OPTIMISATION OF WASTE STEEL LED THE DESIGN OF LOW-CARBON PUBLIC INFRASTRUCTURE

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Abstract:

This public infrastructure project, a 60m long footbridge over a live railway, finds itself at the convergence of existing and new digital tools, new regulations surrounding steel reuse, the publication of carbon libraries, and the emergence of an industry for steel reuse. It is the result of a close collaboration between the main client and the design team. The pioneering use of waste steel within the bridge (also referred to as repurposed steel) was a focal point of the design process. This was made possible with extensive use of digital techniques that facilitated the choice of a structural typology to match a known available stock of previously unwanted material, a process known as 'stock-led design'. This is the inverse of the norm, where the designer chooses a form via experience and intuition and only then considers the arrangement, material and profile of the elements that make up the structure, thus constraining the potential to maximise waste material. The use of generative digital methods permitted an iterative and flexible design process, and allowed any material and embodied carbon savings arising from different options to be tracked. Carbon tracking was used as an informative tool to support the decision-making process throughout the entire design and fabrication stages. Footbridges are long-lasting pieces of public infrastructure and are vital elements in the development of communities. A footbridge can also become a destination and help to develop a safe pedestrian route within the urban tissue. They are functional objects, and their design is sometimes secondary to other practical constraints. As both designer and structural engineer on the project, we had the opportunity to refine, optimise and test the structural efficiency of various designs with the goal of a highly sustainable, optimised design which was practical and which did not compromise on aesthetics. For this, we used a mix of multi-objective data-driven computational methods and conventional design methods via physical models in tandem with hand sketching. A key aspiration for this bridge was sustainability. While many avenues were explored in the early design stage, the process coalesced around the imperative to reduce embodied energy for this particular bridge and be a case study for those which follow. The use of existing pieces of steel, discarded or unused by others, quickly became an evident, simple solution to implement. From the client to the contractor, everybody could grasp the climate-driven benefits of this idea. At the time of starting this project, a known stock of repurposed tubes led us to explore typologies that could use these in a structurally efficient way. Once settled on this with the wider design team, multi-parameter digital optimisation was used within the stock-led design process to refine the geometry of the bridge. Not just the topology of the primary members but also their arrangement: numbers, inclinations, spacing. The output goals were to focus on minimising material while respecting the minimum deflection criteria, maximise the utilisation of each member, and ensure

safe horizontal and lateral natural frequencies of the footbridge. Thanks to the publication of the SCORBS rating system, published by the Institute of Structural Engineers, embodied carbon was tracked throughout the design and construction programme of the bridge with a digital tool embedded in the workflow. The ambition at the outset of the project was to keep the bridge equivalent to, or better than, SCORBS rating A. The as-built carbon met that aspiration with an upfront embodied carbon of 677kgCO2e/m2 for stages A1-A5, an extremely low value for a tall and wide bridge elevated over a railway. It is a great example of how computational workflows can facilitate the delivery of a low-carbon national infrastructure. Compared with the rail authority's catalogue of conventional solutions, our project saved 50% carbon, 25% was thanks to the use of repurposed steel, 25% directly due to the site-specific optimised solution.

1. Introduction

This paper describes a 53m-long pedestrian footbridge completed in November 2024. The bridge was commissioned by national rail authorities to replace two small non-compliant bridges over a major train route. The bridge extends from a public park to a new residential and leisure development and is elevated 5.5m above the rails. Refurbishment of the existing structures was deemed impractical due to their poor state of repair, as well as the subsequent disruption of closing the railway during the refurbishment of the old structures. The client's preference was for a single direct line of travel bridge across the railway instead of directly replacing the two old disconnected links. The height of the new bridge was determined by the need for a 5.2m minimum clearance over the rails and by the sloping topography of the ground at each end. A large central island between the rail tracks left a decision between two or three equal spans within the 53m deck length.

The new bridge was fabricated and erected to a tight programme in order to keep the installation within a pre-planned rail possession window. The structure had to fit within a very constrained site boundary and needed to be delivered by road and rail in large prefabricated elements. Whilst taking into account the technical and constructional challenges, the bridge was to be attractive in appearance and complementary to its surroundings. The Client's brief emphasised the need for low-carbon innovation. The design was led by the engineers, with practical and aesthetic considerations being balanced by the same in-house team. The structural design of the bridge used a custom digital workflow with the innovative use of a pre-existing catalogue of repurposed steel tubes. Computational techniques were essential in balancing the properties of the steel tubes that were available with the functional/cost/embodied energy and practical requirements of the bridge design, and led to a successful outcome. This was a first for a rail bridge in the UK. However, being the first does mean that lessons were learned along the way, which are summarised in this paper.

2. Sustainability Framework

Aside from the need to deliver a functional but visually elegant bridge on an acceptable budget, the client wanted the scheme to be an exemplar for low-carbon design and one which would set a benchmark for future rail projects. They were willing to explore unusual typologies, materials and procurement techniques, and they were supportive of the application of original research. The moral and practical need to implement low-carbon design has accelerated in recent decades and is now enshrined in published best practice guides and design standards, most notably PAS 2080:2023 Carbon management in buildings and infrastructure, a framework which the client has committed to. In addition to this, the Engineering Designers are signatories to several industry low-carbon advocacy groups and were determined to explore a scheme which adhered to the tenets of those.

3. Design brief

In addition to the pressing need to deliver a low-carbon exemplar project, the initial objective was to minimise the deck depth. The thinner the deck, the easier it was to fit in the strictly given access boundaries. It was also agreed that this would facilitate any future ramp installation. Additionally, the brief required a balance between statutory safety requirements, specifically a minimum 1.8m barrier height, and the aesthetic goal of "openness." The overall design brief parameters can be summarised:

- Visual Lightness: The top structural chord was designed to be unobtrusive.
- Visibility: Parapet opacity was minimised through a perforated pattern to allow views while maintaining the required solidity.
- Logistics: Components were sized for rail delivery, requiring clearance under existing low-headroom structures.
- Structural Assembly: Based on early contractor engagement, the bridge was prefabricated in two primary segments for a mid-span pin-joint connection.
- Durability: The design life is specified at 120 years, with a low maintenance approach to minimise future railway disruptions.

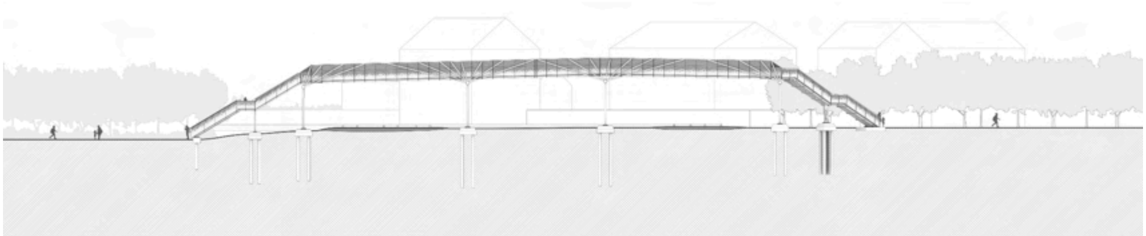

Figure 1. Elevation - 56m total span, 3 spans, Fan arrangement

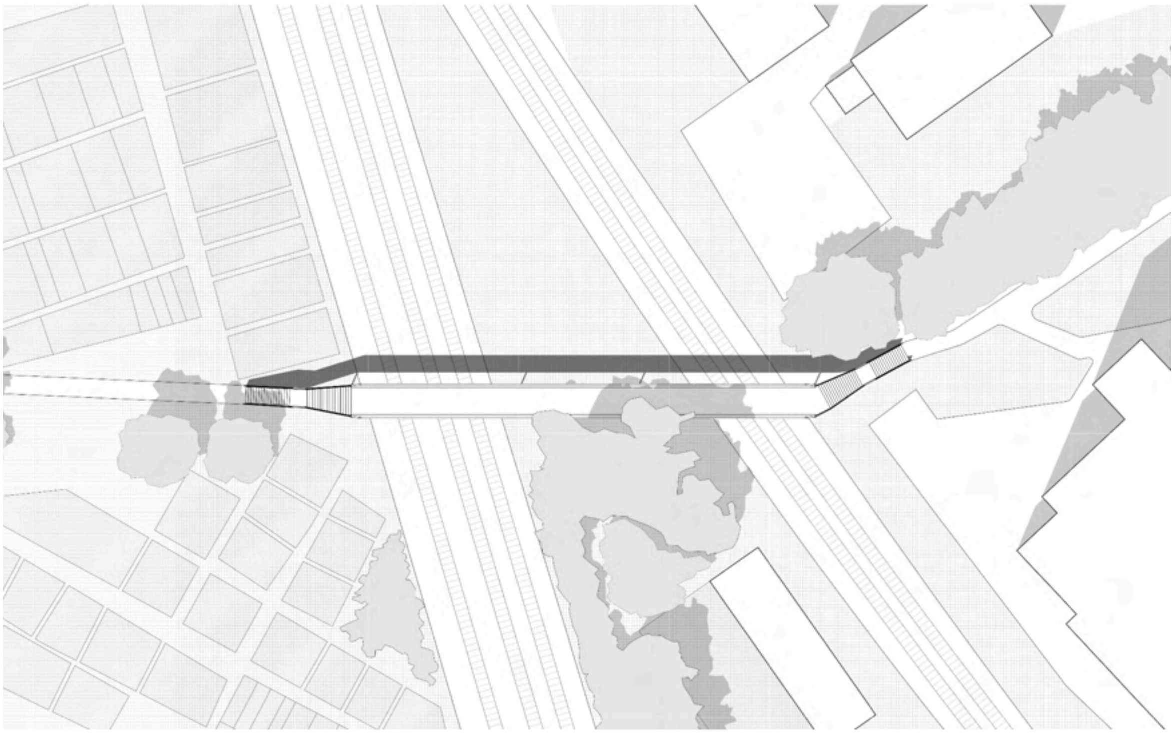

Figure 2. Plan view - 56m span with 2 stairs access.

4. Design methodology

This project design methodology expresses the clear steps followed to shift from a Demand-Led Design to a Material-Led Design. This combines the use of digital plugins, classic engineering design strategies and public carbon database. It shows the power of a tight, circular, iterative and flexible workflow and the importance of data recording as part of a design process. The integration of reused/repurposed material does not fit the conventional linear design strategy.

Unlike traditional approaches, where structural typologies are derived from intuition or historical precedent, the design was dictated by material availability. In this case, the project utilised a pre-existing inventory of repurposed steel circular hollow sections, with varied steel grades, geometry, and thickness, which served as the primary constraint and driver for the final structural arrangement. Steel CHS were chosen both for their durability and their known availability at the beginning of the project. The chosen fan-like typology (referred to in more detail later in this paper) allowed the use of long lengths of CHS whilst embracing the openness requested by our client and, importantly, minimised the top chord member sizes. Once that choice had been made, a number of digital tools were used to choose the fan-like arrangement of members that represented the best compromise between cost, beauty and embodied energy. The use of generative digital methods also facilitated an iterative and flexible design process, which allowed material and embodied carbon savings arising from different options to be continuously monitored in one workflow and then rapid decisions made depending on the outcomes.

The project is a good illustration of how to manage carbon reduction by making informed early design decisions.

4.1. Repurposed Steel

With a strong emphasis on low-carbon design , a 120-year design life and low maintenance, the use of repurposed steel quickly became a promising option. The non-extractive approach of circular-led design is widely recognised. By using a resource already available, the need to extract or quarry new resources from a site is deemed unnecessary. This has a beneficial carbon impact on reducing transport and raw material transformation processes, but also a non-measurable beneficial impact on the wider biodiversity[1].

This project prioritised the use of repurposed steel, distinguishing it from 'recycled' or 'reused' variants. Unlike recycled steel, which requires energy-intensive smelting, or reused steel, which typically involves reclaiming components from demolished structures, repurposed steel in this context refers to surplus stock sourced from diverse industrial sectors. These materials often constitute high-quality, unused resources that are frequently diverted to scrap and recycling despite their structural integrity. Using repurposed steel is a way to dynamise a market that values circularity in a closed loop and minimises re-processing.

For an infrastructure project with a 120-year design life, repurposed steel provides a distinct advantage: a traceable "paper trail" of provenance and no previous loading life. This guarantees the absence of fatigue damage from prior service, an important assurance for bridges over railways. While the scale of this footbridge suggests that fatigue is not a concern, the use of repurposed steel provided a "low-risk" entry point for the client to adopt circular procurement.
In terms of embodied carbon. It is acknowledged that repurposed steel is a low-carbon option, as it is deemed that much of the fabrication energy was expended during the fabrication process for its original purpose.

4.2. Workflow

At the outset of the project, a 'high-level' study into the carbon efficiency of two or three approximately equal spans was carried out using basic truss typologies. This concluded that three similar spans of 20m were more material and energy-efficient than two longer spans of 30m. Once that early choice was made, we as Engineering Designers, with the client, looked in more detail at the typology of the structure. From experience of other projects that successfully used waste steel we proposed that it be employed on the bridge This would be a first for a national rail bridge. From that point the design workflow mapped out as follows:

[1] Embodied biodiversity - Impacts of construction materials, ICE Report, November 2023, ICE, Expedition

- Inventory mapping: An initial discussion with a waste steel tube supplier brought confidence that many tube sizes were available in a multitude of grades, diameters, and thicknesses. From that discussion, we were able to map out tube diameters and lengths within a practical tube wall thickness range, i.e., tubes too thin are inadmissible for bridge design and too thick would be too heavy and wasteful. Steel has the advantage of being able to be re-welded, which simplifies the discrete allocation of the elements on the scheme. In other words, the length of each item was not a factor in this circular project.
- Initial structural intuition: Working with the principle that the design brief calls for a tall parapet, a thin top chord, but also a shallow deck, we devised a structural arrangement which utilised the parapets as primary structure, but which was not a conventional truss. This was done in order not to overload the top chord, which then allowed for a physical split in the bridge sections to facilitate prefabrication. Our solution, based on Engineering intuition within these constraints, was a radiating steel tube fan column from which a relatively conventional steel plate U-Frame could be suspended, a small top chord working in tension, coupled with exploiting more repurposed tubes as a compression bottom chord.
- Multi-Objective Optimisation (MOO): Based on the three span fan column solution, a more detailed 2D multi-objective optimisation model using Octopus arrived at a tube number and arrangement which was the best compromise between complexity, structural performance and cost, judged on least steel weight. That study had the benefit of giving a good indication of what would be a successful typology.
- Selected catalogue: Following these initial results, we narrowed down a selection of tube sizes for the patterns and solutions that were the lightest. We engaged with the steel tube supplier with our condensed list of tube sizes with associated grades. They then gave us a selection of potential closest sections.
- Data-driven decision making: Next, a ‘master’ model was developed in the Rhino3D/Grasshopper parametric scripting environment[2] which used the Karamba3D structural analysis and an in-house cartoon calculator plug-ins coupled with Design Explorer. This design exploration ranges from the number of connections/number of tubes/inclination of tubes/ parapet vertical spacings. This automatically carried out thousands of structural analysis models, which are presented as an interactive graph. The different parameters and output can be manipulated on-screen to narrow down the best design compromise between factors which have a direct influence on: aesthetics, performance, carbon and cost. In effect, engineers, having been presented with a catalogue of solutions, can use their design flair to effectively act as a ‘puppeteer’
- Specifications: The final length and specifications of tubes were given to the contractor and fabricator.

[2] Robert McNeel & Associates – Rhino3d - https://www.rhino3d.com/

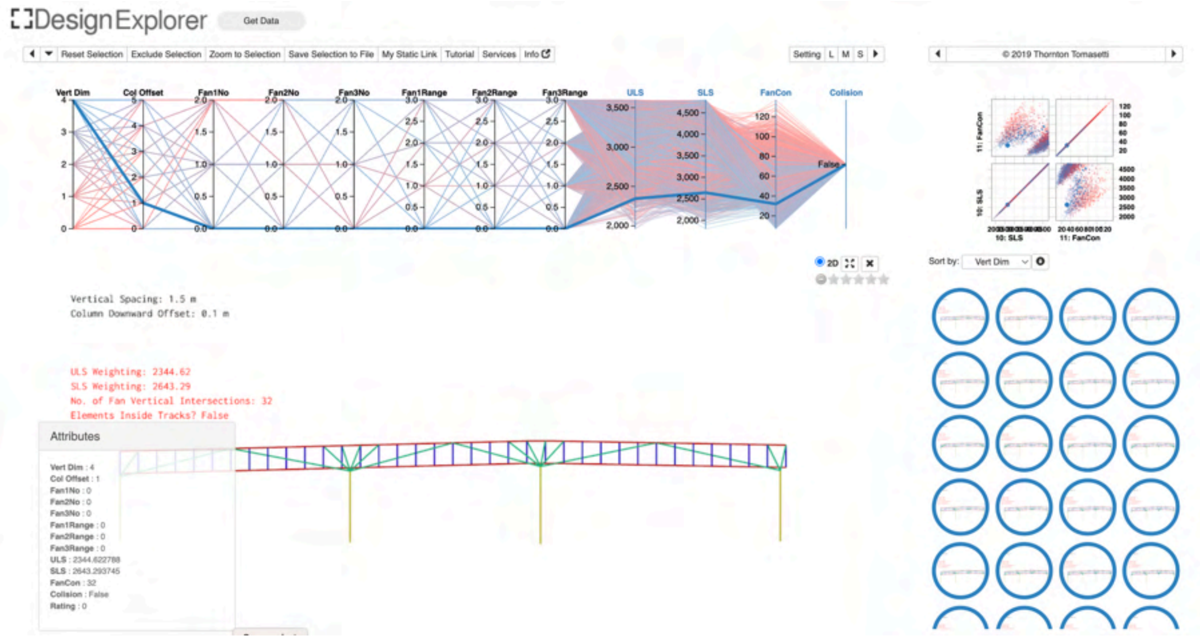

Figure 3. Design Explorer Multi-Objective Optimisation

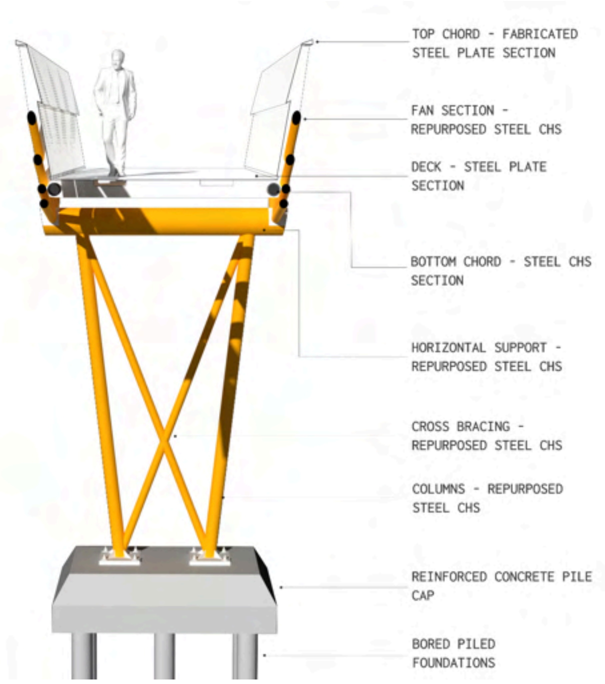

Figure 4. Cross-section - In orange, all repurposed sections

5. Project outcomes

The project was substantially completed in November 2024 during a two-night track possession window. The strategic decision to prefabricate the structure in two segments for rail delivery was validated by the successful installation within the allotted timeframe. However, the transition from a digital "circular" model to physical infrastructure revealed several critical lessons regarding integrated workflows and material procurement.

Integrated digital workflow:
The success of the optimisation process was largely due to the multidisciplinary nature of the design team, which managed both architectural intent and structural optimisation. In conventional practice, the separation of design, engineering, and carbon auditing into distinct entities often creates silos that inhibit material savings. While a unified digital workflow mitigates this, the "human factor" remains central; data must be hierarchised and shared at critical decision points to remain effective.

Buildability, Site and Carbon:
Contractors' input on delivery, installation and buildability has a fundamental impact on material usage. In this project, even though the design was led by an experienced team working in close collaboration with a contractor, some site-specific decisions had an impact on the total carbon. Whilst carbon is often considered at the design stages, cost and time are still the main drivers of a successful on-site delivery. Notably, the "circular mindset" extended beyond the primary structure: the contractor repurposed excavated topsoil and used leftover timber panels to make shed structures for the nearby allotments, demonstrating a holistic approach to waste reduction.

Procurement:
- The client buying into the concept early on was key to the delivery of this project. As with any unconventional idea, there were many occasions where, without the client's support, this would have been discarded.
- In this project, for internal procurement and funding reasons, the client was unable to reserve the stock before fabrication. Unfortunately, the steel fabricator’s contract was finalised just before they were due to commence work. This meant that our selected steel sections were at risk for several months, but also meant that no further investigations had been carried out on the tube's provenance and grades. After some confusion on the provenance of a specific batch of steel, testing became a sudden necessity.
- The steel supplier had offered to reserve a batch with a deposit at any stage of the project, but this offer was not taken up by the client for similar reasons as noted above.

Material Testing:
- The timeline for material testing is approximately 7 to 15 days. Ideally, this would be factored into a project timeline, but in this case, it was left to the very last minute; the extra 10 days required for testing almost derailed the project delivery.
- Multiple tests are required to ensure structural grading, depending on provenance and previous loading life. The testing regime follows the Eurocode recommendation EN1993-1-10. For this project, tensile testing and Chemical analysis were required. The associated cost per sample is only a few hundred pounds.

Cost:
- From verbal correspondence with the steel stockist and other case studies, we understand that repurposed steel is generally around 20/30% cheaper than new steel. This does not account for testing or any remanufacturing/reprocessing required to use the section.
- No data has yet been provided to us on this project to confirm that assertion.

Typology:
Whilst all elements of the main structure (including the repurposed steel) were carefully reviewed and optimised in the context of a rail bridge, the 1.8m parapet still represents 25% of the final carbon total. We have reflected on this and are now integrating parapets in our early calculations to ensure this is captured in early design decisions. In the absence of repurposed/second-hand appropriate panels, and in the context of this relatively long and narrow bridge, the perforated stainless steel parapets bring many comfort qualities that a solid parapet would have missed.

Design:
As a rule of thumb, studies[3] have shown that if the choice of the repurposed/reuse section requires an increase in total tonnage of more than 30%, consideration should be given to use a new section instead. This allows another project to use this material to a fuller utilisation However, to support the emerging market of second-hand material, opinions diverge on the extent to which this should be applied, and this should not become a barrier to the use of repurposed material.

The positive unexpected:
The use of repurposed steel was overall a positive experience, and the client has since been pursuing other projects with that material. If we briefly leave the carbon narrative, the use of repurposed steel was a convincing way to integrate a low-carbon framework in the context of conventional infrastructure workspace. The idea to use a piece of unused steel was very simple for all parties invested in the project to visualise, and when the procurement and testing route was clearly explained, the benefits were broadly agreed. The discussion around repurposed/reused material also allowed a rare opportunity to debate about material provenance and conventional recycling methods, which are essential but often forgotten in conventional projects.

[3] Chapter 15.3 The case of Reuse - The institution of Structural Engineers - Circular Economy and Reuse: Guidance for designers.

Figure 5. Perspective - In orange all repurposed sections

Figure 6. Satellite view of the bridge installed

5.1. SCORBS rating

Thanks to the publication of the SCORBS rating system[4] in the UK and design guides published by the Net Zero Bridges group[5], embodied carbon was tracked throughout the design and construction programme of the bridge. The client's ambition, shared by the designers, was to keep it equivalent to, or better than, the SCORBS rating A. The footbridge, as built, met that aspiration with an upfront embodied carbon of 677kgCO2e/m2 for stages A1-A5. This figure includes all structural superstructure and substructure elements, finishes and parapets, and considers the reduced emissions associated with the use of repurposed steel. For a bridge with very tall parapets and substantially elevated above ground level, this is a very successful outcome. The client now uses Tan House Bridge as a reference point when discussing other schemes.

Based on the available research available to us at the time of the project, a 95%[6] carbon saving compared to new steel was used for the repurposed steel. The carbon gain was a positive way to encourage a shift in mentalities in this project.

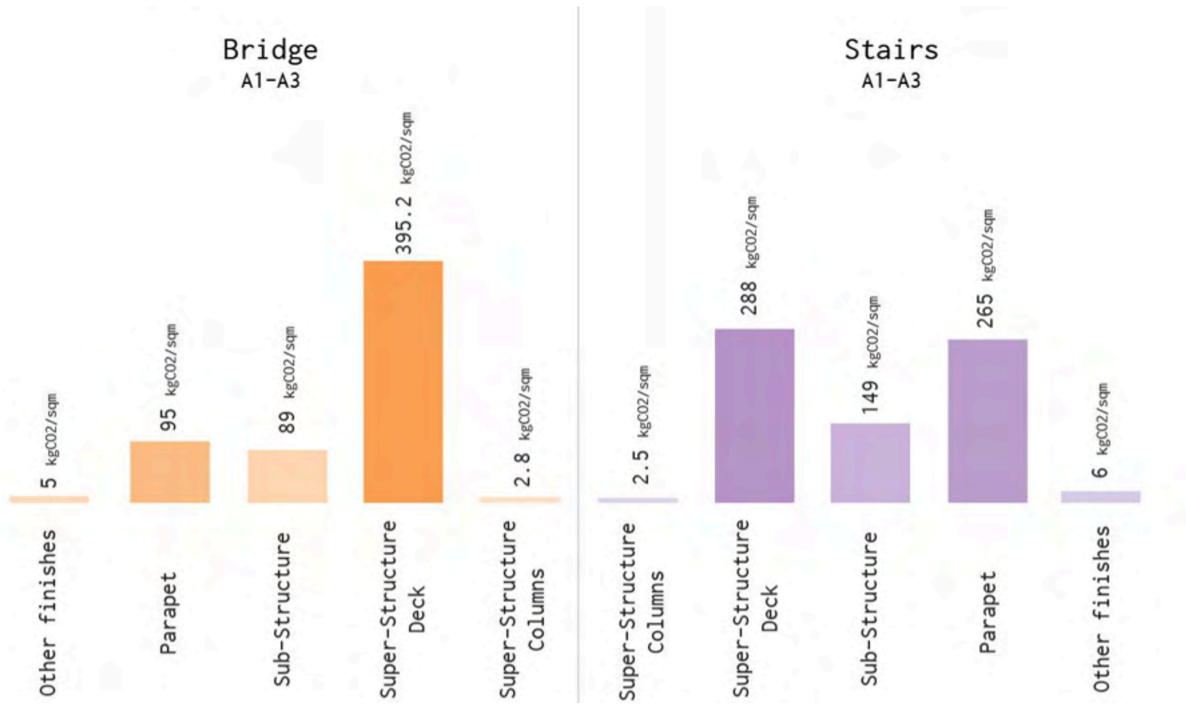

Figure 7. Carbon and Tonnage numbers per elements - A1-A3

[4] **The Structural Engineer,** Volume 99, Issue 10, 2021, Page(s) 5Carbon targets for bridges: a proposed SCORS-style rating scheme - Cameron Archer-Jones and Daniel Green

[5] Net Zero Bridge Group - **Guidance Note: Carbon Calculations for Bridges.** https://www.netzerobridges.org/library

[6] Giraffe Innovation study, ordered by Cleveland Steel and Tubes and the UKGBC CE Forum - CST_Sustainability_Greener_Steel.pdf

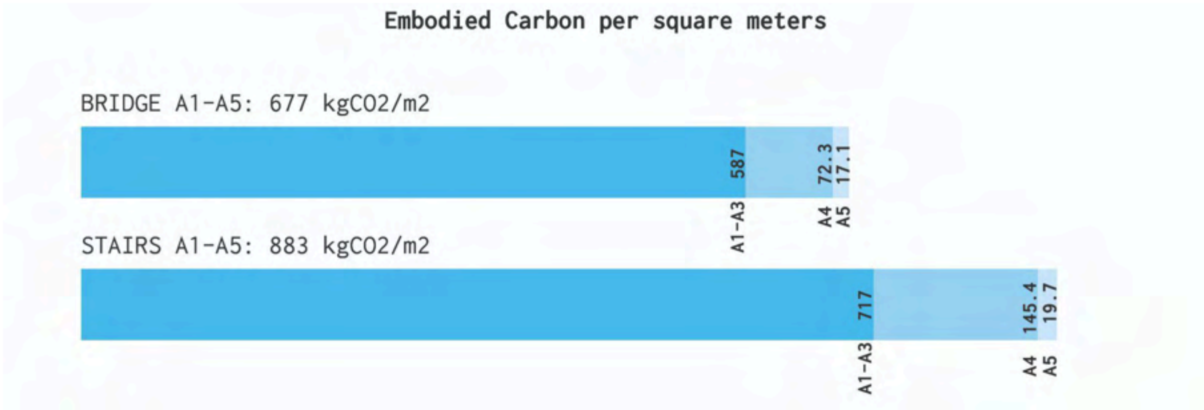

Figure 8. Stair and Bridge carbon numbers - A1-A5

6. Summary

Tan House Footbridge was a close collaboration between Client and Engineers, which required pioneering solutions that would prove the use of non-virgin materials, namely repurposed steel. This required original research, inventiveness, close collaboration and in-house and open source digital tools that facilitated a refinement of structural topology to match the stock of previously unwanted material. This approach is believed to be the first in the UK. At the time of writing, we believe this footbridge to be the lowest embodied carbon footbridge that the client has built on a live site. An internal client study has determined that it is considerably lower in CO2 than their own standard rail bridges. This proves that a bespoke, site-appropriate design does not have to be costly in capital expenditure or embodied carbon. Many lessons have been learned on the project, which have been fed back into industry via several publications, lectures and industry groups.