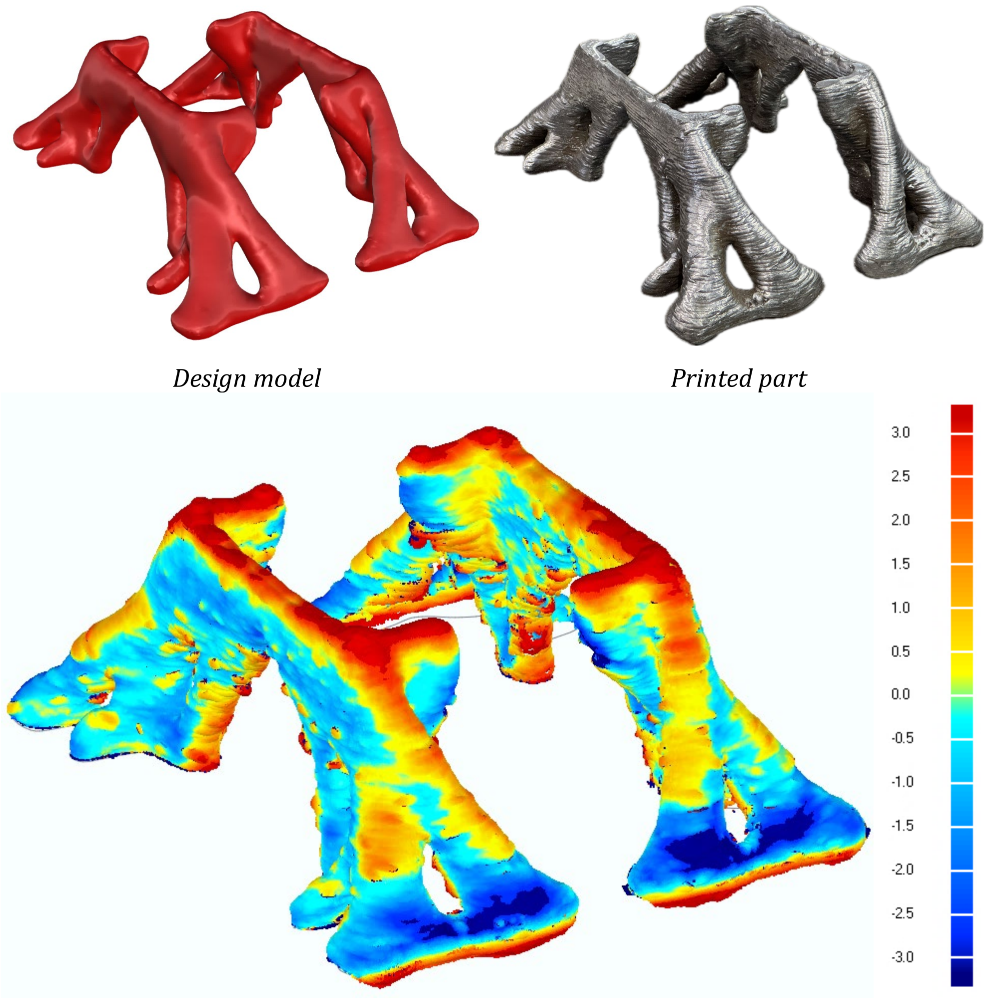
The hybrid nodes were produced by printing the optimised WAAM components directly onto the chord members using a 6-axis robotic arm and MIG welding system, followed by conventional welding of the brace members.



Typical hybrid nodes in four configurations, with close-up views of the WAAM parts

Checking the Geometry

After fabrication, the WAAM components were laser scanned using a high-precision FARO Design ScanArm 3D scanner. The captured point-cloud data were processed to assess deviations between the printed and design geometries that could affect structural performance.



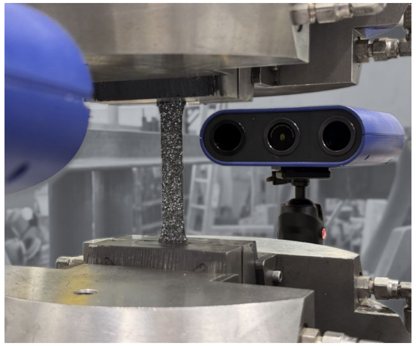
Geometric deviations of WAAM components in typical hybrid node (all units in mm)

Proving the Concept

Structural and material tests verified the performance of the optimised hybrid nodes, confirming the effectiveness of the hybrid approach. Structural tests examined load-deformation behaviour and failure modes, while material tests evaluated how WAAM surface undulations affect the mechanical properties.

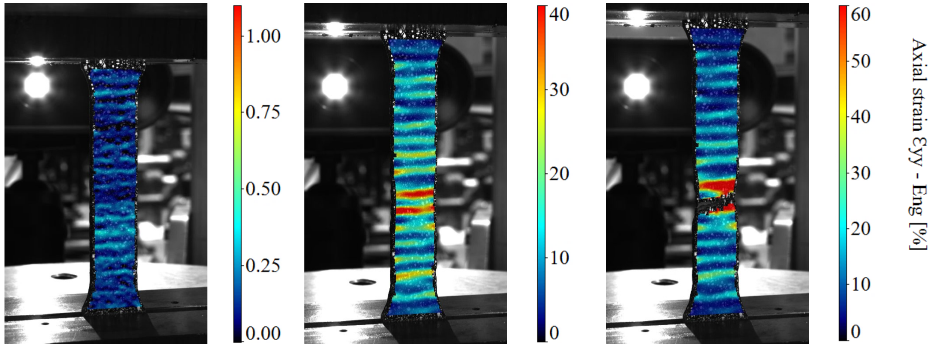
Node specimens were tested under brace compression with simply-supported boundary conditions. Chord lengths (700-1160 mm) were chosen carefully to minimise boundary effects while avoiding excessive bending. Both tests were monitored using stereo digital image correlation (DIC) systems to capture full-field displacement and strain data, with all specimens spray-painted with speckle patterns for DIC measurement.

Structural (node) test setup



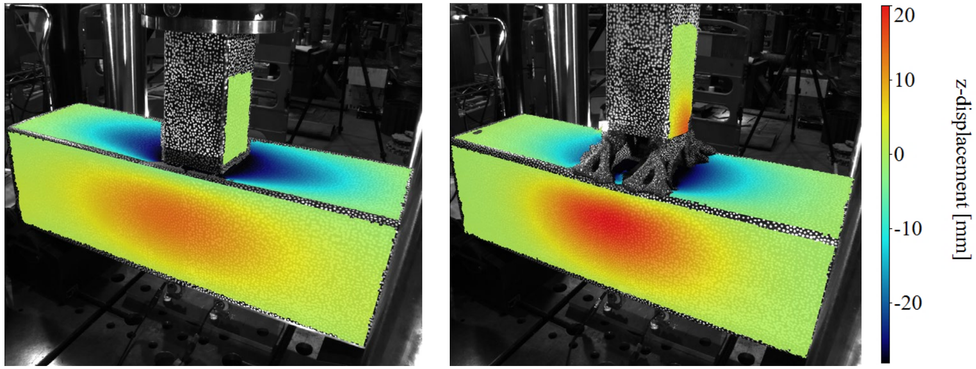
Material (tensile coupon) test setup

DIC measurements and recorded loads were used to generate stress-strain curves and determine key parameters (e.g. Young's modulus, yield strength, ultimate strength, and fracture strain) for understanding material behaviour.



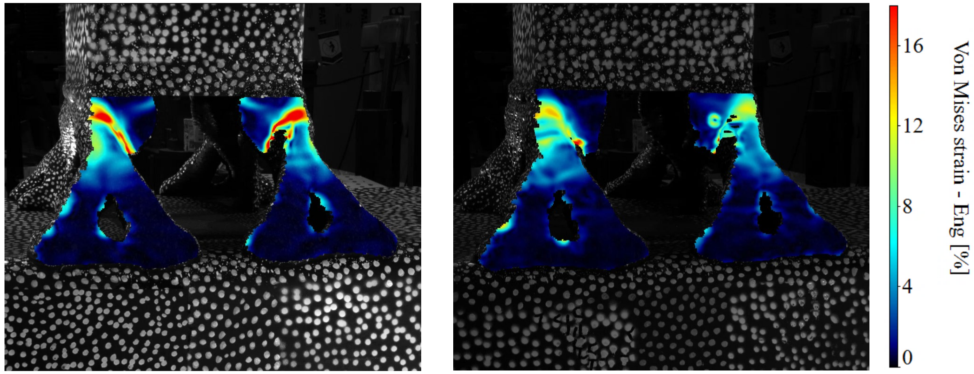
Evolution of axial strain in a typical tensile coupon during testing

The DIC results revealed a distinct shift in failure behaviour between the benchmark and hybrid nodes. As shown in the images below, the benchmark node (left) exhibited larger out-of-plane deformation at the chord face, whereas the hybrid node (right) showed greater deformation in the sidewalls. This confirms that the WAAM parts successfully redirected load away from the chord face, leading to higher strength and validating the optimisation concept.



Out-of-plane deformation fields from DIC images

At failure, DIC strain maps showed that thinner WAAM walls (left) deformed more than thicker ones (right), reflecting their expected structural behaviour.



Surface strain distributions of WAAM regions from DIC images

Scaling the Idea

Building on the proven node concept, the design was scaled to a 10-metre 3D truss, a world-first demonstration of WAAM-enabled hybrid design at structural scale. Following the same workflow established for the hybrid nodes, the truss was designed through optimisation, analysed using nonlinear simulation, and fabricated robotically, with testing to follow to confirm the predicted efficiency.

Developed within a 1 × 1.3 m inverted-triangular domain, the truss was optimised for strength and stability. Its refined layout – two top compression chords, a single bottom tension chord, and interconnecting bracing – is enabled by WAAM nodes that eliminate the complex profiling and welding required in conventional fabrication. This approach opens new opportunities for both structural efficiency and expressive design.

The hybrid truss and nodes form part of the EU Pioneer Project, which aims to make manufacturing smarter and more sustainable by linking design, simulation, and production data. Together, they show how selective 3D printing can enhance efficiency, automation, and design freedom in the next generation of steel construction.

Acknowledgement

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Reflection

The hybrid nodes achieved remarkable efficiency gains, with stiffness up to ten times greater and strength increased by more than 160%. These improvements arose mainly from the optimised geometry enabled by 3D printing, made scalable through a hybrid approach that offsets the cost and speed limits of fully printing by combining robotic freedom with conventional fabrication.

This strategy delivers efficiency, sustainability, and design freedom. Material is used only where most effective, reducing waste and embodied carbon, while automation improves safety and reduces manual work. Freed from conventional constraints, geometry follows structural logic, uniting performance with architectural expression. The concept is adaptable – from bridges to canopies – enabling structures that are both efficient and distinctive.

Not everything worked perfectly. The process showed how print quality affects structural performance, and the most efficient forms were often the least printable. Future progress depends on process standardisation and simplified design methods to make application reliable at scale.

Innovation demands both creativity and restraint – knowing where technology truly adds value and where tradition still leads. If the MX3D bridge showed we can print entire structures, this project shows we shouldn't have to.

We only need to print where it matters.