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The reuse of load-bearing components

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Abstract. Load-bearing systems of buildings are poorly valued when they reach functional obsolescence. Still, they contribute the most to the material weight and embodied impacts of buildings and infrastructures. The reuse of structural components therefore offers great potential to save materials, energy and resources. While historic and contemporary projects highlight the environmental, time or cost benefits of building with reclaimed elements, many technological challenges remain. This paper gives an overview of buildings that efficiently reuse structural components as well as a review of current research efforts addressing structural reuse. The first case study is the design process of an elastic gridshell made from reclaimed skis. This project demonstrates the potential of ensuring structural performance while working with uncharacterized and heterogeneous materials. In general, designing structures from a stock of reclaimed elements entails reversing the conventional structural design process. The synthesis of structures has to follow the availability of elements and their mechanical and geometric properties. Developed tools that facilitate such design from reused elements while minimizing embodied environmental impacts are presented in this paper. A second case study demonstrates the relevance of such tools through a conceptual train station roof made from electric pylon elements. Lastly, some key challenges related to the design of structural systems from reused elements are presented. These research initiatives constitute a first step to understand and support the design of load-bearing systems from reused elements and hence to bring the construction industry closer to circular economy.

Keywords: Building structures, load-bearing systems, component reuse, circular economy, case studies, structural design, optimization

1. Introduction

The building sector is responsible for three environmental hazards: resource depletion, energy consumption and waste generation. Up to 50 % of the total material use in Europe is associated to buildings and infrastructure [1]. Further, energy is spent for the production of building components, the construction, and the use of buildings and infrastructure. The building sector is responsible for about one third of all carbon emissions worldwide [2]. Recently developed technical standards (e.g. LEED, BREEAM, Passivhaus) aim mostly at reducing the operational energy of buildings, e.g. through better insulation and more efficient technical equipment. However, little attention has been given to the embodied share, even though it significantly contributes to the total impacts [3, 4]. In particular, load-bearing systems have a major effect on the embodied energy and carbon because of the used materials, their substantial mass, and their intensive manufacturing process [5, 6]. In addition, at the end of life, large amounts of construction and demolition waste originate from building structures.

These observations suggest that the design and construction of buildings has to improve towards a more efficient use of materials. The exploitation of natural resources and the generation of superfluous waste can be avoided by adopting *circular economy* principles in the building sector. Circular economy aims at extending the value and longevity of materials and components through closed loops within their service life [7].

Recycling is the common approach to treat products after their use. Yet, recycling requires energy to process materials (e.g. melting steel) and often results in a loss of quality (e.g. crushed concrete for road construction). An often more sustainable option is *reuse*, which implies only minimal physical transformations and the use of already embedded technology.

The following circular pathways for the reuse of load-bearing systems and components are possible:

1. In-situ adaptive reuse and renovation of building structures
2. System reuse at new location for same purpose
3. System reuse at new location for different purpose
4. Component reuse at new location for same purpose
5. Component reuse at new location for different purpose

Option 1) reduces interventions on existing load-bearing systems to a minimum and prevents demolition. However, buildings are typically not designed to accommodate new uses easily within the existing load-bearing system. This frequently leads to the demolition of buildings where only materials are recovered (recycling). An exception are temporary structures that can be assembled and reassembled at different locations for identical or new purposes, options 2) and 3) respectively. Examples are modular systems (building blocks, containers, scaffolds) and hall or tent structures. The design space of such systems is predetermined by the individual modules and often the same layout must be reconstructed.

Instead, this paper focuses on options 4) and 5) of reusing reclaimed structural components and their reconfiguration in new structural arrangements. Because it avoids sourcing raw materials and requires little energy for reprocessing, reusing structural elements over multiple lifetimes offers an under-explored opportunity to reduce the environmental footprint of the building sector [8]. Currently, this paradigm is easier to employ in the case of steel and timber structures composed of linear elements (bars, beams, cables) because they are often assembled with reversible connections. In addition, element ends can be easily cut and reshaped. This is not the case when structural concrete components are joined with cast-in-place connections for instance. Research initiatives and projects on *design for disassembly* (DfD) extend the realm of structural systems that are designed with reversible connections to allow for greater component reuse [9]. DfD also facilitates the reuse of complete structural systems in options 2) and 3).

In the following an overview of case studies and ongoing research initiatives involving component reuse strategies are presented. Section 2 highlights historic and contemporary examples of structural typologies where single structural elements could be successfully incorporated into new designs. In section 3 an educational case study of a small-scale gridshell pavilion made of 210 reclaimed skis is presented. Section 4 introduces state-of-the-art computational tools that facilitate the design of reticulated structures from a stock of reclaimed structural elements.

2. Historic and contemporary examples

This section presents a non-exhaustive list of historic and contemporary projects where structural components have been successfully reused either for the same or a different purpose, i.e. options 4) and 5) respectively. Further distinction is made whether elements are reused locally or in a new setting and whether remanufacturing or element adaption (e.g. cutting) was necessary.

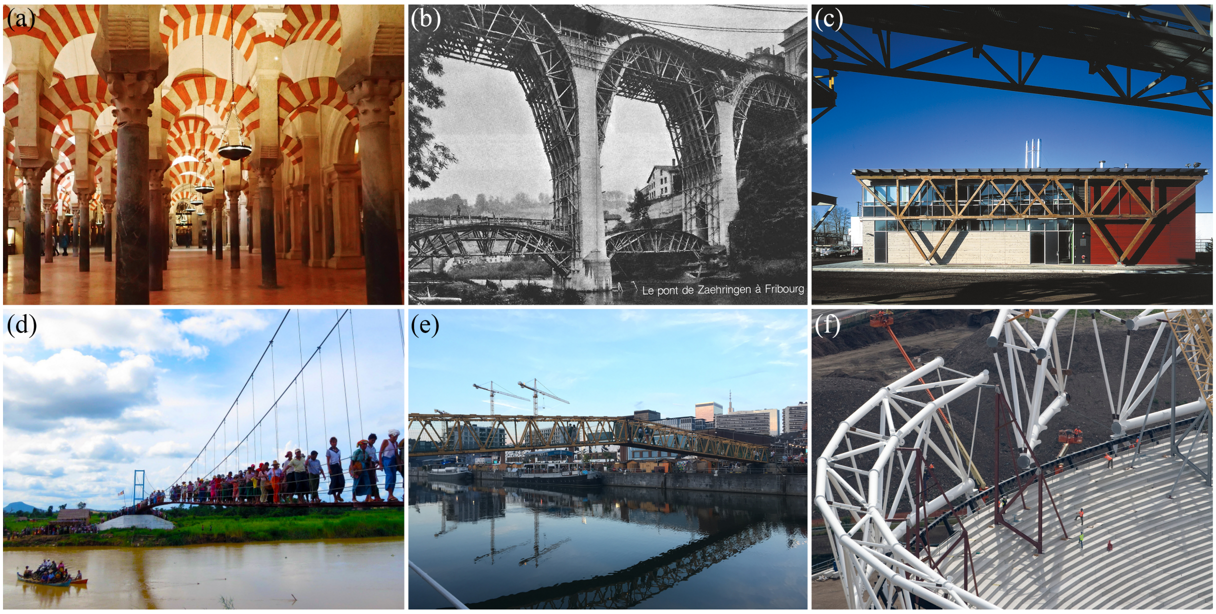

Figure 1. Historic and contemporary examples of structural element reuse: (a) Mezquita, Cordoba, 8th Century; (b) Pont de Zähringen, Fribourg, 1924 (Courtesy: Fonds Bourgarel - Pro Fribourg); (c) Materials Testing Facility, Vancouver, 1999 (Photo: Martin Tessler / Courtesy: Perkins+Will); (d) suspension bridge, Myanmar (Courtesy: Toni Rüttimann); (e) temporary bridge, Brussels, 2014; and (f) London Olympic Stadium roof truss, 2012 (Courtesy: ODA).

Before industrialization, most building materials were sourced locally because it was more cost and time efficient than new production [10]. The scarcity of building materials had to be considered in design and construction. Examples of reusing structural components can be found in different historical eras. Ancient Roman, Greek or Egyptian civilizations reused stones or bricks, known as *spolia* (Latin, 'spoils'), from destroyed buildings. The labor to clean and reuse stones and bricks for the same purpose was much less than the amount of work needed for the hewing or producing of new ones [10]. Figure 1(a) shows some of the 142 marble columns supporting Moorish double arches inside the *Mezquita* in Cordoba (Spain), which was built in the 8th century. These columns originate from nearby ruins of Roman and Visigoth buildings [11] (p. 24) and could be directly reused for the identical purpose.

In 1921, Richard Coray was appointed to design and construct the timber centering and formwork for the 550 m long *Pont de Pérolles* in Fribourg (Switzerland). The bridge contains 15 arches of which five have a span of more than 60 m. The supporting centering was made of wooden logs of only two different cross section sizes, which were connected with bolts of only a single size [12]. This simplified the (dis)assembly of the structure and allowed to reuse the components in a similar configuration and without much remanufacturing for the construction of the *Pont de Zähringen* [12], which is shown in Figure 1(b) and located in Fribourg as well. Coray's approach could also be interpreted as the reconstruction of a complete structural system at different location 2). At that time, shortly after the First World War, construction materials were scarce and of high value, making reuse a beneficial and economic option.

Another example of locally reusing timber members for the same purpose and structural typology is the *Materials Testing Facility* in Vancouver (Canada), 1999. The design consists of two external trusses (Figure 1(c)), which comprise the best members taken from four existing trusses of a demolished warehouse [13]. The existing connections were kept such that refurbishment could be reduced [13].

Examples for the reuse of elements that are originally external to typical construction are the suspension bridges realized by Toni Rüttimann. Donated cables from ski lifts or oil companies are reused as tension elements in bridges constructed in developing countries and remote areas (Figure 1(d)) [14]. Every year many kilometers of cables are taken out of service and replaced. The cables can be safely reused, because only a portion of the original cable tension capacities are utilized, when the suspension bridges are under load [14]. A similar example of a structure incorporating non-standard building components is Gijs Van Vaerenbergh’s temporary truss bridge located in Brussels, Belgium. The bridge repurposes standard crane tower modules and connects them via custom casted joints [15]. As Figure 1(e) shows, complete crane modules of half the bridge span were reused. This reduces the number of custom connections and decreases the assembly times, as the bridge is recurrently rebuilt since 2014.

In the previous examples the element specific loading type and direction that is present in the original setting is maintained when reusing the components, for instance columns are reused as columns in the case of the Mezquita in Cordoba. Conversely, the designers of the 2012 London Olympic Stadium integrated 2’500 tons of pipeline tubes into the roof truss (Figure 1(f)). In a pipeline, these tubes usually resist internal pressure. As truss members, they are subject to axial forces. To guarantee the structural resistance of the elements, coupons of the originally 12 m long tubes were tested and then multiple pieces were welded to 15 m elements as specified in the structural design [2]. The increase in time for the design process was marginal and reusing elements eventually resulted in a small cost benefit [2].

The above presented examples show that versatile solutions for the reuse of elements in load-bearing systems can be achieved through engineering creativity, especially when resources are constrained and elements are locally and readily available.

3. A gridshell made of reclaimed skis – high-efficiency reuse of wasted embedded technology

3.1. A manifesto

The elastic gridshell pavilion shown in Figure 2(a) is made of reclaimed skis and was designed by researchers at EPFL’s Structural Xploration Lab as a manifesto for high-efficiency reuse of wasted embedded technology [16]. The purpose of the pavilion was to raise public awareness about waste problematics, to introduce the topic of *reuse* to students, and to identify the impacts on the profession as well as to categorize research opportunities. The pavilion can be assembled from a kit-of-parts and was showcased at different events and locations in central Europe.

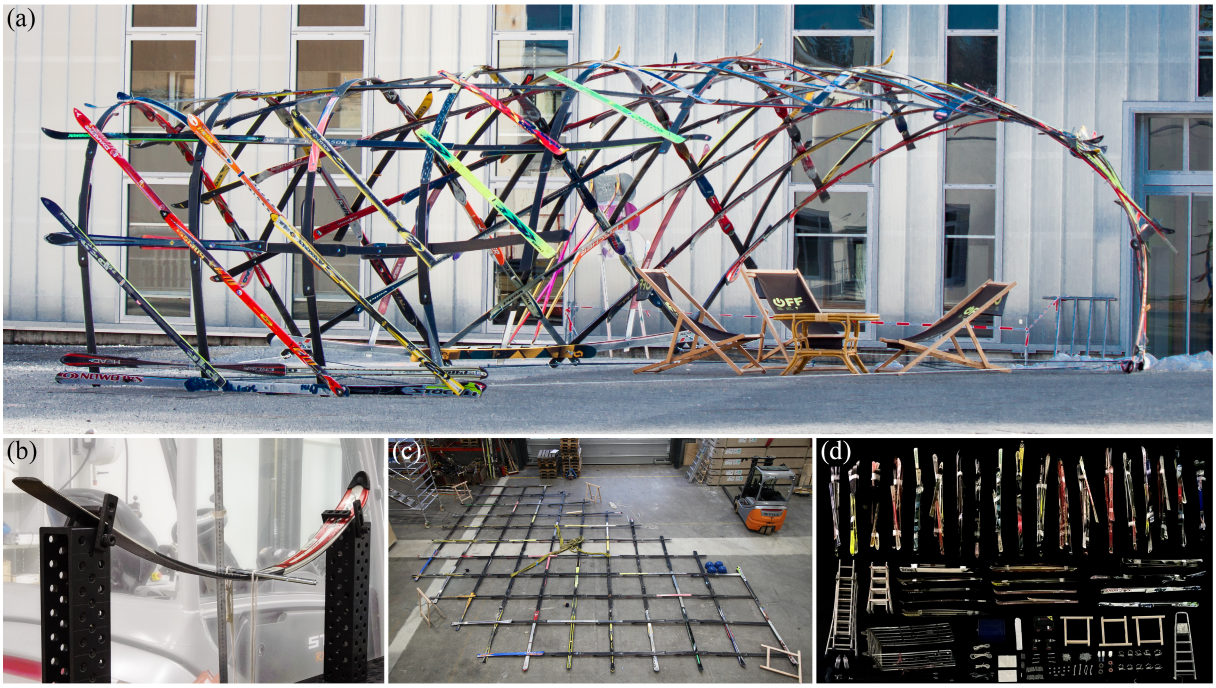

Figure 2. Ski gridshell: (a) actively bent structure with diagonal bracing, (b) testing of ski stiffness, (c) flat grid, and (d) all skis and tools used for construction.

Gridshells are acknowledged as lightweight and easily constructible systems for covering large spans and complex structural forms by means of small components, usually timber laths. A pavilion made of reclaimed sport equipment suitable for bending involves the idea that such components should be locally sourced. The large availability of discarded skis in Switzerland became the starting point for further reflections. Thousands of skis are discarded every year in Switzerland alone. To retrieve the embedded technology of those skis is not only opportunistic but also prevents other resources to be used instead. The choice for skis was also suggested by the recognized potential of fiber-reinforced polymers as a recommended material for bending-active structures. In addition, the environmental footprint for the treatment of 1 kg of wasted skis in terms of global warming potential is approximately 2.27 kgCO_2eq [17]. Such amount of carbon for instance lies in the range of the GHG emissions caused through producing 12 kg of concrete. This comparison highlights the need for extending the lifetime of discarded skis.

3.2. Gridshell design and results

The design of the ski pavilion draws on the recursive relationship between form finding, construction methods and material performance. A digital form-finding method was employed to simulate the bending process and the structural performance of the pavilion. Because an additional variable in the design was the varying nature of the skis (dimensions and bending stiffness), an inventory of the collected skis has been set up from surveying their geometrical and mechanical properties. Widths and thicknesses were measured along the ski. To take into account the heterogeneous nature of the collected set of skis, a non-destructive bending test, which is shown for one ski in Figure 2(b), has been performed on all collected skis. The result was a load-displacement relationship, a value that characterizes the bending stiffness of every individual ski. Having information about the bending stiffness then allowed to adapt the design and place every ski individually at its best location in the grid. Skis that are more flexible were positioned at regions of higher curvature in the shell, in order to avoid their breaking in the bent state. Rigid skis were positioned at regions of low curvature, in order to bring higher stiffness to the system. The individual lines of the flat, orthogonal grid, which is shown in Figure 2(c), were prefabricated and brought to site as folded packages (Figure 2(d)). Once in position, the packages are unfolded on the ground and connected with bolts. A block and tackle system is used to erect the shell through a simultaneous inward movement of the foot points and lifting of the center. A diagonal bracing is then added to fix the sheared squares in their current shape and to stabilize the whole shell.

A life cycle assessment (LCA) has been conducted both on the ski gridshell and on a hypothetical timber gridshell [16]. It was identified that reusing skis resulted in reduced environmental impacts, especially in terms of cumulative energy demand, non-renewable and global warming potential indicators. However, the transport stage contributed the most to the overall impacts when reusing skis. As a result, future collections of discarded skis should not exceed a limit distance of transport [16].

In conclusion, it was possible to reuse the embedded technology in discarded sport equipment to design a pavilion structure while avoiding the production and use of conventional materials such as fiber reinforced polymers or timber.

4. Computational methods to design truss structures from reused elements

4.1. Structural optimization

As pointed out by Gorgolewski [18], designing structures from reused elements is a particular challenge: “In future [...] the starting point for a new design may be an inventory of the available materials from salvage. For structural design the size and length of the available members will then determine the spans and spacing possible in the new structure, thus maximizing structural efficiency from the available components […]” (p. 180). Contrary to the conventional structural design process, this reversed approach is neither typical nor supported by guidelines.

Structural optimization is frequently used to design structures for a given set of boundary conditions, e.g. load cases and support conditions. Structural optimization methods have been extended in [19] to incorporate the reuse of available structural elements from a stock. This optimization approach takes into account the number of available elements, their length and their structural capacity (e.g. normal forces in tension and compression). In an iterative sequence, the structure topology, the element assignment and the system geometry are optimized. The primary objective of the optimization sequence is to reduce the weight of the structural design. Light cross sections of the stock are preferably used, which results in a high utilization of their capacity and oversizing is consequently reduced. The second objective of the optimization is to avoid the cutting of elements and by that to further reduce waste generation. Therefore, geometry optimization and form-finding techniques are employed to optimally shift the positions of truss nodes to match assigned element lengths.

4.2. Case study – A train station roof made from electric pylon elements

The computational approach introduced in previous section 4.1 was applied to a case study where disassembled transmission towers become the source for structural elements. Details of this case study have been previously presented in [20]. The disassembly of the towers of six power lines, one of which is shown in Figure 3(a), is currently under planning in the Swiss canton Wallis. Because the L-section members of the pylons are connected with bolts, as shown in Figure 3(b), it is possible to take down the masts piece-by-piece. In order to characterize an element stock for reuse, archive plans, such as the one shown in Figure 3(c), have been used to determine the amount, length, material and cross section of all members in one power line. One single line comprises about 50 pylons, totaling up to 19’000 bars. Finally, elements with similar lengths and cross sections were grouped into 332 different sets.

Figure 3(d) presents a schematic view of the intended roof design. The structure, comprising three central units (black) and two side units (blue), spans over four double-tracks to form an array of three-hinged frame trusses. The topology and shape of these primary units has been obtained via the optimization method, taking into account the pylon element stock. The involved geometry optimization step successfully shifted the node positions such that most elements could be reused without cutting, which further would permit to reuse most of the existing bolt holes.

Parallel to the tracks, secondary trusses (orange) span 10 m between transverse sections. The secondary trusses are taken from the pylons as complete modules. Compared to an individual component reuse, this restricts the design freedom but on the other hand reduces labor and time for disassembly.

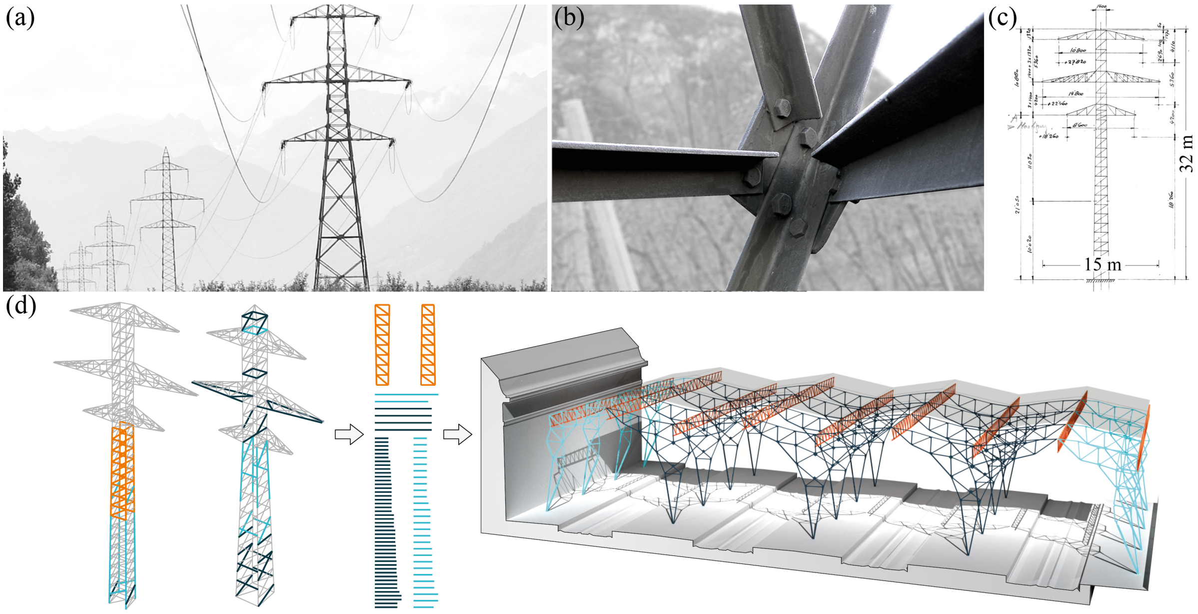

Figure 3. Case study Lausanne Train Station roof: (a) typical power line and electric pylons (Courtesy: Swissgrid), (b) connection detail at a pylon corner, (c) archive plan of an electric pylon (Swissgrid), and (d) roof design strategy and concept.

4.3. Comparison of environmental impacts

The roof structure made from reused elements has been compared to a new structure with identical layout (topology and geometry) optimized for minimum weight [20]. For this benchmark case with new elements made of conventional recycled steel, no restrictions on the element cross sections, lengths or number of available elements exist. Table 1 gives obtained results for one transversal section with three central units and two side units. The structure made from reused elements (b) has 50 % more mass with respect to the weight-optimized solution (a) which could be made of elements of smaller cross sections resulting in a better capacity utilization. This indicates that structures made from reused elements might be oversized when light cross sections are not available in sufficient quantity or length.

An assessment of the embodied energy and carbon of the reuse as well as the benchmark case was performed. For details on the assessment, the reader is referred to [19] and [20]. Only the impacts of sub-processes that are different in the reuse and the recycling scenario have been considered. For the reuse case, these are the impacts caused by the selective deconstruction of obsolete steel buildings, computed via data from [21], as well as the element transport over 200 km. In the new element case, the production impacts of sections from typical recycled-content steel as well as their transport over 70 km are considered. Transport and new steel production impacts are calculated via the German LCA database Ökobaudat [22]. The study period ends with the transport of the truss elements to the building site. As indicated in Table 1, the embodied energy and GHG emissions of the structure made of reused elements are 63 % and 56 % lower respectively than those of the weight-optimized solution.

Table 1. Environmental impacts of (a) the benchmark case (b) the reuse case [20].

Metric	Unit	(a) New elements	(b) Reused elements	(b) vs. (a)
Mass	[kg]	4’400	6’600	+50 %
Mean cross section area	[cm^2]	9.8	12.00	+ 22 %
Mean element utilization	[%]	84 %	62 %	- 22 % (abs)
Embodied energy	[MJ]	58’200	21’400	- 63 %
GHG emissions	[kgCO2eq]	4’100	1’800	- 56 %

5. Conclusion

This paper presents historic and contemporary examples as well as current research trends focusing on the reuse of components for structural purpose. The list of realized projects shows that through engineering creativity it is possible to incorporate component reuse into the design of load bearing systems for buildings and infrastructures. The case study of a pavilion made of reclaimed skis shows that uncharacterized and unusual components can be integrated into structural design processes.

The computational approach presented in this paper facilitates the design of structures from a stock of elements. It has been successfully applied to a realistic case study. The comparison of the environmental impacts shows that the studied roof structure made from reused elements embodies significantly less energy and carbon than an equivalent system made of recycled steel. However, Life Cycle Impact Assessment often contains many uncertainties, for instance the impacts of deconstruction processes might strongly vary. Future work could investigate these processes in more detail.

In addition, reusing structural components can result in oversized structures because the availability of elements with optimal sections is constrained. In the future, more buildings might be designed for disassembly such that larger element stocks can be considered and oversizing is avoided.

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