Enhancing Circular Construction Through Structural Steel Reuse: Case Study of Champlain Bridge

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Abstract – The construction industry plays a critical role in tackling the challenges of climate change, carbon emissions, and resource consumption. Current practices predominantly adhere to a linear supply chain model that gives insufficient attention to the End-of-Life (EOL) phase of structures. Transitioning to Circular Construction (CC) is essential for minimizing waste and mitigating negative environmental impacts. While recycling structural steel is widely utilized at the EOL, it is energy-intensive and may degrade material quality. In contrast, steel component reuse presents a more sustainable option, requiring minimal alterations and significantly reducing embodied energy and Greenhouse Gas emissions. The main aim of this study is to advance CC by developing a framework for the catalyzing factors that can enhance the efficacy of the deconstruction process and structural steel component reuse. These factors were gathered through a comprehensive literature review. The identified factors were then mapped to a high-profile deconstruction project, the original Champlain Bridge deconstruction, to assess the challenges and initiatives involved in improving deconstruction efficiency and optimizing the reuse of structural steel components. The data of the deconstruction process and structural steel reuse were obtained through series of meetings with the Jacques Cartier and Champlain Bridges Incorporated (JCCBI) team. The numerical data regarding quantities and weights of structural steel was analyzed to assess the types of reusable steel components. Finally, the paper highlights future research areas for improving the efficiency of the value chain processes, maximizing the steel component reuse, improving the decision-making at the EOL.

Keywords –
Deconstruction; Circular Construction; Infrastructure Sustainability; Structural Steel Reuse; Adaptive Reuse; End-of-Life Management; Champlain Bridge.

1 Introduction

Effective construction waste management has gained paramount importance in recent years due to increasingly stringent regulations focusing on material recycling and reuse [1]. The construction industry is responsible for about 40% of the global natural resource exploitation [2, 3]. The current practices in the construction industry follow a linear supply chain model (take-make-dispose) with minimum consideration of the End-of-Life (EOL) phase of the structures [4]. There is a need to change this model to a circular model that aims to keep resources in use for as long as possible, which will minimize waste and reduce the negative environmental impact [5, 6]. Adopting Circular Construction (CC) is highly dependent on the way of handling the structure's components at the EOL phase, where two main options are available: demolition or deconstruction [7].

Demolition involves dismantling the structure, with most steel being recycled, although some steel end up in landfills due to contamination or recycling limitations. Deconstruction is a more methodical approach that focuses on carefully disassembling the structure to maximize the recovery of valuable components [8]. Following deconstruction, recovered materials can be managed through two main pathways: reuse or recycling. In practice, a combination of reuse and recycling often occurs. Recycling is a common approach for handling materials at the EOL, but it entails energy-intensive processes, such as steel melting and fabrication, which can elevate energy consumption. Additionally, these processes may compromise material quality, potentially leading to increased demand for new materials in future applications [9]. Alternatively, reuse often presents a more sustainable approach, as it involves minimal physical alterations [10]. Furthermore, the embodied energy and Greenhouse Gas emissions of the structures made of reused components are 63% and 56% lower, respectively, than those of the new components [11]. However, implementing deconstruction and reuse practices necessitates radical changes in the construction industry, moving away from the traditional approach of fixed-lifespan structures to a more flexible approach that facilitates deconstruction and component reuse [12]. This will require the adoption of new business models and technologies that prioritize deconstruction and support CC [13].

While several studies have recognized the importance of the EOL phase of existing steel structures, and the opportunity of their component reuse, there is a significant gap in the development of a comprehensive methodology that integrates the catalyzing factors necessary to facilitate the reuse of structural steel after deconstruction [14 – 16]. Accordingly, this paper aims to promote CC by developing a framework that enhances deconstruction efficiency and facilitates the reuse of structural components, incorporating key factors and actionable insights to support sustainable deconstruction strategies. The study is structured into two main stages. The first stage involves identifying the catalyzing factors that promote the efficient reuse of structural components, encompassing technological, regulatory, and economic influences, which were sourced from various scholarly references. The second stage involves mapping these factors within a high-profile deconstruction project, the original Champlain Bridge deconstruction project in Montreal, Canada, to identify successes and challenges associated with the deconstruction process and the reuse of structural steel components. Finally, the research highlights future directions for enhancing value chain processes, promoting component reuse, and improving decision-making through the integration of advanced technologies.

2 Catalyzing Factors for Enhancing Structural Component Reuse

This section focuses on catalyzing factors aimed at enhancing the efficiency of the deconstruction process and maximizing the reusability of structural components. These factors were determined through a comprehensive review of recent research papers, conference proceedings, books, and review articles.

2.1 Structure Attributes

(1) Structural Design: The design of structures plays a crucial role in determining both the efficiency of the deconstruction process and the potential reusability of their components. Steel structures are not only highly recyclable, but also easy to dismantle and store [17]. The modular design of structural components is a potential approach for designing structures that can easily adapt, be moved, dismantled, and reused [18]. Mechanical connections such as bolts and fasteners can facilitate easier disassembly during the deconstruction process. Properly designed connections that allow for straightforward removal without damage to the components or surrounding materials simplify the extraction of reusable parts [19].

(2) Component Condition: The condition of the components and desired reuse application influence the level of refurbishment required. The examination of several key subfactors related to a structure's condition, including structural integrity, historical value, and cost-effectiveness informs decisions and strategies in managing deconstruction, emphasizing practicality and sustainable outcomes [20].

(3) Location: The strategic location provided easy access for heavy machinery and transportation, enabling efficient removal and transport of salvaged materials. Efficiently matching of supply and demand for reused components reduces logistics costs in deconstruction projects [21].

2.2 Business Attributes

(1) Willingness to Reuse: Finding a client willing to take a risk and pay a premium for CC or reuse solutions decreases the cost risks for value chain actors [22].

(2) Organization Competences and Circular Readiness: The project team’s compatible skills, and innovative approach facilitate creative solutions for implementing structural component reuse, resulting in high reuse rates and reduced transition costs and time for efficient circular processes [23].

2.3 Value Chain Activities

(1) Deconstruction Planning: Effective deconstruction planning is crucial to minimize the risks of deconstruction processes and ensure the maximization of reusable structural components [24]. Digital technologies enhance the efficiency in inventorying and tracking components. Also, visualizing the deconstruction process over time using 4D simulation aids in efficient resource allocation, minimizes disruptions, and improves cost efficiency through identifying and eliminating non-value-added activities [25]. Quality management ensures that salvaged components meet standards for reuse. The use of heavy machinery enables the safe dismantling of structures. Implementing a reusing and recycling program promotes sustainability by diverting materials from landfills and integrating them into new construction projects [19]. For certifying reused steel or quality control procedures in the steel industry, both ISO [26] and ASTM [27] standards provide essential frameworks. These standards involve evaluations such as material non-destructive testing and inspections of structural integrity to ensure the steel's reliability and safety in new applications. Environmental monitoring ensures compliance with regulations and minimizes environmental impacts [21].

(2) Safety Planning: Safety planning in the deconstruction process is critical for mitigating risks and protecting both workers and the environment. This involves conducting risk assessments, training programs, regular site safety audits, and an emergency response plan [20, 21].

(3) Logistics Optimization: Careful logistics planning minimizes environmental and economic costs associated with component transportation, preserving the value potential of reusable components and reducing transportation expenses [28]. Value chain actors can efficiently access information on available reusable components and their locations. Moreover, verifying the environmental benefits of refurbished components in Environmental Product Declarations enhances demand for building component reuse. Furthermore, establishing metrics for tracking progress, component recovery rates, and types of components salvaged, enables real-time adjustments and reporting on reuse success for future projects [19].

(4) Storage Conditions: Good-quality storage enables the value of salvaged components to be preserved and minimizes risk of additional costs [21].

(5) Lean Processes: Lean processes could meticulously identify each step involved in deconstruction, allowing for the elimination of unnecessary tasks, optimization of workflows, and minimization of wastes [19]. Quality control measures, such as regular inspections and evaluations, enforce rigorous standards for reusable materials and minimize defects. Moreover, training programs provide workers with the necessary skills and knowledge in best refurbishment practices, reducing errors and enhancing safety [29].

2.4 Project Management

(1) Public Consultation and Stakeholders' Involvement: An effective advertising campaign for sustainable deconstruction educates the public and promotes awareness and support. Collaboration among stakeholders streamlines processes and maximizes resource reuse. Working with nearby city administrations aligns regulations and enhances regional planning. Pilot projects provide experiential learning, helping refine best practices. Influencing industry attitudes encourages broader adoption of sustainable practices, driving long-term resource conservation in the built environment [30].

(2) Performing Feasibility Study: The feasibility study can improve deconstruction efficiency by evaluating methods that align with sustainability goals, focusing on minimizing environmental impact and maximizing component recovery [3].

2.5 Legislations

Regulatory support is crucial with policies that streamline permitting processes for projects incorporating salvaged components, thereby facilitating the efficient reuse and promoting environmental sustainability in the construction sector. Sustainability programs initiated by governments prioritize sustainable construction practices, incentivizing the reuse of components from deconstruction projects. Legislative financial incentives encourage the usage of reused components in construction, increasing profitability and accelerating the construction sector's transition to circular practices [31].

Several initiatives are being actively implemented to enhance the reuse of steel components, focusing on reducing waste and advancing sustainability within the construction sector. For example, the Toronto Green Standard (TGS) sets environmental performance standards to accelerate GHG reduction, aiming for near-zero emissions by 2030. Higher tiers mandate embodied carbon assessments (e.g., LCA) to measure material and construction emissions. Compliance is enforced through the Site Planning Approval process [32].

3 Champlain Bridge Deconstruction and Steel Component Reuse

The original Champlain Bridge is one of the largest infrastructure projects in North America. It was built in 1962 by Jacques Cartier and Champlain Bridges Incorporated (JCCBI). It has a total length of 3.4 km, with six lanes for vehicular traffic, three in each direction. The original Champlain Bridge faced several significant structural problems that contributed to its eventual deconstruction. The primary issue was severe corrosion, exacerbated by de-icing salts and an inadequate drainage system in its original design. The absence of a proper drainage system in the bridge's design led to the accumulation of water and salt on critical structural elements, worsening corrosion and compromising the integrity of the bridge. Throughout its service life, the bridge required frequent and significant maintenance activities, including repainting the steel structure, repairing piers, replacing the concrete deck with a steel deck, and reinforcing girders. Despite these efforts, the bridge's deterioration continued to worsen, compromising its performance and reliability [33]. In 2013, the need to replace the original Champlain Bridge was further confirmed when sensors detected unusual deformations in the edge girders. In response, the bridge was closed, and a 75 tonne, 56-meter steel "super beam" was installed to reinforce a cracked girder, reducing traffic capacity by one lane. Five months later, the super beam was replaced with 50 tonnes of steel modular trusses. Despite these measures, the aging bridge's condition continued to deteriorate, highlighting the need for a full replacement [34].

The planning of the original Champlain Bridge's deconstruction began in 2017. The planned deconstruction cost was around Can$225 million, while the overall investment cost was Can$400 million. Design-build of the deconstruction was chosen as the project delivery method, and work on-site began in July 2020. The deconstruction process finished in November 2023.

3.1 Mapping the Catalyzing Factors to the Case of Champlain Bridge Project

The data were derived from the JCCBI website [34], the steel components catalogue [35], consultation reports [36], the competition report [37], alongside meetings with the JCCBI team.

(1) Structure Attributes: The main part of the original Champlain Bridge was steel truss cantilever with approach viaducts constructed of prestressed concrete beams supporting a prestressed concrete deck paved with asphalt. A total of 413 standardized steel components, with a total weight of 401 tonnes, were identified for potential reuse in other steel construction projects. Mechanical connections enable easier component separation during deconstruction, using techniques like heat cutting for large elements, unbolting, and removing rivets.

For the component condition, the bridge's deconstruction produces approximately 25,000 tonnes of steel, with structurally viable components for salvaging and repurposing. Moreover, some components were used for non-residential structures (e.g., car canopy) which were not subject to high structural requirements, reducing bureaucracy and enabling the simplification or avoidance of cost-intensive steps related to element recovery, inspections, repairs, and certification.

Pertaining to the bridge location, the proximity of the bridge to the surrounding infrastructures facilitates the deconstruction process and the reuse of components by providing easy access for logistics, as well as enabling efficient removal and transport of salvaged materials. Also, the bridge's legacy and historical significance added intrinsic value to its components, making them appealing for preservation and reuse in heritage projects. The urban setting increased demand for reused components, promoting interest from local builders and developers in acquiring salvaged components. Moreover, due to the environmental considerations, the contractor has to propose a greenhouse gas compensation strategy for ensuring a carbon-neutral project.

(2) Business Attributes: JCCBI set sustainability targets for handling and transportation, emphasizing the innovative reuse of components rather than traditional recycling. They also implemented continuous performance monitoring to improve the project's profitability. Furthermore, a sustainability decision support tool was created, incorporating environmental, economic, social, and technical factors. The tool was utilized to evaluate different scenarios and compare all the available deconstruction methods, possible ways for the reuse/recycling of the components, and transportation methods.

(3) Value Chain Activities: JCCBI enhanced logistics by devising a phased deconstruction strategy that prioritizes the safe removal of components while minimizing disruption to surrounding areas. A comprehensive assessment was conducted to evaluate the bridge's structural integrity and determine which components were suitable for reuse. Also, they developed a 4D model for the bridge's deconstruction to facilitate comprehensive planning, scheduling, and coordination. Visualizing the deconstruction process over time aids in efficient resource allocation, minimizes disruptions, and improves cost efficiency through identifying and eliminating unnecessary activities. Moreover, non-destructive tests were performed to evaluate the quality of the bridge components. The structural steel components were dismantled using specialized equipment, including cranes, barges, and excavators. Additionally, JCCBI implemented a reusing and recycling program as they directed the contractor to meet specific reuse and recycling targets, including 100% steel reuse or recycling and a 90% overall component recovery from the bridge, with penalties for non-compliance. The contractor was bound by the design-build requirements to recycle the components within a 150 km radius from the project site.

Moving to safety planning, the deconstruction process involved 200 specialists and laborers with specialized training in safe deconstruction practices, machinery operation, and emergency response protocols. Regular safety audits and inspections were carried out to ensure compliance with safety regulations and to address any emerging risks. An emergency response plan was established, detailing procedures dealing with accidents, injuries, or other unforeseen incidents.

For logistics optimization, a phased deconstruction strategy was developed to prioritize the safe removal of components while minimizing disruption. To facilitate data access and flows, a data labeling system was implemented for each reusable component. Additionally, a traceability protocol using QR codes was established to monitor the materials, enabling precise georeferencing of each component from its origin to its destination. Reusable components were systematically stored on-site in designated areas specifically allocated for sorting and inventory management. These storage areas were equipped with protective measures to shield components from adverse weather conditions and potential damage.

To mitigate deconstruction waste, JCCBI integrated specific clauses into the design-build contract of the deconstruction to establish a comprehensive sustainability program. This program prioritizes the reuse of components wherever feasible, thereby reducing waste and advancing sustainable practices throughout the project. For quality control, they conducted regular inspections and evaluations of reusable steel components. Also, they provided training for employees on best practices for refurbishment.

(4) Project Management: The community was engaged through an extensive multiplatform advertising campaign to gather innovative ideas regarding sustainable development, environmental protection, and component reuse. The consultation involved 4,186 participants via various channels. An advisory committee was established consisting of representatives from different environmental and cultural organizations to provide strategic guidance and expertise throughout the project. Moreover, JCCBI searched similar projects and identified the Bay Bridge deconstruction project in San Francisco as a relevant example [33]. The California Department of Transportation initiated a program to repurpose components of the bridge but reused less than 1% of the bridge's steel. In contrast, JCCBI developed its reuse program earlier in the project, aiming to achieve a significantly higher percentage of component reuse.

In 2017, JCCBI commissioned the PTA Consortium (Parsons/Tetra Tech/Amec Foster Wheeler) to conduct a feasibility study and targeted environmental analysis for the Champlain Bridge deconstruction, assessing different options for deconstruction methods, transportation of components, and component recovery. The study evaluated various scenarios based on sustainable development criteria, focusing on technical feasibility, economic viability, environmental impacts, and social acceptability.

(5) Legislations: The Government of Canada has shown a robust commitment to sustainability, requiring all ministries and agencies to contribute to the "United Nations Sustainable Development Goals" and align with Canada's national sustainability strategy [38]. Consequently, the deconstruction of the original Champlain Bridge is designed to promote environmental performance for future projects, reflecting both national and international sustainability objectives. The deconstruction of the original Champlain Bridge and the reuse of its components have been supported by various financial incentives, including public funding sources such as local tax revenues, federal funds, fares, and bonds.

3.2 Data Analysis

The authors conducted an analysis of the data provided in the catalogue to gain insights into the quantities and weights of different types of reusable steel components of the Champlain Bridge [35]. The methodology involved classifying the reusable steel components based on their location, followed by calculating the amount of reused steel components and the weight percentage for each category. Figure 1 shows the histogram of the reusable steel components in terms of their quantity. The horizontal axis categorizes the different types of structural components in the Champlain Bridge, including Diagonal, Bracing, Vertical, Top chord, Lower chord, and Deck beam. The vertical axis represents the number of reusable steel components, showing how many structural elements of each type were identified for reuse. This histogram visually compares the distribution of reusable components across these categories.

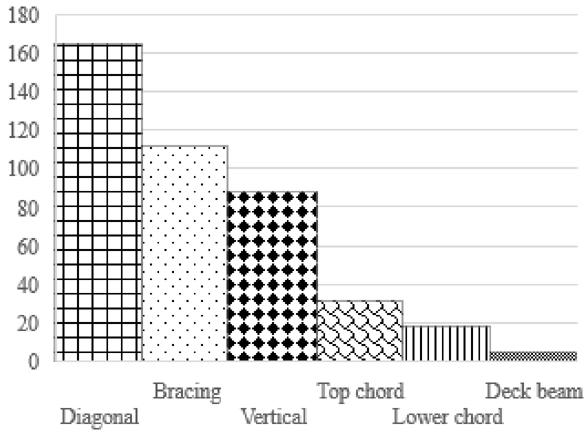

Figure 1. Quantity histogram of reusable steel components

The histogram shows that diagonal components are the most abundant, totaling 165 units. Bracing and vertical components follow with significant quantities of 112 and 88 units, respectively. Top and lower chord components have moderate quantities, at 31 and 18 units, while deck beams are the least numerous with only four units. Figure 2 shows the percentage of reusable steel components classified by their weight. The analysis of steel component weights reveals that the top chord components have the highest proportion by weight (23.7%). Lower chord components are significant in both quantity and weight, suggesting they are moderately heavy. Vertical components reflect a balance between their quantity and weight. While diagonal components are numerous, they are relatively lighter compared to components in other locations, indicating these components are heavier per unit. Deck beam components have low quantities but higher weight percentages (8.9%), suggesting they are dense despite their limited numbers.

The analysis indicates a varied distribution of steel in terms of quantity and weight, reflecting their different applications and structural roles. Understanding these distributions aids in planning the reuse of these components in future projects.

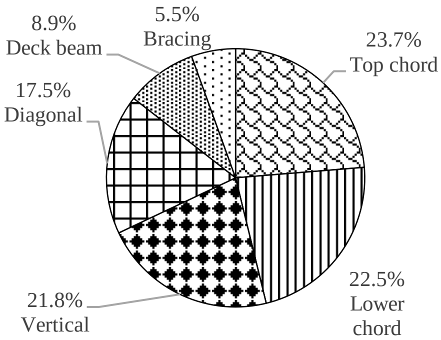

Figure 2. The weight percentage of reusable steel components

4 Future Research Areas

For improving the efficiency of the processes related to value chain activities, maximizing the reuse of components, and supporting the decision-making, the following future research areas can be considered:

(1) Automation in Deconstruction Planning and Optimization: AI algorithms can be applied for identifying the optimal sequence of steel components deconstruction based on their structural importance and condition. Also, it helps to simulate potential problems during the deconstruction process and automate the decision-making [39]. Furthermore, automated systems can classify components by category to facilitate repurposing [40].

(2) 3D Scanning and Digital Twin Technologies: Adopting 3D scanning and developing digital twin of the structure can assist in the efficient deconstruction processes and the precise planning for maximum reuse of steel components. It provides a highly accurate, real-time representation of the structure's condition, including the identification of critical components and potential structural weaknesses [41].

(3) Material Passport System: Material Passport is a digital record that details the composition, origin, lifespan, and condition of each component used in the structure. It has the potential to maximize the reuse of structure components, reducing costs, and environmental impact through matching deconstructed components to future construction projects. Radio Frequency Identification could be used to track the component throughout its lifecycle, facilitating the efficient identification and recovery of valuable components during deconstruction [42].

(4) Advanced Robotics: The use of autonomous robots or drones in the process of scanning, dismantling and sorting of bridge components can improve accuracy and reduce the associated risks. For instance, robots can be designed to safely remove steel components while conserving their integrity for reuse [43].

(5) Enhanced Workers Training with Virtual Reality (VR) and Augmented Reality (AR): VR and AR can ensure that workers are adequately trained for the deconstruction process. These technologies allow workers to simulate deconstruction scenarios and understand the best practices for handling components, improving safety, and maintaining the integrity of reusable components [44].

5 Conclusions

The transition toward CC is increasingly vital as the construction industry confronts pressing challenges related to climate change, carbon emissions, and resource depletion. Adopting a circular approach offers a sustainable solution by minimizing waste, conserving resources, and lowering embodied energy, making it a key strategy for addressing these critical issues. This study emphasizes the need for a shift towards CC, particularly through the reuse of structural steel components. It begins by identifying the key factors that could catalyze the deconstruction process and enhance the reuse of components. The factors include the structure attributes, business attributes, value chain activities, project management, and legislations. These factors were applied to the Champlain Bridge deconstruction project to evaluate process effectiveness, identify challenges, and define the potential for optimizing the reuse of structural steel components.

The analysis revealed several success criteria, including the development of a phased deconstruction strategy, comprehensive audits of structural integrity, and the integration of digital technologies for effective planning and coordination, thereby enhancing overall project efficiency. Additionally, incorporating specific sustainability clauses into the deconstruction contract significantly increases the potential for steel reuse. Furthermore, presenting a sustainability decision support tool to evaluate various deconstruction methods can facilitate informed decision-making. Engaging the community and collaborating with environmental organizations, along with organizing competitions for innovative reuse ideas, further fosters a culture of sustainability within the construction industry. Finally, the research provides future research areas for supporting the processes of the value chain activities, increasing the potential of reusing components, and enhancing the decision-making. The future research areas emphasize the integration of advanced technologies such as artificial intelligence for deconstruction planning, robotics for precision dismantling, 3D scanning for accurate modeling, and material passport systems for enhanced traceability. However, while this study provides valuable insights for enhancing deconstruction processes and the structural steel reuse, it lacks detailed quantitative analysis for the environmental and economic benefits in comparison with the traditional steel recycling. Future research could focus on conducting scenario analysis for the EOL of structural steel utilizing sustainable life cycle approach. This would include a detailed comparison of the environmental and economic benefits of reuse relative to traditional recycling.

The research results could improve the decision-making process for EOL phase of structures by adding comprehensive qualitative analysis towards sustainable management and conservation of resources. These results align with Canada's international commitments to sustainable development, including the United Nations Sustainable Development Goals, particularly Goal 12 (Responsible Consumption and Production). Furthermore, this study provides numerical data and actionable insights that will support the Canadian government's objectives related to sustainability, economic efficiency, and environmental responsibility, contributing to a more sustainable construction industry.

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