Sustainability through reuse: a reconfigurable structural system for residential and office buildings

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Abstract. Current load-bearing systems for buildings rarely have a beneficial end of life. Modular design is a proven solution for revalorizing obsolete structures, but it hardly competes with conventional solutions: the range of future spatial configurations that the modules will accommodate is usually too limited to balance additional upfront costs due to necessary oversized elements and extra connections. Through a review of building demolition cases, this paper first presents motives, challenges and requirements for overcoming adverse end-of-life environmental impacts of building structures. Then a new structural system addressing the specified design constraints is introduced. The system is a highly versatile kit of slab and column elements. Contrary to existing modular solutions, its element dimensions do neither constrain the positioning of columns nor the shape of floor plans. Slab elements are stacked vertically to tune bending and shear stiffnesses locally and ensure serviceability requirements for a wide range of column and load cases layouts. All connections between elements are reversible and ready for reuse. Accordingly, the proposed structural system is well-suited for multiple service cycles and architectural needs, mitigating the detrimental effects that buildings have on the environment.

1. Introduction

The context of the building sector needs to be framed considering societal and environmental parameters besides state-of-the-art practices, materials and developments in order to make accurate predictions regarding its future direction. Today, worldwide annual resource consumption is 1.7 times greater than what the planet can sustainably provide [1], while the construction industry is responsible for 35% of all materials used [2]. The trend is expected to increase as it is projected that by 2050 about two thirds of the world population will live in urban areas [3]. As a consequence, in cities the value of land will rise, putting economic pressure on existing buildings and increasing their obsolescence risk. This leads to more buildings being demolished and replaced for new functional requirements, meanwhile generating large amounts of construction and demolition waste (CDW). Already today, more than 30% of total global waste is attributed to the construction industry [4]. CDW does not only represent a loss of valuable resources; it also involves the loss of embodied energy, embodied greenhouse gas emissions and manufactured technology.

From conceptual design to structural dimensioning, from materials production to construction techniques, all building-related processes must improve to address increasingly pressing environmental challenges. Current strategies to reduce greenhouse gas emissions, material depletion, and waste generation of building systems consist in sourcing materials locally, using them efficiently to reduce consumption, and employing low-carbon materials. The latest practice in the field has shown an increasing interest in tall timber buildings. Examples like Tamedia building [4], Tall Wood House [6] or Treet building [7] are models to follow when shifting towards low carbon alternatives. Prefabrication, modularity, and low carbon materials combined offer important advantages and reduced GHG emissions compared to conventional building solutions [8]. Yet, none of these strategies deal with what happens to the building beyond its end of life. There are yet too few examples [9] where structural components survive the obsolescence and demolition of the building they supported. A less common but promising approach is to design the structure with the aim of allowing the reuse of its components in further life cycles [9]. This approach delays material obsolescence beyond the demolition of the building, which is complimentary to existing approaches needed by current and future societal and environmental contexts.

2. Necessity and significance of reusable building systems

In order to express the necessity of reusable building systems, first a study on past examples of voluntarily demolished buildings is conducted in this work. The aim of this study is to determine the main reasons for demolitions, to understand at what building age these demolitions take place, and to give an overview of the detrimental impact that demolitions have on the environment. The selection of the demolished edifices was based on the following criteria: they have been residential or commercial buildings (i.e. hotels, offices, shopping centers) of at least 20 m height and located in urban areas. The research method consists in collecting information about demolished buildings from online sources and in the statistical evaluation of the collected data. In a second step, material quantity approximations are used in order to estimate the global warming potential (GWP) attributed to these demolished buildings. Liu et al. [10] presented a similar study on the lifespan of 1732 low-rise demolished buildings in Chongqing region in China. They determined that the average lifespan is 34 years and it is mostly influenced by external factors (i.e. location).

2.1. Data collection and evaluation

A total of 193 demolished medium and high-rise buildings have been obtained from online sources. Figure 1 shows the distribution of countries where the identified demolitions took place. The building height varies from 20 m to 215 m with an average of 88.6 m. The number of floors varies from 7 to 52. Years of construction are between 1885 and 2009, while years of demolition range between 1931 and 2019. The life span of the buildings – which varies from >100 years to being demolished before construction was ever completed – is on average 39.1 years with a standard deviation of ±19 years (Figure 2). The most used structural solution is reinforced concrete slabs with reinforced concrete columns.

More interestingly, the study reveals that buildings were demolished for various reasons. In this study two main reasons are distinguished: structural damage or functional obsolescence. Structurally damaged buildings are buildings whose structural integrity is affected due to external circumstances (i.e. fire, earthquake, terrorist bombing, tornado or hurricane), insufficient maintenance, material degradation, poor structural design or low building quality. On the other hand, obsolete buildings are demolished to make way for new developments, to free land, because of non-structural design errors, because they are considered unfit for their purpose, or simply because they are abandoned due to relocation of businesses.
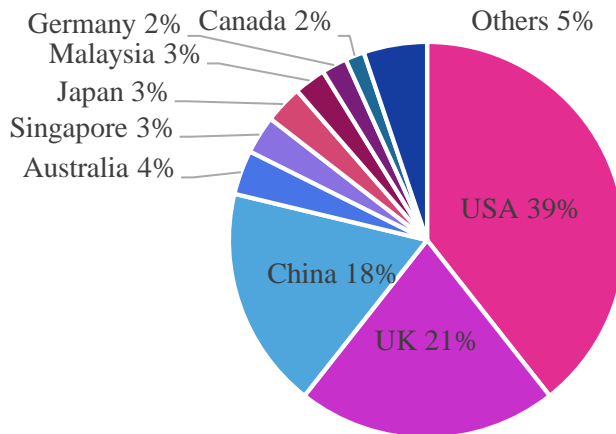
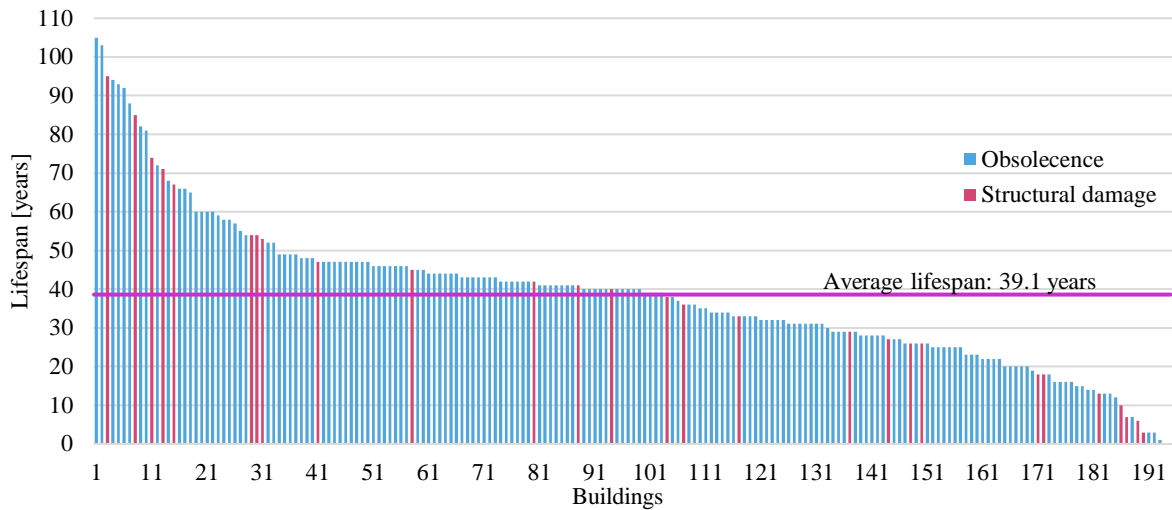*Figure 1. The 193 studied demolition occurrences grouped by country*

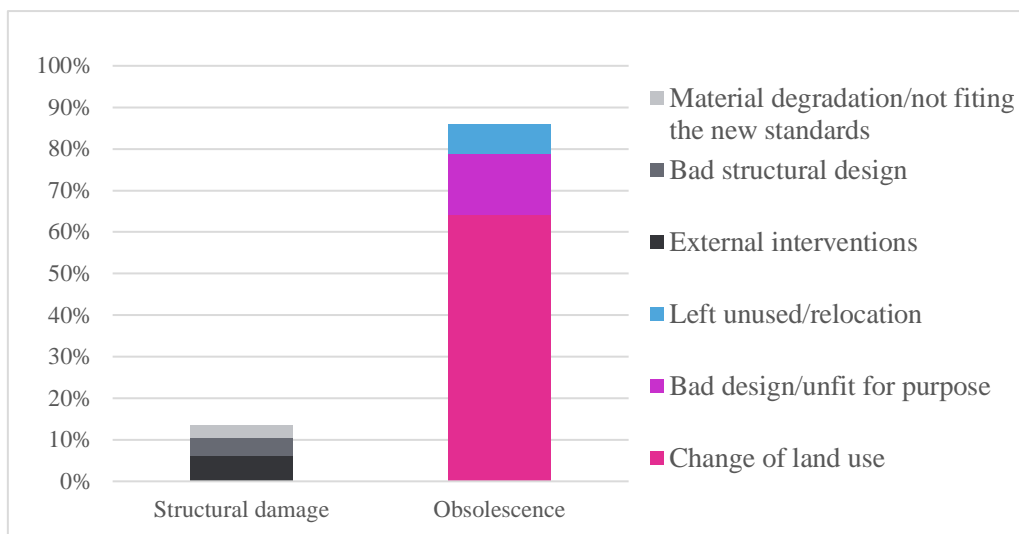*Figure 2. Building lifespan and reason for demolition of all 193 studied cases.*

Figure 3. Comparison of the demolition reasons.

Only 14% of the demolished buildings are in the structural damage category. The other 86% fall within the functional obsolescence category. A detailed overview of the reasons for all studied demolitions is shown in Figure 3.

2.2. Significance of demolitions

Two important parameters that help estimating the environmental impact attributed to the construction of the demolished edifices are the floor area and the number of floors of each building. On average, buildings have 23 floors with a mean gross floor area of 1600 m^2 per floor. In general, reinforced concrete with a density of 2500 kg/m^3 and a reinforcement rate of 150 kg/m^3 is considered. Even if not all buildings have a structure solely made of reinforced concrete, for simplification it was assumed that all structural material is concentrated in the slabs. In other words, the material mass of vertical structural elements (columns, walls) is added to the slab thickness. The average thickness t_f of all slabs including the volume of vertical elements is assumed to be 20 cm. These assumptions were drawn after analysing five of the 193 demolished structures in detail through shop drawings. The total volume of concrete (V_c) is computed via Eq. 1, where n represents the total number of buildings, $n_{f,m}$ is the average number of floors, and $A_{f,m}$ is the average floor area.

$$V_c = n \cdot n_{f,m} \cdot A_{f,m} \cdot t_f \tag{1}$$

Eq. 1 gives an average volume equivalent to 7800 m^3 per building. Reinforcement steel corresponds to 1170 tons per building. After demolition, all this structural material ended up as waste. Greenhouse gas (GHG) emissions attributed to the production of concrete are estimated to 350 $kgCO_2eq/m^3$ [11] and that for reinforcement steel 1.83 $kgCO_2eq/kg$ [12]. These values are representative of today's fabrication technologies which presumably improved in terms of energy efficiency and emissions compared to those of 1960 (the average construction year for the demolished buildings). Therefore, the real GHG emissions are assumed to be underestimated. Nevertheless, in contrast to their relatively short lifespan the 193 studied structures are responsible for approximately 1.0 million tons of CO_2eq, i.e. 141 $kgCO_2eq/m^2$. In addition, 3.8 million tons of concrete are wasted, hence stressing the need for alternative ends of life.

3. Search for a new solution

As the main cause of premature building demolition is determined to be socio-economical rather than technical, the current environmental impact mitigation methods will not be effective unless they are combined with circular economy principles in order to ensure reusability of all the components beyond the obsolescence point. Pomponi et al. [13] suggest that in order to enable circular economy paths to be used in the building industry, this has to undergo significant technological development. Fivet et al. [9][14] proposes a series of mandatory characteristics for building systems in order to ensure open-ended reuse. Those characteristics are durability, versatility, modularity, reversibility and adaptability and concern not only the components or connections, but they also refer to assemblies, sub-systems and systems. Figure 4 illustrates the idea of reemploying structural components for multiple service cycles which allows the elements to maintain their value past the point when the value of their encompassing assembly is lost.
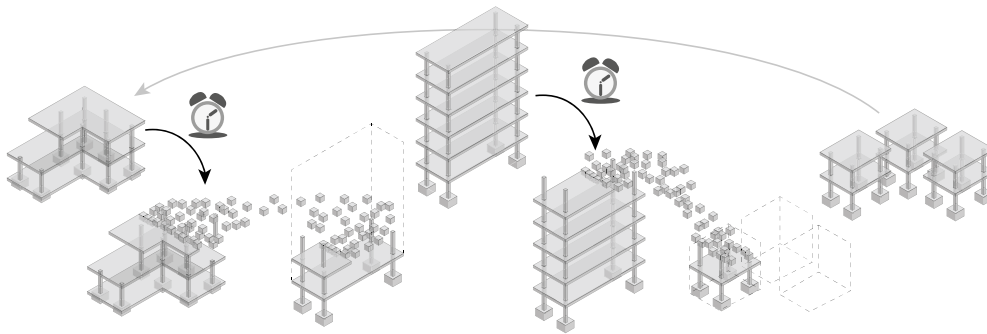
Figure 4. Circular economy paths in structural systems

3.1. Structural system

In the following, a novel technical solution specifically developed to fulfill all the constraints imposed by reusability, serviceability and structural requirements is introduced. It consists in a modular structural system composed of interconnected slab modules (Figure 5a) that can be combined into multiple rectangular floor plan shapes, while allowing numerous column layout configurations. The shape of the slab module is a grid of orthogonally interconnecting beams (Figure 5b) and it is designed such that it allows the passing of columns through its vertical openings while supporting the slabs. This design is facilitating fast assembly and disassembly, allowing the elements to be reemployed in new floors shapes and new building configurations without being constrained by the initial configuration. Extending an existing building that uses this system can be easily done by just attaching new components (newly manufactured or reused from other applications). Often, during renovations, buildings need to undergo important structural interventions, e.g. the introduction of new openings in the slabs for installation shafts or stairwells and elevators. Besides being costly, these interventions present technical challenges that in some cases cannot be overcome, potentially leading to demolitions. An important advantage of the proposed system is that it already contains small vertical shafts for installations, and if needed, modules can be dismantled in order to allow the creation of larger openings.

Another feature that ensures reusability of the system is the potential of the slab modules to be stacked vertically in order to increase the static height and thus the stiffness of the slab, which allows configurations with larger spans or higher loads. This stacking approach alleviates oversizing effects, allowing optimum weight distributions which in turn reduces material usage.
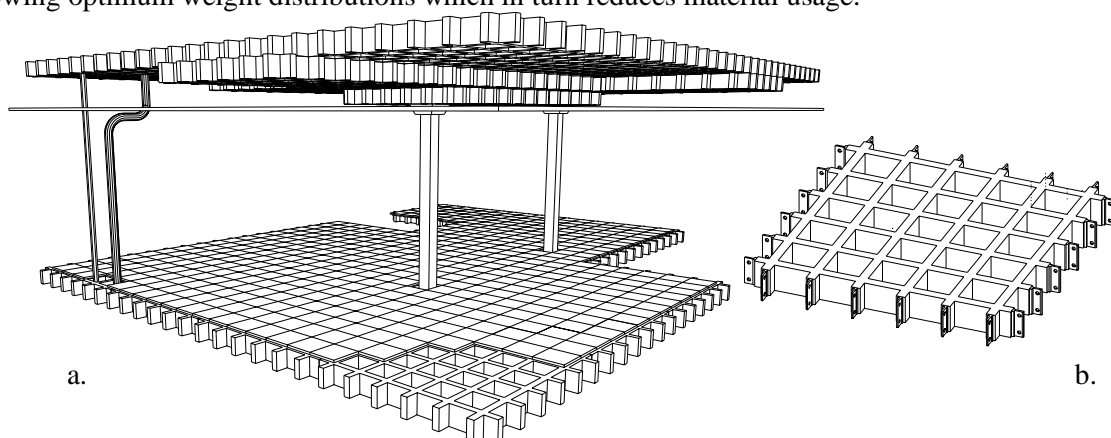

a.   b.

Figure 5. Schematic exemplification of the structural system (a), and slab module (b)

The selection of materials appropriate for this system is based on environmental aspects, therefore slab modules are preferably made of engineered timber which is considered a low carbon alternative to other structural materials. Yet, this is not the only option that could be employed. Modules with similar reconfiguration potential could also be made of ultra-high performance concrete or steel. Connections

between modules must be designed to withstand the equivalent loads (bending moment and shear) as the section of a continuous beam element would do. The use of bolted steel plates is estimated to be able to ensure the necessary load carrying capacity. These steel plates are connected to the timber element through glued-in threaded rods. Depending on the building height, the spans, and the number of floors, the columns can be made of mass timber. Nevertheless, steel and reinforced concrete remain desirable options for columns, given their higher strength.

Another modular element that completes this system is the floor finishing tile. This element is used to create the walkable surface covering the vertical openings in the slab module (Figure 6). Besides the finishing role, this element is supposed to integrate insulating materials for thermal insulation and phono absorbent materials that help protect against acoustic and vibration issues.
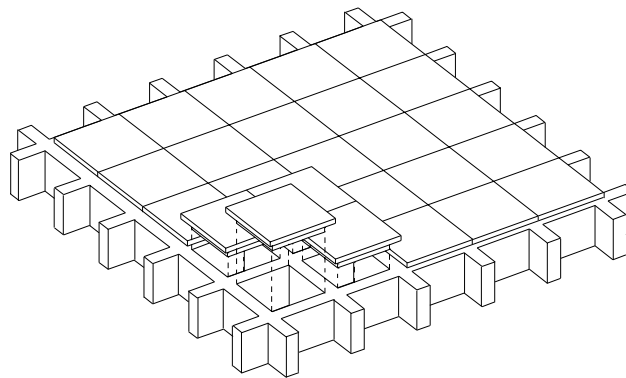

Figure 6. Slab element covered by tile elements

To increase the reusability potential, the presented structural system must be accompanied by modular non-structural elements to build partitioning walls, ceilings and floorings, and the envelope (i.e. façade and roof) (Figure 7). When the building system is designed such that all its elements are reusable then the environmental impact due to waste pollution can be further reduced.
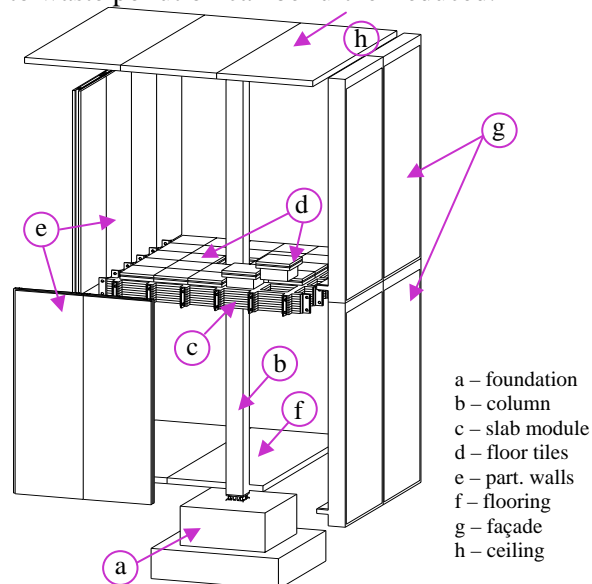

a – foundation
b – column
c – slab module
d – floor tiles
e – part. walls
f – flooring
g – façade
h – ceiling

Figure 7. Complete building system

4. Barriers and challenges for implementation

On a smaller scale, the challenges that this system might encounter are of technical nature. For example, structural limitations in terms of attainable heights or extreme load conditions (wind, earthquake) could be detrimental. Ensuring durability of the components while undergoing multiple assembly-disassembly

cycles, complying to strict fire regulations or fabricating the components within exigent tolerance limits might as well be challenging. Through further developments of the system these challenges can be overcome, for instance by employing already existing structural systems (e.g. bracing systems, structural cores, external fire protection) and through advanced manufacturing (e.g. digital fabrication).

On a larger scale, economic viability and competitivity with current construction methods could be seen problematic due to the novelty of the proposed system, even if skills required to design and build it are not significantly different to conventional solutions. This is in line with Blismas et al. [15] who conclude that the main challenges that the construction industry is facing are knowledge related, especially when it comes to shifting towards novel procedures as offsite manufacturing and prefabrication.

To ensure environmental impact reductions, the material used in the timber variant of this structural system should be locally sourced and come from sustainable forestry. This may not be feasible in certain regions of the world. In this case the concrete or steel option should be considered.

5. Mitigation potential

Reductions of adverse environmental impact through reusing structural elements are obtained even in cases of one-time reuse and when considering relatively long transport distances and oversizing [16]. Moreover, the proposed structural system is designed considering a usage of its parts for at least three life cycles. This is in line with collected examples where three buildings have been consecutively built on the same site. If the average lifespan of a building is assumed to be that of the average age determined in section 2 (~40 years), the minimum lifespan of the system components must be 120 years. Historic examples of timber construction show that such long lifespans are not unusual if the structure is well maintained and protected from weathering. It is therefore assumed that timber is suitable also for this application. Reductions of structural capacity due to cycles of loading and unloading are expected to be overcome thanks to the possibility of the system to adapt its stiffness and strength through stacking of modules. Alternatively, reduction of structural loading in subsequent reconfigurations can be achieved through a reduction of spans between columns.

In a hypothetical case where all 193 buildings had been built with this system, even though they reached their end of life and have been disassembled, the embodied carbon would not be wasted since the components would still be available for further reuse cycles.

Offsite manufacturing and modular building systems can reduce GHG emissions compared to conventional construction [17], [18]. Besides environmental benefits, offsite manufacturing could offer important economic gains through optimized fabrication processes, reduced time on site and reduced manpower needed.

6. Conclusions and discussions

Most of the demolished buildings studied in section 2 are well known architectural examples, therefore they are easy to find. Future work should complete the missing data and extend the database to more entries. More dimensions and measurements (i.e. floor plans) of structural elements could increase the accuracy of computed material quantities.

If the trend of buildings being demolished after less than 40 years continues in the future, by 2060, there will be numerous cases of buildings built in present days that will be torn down. This loss will ultimately generate useless waste, unless principles of circular economy are fully implemented. The need for reusable building systems is neglected by the current industry with the argument that existing modular solutions do not provide enough flexibility and versatility to fulfill unforeseeable future needs. Instead, this paper and the proposed structural system show potential ways to overcome these problems, benefitting from the environmental point of view as well as the economical one.

The technological solution proposed in this paper combines three key features, open-ended reusability, offsite manufacturing and low carbon materials to help reduce the environmental impact of the building industry to the minimum.

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