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Automated design and fabrication framework to enhance steel reuse through structural optimization and metal 3D printing

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A R T I C L E I N F O

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A B S T R A C T

The environmental impact is currently one of the key issues influencing the construction industry from a production standpoint. For this, structural designers are increasingly adopting circular construction strategies aimed at reducing greenhouse gas emissions. Among the most significant shifts in steel construction is the practice of reuse: especially in countries with a high concentration of historical buildings, steel reuse is emerging as a necessary alternative to demolition and waste disposal. This research proposes a structured methodology to automatically design optimized shell-like structures from a dataset of reclaimed steel members, combining global and local optimization algorithms. First, the components recovered from decommissioned steel structures are stored in a dedicated dataset. From this dataset, elements are randomly selected by an algorithm to compose an optimized gridshell structure. The algorithm assembles the gridshell using the best-performing components available in terms of structural utilization and environmental impact. The objective is to minimize the use of new materials by achieving an optimal structural configuration (best fit) using almost exclusively reused elements. The research also investigates the challenge of connecting reused components, which are often non-standard and geometrically diverse. Through a topological optimization study, custom steel joints are designed and validated for fabrication using large-scale metal 3D printing technology known as Wire-Arc Additive Manufacturing (WAAM), allowing for the efficient and precise assembly of the reused elements within the gridshell structure.

1. Introduction

The iron and steel sector, responsible for 3.6 Gt of CO_2 emissions and over 8% of global energy use, is highly resource-intensive. Mitigation strategies, as outlined in the Iron and Steel Technology Roadmap, emphasize technological improvements and material efficiency, which could account for 90% of sectoral emission reductions by 2030 [1]. A paradigm shift in design toward optimized, sustainable steel structures is needed, supported by computational design tools. However, conventional fabrication methods limit innovation due to high energy use and material waste.

Global demand for raw materials is expected to double by 2060 due to industrialization, population growth, and construction needs [2]. To address this, a Circular Economy approach is essential to focus on maximizing material value, minimizing raw material use, and preventing waste. For steel construction, applying Circular Economy principles involves strategies like reducing raw material use, designing for circularity, reusing and repairing components, remanufacturing second-hand products, and repurposing materials for new functions. These approaches are crucial for green growth and sustainable development.

Direct reuse of structural steel components offers significant environmental and economic benefits compared to recycling, particularly in construction due to steel prefabrication and ease of dismantling. While reuse was common before industrialization, it has largely been abandoned in modern practices. Recent projects in the UK, Japan, Canada, and the US demonstrate its potential [3–5], but widespread adoption faces challenges such as lack of standardization, automated processing, performance assurance, and quality control of reclaimed components [6–8].

To overcome these barriers, comprehensive guidelines and protocols are essential for the entire lifecycle of reused steel, from surveying and reclaiming to design and installation. These protocols will foster sustainability in the construction sector. Hence, a new structural protocol

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for reused steel members is needed to account for all the process chain steps towards a new generation of hybrid and circular steel structures.

Steel reuse has gained significant importance to enhance sustainability and resource conservation for the steel construction sector. However, up to now limited structural design guidelines present design approaches ad-hoc tailored for reused steel members, essential to determine the trajectory for hybrid and circular steel construction in the future [9].

The most critical aspect to draw such guidelines is the assessment and classification of the reclaimed stock, through the adoption of breakthrough monitoring systems for inspection and qualification, as well as ad-hoc developed machine learning algorithm to draw statistical analysis on the key mechanical parameters of reused steel members. Moreover, new predicting formulations for the design of the newly conceived hybrid steel structures will be developed through AI tools based on experimental and numerical data (from machine learning algorithm). These formulations will be essential to create a new type of hybrid steel construction with minimized environmental impact.

Computational design technologies have enabled the creation of complex efficient structures, but their application in construction remains limited due to traditional building practices and the constraints of conventional manufacturing. Algorithm-aided design holds potential to improve structural efficiency and reduce environmental impacts, but it requires skilled professionals to implement automation from design to production [10].

To fully leverage these tools, optimization methods must account for the specific challenges of digital fabrication, such as material anisotropy, surface irregularities and design constraints [11]. Recent studies proposed global optimization algorithms to adapt topology and shape optimization frameworks to stock-constrained libraries, typical of reuse cases (see e.g. [12–14]). For reclaimed structural components, integrating a computational design framework is critical to efficiently reuse materials while ensuring performance and enabling innovative design solutions for connections, strengthening and other applications through steel 3D printing [15]. Recent work has been devoted to developing new computational design algorithms to enhance steel reuse to realize new gridshell and exoskeleton structures (see e.g. [16–18]). However, these design solutions were focused at the global scale of the structure only, without accounting for the local details at the connection scale of the new and reused steel members.

The digitalization of construction, particularly through 3D printing technologies like Wire-Arc Additive Manufacturing (WAAM), offers significant potential to create efficient structures, reduce waste and enhance safety [19–21]. WAAM is well-suited for large metal components due to its high deposition rates, cost-effectiveness, and design flexibility, enabling topologically optimized geometries [22]. It has been successfully applied in structural, aerospace, and marine projects, showcasing its versatility [23–26]. However, several challenges remain, including the lack of standardization, guidelines, and performance validation for 3D-printed steel components [27]. Addressing these issues requires an integrated design-for-fabrication approach, updated standards, and thorough testing methods. Additionally, balancing productivity with quality in terms of surface finish and microstructural integrity remains a hurdle [28].

This work aims at proposing a new structural design framework for steel reuse which combines: (i) advanced analysis of the donor building to define the inventory of reused stock from structural thresholds, (ii) global and local optimization of the new hybrid structure, (iii) large-scale steel 3D printing for complex-shaped joints.

The study is based upon design guidelines for steel reuse as recently proposed to be included in the next generation of European structural design procedures (see e.g. [9]). The framework is intended to combine steel reuse with new advanced techniques in design optimization and digital fabrication to enhance the circularity in steel construction, while ensuring good structural performances. The optimization approach is based upon the so-called “blended structural optimization” algorithm proposed by some of the authors (see e.g. [29,30]) to combine global and local optimization of complex-shaped structures when applying large-scale metal 3D printing techniques for production, such as Wire-Arc Additive Manufacturing (WAAM, also known as DED-Arc).

The framework proposed in Section 2 is validated on an applied case study. First, a donor building is selected among the dismantled lattice towers. For this, the Turner Broadcasting Tower is studied in terms of its structural details (Section 3), from which a catalogue of reclaimed stock members is defined. The global (Section 4) and local (Section 5) optimization is then carried out on the case study of a new organic-shaped gridshell structure to be built with both reclaimed and new steel members, connected through optimized joints produced with WAAM technology.

2. The proposed framework for enhanced steel reuse

The automated design and fabrication framework for steel reused is conceptually depicted in Fig. 1. The framework is intended for any set of new structures to be fabricated combining new and existing steel members, with the use of large-scale metal 3D printing technology (in this case, Wire-Arc Additive Manufacturing) to realize complex-shaped joints to be adapted to both the new and the existing members.

The framework is divided into the following conceptual steps:

- Identification of the donor building: first, one or more donor buildings are selected among the dismantled steel structures. The donor building should come with a defined set of information regarding its structural history, in terms of detailed structural design as conceived and as constructed. Additional information regarding its development during its lifetime (i.e. any maintenance or substitution work) should also be included. The donor building should be properly analyzed through Finite Element models to identify the predicted lifetime utilization factor of each of its members, needed to define the threshold for reusability.
- Definition of the catalogue of reused members: from the results of the structural analysis on the donor building, a catalogue of reclaimed stock is produced to be adopted in the design phase of new structures. The catalogue is based upon the threshold identified in the first step, in which only the members having a lifetime utilization factor lower than the threshold (usually around 80% of the plastic limit for steel members) could be directly accounted for reuse. The definition of the catalogue of reused members from structural design thresholds could simplify the reusability of steel structures. However, this approach should first be validated through detailed investigations on reused members with both non-destructive and destructive testing.
- Global optimization of the new structure: from the catalogue of reclaimed stock, the design of the new structure is developed through a global optimization algorithm. During this step, the evaluation of the compatibility of the catalogue of reused members is checked and, in case of insufficient members availability, eventually implemented with new members. Thus, the catalogue of available members will be a hybrid inventory combining both new and reused members.
- Local optimization of the joints in the new structures: when considering a hybrid new structure, designed combining both new and reused members, ad-hoc steel joints should be designed and fabricated to be adapted to the different members cross-sections and dimensions. Thus, local optimization is implemented in this step to provide a new generation of complex-shaped steel joints to be fabricated with Wire-Arc Additive Manufacturing (WAAM) technology.
- Final validation of the new structure: the final step of the framework is the structural analysis and validation of the new structure, conceived adopting new and reused steel members and WAAM-fabricated complex-shaped steel joints.

The framework is intended to provide an integrated platform for

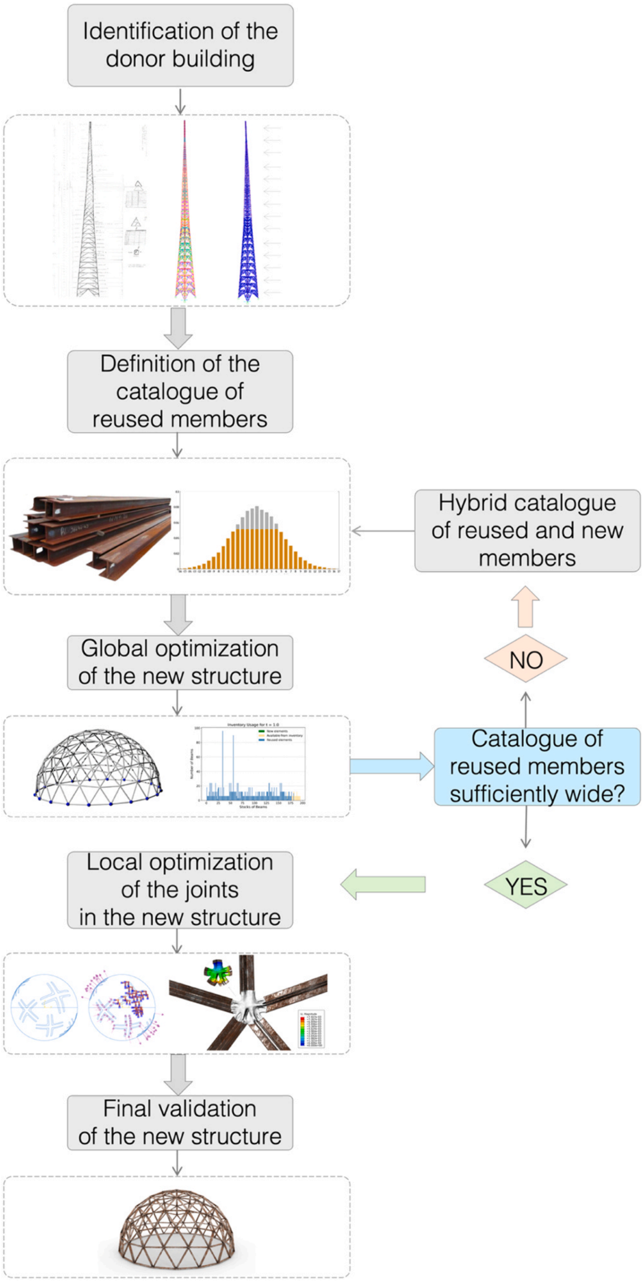


Fig. 1. Conceptual framework to integrate global-local optimization for hybrid gridshells by adopting steel reused members.

structural design, optimization and fabrication for complex-shaped hybrid structures combining steel reuse and metal 3D printing. The result will provide a preliminary design of the new hybrid gridshell structure, able to accommodate the structural requirements while maximizing the use of reclaimed stock. However, further analyses at a more detailed level will be required to verify the structural performances of the hybrid gridshell both at the global and local scale.

The proposed framework is hereafter validated through a case study, by considering a real dismantled lattice tower to populate the reclaimed stock library, to design a hybrid gridshell optimized based on various levels of adoption of reused vs new members. At the local scale, Wire-Arc Additive Manufacturing (WAAM) technology will be employed to realize complex-shaped steel joints optimized to connect various cross-sections (either from reused or from new members).

3. Structural analysis of the donor lattice tower for the reclaimed stock inventory

From the framework in Fig. 1, this Section addresses the basic requirement of historic documentary research while capitalizing on an opportunity to streamline donor building surveys. While a complete modelling process for the donor structure may be labor-intensive, this process could be broadened on a typology-by-typology basis, such that for particular structural types (e.g. portal frames, multistory shear frames, trusses, lattice towers) it is already known which components tend to experience lower stresses in their service life and therefore would be better suited to reuse.

The elements composing the lattice tower were catalogued in a dedicated database and subsequently reused by the algorithm to generate new structural configurations, aiming to maximize the percentage of reclaimed material while minimizing the introduction of new elements. The procedure was applied to the case study of the Turrner Broadcasting Tower, located in Atlanta, GA and dismantled in 2010.

3.1. *The pre-deconstruction audit*

In order to build a detailed library of reclaimed stock from a dismantled steel structure, current design guidelines for reuse suggest to run a pre-deconstruction audit (see e.g. [31]). The pre-deconstruction audit (PDA) is a preparatory activity that gathers information about the materials present in a building slated for demolition. In the context of deconstruction and reuse, the PDA is geared at identifying components that are suitable for reuse in order to inform the deconstruction strategy.

The PDA is executed by qualified individuals and includes:

- Documentary research: To know building age and constructive technologies, estimate material quantities and their properties, and record any major events (damages, modifications) in the history of the structure, among other things.
- Field survey: To confirm information obtained in documentary research, assess conditions of materials, obtain preliminary in situ test data (geometric scanning and/or non-destructive testing) and extract samples for laboratory testing.

The level of information acquired during the PDA (categorized into “Classes” in [31]) directly informs the required material testing protocol.

Hradil et al. [32] proposed a “reusability indicator” metric, also republished in [33], which assigns a value r between 0 and 1 to a steel component indicating its suitability to reuse. The calculation is based on a weighted sum of the difficulty of salvaging the component (ρ) with respect to several categories (w): deconstruction/disassembly, separation/cleaning, handling/manipulation, quality/control, geometry checking, redesigning, repurposing, and alteration/modification. The categories are each assigned a percentage (the weight), multiplied by a value between 0.2 (very difficult) and 1.0 (very easy), then summed.

$$r = \sum \rho_i w_i \tag{1}$$

Notably, “quality control” is weighted at $w = 15\%$ and relates to the knowledge of loading histories; its difficulty is represented by demands for laboratory testing. “Redesigning” is weighted at $w = 10\%$ and relates to the component’s compliance with today’s design codes, based on knowledge from prior documentation or certifications.

The proposed addition to the framework takes inspiration from Hradil’s reusability indicator calculation and can be applicable to the “quality control” category, but seeks to go further in depth than a qualitative assessment of the level of existing knowledge. This element is critical given that, as noted in all guidelines, any steel subject to global or local plasticization is not acceptable for reuse.

If early in the reuse process chain, an engineer completes a structural analysis using real historic loading information (e.g. extreme wind events), then the members that would have seen high stresses and potential plasticization in the building lifespan can be identified early and excluded from the reuse batch. At the same time, the knowledge about the building increases, and from a reliability standpoint it may be possible to execute less intensive testing protocols on the eligible steel or calibrate safety factors less conservatively.

3.2. *Case study: Turner Broadcasting Tower*

This section provides the detailed analysis of the Turner Broadcasting Tower, a dismantled steel lattice TV transmission tower from Atlanta, Georgia, USA, and demonstrates the methodological steps of the proposed process, highlighting opportunities for further research (Fig. 2).

The choice of a lattice tower was made with an eye towards the potential to generalize the process to the typology as a whole. Steel lattice towers are virtually ubiquitous, used around the world for power, TV and radio transmission. They are seen in a number of fairly standard structural truss layouts, so the behavior of one may be easily extrapolated to others that are similar. They are also often found in groups of repeated structures, making them a potentially large repository of structural sections available in duplicates.

Turner Broadcasting Tower was completed in 1967 and served as a TV transmission tower originally for the news network WJRJ (initialed for its owner Jack Rice Jr.) changing hands several times before going out of service in 2009 and being dismantled in 2010. The total height of the Turner Broadcasting Tower was 314.3 m (1034 feet), being one of the tallest steel lattice structures in the world at the time. Therefore, its dismantle could have been a major supply of reusable material for new structures.

Fig. 2. Turner Broadcasting Tower.

The historical document research and estimation of strengths presented here in the modelling process are already a requirement of the pre-deconstruction audit process, regardless of whether a model is produced or not. To that end, this description also demonstrates the level of effort required of the PDA process (Fig. 3).

Original structural drawings are housed in the collection of the Atlanta History Center and staff provided images of the drawings (courtesy of Dresser-Ideco Company, 1966). The drawing set was produced by the Dresser-Ideco Company of Columbus, Ohio, and is titled *1049' S.S. TV Tower: WJRJ-TV*. “S.S.” stands for “Self-Supporting.”

Based on the design drawing, the original lattice tower was designed to the Electronic Industries Association (EIA) document RS-222, “Structural Standards for Steel Transmitting Antennas, Supporting Steel Towers” published in 1959.

The tower was an open structure with a triangular base, whose main three legs are comprised of high-strength solid cylindrical steel. There were three tiers, distinguished by different inclination. In total there were approximately 3000 individual members.

3.2.1. *Structural analysis of the dismantled lattice tower*

From the historical documentation of the structure, it was possible to identify most of the elements composing the tower, and a dedicated database was created. The database includes all the geometric characteristics describing each individual truss element that defines the tower. In addition, it was considered necessary to enrich the dataset with stiffness parameters and definitions of the moment of inertia in order to achieve greater accuracy in the description of the structure to be redesigned using elements recovered from the dismantling process. This initial characterization of the elements is fundamental, as it is necessary to anticipate the combination of multiple components; therefore, in order to define the joints, it is essential to have detailed knowledge of the physical and mechanical properties of the elements to be connected.

The elements included in the database must be accompanied by their stress history. By stress history, this study refers to the determination of the loads to which each element has been subjected during its service life, such as seismic and wind actions. For the present case study, the wind load was considered the main affecting one. Therefore, historic weather data from Weather Spark for 1967–2010 was studied, showing a maximum wind speed in Atlanta of 84 mph (miles per hour) registered in the year 2000. From this information, a detailed structural analysis can be carried out to identify the maximum utilization factor of each element composing the lattice tower. The expectation in this particular case study is that utilization factors will mostly be low, because the historic high wind speed of 84 mph is lower than the 100 mph that it would have been designed for per RS-222. The catalogue includes all recoverable steel elements from the tower, with detailed information on their lengths, cross-sections, and original positions within the structure.

To preliminarily determine the behavior of the individual truss members, it was deemed necessary to perform an analysis using the SAP2000 finite element simulator. This step is essential for estimating the residual strength values of the elements, even at a preliminary level. The structure was first modelled in AutoCAD 3D and then imported to SAP2000.

The general notes on sheet D1C says that “All structural shapes are ASTM A36 steel,” which has a yield strength of 36ksi (248.21 MPa). For specific elements, such as the solid cylindrical bars and rods, higher strengths are noted in the drawing. Tables 1 and 2 summarizes the materials adopted for the structural analysis model in SAP2000.

The background research presented here on the Turner Broadcasting Tower is commensurate with reuse guidelines; it is expected that historic drawings should be sought and data collected on historic materials.

Note the production of a model also allows for the creation of a database of pieces that are useful for the used material marketplace, as well as for input in design by optimization. At the same time, a database of information for representative structures could be developed that shows typical stress patterns. This can guide the focus of pre-

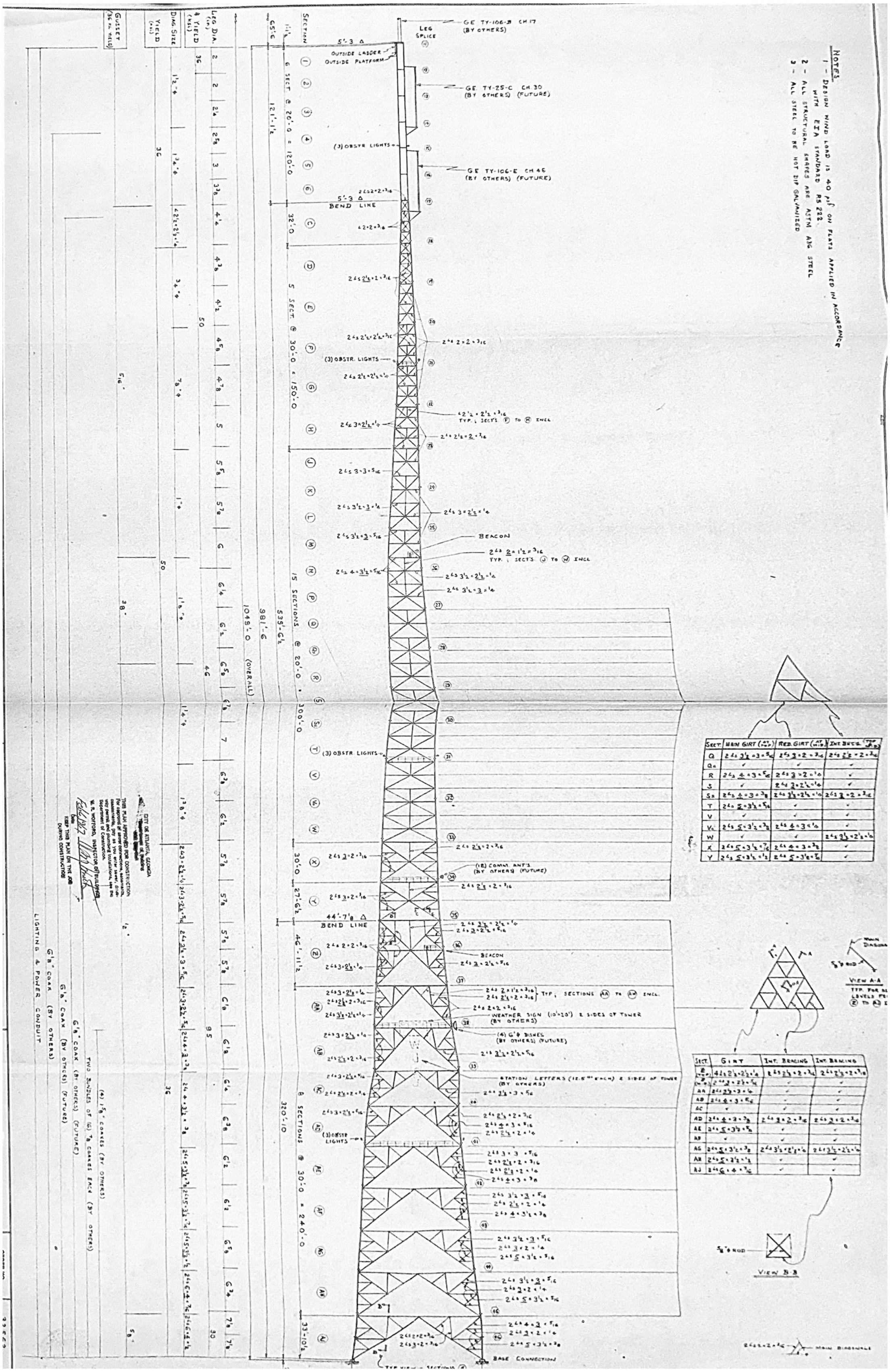


Fig. 3. Turner Broadcasting Tower historic design drawings by the Dresser-Ideco Company (Provided by Atlanta History Center).

Table 1

Turner Broadcasting Tower archival drawing list.

Sheet Number	Sheet Title	Sheet Contents	Original Date	Revision Date
32562-D1C	Design Drawing	Overall drawing of single face, with member sizes; General notes for structure	12/21/66	01/11/67
32562-D2B	Leg Splice Design	Splice schedule and details for main legs	01/04/67	01/25/67
32562-FD1	Foundation Design	Caisson details and connection of structure to caissons; general notes for foundation	01/12/67	N/A

deconstruction audits towards problem areas and avoid unnecessary time and testing on low-stress zones of the building.

The extra steps required to model and conduct the structural analysis are worth the effort if they produce the results able to: (i) streamline the pre-deconstruction audit by focusing attention on potential risky areas (e.g. zones with possible plasticization) and (ii) render more material suitable to reuse if it is found that actual loading conditions were low compared to historic design codes (as in this example, considering historic wind loads).

At the same time, a database of information for representative structures could be developed that shows typical stress patterns. In the context of lattice towers, for example, one might find that towers with chevron braces tend to show higher stress in certain members, while for towers with cross bracing other components are typically more at risk. This can guide the focus of pre-deconstruction audits towards problem areas and avoid unnecessary time and testing on low-stress zones of the building.

While factors such as the state of conservation, fatigue history, and corrosion exposure should generally be considered when assessing reclaimed elements, transmission towers are assumed to have relatively short service lives and minimal fatigue-related degradation. As such, their components are considered suitable for reuse without significant mechanical compromise. By having access to the original design drawings and to the historical records of measured wind parameters, it is possible to simulate the entire truss structure through FEM analysis and to validate its structural reliability with greater accuracy.

As previously stated, in order to validate all the parameters identified through an accurate analysis of the historical documentation related to the structure under investigation, finite element FEM simulation of the lattice structure was carried out using the SAP2000 simulation software. The simulation process began with the import of the geometry previously developed in AutoCAD. Yielding and ultimate strength parameters, as derived from the collected historical documents, were then assigned to each structural elements. The software requires the definition of the basic cross-sections of the elements, and it was observed that, once these fundamental parameters were properly defined, it was possible to proceed with the required simulations. It should be noted that the documentation obtained during the cataloging of the tower elements included extensive historical data related to strong wind elements recorded in the area. As wind represents one of the most critical loads the structure has been subjected to, particular importance was given to the development of a FEM simulation applying the maximum wind load recorded in the dataset. A high risk scenario was intentionally adopted in order to increase the reliability of the structural simulation. The total wind force corresponding to the highest recorded wind value was applied as a uniformly distributed surface load. The wind action was modelled using an equivalent height-dependent profile, defined based on realistic conditions derived from historical wind speed data for the Atlanta (Georgia) area over the period 1967–2010, with a recorded maximum value of 84 mph (37.55 m/s) in year 2000. The results show a low utilization factor for all structural elements composing the lattice tower. This evidence was expected given that the adopted value for the analysis (corresponding to the maximum wind action experienced by the lattice tower during its lifetime) is lower than the 100 mph (44.70 m/s) design wind speed specified by the RS-222 standard. Fig. 4 reports the SAP2000 model of the deformed Turner broadcasting tower and the shear distribution over height.

From these results, all structural elements composing the lattice tower were considered valid for reuse purposes. Hence, a reusability indicator value r equal to 1 was assigned to each member. It should be noted that these results provide preliminary structural analyses and further details on fatigue-related issues should be accounted for a more detailed structural verification.

4. Global optimization of the reused gridshell

4.1. The optimization algorithm

4.1.1. Input data

The optimization problem takes as input an inventory of structural beams and a target gridshell, together with prescribed loading and boundary conditions. The beam inventory comprises all available elements derived from the donor structure and is encoded as a matrix of uniform stock elements, i.e., with equal lengths and cross sections. The geometry of the gridshell is represented as triangular mesh $M_0 = \{V, E, F\}$, where V denotes the vertices (structural nodes); E the edges (beams); and F the mesh faces.

The optimal assignment of inventory elements to the target structure is computed iteratively using Integer Linear Programming (ILP). To ensure feasibility of the design problem, the inventory is augmented with newly fabricated beams that can be introduced on demand. At each ILP iteration, both reclaimed stock elements and newly fabricated beams are assigned to the gridshell members according to structural utilization requirements. Throughout the optimization, the mesh topology remains

Table 2

Historic material property assignments for modelling purposes.

Member Group	Yield Strength per Historic Drawings	Equivalent Specification per DG15	Ultimate Strength per DG15	Expected Value Ratio per FEMA 356	Notes
	F_y		**F_u**	**Yield/Ultimate**	
A36 steel members	36 ksi (248.21 MPa)	A36-62T	58 ksi (399.90 MPa)	1.1/1.1	True spec
Ø ¾″–6″ bars	50 ksi (344.74 MPa)	A242-63T or A441-63T	70 ksi (482.63 MPa)	1.1/1.1	Thicknesses do not match with historic specs
Ø 6¼″–7″ bars	46 ksi (317.16 MPa)	A242-63T or A441-63T	67 ksi (461.95 MPa)	1.1/1.1	Thicknesses do not match with historic specs
Ø 6$^{3}/_{8}$″–6¾″ bars	95 ksi (655.00 MPa)	A514	110 ksi (758.42 MPa) (interpolated between 105 ksi minimum for F_y=90 and 110 ksi for F_y=100)	1.1/1.1	Thicknesses do not match with historic specs
Ø 7$^{1}/_{8}$″ bar	90 ksi (620.53 MPa)	A514	105 ksi (461.95 MPa) (minimum of range)	1.1/1.1	Thicknesses do not match with historic specs

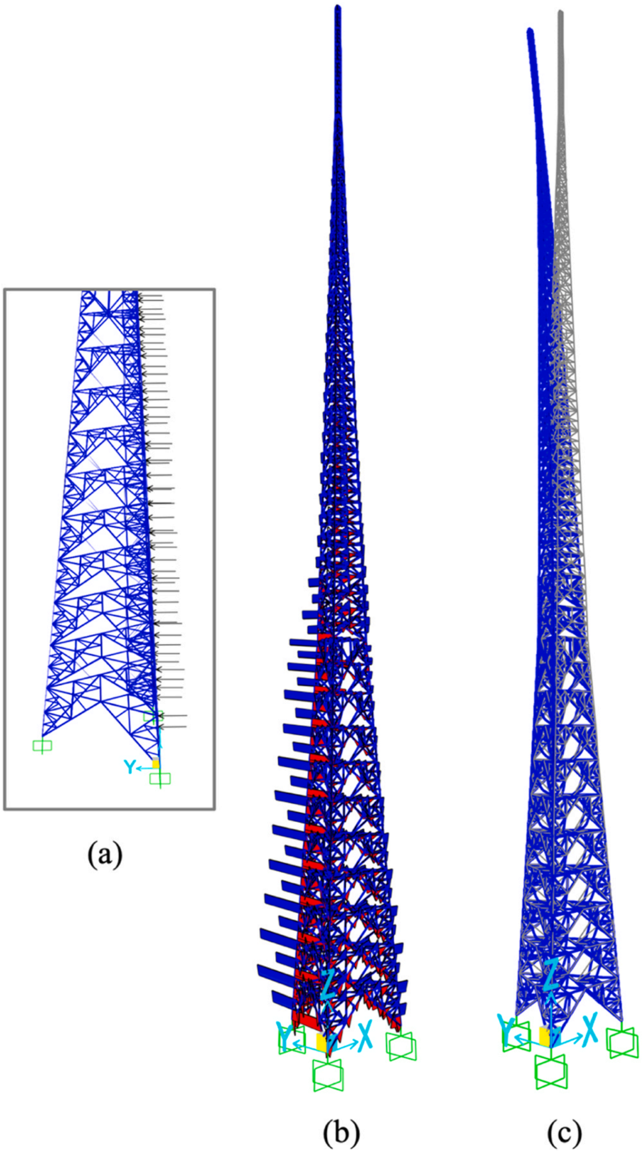


Fig. 4. FEM model of the Turner Broadcasting Tower: (a) zoom of the wind load distribution, (b) shear diagram, (c) deformed shape.

fixed; therefore, neither the element lengths nor the node orientations are modified. As a result, reused beams must be cut to the required lengths, generating waste in the form of residual beam segments.

4.1.2. *Initialization and matching problem*

The optimization framework employs a simplified linear static analysis of the gridshell based on a two-node Euler–Bernoulli beam model with linearly interpolated endpoint forces. This formulation enables rapid computations while maintaining sufficient accuracy for gridshells subjected to nodal loading only.

As an initial step, a uniform tentative cross section is assigned to the entire structure; all beams are modeled as identical solid tubular members fabricated from new steel. Subsequently, the cross sections are updated through a gradient-based sizing optimization in which the radius of each beam, which is treated as a single geometric design variable per element, is adjusted to minimize beam strength underutilization:

$$U = \sum_{i=1}^{n} f_{yd,i} - \sigma_{vm,i} \tag{2}$$

Where $f_{yd,i} = f_{yk,i}/\gamma$ is the design strength and $\sigma_{vm,i}$ the von Mises stress for each i -th beam. Cross section radii are given within a fixed domain. The result is a properly sized, efficient, all-new gridshell.

For the target structure, the combinatorial inventory assignment problem is solved to determine the optimal allocation of either reclaimed or newly fabricated elements. This problem can be formulated as a labeling task and is addressed through functional minimization using an Integer Linear Programming (ILP) approach. In this formulation, the data points correspond to the gridshell beams, while the labels represent the available beam lengths in the inventory. Let the input mesh contain n edges and let the inventory be composed of m bins of beam elements with lengths $\{l_1, \ldots, l_m\}$, each available in finite quantities $\{c_1, \ldots, c_m\}$. The objective is to determine the values of the binary decision variables $b_{i,j}$ defining the assignment matrix, such that the objective function is minimized:

$$B_{i,j} = \left[b_{i,j}, b_{i,m+1}\right] \tag{3}$$

where $b_{i,j} = 1$ if edge e_i is assigned to inventory length l_j, and $b_{i,j} = 0$ otherwise. The optimization is subject to the following practical constraints:

- each edge e_i must have a length less than or equal to that of the stock element to which it is assigned;
- the number of beams assigned to a given stock bin j must not exceed its available quantity c_j;
- for each beam, the structural safety constraint $\left(f_{yd} - \sigma_{vm}\right) \geq 0$ must be satisfied.

If a beam cannot be matched to any available inventory element, it is assigned to newly fabricated material, which is modeled as an additional bin with infinite availability c_{m+1} and prescribed length l_{m+1}.

4.1.3. *Inventory-constrained statics-driven matching*

The objective function considers both structural performance S and embodied carbon C:

$$\min \sum_{i=1}^{n} \left[\left(\lambda S_{i,j} + C_{i,j}\right) : B_{i,j}\right] \tag{4}$$

where:

$$S_{i,j} = A_j l_j f_{yd,j} - A_i e_i \sigma_{vm,i} \tag{5}$$

is an indicator of structural efficiency, i.e. difference between the maximum theoretical stress an inventory beam can withstand and its current stress (assuming for simplicity the beam stressed at its maximum $\sigma_{vm,i}$ over its entire volume $A_i e_i$). If S is minimized, the beam utilization is maximum. The coefficient $\lambda > 1$ makes S the dominant term in the objective function.

The other term C relates to the LCA and is computed using the approach in Brütting *et al.* [34], Warmuth *et al.* [35]. Accordingly, the environmental impact expressed in terms of greenhouse gas emissions (GHG) measured in units of equivalent carbon $kgCO_{2eq}$ is:

$$C_{i,j} = \sum_{i=1}^{n} \left(0.3546 \cdot M_j + 0.11 \cdot M_i + 0.8973 \cdot M_{new}\right) \tag{6}$$

In this formulation, the numeric coefficients ($kgCO_{2eq}/kg$) account for a theoretical supply chain encompassing deconstruction, transport, assembly, demolition and production, assuming hypothetical distances between fabrication facilities and the construction site. The distances considered are 100 km from the demolition site to the production plant. The fabrication workshop is located 20 km from both the construction site and the recycling plant. The terms M denote steel masses, in particular $M_j = M_i + M_w$ refers to the inventory elements employed, comprising the mass of reused elements M_i and the mass of cut-off waste M_w. The term M_i represents the reused portion of the inventory elements, while M_{new} denotes the mass of newly fabricated elements. The optimization problem additionally enforces a reuse percentage ratio on the term C:

$$f(C) \geq \frac{r}{n} = t \tag{7}$$

Where r is the number of reused elements, and $t \in [0, 1]$.

The ILP problem is solved using Gurobi [36]. The gradient-based sizing optimization implements the loss function defined in Eq.2 using automatic differentiation and gradient descent in PyTorch (Paszke et al. [37]), with the Adam optimizer (Kingma and Ba [38]). Initially, all beams are modeled as solid steel tubes of grade A36 with a uniform diameter of 50 mm.

At each iteration, the gradient-based sizing optimization updates the beam radii prior to solving the ILP assignment problem. In Eq.4, the weighting coefficient $\lambda = 100$ is selected empirically.

During the assignment process, the cross sections of newly fabricated elements are dynamically updated at each step to accommodate changes in local stiffness and strength demands induced by the inclusion of reused elements, which may not locally satisfy the structural requirements in an optimal manner.

4.2. *Application to the gridshell case*

A quasi-membrane gridshell is used to evaluate the proposed framework. The structure is defined over a freeform boundary and fits within a bounding box of $30.74 \times 28.57 \times 7.69$ m. Its geometry is discretized using an isotropic triangular tessellation consisting of $|V| = 675$ vertices, $|E| = 1941$ edges, and $|F| = 1267$ faces, with an average member length of $\bar{l} = 1.29$ m (Fig. 5). The design boundaries of the gridshell suggest its use either as rooftop or for a small pavilion applications.

The beam inventory comprises reclaimed structural elements from the Turner Broadcasting Tower having heterogeneous lengths and cross-section dimensions. Stock elements with unknown or incomplete cross-sectional information are excluded from the inventory. Although composite members assembled from two or four L-profiles are physically feasible, the assignment process is restricted to single-profile elements. Allowing composite sections would require a more elaborate matching strategy, as individual L-profiles could otherwise be ambiguously interpreted either as standalone beams or as components of composite members.

All beams are modeled as A36 structural steel with linear elastic isotropic properties, Young's modulus $E = 2.1e + 5\,MPa$, Poisson's ratio $\nu = 0.3$. An Ultimate Limit State (ULS) uniform surface load of $5.0\,kN/m^2$ is applied in the gravity direction, distributed to the nodes using tributary areas derived from the Voronoi diagram of the triangular mesh. Additionally, the self-weight of the beams is included as a lumped nodal load, based on a material density. This latter loading condition is updated at each optimization step, accounting for different beam assignments. All ground-level nodes are fixed.

The results presented in Fig. 6 underscore the inherently multivariable characteristics of design optimality, wherein distinct optimization targets are defined across a range of reuse ratios, $t = 0.2$ to $t = 1.0$. High structural utilization is observed for lower values of S, representing configurations that integrate both reclaimed and newly manufactured beams. Conversely, designs with higher reuse ratios exhibit diminished structural efficiency accompanied by increased greenhouse gas emissions. Although the demand for newly fabricated material is reduced, the volume of off-cut waste correspondingly increases.

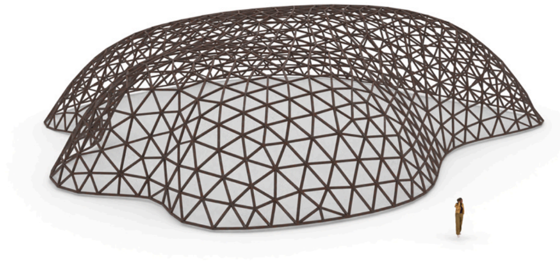


Fig. 5. Gridshell adopted for the case study.

As expected, the optimization procedure strictly satisfies the prescribed reuse target parameter t. Consequently, the values of C, which are directly bound to the constraint, remain relatively constant throughout the optimization process. Fig. 7 illustrates the optimization results for varying target reuse ratios, with the performance metric evolution shown on the left and the final assignment on the right. The optimization progress reveals that this constraint-driven behavior can only offer a reduction in structural cost. Overall, the initial member-sizing-based assignment provide an effective heuristic for reuse-oriented optimization, and the algorithm demonstrates rapid convergence, particularly at low reuse ratios, even though the efficiency of the solution is somewhat limited under these conditions.

As illustrated in Fig. 7a–b, the matching problem is comparatively simple and converges in less than 40 iterations. This behavior is due to the high likelihood of identifying reusable elements that closely match the initially sized beam profiles. Such availability stems from the inventory characteristics, which exceed the target number of reused elements (2067 inventory elements vs $0.2 \times 1941 = 388$ and $0.4 \times 1941 = 776$ target elements, respectively), and from the broad distribution of cross-sectional types and member lengths.

In these cases, the structural performance metric S remains approximately constant (see left plots), as the substitution of elements through reuse induces only minor perturbations to the structural response of the gridshell. Conversely, Fig. 7c–e show that increasing the target reuse ratio leads to greater variation in S. This moves the initial assignment farther from the optimum, thereby requiring more optimization steps to reduce the performance metric. However, as iterations progress, the solution gradually approaches a plateau. Across all scenarios, the cost metric C remains nearly constant, reflecting the influence of the weighting factor λ, which prioritizes the minimization of S.

5. Local optimization of the steel joints

Data on best assignment from inventory generated at global optimization is extracted for nodes using their indices, with the help of visual presentation of geometry for maneuvering. Each node is uniquely defined with corresponding incident profiles (cross-sections) and resulting forces at nodes from the previous stage, both related to the reusability factor (Figs. 8–11. Topology optimization is then conducted

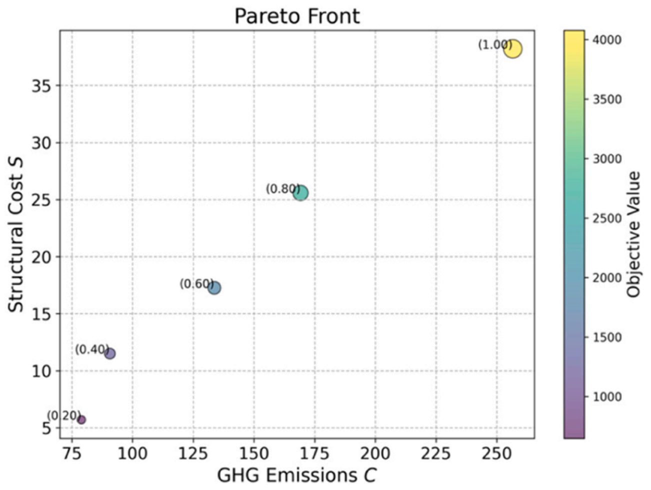


Fig. 6. Pareto front reporting each target reuse ratio.

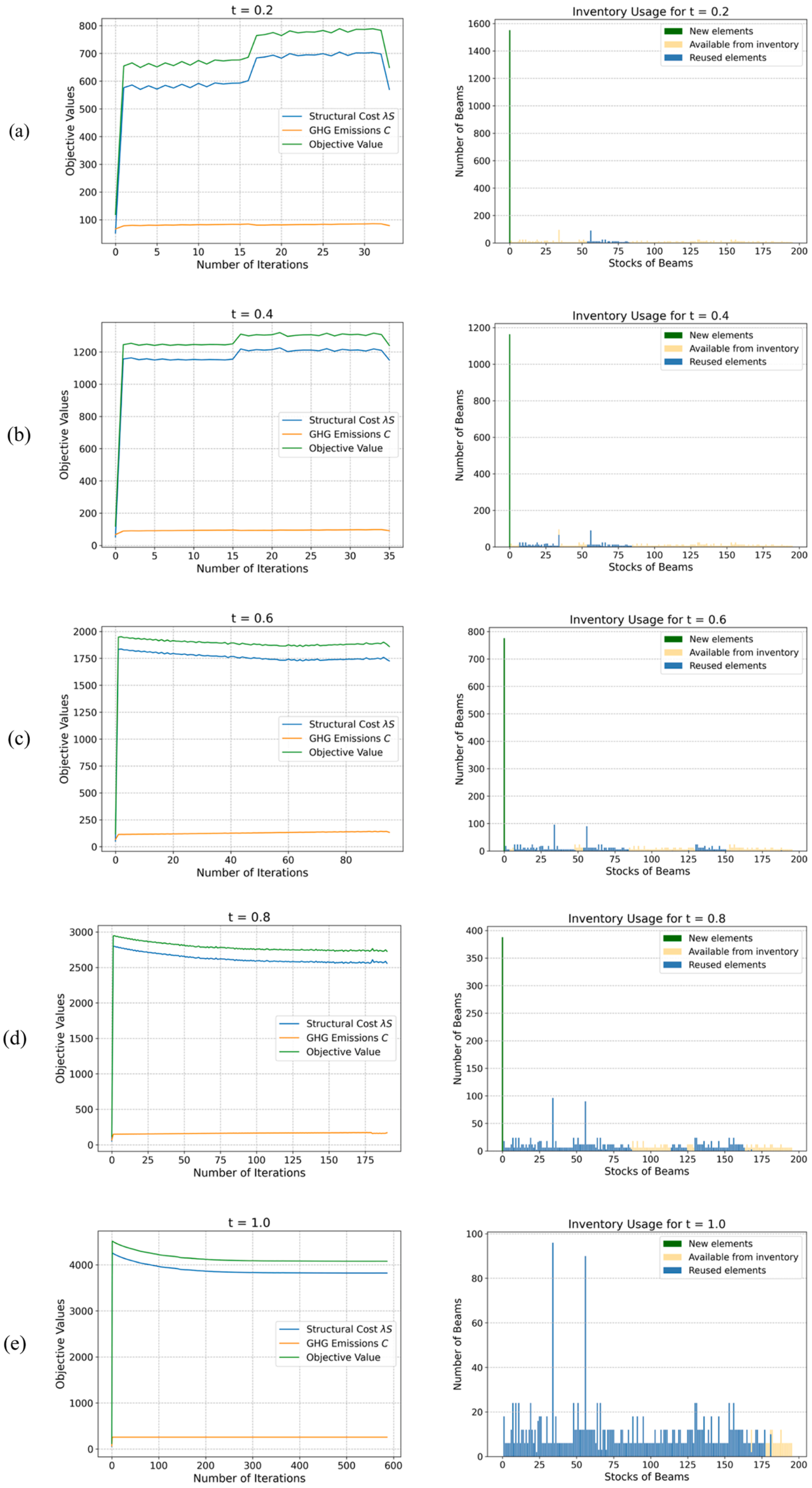
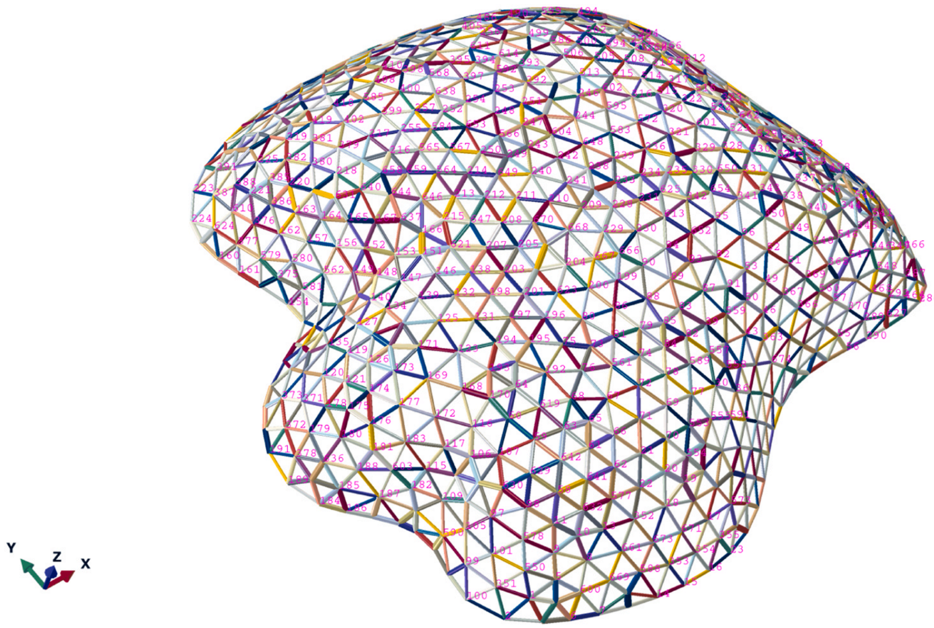


Fig. 7. Optimization history (left column) and inventory usage for diverse reusage scenarios t (right column): (a) t = 0.2; (b) t = 0.4; (c) t = 0.6; (d) t = 0.8; (e) t = 1.0.

for nodes based on their unique configuration, including above-mentioned forces, assigned cross-sections, and inclinations, i.e. incident angles. To showcase the streamlined global-local optimization, here one node is selected with index 450, as enumerated in the previous step.

First, the data is extracted for that particular node and all the intersecting elements through index (number) and normal (geometry/position) recognition. Cross-sections are assigned to the elements in its three-dimensional form to materialize the solid intersection between each other, precisely at the node.



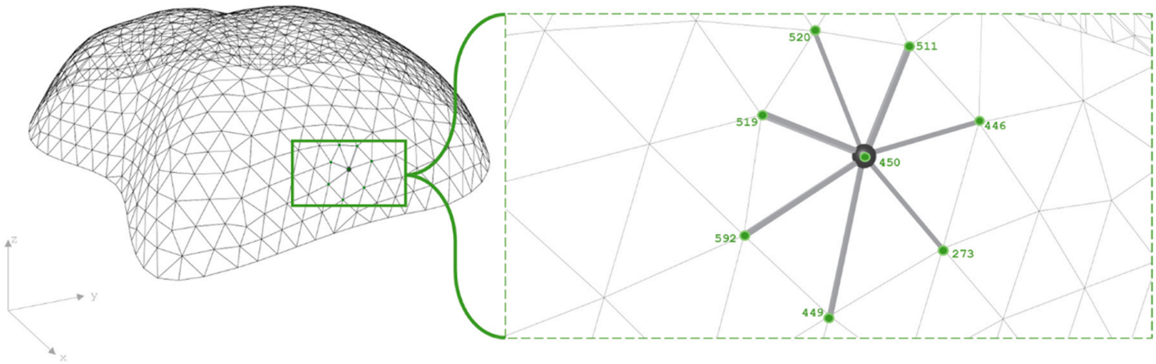


Fig. 8. Node position and indices of incident elements for data extraction.

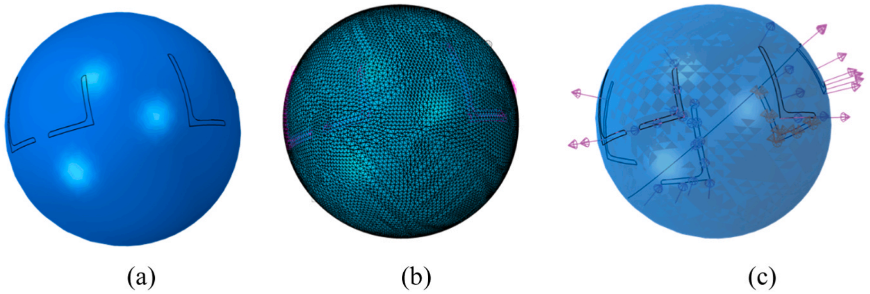

(a) (b) (c)

Fig. 9. Design domain (a) as a sphere with contours of cross-sections for boundary conditions application, (b) tetrahedral mesh and (c) pressure applied to contours (total force) in TOSCA optimization tool [39].

A sphere is created at the place of intersection as future “design domain” for topology optimization, of volume significant to replace the otherwise complex steel connection.

Solid intersection in CAD (here done in Rhino 3D) results in a full-volume closed sphere with the contoured incident cross-sections on its surface for boundary conditions and non-design domain definition to be used at the topology optimization stage, that is performed in TOSCA plug-in of Abaqus FEM software.

The mesh in TOSCA [39] is generated using global seeds of 15-mm size for general element and more refined edge seeds of 4 mm at the contours of the elements cross-sections intersecting at the node. A quadratic tetrahedral mesh (element type C3D10) has been defined according to previous sensitivity analysis to optimize computational effort and time. The total number of mesh elements resulted in 211679.

Pressure is applied in form of a total force (in kN) from Table 3 at node 450, where at least one contour surface is used as a fixed support to maintain static equilibrium for optimization. Optimization is done in a way to minimize the sum of strain energy of the input sphere with non-

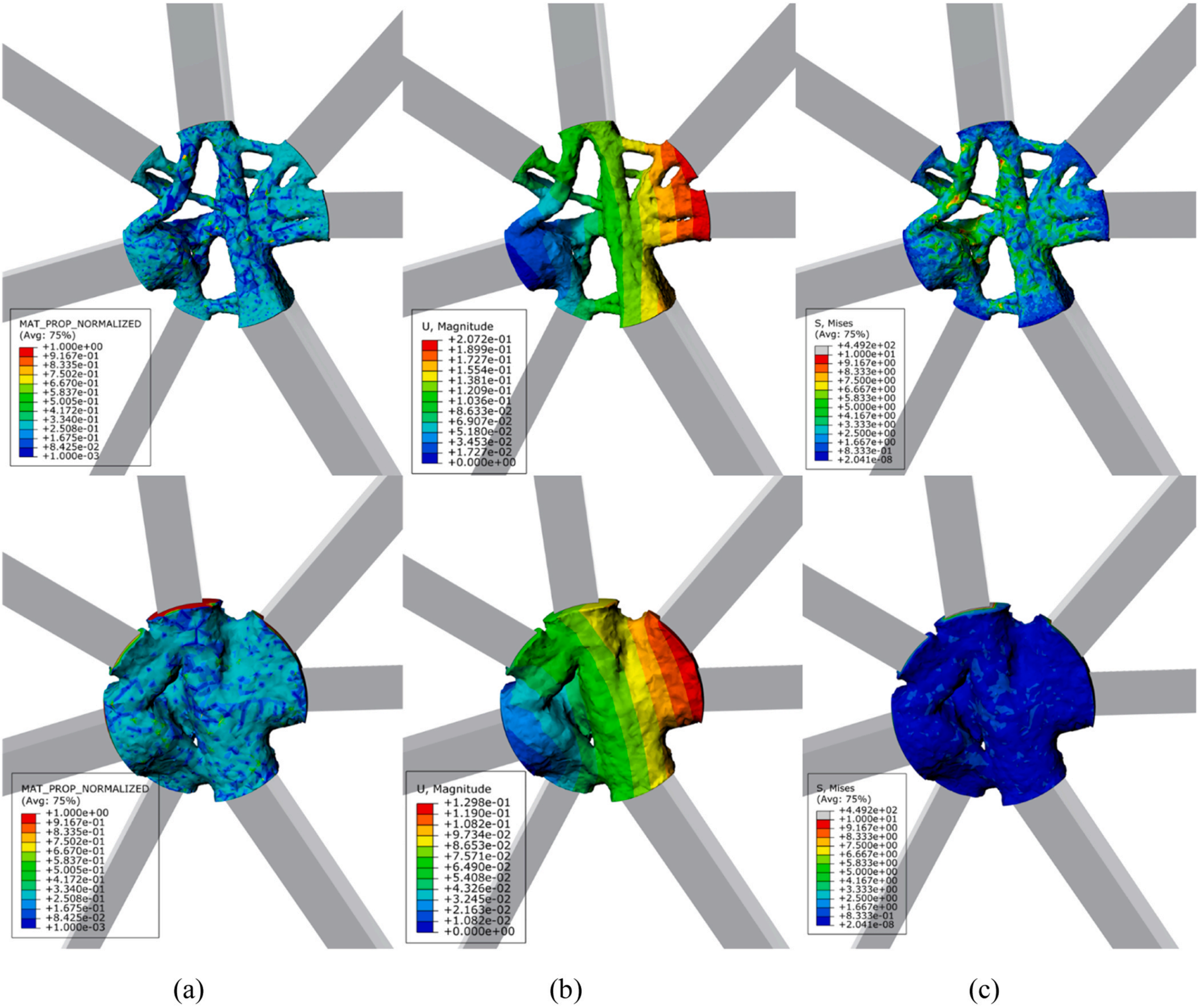


Fig. 10. Example of two nodes with volume constraint at 10% and 30%: (a) material property density distribution (0−1), (b) displacement in [mm] with zero being at one end that is fixed for optimization equilibrium, and (c) Von Mises stress in [MPa].

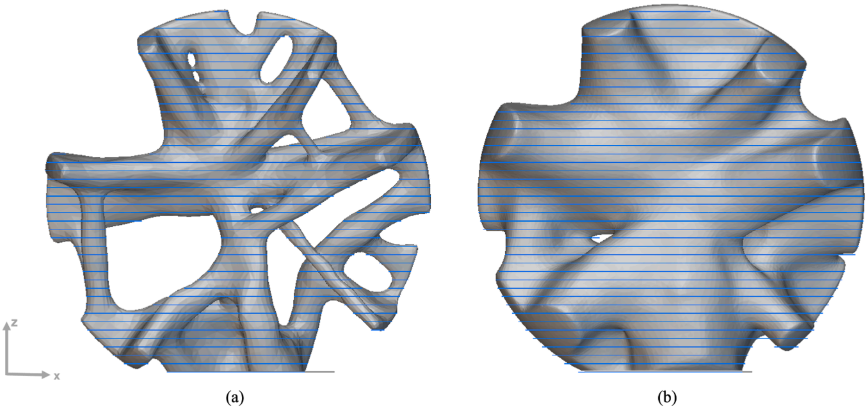


Fig. 11. Slicing for WAAM on the optimized nodes: (a) 10% volume-constrained, (b) 30% volume-constrained.

design domain being contours of cross-sections. Volume is used as the optimization constraint, set to 30%, 20% and finally 10%, when and if the convergence allows.

The material properties were set according to WAAM-produced carbon steel thin elements (see e.g. [40]). The material constitutive model is simplified into a linear elastic one, for a stiffness-constrained

Table 3
Data extraction from global optimization for local optimization - example on node 450.

Element (start node - end node)	450–520	450–511	446–450	273–450	449–450	450–519	450–592
Cross-section [in]	L3 x 2 x.1875	L3 x 2 x.1875	L2 x 2 x.1875	L3 x 2 x.1875	L2 x 1.5 x.1875	L3 x 2.5 x.3125	L2 x 2 x.1875
Length [in]	203	229	150	225	120	257	152
Axial force at start node [kN]	+21.60	+9.57	-15.69	+23.16	+16.04	-4.52	-3.80
Axial force at end node [kN]	-21.60	-9.57	+15.69	-23.16	-16.04	+4.52	+3.80

analysis.

In line with the so-called “blended” optimization approach (see e.g. [29,30]), the optimal designs are finally checked for the manufacturing constraints proper of WAAM technology. Among others, the most critical aspect is for the overhang, setting a maximum value of 45° with respect to the vertical axis. For this, both 10% and 30% volume-constrained nodes have been analyzed and simulated in their manufacturing processes in nTop simulator [41].

The contour that was selected for fixing support to ensure static equilibrium will have more material localized compared to other incident non-design domains, imposing then the best built orientation for self-supported manufacturing, as shown in Figs. 12 and 13. Given the difficulties that could arise when printing the 10% volume-constrained node, the final design of the gridshell was done considering a 30% volume-constraint for all optimized nodes (Fig. 14).

6. Conclusion

This study presented an integrated design-to-fabrication framework aimed at enhancing the adoption of steel reuse in construction. The proposed methodology combines pre-deconstruction structural assessment, inventory-based global optimization and local joint optimization enabled by large-scale steel 3D printing. By explicitly embedding reclaimed steel members into the early stages of structural design, the framework addresses key barriers that currently limit the large-scale adoption of reuse-oriented steel construction, such as: (i) uncertainty in material performance, (ii) geometric incompatibility, and (iii) lack of suitable structural joints for different cross-sections.

At the global scale, an inventory-constrained optimization strategy was developed to assign reclaimed and new steel members to a target gridshell structure while simultaneously accounting for structural efficiency and embodied carbon emissions. The case study based on the dismantled Turner Broadcasting Tower demonstrated that high levels of steel reuse can be achieved while maintaining structural feasibility. The results highlight that reuse-oriented optimality is inherently multi-objective and constraint-driven, and that intermediate reuse targets often provide the most balanced solutions in terms of structural efficiency and environmental impact. The use of historic structural analysis to populate the reclaimed stock catalogue proved particularly effective in filtering unsuitable members early in the process and in increasing confidence in the residual performance of reused elements.

At the local scale, the study showed that topology optimization combined with Wire-Arc Additive Manufacturing (WAAM) enables the realization of customized steel joints capable of accommodating heterogeneous cross-sections and force paths arising from reuse-driven design. The optimized joints achieved substantial material savings compared to conventional connection solutions and were shown to be compatible with WAAM technology constraints through process-aware validation.

Overall, the proposed framework provides a coherent and extensible approach for designing hybrid steel structures that integrate reclaimed components, advanced optimization techniques, and digital fabrication.

CRediT authorship contribution statement

Luigi Malomo: Software. **Elisabetta Savino:** Writing – original draft, Investigation. **Giada Gasparini:** Writing – review & editing, Supervision. **Vittoria Laghi:** Writing – original draft, Visualization, Validation, Conceptualization. **Neira Babovic:** Visualization, Validation, Software. **Francesco Laccone:** Visualization, Validation, Software.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Given the role as Guest Editor in the Special Issue "Low-Carbon Footprint

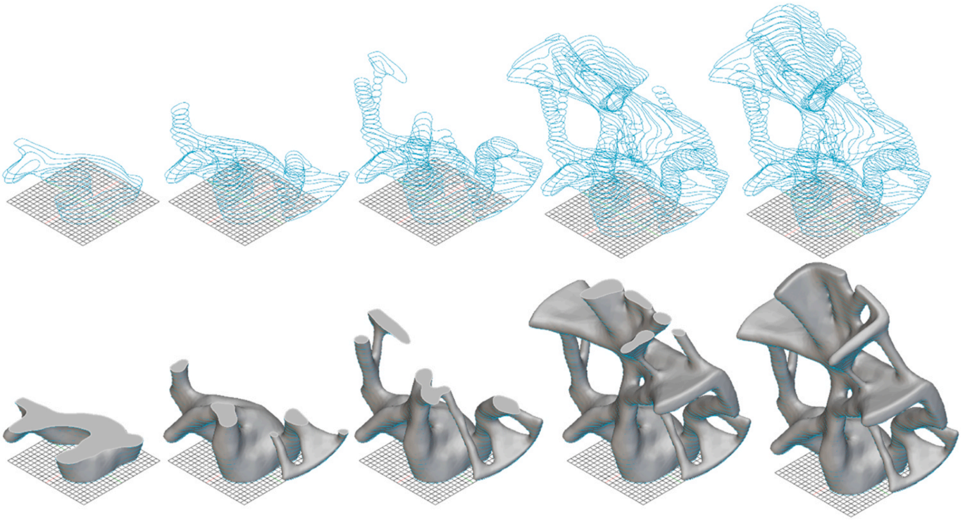


Fig. 12. Manufacturing process with proposed built orientation for 10% volume-constrained node.

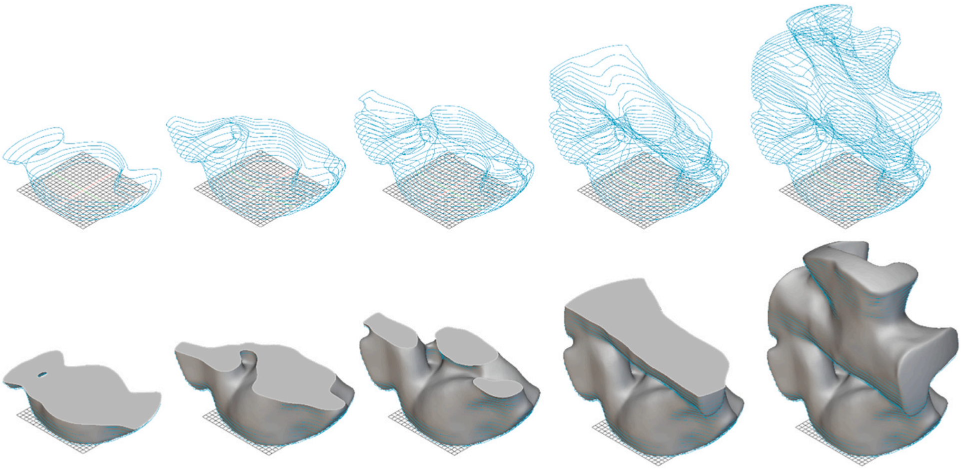


Fig. 13. Manufacturing process with proposed built orientation for 30% volume-constrained node.

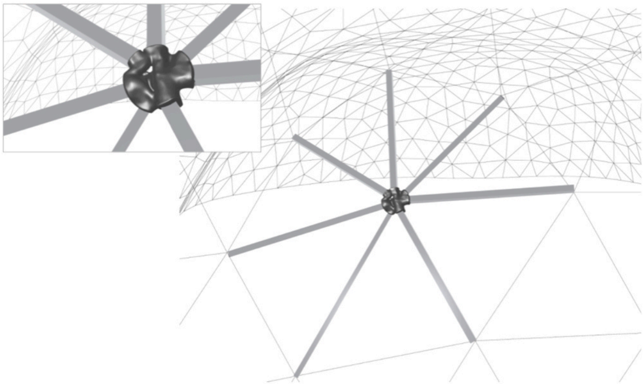


Fig. 14. Optimized node within the hybrid gridshell: final design.

Structures", Dr. Laghi will have no involvement in the peer review of this article and will have no access to information regarding its peer review. Full responsibility for the editorial process for this article will be delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] International Energy Agency, Iron and Steel Technology Roadmap, 2020.(accessed September 26, 2023)⟨https://www.iea.org/reports/iron-and-steel-technology-roadmap⟩.

[2] OECD, Environment at a Glance 2020, OECD, 2020. https://doi.org/10.1787/4ea7d35f-en.

[3] Densley Tingley D, Cooper S, Cullen J. Understanding and overcoming the barriers to structural steel reuse, a UK perspective. J Clean Prod 2017;148:642–52. https://doi.org/10.1016/j.jclepro.2017.02.006.

[4] Fujita M, Fujita T, Iwata M, Iwata Y, Kanemitsu T, Kimura U, et al. Japanese efforts to promote steel reuse in building construction. J Struct Eng 2023;149. https://doi.org/10.1061/(asce)st.1943-541x.0003473.

[5] B. Falconer, I. Kim, Moynihan Train Hall, Structure Magazine (2022).

[6] Gorgolewski M. Build Res & Inf Des reused Build Compon some Chall Des reused Build Compon some Chall 2008. https://doi.org/10.1080/09613210701559499.

[7] Bartsch H. Reuse of reclaimed steel components in construction: a systematic review of potential, challenges and future directions. Structures 2025;80:110057. https://doi.org/10.1016/J.ISTRUC.2025.110057.

[8] H. Bartsch, F. Eyben, M. Feldmann, On the Development of European Design Rules for Re-Used Steel Components, (2024).

[9] H. Bartsch, J. Knobloch, M. Feldmann, M. Stroetmann, R. Charlier, M. Husson, , Guidance on establishing European rules for the design of reclaimed steel components for reuse, in: n.d. https://doi.org/10.2760/9138843.

[10] Mei L, Wang Q. Struct Optim Civ Eng A Lit Rev 2021;11:66. https://doi.org/10.3390/buildings11020066.

[11] Li S, Yuan S, Zhu J, Wang C, Li J, Zhang W. Additive manufacturing-driven design optimization: Building direction and structural topology. Addit Manuf 2020;36:101406. https://doi.org/10.1016/j.addma.2020.101406.

[12] Favilli A, Laccone F, Cignoni P, Malomo L, Giorgi D. Optimizing Free-Form Grid Shells with Reclaimed Elements under Inventory Constraints. Comput Graph Forum 2025;44. https://doi.org/10.1111/CGF.70047.

[13] Tomei V, Grande E, Imbimbo M. A combined topology-sizing optimization approach for the sustainable design of steel gridshells with reclaimed bars. Structures 2025;77:109114. https://doi.org/10.1016/J.ISTRUC.2025.109114.

[14] Van Marcke A, Laghi V, Carstensen JV. Automated planar truss design with reclaimed partially disassembled steel truss components. J Build Eng 2024;84. https://doi.org/10.1016/j.jobe.2024.108458.

[15] Meng X, Gardner L. Hybrid construction featuring wire arc additive manufacturing: review, concepts, challenges and opportunities. Eng Struct 2025;326. https://doi.org/10.1016/j.engstruct.2024.119337.

[16] Ascione F, Esposito F, Faiella D, Mele E. Steel reuse for sustainable design of large-span structures: the case of gridshells. J Constr Steel Res 2025;234:109743. https://doi.org/10.1016/J.JCSR.2025.109743.

[17] Esposito F, Ascione F, Faiella D, Mele E. Stock-constrained optimization of diagrid exoskeletons using reclaimed steel for seismic retrofit of RC buildings. Structures 2026;86:111304. https://doi.org/10.1016/J.ISTRUC.2026.111304.

[18] Tomei V, Grande E, Imbimbo M. A novel optimization approach for the design of environmentally efficient gridshells with reclaimed steel members. Adv Eng Softw 2025;200:103825. https://doi.org/10.1016/J.ADVENGSOFT.2024.103825.

[19] Kokare S, Oliveira JP, Godina R. A LCA and LCC analysis of pure subtractive manufacturing, wire arc additive manufacturing, and selective laser melting approaches. J Manuf Process 2023;101:67–85. https://doi.org/10.1016/J.JMAPRO.2023.05.102.

[20] Laghi V, Gasparini G. Explorations of efficient design solutions for wire-and-arc additive manufacturing in construction. Structures 2023;56:104883. https://doi.org/10.1016/J.ISTRUC.2023.104883.

[21] Laghi V, Savino E, Gasparini G. Reduction of the environmental impact of complex-shaped steel joints through topology optimization and large-scale metal 3D printing. Results Eng 2025;27:105610. https://doi.org/10.1016/J.RINENG.2025.105610.

[22] Buchanan C, Gardner L. Metal 3D printing in construction: a review of methods, research, applications, opportunities and challenges. Eng Struct 2019;180:332–48. https://doi.org/10.1016/j.engstruct.2018.11.045.

[23] Treutler K, Wesling V. The current state of research of wire arc additive manufacturing (WAAM): a review. Appl Sci 2021;11:8619.

[24] MARILIGHT project, (n.d.). ⟨https://marilight.net⟩ (accessed December 19, 2024).

[25] MX3D Webpage, (n.d.). ⟨www.mx3d.com⟩.

[26] Gardner L. Metal additive manufacturing in structural engineering – review, advances, opportunities and outlook. Structures 2023;47:2178–93. https://doi.org/10.1016/J.ISTRUC.2022.12.039.

[27] Meng X, Gardner L. Standardisation framework for metal additive manufacturing in construction. Autom Constr 2025;176. https://doi.org/10.1016/j.autcon.2025.106267.

[28] Meng X, Weber B, Gardner L. Influence of process parameters and common printing problems on tensile behaviour of DED-Arc. J Constr Steel Res 2026;237. https://doi.org/10.1016/j.jcsr.2025.110053.

[29] Laghi V, Palermo M, Bruggi M, Gasparini G, Trombetti T. Blended structural optimization for wire-and-arc additively manufactured beams. Prog Addit Manuf 2022. https://doi.org/10.1007/s40964-022-00335-1.

[30] Laghi V, Babovic N, Benvenuti E, Kloft H. Blended structural optimization of steel joints for wire-and-arc additive manufacturing. Eng Struct 2024;300:117141. https://doi.org/10.1016/J.ENGSTRUCT.2023.117141.

[31] P. Hradil, L. Fülöp, E. Paukku, T. Vainio-Kaila, V. Dehan, F. Grogna, de Paula Filho ArcelorMittal Belval, 2 (100) Deliverable: D2.1 Report on the Circular Economy of Steel-Based Components Confidentiality: Public, (n.d.).

[32] P. Hradil, A. Talja, V. Ungureanu, H. Koukkari, L. Fülöp, Reusability indicator for steel-framed buildings and application for an industrial hall, (2017).

[33] M. Kuhnhenne, D. Pyschny, P. Hradil, M. Sansom, J. Kesti, D. Dubina, , 2 (84) Deliverable: D 1.2 Report on the reuse potential of single-storey steel buildings Confidentiality: Public, (n.d.).

[34] Brütting J, Vandervaeren C, Senatore G, De Temmerman N, Fivet C. Environmental impact minimization of reticular structures made of reused and new elements through life cycle assessment and mixed-integer linear programming. Energy Build 2020;215:109827. https://doi.org/10.1016/J.ENBUILD.2020.109827.

[35] J. Warmuth, J. Brütting, C. Fivet, Computational tool for stock-constrained design of structures, (n.d.).

[36] L.L.CGurobi Optimization Gurobi Optim Ref Man2019.

[37] Paszke A, Gross S, Chintala S, Chanan G, Yang E, Facebook ZD, et al. Autom Differ PyTorch 2017.

[38] D.P. Kingma, J.L. Ba, Adam: A Method for Stochastic Optimization, 3rd International Conference on Learning Representations, ICLR 2015 - Conference Track Proceedings (2014). ⟨https://arxiv.org/abs/1412.6980v9⟩ (accessed December 18, 2025).

[39] Dassault Systèmes, SIMULIA Tosca Structure, (2024).

[40] Huang C, Kyvelou P, Gardner L. Stress-strain curves for wire arc additively manufactured steels. Eng Struct 2023;279:115628. https://doi.org/10.1016/J.ENGSTRUCT.2023.115628.

[41] nTop, (n.d.). ⟨https://www.ntop.com⟩ (accessed December 18, 2025).