Circular Metals Case Study:

Challenges and opportunities in the steel frame construction industry: increasing circularity through reuse.

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Introduction

Structures built with steel frames primarily use steel beams and columns for their core structure, with other materials like concrete, glass, or plastic forming the walls and roofs. The frame bears the building's weight and provides the essential structural support. Steel and concrete buildings have long become mainstream in the built environment due to their technical characteristics, such as, relative strength and low cost, adaptability and allowing for short constructions times. Concrete and steel structures made up around 75% of embodied carbon of residential buildings in 2018. From this figure around 60% may come from cementitious materials (with a range of variation among building types) and 11-15% from steel structures (Drewniok *et al.*, 2023). Therefore, more emphasis is being drawn into ways to lower embodied carbon (UNDP, 2024).

In the realm of the steel frame construction industry, the concept of the circular economy is gaining momentum. Traditionally, recycling has played a pivotal role in lessening the environmental footprint of steel production and currently steel is among the materials with highest recycling rates globally (UK Steel, 2022). Even more interesting is the more recent focus on reuse of steel structures. The reuse of steel structures and elements enables a tighter loop of materials circularity, reducing environmental impacts of construction and steel recycling.

Steel structures and construction products can be designed in a way that facilitates being disassembled and reused. When the possibility of future deconstruction is considered during the design phase, there's no technical barrier to viewing steel buildings as a substantial 'reservoir of components' that can be reused in the future (BCSA, 2020). This is particularly relevant in the UK, where the use of steel frames is comparatively higher than in other countries that tend to favour using more reinforced concrete, where steel is in rebars embedded in the concrete, making them difficult to recover for reuse (Allwood and Cullen, 2012).

These reusable steel sections can be recovered from existing structures during demolition.[1] Figure 1 presents the typical steps of recovering and reusing steel from structures in existing buildings.

[1] Reusable steel can also originate from structures that were not built (cancelled projects that had already purchased materials or that have part of the structures already on the ground). As the steel from this type of projects is usually reused, many of the barriers presented in this document do not apply in this case.

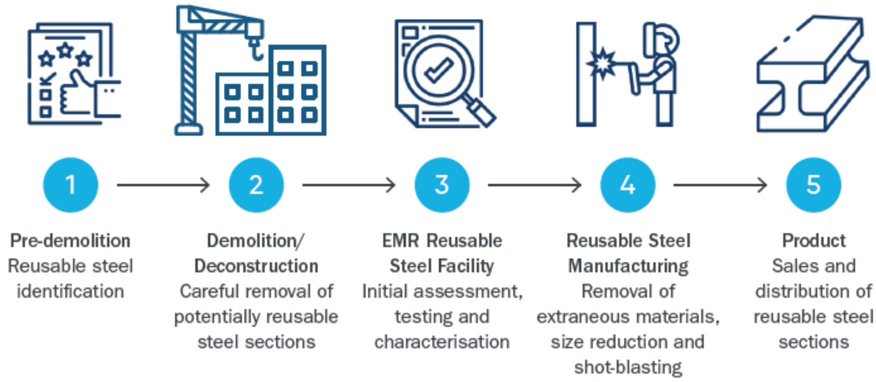

Figure 1: Typical reused steel workflow (EMR, 2022)

The UK already boasts high recovery and recycling rate for steel used in buildings. A survey conducted in 2012 showed that close to 91% of steel from demolished buildings was recycled and close to 5% was reused (Samson and Avery, 2014) and a more recent document from the Steel for Life claims that 99% of structural steel is being recycled (Steel for Life, 2021). However, reuse rates of structural steel are still relatively niche, with close to 10% of structural steel and 5% of the total steel in building being reused (Samson and Avery, 2014).

This relatively low current rate of steel reuse points to opportunities but also barriers for the reuse of steel frames in the building sector. The first Environmental Product Declaration (EPD) on reused steel from European Metal Recycling (EMR, 2022) reports emissions of around 47 $kgCO_2e/t$ for the LCA stages A1-A3, which cover raw material supply, transport from the material extraction site and the manufacturing facility, and manufacturing (Kanyilmaz *et al.*, 2023), which contrasts drastically with the approximately 300 $kgCO_2e/t$ generated when producing secondary steel from scrap in electric arc furnaces in the UK (EAF route), and even more with the close to 2000 $kgCO_2e/t$ emitted in the production of primary steel in the UK through blast furnaces (BF-BOF route) (UK Steel, 2022).

Barriers and challenges

Economic barriers

There is no clear business case for reusing steel frames in the building sector. According to Elliot Wood, a structural engineering consultancy company with experience in steel reuse, the current price of new steel long products in the UK is around £1300/t (*CE Week*, 2022). If the steel recovered from demolished buildings is sold as scrap, it typically yields around £300/t, allowing for a positive business case only if the cost of processing steel for its reuse is below £1000/t (assuming that reused steel could be sold at the same price as new steel) (Gowler, 2022). Alternative data presented by Dunant *et al.*, (2018) shows that the difference between new steel pieces for construction and scrap is very volatile, highly dependent on international energy prices and manufacturing costs. Scrap steel prices showed a variation between £200/t and £700/t for the UK in the period from 2000 to 2016. This volatility presents a challenge in establishing a stable long-term market, as if the cost of processing steel for reuse is higher than this difference, it is more profitable to sell the steel as scrap rather than process it for reuse. Therefore, depending on the processing costs associated with reused steel, there could be periods when reuse is not economically attractive, rendering any measures to facilitate market operations ineffective.

Although some cases may present interesting cost savings from reusing steel frames, the cost of reused steel varies depending on several factors, such as condition of the steel, the complexity of its extraction from existing structures, and the necessary treatments to make it reusable steel (Kanyilmaz *et al.*, 2023). Therefore, the economic savings from steel reuse are not universally fixed and depend on the specific circumstances of each project. A study that addressed costs of reused steel in the UK put in evidence that under the market conditions from 5 years ago, reused steel had an average cost 10% higher than newbuilt steel, except in certain circumstances such as when the reused elements were available from a nearby site or when testing elements could be avoided (Dunant *et al.*, 2018).

As the market is currently relatively small, there are usually mismatches between demand and supply of reusable steel. This means that the steel to be reused needs to be disassembled and stored until it may be required by a client, which translates in upfront costs without a secured return on this investment. Conversely, a building developer may not be interested in waiting until a specific set of reusable steel pieces becomes available.

Technical barriers

Recovering useful steel from buildings requires technical expertise which goes beyond traditional demolition techniques and in some cases requires a deconstruction process (careful removal of each piece), which is time and labour intensive, and requires specific expertise. In many cases, demolition projects are time constrained and a deconstruction process that allows for the recovery of steel elements is costly or technically unfeasible (SteelConstruction.info, 2022). The last point is accentuated by the way buildings have been traditionally designed that results in additional costs for steel recovery in the decommissioning phase of a building.

In addition, building design usually does not consider or has an understanding of the availability of reusable steel pieces. This leads to very specific and tailored designs and shapes which require precise re-work and cut of the structural beams and connections. Also, to preserve the long clean pieces that are likely to be used, considerations need to be taken at the design stage to enable their clear and easy access before demolition. This also leads to a potential increase in the cost of the reusable pieces, which have not been designed to be reused.

Some of the steel for reuse may come from cancelled projects or over-procurement, where part of the material is produced and in a near-new condition, available for reusing. However, most of the potential reusable stocks are accumulated in buildings and only become available after demolition. In these cases, one critical aspect is to have access to the specification of installed steel. In newer buildings this information is found in BIM models but can be more difficult to find out for historical stock. If the age and producer of the steel elements is known, properties can be found in design guides (Smeets, Wang and Drewniok, 2019). For a large part of the existing stock, this information is not usually available. This poses additional testing costs for specifications, safety and insurance purposes.

Moreover, reuse of steel requires material disassembling, sorting, testing, reconditioning, transporting and storing. All these processes are labour, space and time intensive, representing an important hurdle for the cost-effective reuse of the material. To guarantee that steel sections remain suitable for reuse and comply with standards, pieces are gathered in batches consisting of members from the same structure with identical shapes, sizes and original functions. Some of the pieces in each group are selected for testing to ascertain their structural attributes. This process is usually undertaken by a third party with expertise in steel testing and certification (Ferrao, 2023).

Regulatory barriers

Materials which have been classified as waste need to apply for exemption and end of waste status for its reuse. However, in the reuse of steel structures, reclamation of material for reuse happens before it becomes waste; This means that it has to be recovered before demolition or as part of a deconstruction demolition, which may require modifying current practices of buildings' end of life waste management processes (Gowler, 2021).

As discussed above, the lack of documentation makes it usually impossible tracing the origin and specifications of reclaimed steel. This means that there is need of a testing and certification process and regulation of the pieces for their reuse as structural parts, which may certainly increase the cost of the final reused pieces.

There is increasing number of standards for reutilisation of steel frame materials, such as the CEN/TC 135 N 1024 Execution of steel structures and aluminium structures a Reuse of structural steel, or the CB/203 - Design & execution of steel structures. These standards though recognise the barriers to mainstream reuse as a common practice by the UK construction sector.

Cultural barriers

Finally, an important set of barriers identified by stakeholders is associated with the culture of how the construction industry operates. The cultural resistance to steel reuse also stems from a systemic preference in the construction sector for conventional business-as-usual approaches, which prioritise speed and certainty over innovation and sustainability (SCI, 2016). In particular, stakeholders, including designers and contractors, often situate reused materials in the "difficult to work with" category due to additional time and effort required for integration into projects (Densley Tingley, Cooper and Cullen, 2017). On the other hand, client demand plays a pivotal role in shaping market trends. Without explicit client requirements for reused materials, the supply chain lacks sufficient motivation to adopt these practices (Densley Tingley, Cooper and Cullen, 2017). Moreover, perceptions on the superiority of new steel over second hand steel decrease the supply driven promotion of steel reuse (Gowler, 2021).

Overcoming these barriers requires targeted awareness campaigns, technical training, and visible leadership by both industry bodies and government entities. For instance, embedding reuse practices into education and professional development programs could address knowledge gaps and gradually normalise steel reuse (SCI, 2016; Densley Tingley, Cooper and Cullen, 2017).

Measures for increasing steel reuse.

Documents and databases

To address some of the barriers above and guide and standardise the process of reusing steel frames, the Steel Construction Institute has issued a document for the UK with guidelines for assessment, testing and design principles focused on structural steel reuse. This guide, called Structural Steel Reuse (Brown, Pimentel and Sansom, 2019) presents recommendation on how to collect data, perform inspection and testing to ensure that reclaimed structural steel can be reused with confidence. However, it does not cover reclaimed steel from structures which have experienced fatigue, high impact or fire, as they are not considered to be suitable for reuse. Also, steel from buildings constructed before 1970 is excluded from these recommendations (although a document for reuse of pre-1970 steel (P440), has also been produced, but it is behind a paywall).

Recently, the Institution of Structural Engineers has issued the "Circular economy and reuse: guidance for designers" a 300+ document that covers from the basic concepts of material reuse to specifics on how to overcome barriers for the reuse of different materials, with an important focus on steel

(IStructE, 2022). Unfortunately, this document is behind a paywall, but Jones, (2023) discusses some of its most relevant aspects.

Another useful document that has been produced recently sets specifications to be followed by suppliers of reclaimed steel. This document titled “Model specification for the purchase of reclaimed steel sections” produced by the British Constructional Steelwork Association (BCSA, 2022). This document outlines a model for the reclamation and reuse of structural steel, defining roles for the different stakeholders, and provides other technical details to guide the process of specifying reclaimed steel for reuse.

In addition, the UK Green building council (UKGBC) is developing a portal to establish a single platform where reusable construction materials can be found (UKGBC, 2023). This platform aims at facilitating the creation of a market by matching supply of and demand for reused materials. This measure could potentially have a high impact boosting the reuse of steel frames. According to Smeets, Wang and Drewniok, (2019), such a platform facilitates the direct re-use of complete structures or individual elements in their original condition and could help to avoid costs of reconditioning, achieving savings in the range of £300/t to £500/t.

Design and digitalisation of information

An important line of action for enabling a higher degree of reusability is to facilitate the process of identifying and disassembling potential reusable pieces. Advancements in technology, particularly in digitalization and artificial intelligence, offer possible solutions to some of the barriers. Digital tools can aid in inventory management, tracing the history of steel components, and assessing their suitability for reuse. Machine learning algorithms can predict the condition and performance of reused steel, ensuring safety and reliability. Structural digital-twin models can estimate performance of buildings a predict the structural health of specific steel elements in the building.

New buildings can be built with detailed inventories of materials and pieces included in the building. Additionally, innovations in demountable connections for steel-framed buildings could facilitate steel component disassembly and reuse, reducing time and cost. This would facilitate to recover the reusable steel. However, this has a cost that can only be offset at the end of the building lifetime and only if there is a market for recovered steel. Moreover, further research is required to correctly design these connections and ensure that demountable joints endure the test of time and can be effectively demounted at the end of the building’s life. In this regard, Kitayama and Iuorio (2023) discuss and summarise recent novel techniques of dismountable connections for increasing the reusability of steel structural members.

Building Information Modelling (BIM) design helps fulfilling several of these requirements by providing information about each element in a building and making material properties much more accessible in the decommissioning phase. This enables traceability and may eliminate the need for testing, which according to Smeets, Wang and Drewniok, (2019) amounts to around £150/t.

The evaluation of the suitability of reutilisation of structural elements is time consuming and requires multiple criteria assessment. The use of digital methods could alleviate the hurdles of this process and include factors such as logistic feasibility, structural performance, life cycle and economic assessment, and safety. Models that use different machine learning techniques to factor in multiple variables have been proposed by various authors (Kim et al., 2021; Birhane, 2022; Kanyilmaz, Tichell and Loiacono, 2022; Perry, Guo and Mahmoud, 2022). These tools usually focus on assessing the reuse potential of end-of-life steel frames and on categorising different building elements to match them with needs in new projects. Some of the criteria used by these tools are easiness of disassembly, requirement of cleaning and modification of the material, requirement of redesign and modifications required to fulfil new projects' needs and environmental impact of the reuse process.

Novel techniques for increasing steel reusability

As mentioned previously, structural steel pieces subject to cycle loading induced fatigue are usually considered as not suitable for reuse. New techniques, such as Electro-pulsing treatments (ETP) could be used to rejuvenate steel pieces that have undergone fatigue, allowing for their reuse (Ben *et al.*, 2019). A recent study performed on stainless steel has shown that fatigue-induced cracks can be healed by applying pulses at specific current densities (Cai *et al.*, 2023).

This technique is currently in its early stages of development, and assessing the full potential of its future application is not yet feasible. However, there is a possibility of envisioning its use in structural steel that has been subject to fatigue, thereby enhancing the material's reusability.

Conclusions

The reuse of steel frames in the construction industry presents a significant opportunity to increase circularity and reduce embodied carbon, yet it remains underutilised. While the emission benefits of steel reuse are substantial, reuse rates remain relatively low due to several intertwined barriers. These barriers include economic challenges such as volatile steel prices and high processing costs, technical hurdles related to design, disassembly and testing, and cultural resistance stemming from industry preferences for conventional methods and perceptions of reused materials as inferior.

Efforts to overcome these barriers are underway, with advancements in digital tools like Building Information Modelling (BIM), the development of new standards and guidelines, and technical solutions such as demountable connections. These innovations aim to address traceability, improve the reusability of components, and reduce costs. Additionally, targeted awareness campaigns are essential to create a functional market for reused steel. While progress is evident, achieving widespread adoption of steel reuse will require concerted efforts from industry stakeholders, government leadership, and continued technological and regulatory development.

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