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Potentials of reusing steel skeleton structures from multistorey parking units for architectural applications

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Abstract

In the context of urban mining, which aims to extend the value chain of building components to conserve resources, save energy, avoid waste, and reduce emissions, the reuse of structural steel has great potential, that has hardly been exploited to date.
In Germany, a significant amount of steel is found within multistorey parking units. Due to the standardised and mass relevant steel used in these structures and considering their diminishing significance in the context of transportation transitions, these buildings offer specific opportunities for reuse.
The research aims to investigate the reuse of structural steel from parking facilities in a new architectural design purpose with focus on multistorey residential buildings, as these will become increasingly important in the future construction due to the predicted growth of the world population and global cities.
The research methodology begins by identifying the reuse potential of structural steel from parking units for future multi-storey residential buildings. The study then delves into the exploration of hybrid construction methods, which involve incorporating standardized steel profiles with clay and reinterpreting historical cap ceilings. These approaches aim to foster the development of innovative architectural solutions.

Keywords

urban mining, re-use, steel, structural steel, steel skeleton, car parks, residential building, multistorey, hybrid, hybrid construction

1 Reusability of Structural Steel

1.1 Relevance

In 2020, the crude steel production reached an all-time high of 1,878 million tonnes per year [1]. Global steel production has thus increased almost fivefold since 1960 and is, according to forecasts [2], projected to increase 1.7-fold by 2050 [3]. However, the production of new steel products is associated with significant environmental impacts [4, 5] (Figure 1). In 2019, the iron- and steel production accounted for around 8% of the global final energy consumption and almost 7% of all process- and energy-related emissions [6]. Thereby, around half of the produced steel is used within the building and construction industry [2] (Figure 2).

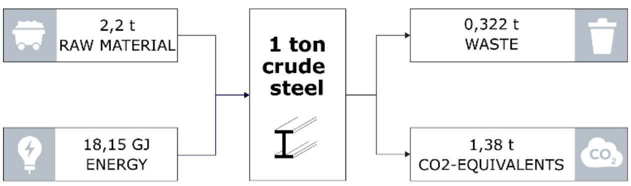

Figure 1 Environmental impacts in the production of crude steel

In Germany, about 6 % of structural steel is reused and about 94 % is recycled. Considering the waste hierarchy at European level, the re-use of steel elements is not only preferable to recycling, but also offers the possibility of saving the energy required for the manufacturing process and avoiding the associated emissions [7,8]. Rising costs for new steel products due to CO2-pricing [9] and future hydrogen processes [10] could also lead to a reverse of the cost issue, considering the financial savings potential in procurement, material testing or processing within the reuse of steel [9].

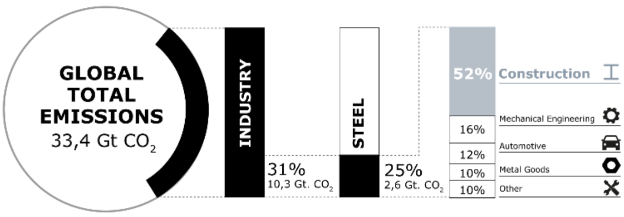

Figure 2 Share of total global emissions caused by the steel industry

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1.2 Suitability for Steel Reuse

The reuse of steel is primarily characterised by individual material-specific advantages in terms of durability, standardisation and demountability. The building material has a high strength and can be manufactured with precision and quality [11]. In addition, structural steel has been produced according to consistent standards and strength classes for several decades [3]. The chemical, physical, and mechanical material properties have remained almost unchanged since the beginning of the 20th century [12] and only deteriorate under extreme influences such as high thermal stress, environmental degradation, or high fatigue loading [13]. The assembly and disassembly times of steel profiles are also short due to the high level of prefabrication and the use of standardised joint details [11].

1.3 State of the Art

The research project "PROGRESS - PROvisions for Greater Reuse of Steel Structures" funded by the RFCS (Research Fund for Coal and Steel) of the European Commission, has already identified and defined methods and conditions for efficient deconstruction as well as criteria and evaluation procedures for the reusability of components of the primary structure and the building envelope of single-storey steel buildings (mainly halls). A guideline for the future planning and design of such buildings complements this investigation [14, 15].

In addition, the REDUCE research project has comprehensively analysed the deconstruction and reuse of composite steel structures, in particular multi-storey buildings. The main focus was on the development of demountable composite floor systems by creating deconstructable nodes using alternative connection techniques [16, 17].

1.4 Research Interest and Methodology

The present work builds on these findings and further investigates the re-use potential of steel sections from multi-storey parking structures for new architectural applications in future residential construction.

The research method is structured as follows:

I. Analysis of the existing potential in the urban mine by examining the load-bearing structures used and determining the masses and components inserted

II. Investigation of the reuse potential by alignment with the structural requirements in future multi-storey residential buildings

III. Identification of the reuse potential in future multi-storey residential buildings using hybrid construction methods

IV. Prospects for new clay-steel hybrids through the reinterpretation of historical cap ceilings

2 Steel Construction in Germany

2.1 Existing Potential within Urban Mining

Reusable steel components are mainly released at the end of a building's life during demolition or dismantling or predominantly when buildings are converted to another use.

In Germany structural steel is mainly found in non-residential buildings in halls and industrial buildings [18, 19]. In relation to the total gross volume of all building completions in Germany in 2019, the share was around 23%. In total, about 42 million m³ of enclosed space was converted into steel construction. Warehouses account for the largest share (39%), followed by factories and workshops (25%) and agricultural buildings (17.5%) [18].

In terms of the total tonnage implemented in steel construction, hall structures account for an average of about 32%, followed by columns and girder structures with about 24% [19]. As multi-storey car parks in composite steel construction cover a market share of about 80% [20], it can be assumed that these are included by a significant share within the last-mentioned category of columns-girder-structures [21] (Figure 3).

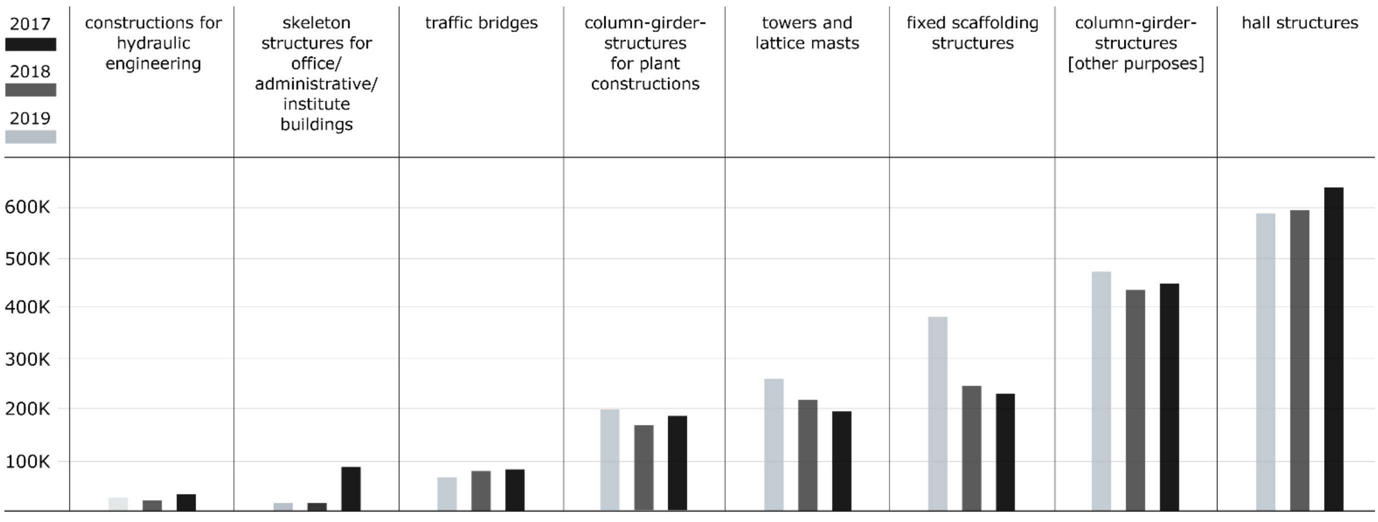

Figure 3 Steel production by structural use according to total tonnage implemented in Germany from 2017-2019

2.2 Steel Structures in Multi-Storey Parking Units

For technical and economic reasons, multi-storey car parks are mainly constructed using composite steel structures [22]. However, traditional composite systems are difficult to deconstruct. As the slabs are cast in concrete with the studs welded to the girders, non-destructive separation during demolition is extremely costly or even impossible. Accordingly, new techniques for non-destructive dismantling have been devised, such as DEMODULOR from the Carnot MECD Institute (Matériaux et Équipements pour la Construction Durable) [23], or various forms of demountable shear connector systems, developed and analysed in the REDUCE research project [16].

In the case of typical demountable and reusable car parks, the composite effect can be dispensed by using friction bond and beams with a high yield strength, e.g., S460 [24]. Slabs and steel girders are simply joined using head bolts and loops [25] so in the event of future demolition the precast slabs can be easily detached [24]. Due to the friction-only connection, this construction method is a proven and economical alternative [26].

The steel structure itself basically consists of vertical columns and horizontal beams as hot-rolled sections. The connections are generally bolted [22].

For sectional columns, it is normally recommended to use HE series elements and S355 grade steel. For larger structures and in certain cases, it may be of advantage to use steel grades up to S460 [24]. The choice of beam depends mainly on the span width and the way the slabs are manufactured. IPE beams in steel grades S235, S355, S420 and S460 are normally used depending on the construction method and the span [24].

Due to the optimal degree of utilisation in terms of space consumption, parking bays with an angle of 90° have become common practice in car parks. Typical dimensions, i.e. the clear depth without intermediate supports, are between 15.50m and 16.50m, depending on the bay (2.30-2.50m) and the associated carriageway width (6.50-5.50m) [27]. The roadway and parking bays are usually spanned without columns. The distance between the supports is determined by the span of the deck and is equivalent to the single (2.3 - 2.5m) or double (4.6 - 5.0m) parking space width [22].

3 Future Potential for Steel Reuse

3.1 Multi-Storey Residential Buildings

According to current developments, many more people will live in ever larger cities [28]. To reduce the additional space required, multi-storey residential buildings will have a significant importance in the future due to their high density [29]. As part of this process, the residential buildings of the future will place new demands on all relevant disciplines in their design and construction. Floor plans with higher structural densities must be harmonised with sustainable building typologies with variable and flexible usability for different forms of living and working while at the same time reducing the consumption of resources and space [30].

3.2 Reusability within Multi-Storey Residential Buildings

Steel has an important role in many areas of application in the construction sector. However, the material is currently hardly used in German residential buildings [18], although short construction times due to a high degree of prefabrication, assured quality and durability, the possibility of implementing variable and flexible space utilisation as well as the recycling and reuse potential are key arguments for its use in such buildings [31].

Within the structural design of traditional multi-storey steel buildings, a basic distinction is made between slab systems with down-stand beams and flat slab systems with integrated beams (slim-floor) [32]. For short to medium spans (grid approx. 11 × 8 m), flat slabs with integrated steel beams are recommended. For larger spans, e.g., within residential building typologies, slabs with down-stand beams are more suitable, as they allow an open floor plan design without the need for additional internal columns [33]. Accordingly, the use of steel girders from previous car parks is very appropriate in this context.

For multi-storey residential buildings in steel construction, where larger column-free areas are required, a primary steel structure is preferred, equally to the structure used for multi-storey car parks. In terms of the steel profiles selected, matching elements of similar steel grades are used. Normally, hollow- or HE-sections are applied for the columns, which are basically integrated into the wall construction. IPE profiles, on the other, are more convenient as floor beams [31, 34].

While the arrangement of columns and beams in car parks is determined by the dimensions of the traffic areas, a functional and efficient floor plan design of multi-storey residential buildings in steel construction results from the slab system, from which the spans, column spacings and the arrangement of the beams are derived. The positioning takes place within a fixed organised grid. Uniaxial load-bearing slabs over 2-6m and beams made of rolled I-beams with spans of 6m up to 16m are typical [31, 34]. Assumed loads for floor slabs in residential buildings are 1,5-2 kN/m² (DIN 1055-3).

It becomes clear, that there are relevant similarities for multi-storey car parks and multi-storey residential buildings, depending on the grid dimensions, profiles, steel grades and loads used (Figure 4):

parking units	residential buildings
column spacing	
2.3m - 5m	2m - 6m
beam spans	
15.5m - 16.5m	6m - 16m
columns | steel profiles & steel grades	
HE-series S355 - S460	HE-series/hollow sections S235/355
beams | steel profiles & steel grades	
IP-series S235 - S460	IP-series S235/355
loads	
2,5 kN/m²	1,5 - 2 kN/m²

Figure 4 Corresponding structural characteristics

3.3 Reuse Potential in New Hybrid Constructions

Multi-storey residential buildings are usually constructed with a high mass proportion of reinforced concrete due to a variety of structural and physical requirements. In this context many building materials are often only able to fulfil the required verifications to a limited extent [35]. Accordingly, new hybrid construction methods are increasingly coming to the fore. During innovative technical advances, wood, for example, is increasingly being used in combination with reinforced concrete or steel in residential and multi-storey construction. New standards and design developments have recently led to the implementation of exemplary buildings [36].

Wood and steel are often combined when high loads need to be transferred at points with large spans. Exemplary references for its use in current residential and multi-storey construction include the SKAIO in Heilbronn by Kaden + Lager [37], the Workspace OR6 in London by Waugh Thistleton Architects [38] or the Building D(emountable) in Delft by Cepezed, which was also designed as a fully degradable system [39].

Against this background, the reuse of structural steel in future multi-storey residential buildings represents the next logical step towards an even more consistent sustainable use of the resources available to us. Due to the mass-relevant steel used in multi-storey car parks, often as standardised design in the form of open rolled sections in column-girder structures [22], the reuse of the components contained therein is highly likely to be implemented in the context of future construction methods in multi-storey residential buildings [40], with the possibility of realising sustainable building typologies of high quality.

In addition to the current developments of hybrid structures using wood and reinforced concrete or steel, the combination of steel from urban mines with clay as a locally and globally available building material also offers great potential for implementation in future building construction, to strive for an even more consistent sustainable use of the raw materials available to us. Compared to wood, clay is locally available worldwide, ecologically harmless and has ideal physical properties. Due to its moisture-regulating and heat-storing material properties, air-dried clay promotes a comfortable indoor climate and can also be recycled many times [41].

Since ceiling structures as part of the primary system account for up to 70% of the total mass of multi-storey buildings, there is a high saving potential in this area [42] and the possibility to significantly promote sustainable and environmentally friendly construction using alternative materials and construction methods [36].

Normally, floor slabs are designed as flat slabs, but this results in an unfavourable load transfer due to bending stresses [35], which contradicts the possible use of purely compressive earthen building materials. Consequently, it is therefore worth looking at the past of German building history, before reinforced concrete was established through industrialisation and predominantly flat-arched solid ceilings, such as the Prussian cap ceiling were widespread. The design of flat arched slabs, in which the load transfer is purely compressive, allows the implementation of much more material-efficient systems, as a high load-bearing capacity can be achieved under uniform loading [43] (Figure 5). Historic vault ceilings are basically made of steel girders between which an arch of brick is spanned at regular intervals [42]. The reuse of steel sections for the tensile elements (columns and beams) and the use of clay for the compressive elements (walls and vaults) offers an interesting approach to developing a structure adapted to the historical example, considering today's requirements, so that it can also be used regionally in the floor construction of the future. Through this symbiosis of biological and technical cycles (Figure 6), high savings can be achieved in terms of energy and raw material use, CO2 emissions and waste generation compared to conventional construction methods [44]. As clay is classified as fire class A1 according to DIN 4102, the use of clay building materials can also ensure increased fire resistance of the reused steel components in the event of a fire [41].

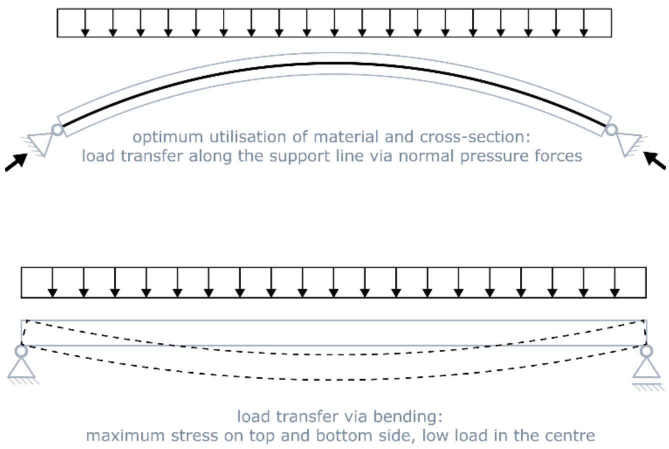

Figure 5 Comparative stress loads of arched structures and flat slabs

4 Conclusion and Outlook

By comparing the structural requirements of the primary load-bearing structure in car parks and residential buildings, it becomes clear that there are relevant similarities in terms of profile geometries, grid dimensions and material properties (Figure 4), so that corresponding elements from previous car parks are well suited for reuse in future multi-storey residential buildings. The potential lies primarily in the large spans and the associated degree of column-free space that can be achieved, with the corresponding flexibility and variability. This means that purely conventional residential buildings as well as new cluster concepts or mixed uses can be realised.

In this context the adapting of historical building methods by using modern manufacturing processes and construction techniques opens up new possibilities and a wide range of research questions regarding the diverse requirements of modern housing. The fulfilment of building physics, structural design and construction aspects in a unified overall concept comes with corresponding challenges and is to be considered in further research through interdisciplinary cooperation. The implementation of the reused profiles in innovative hybrid constructions also demonstrates new perspectives for sustainable building in the future.

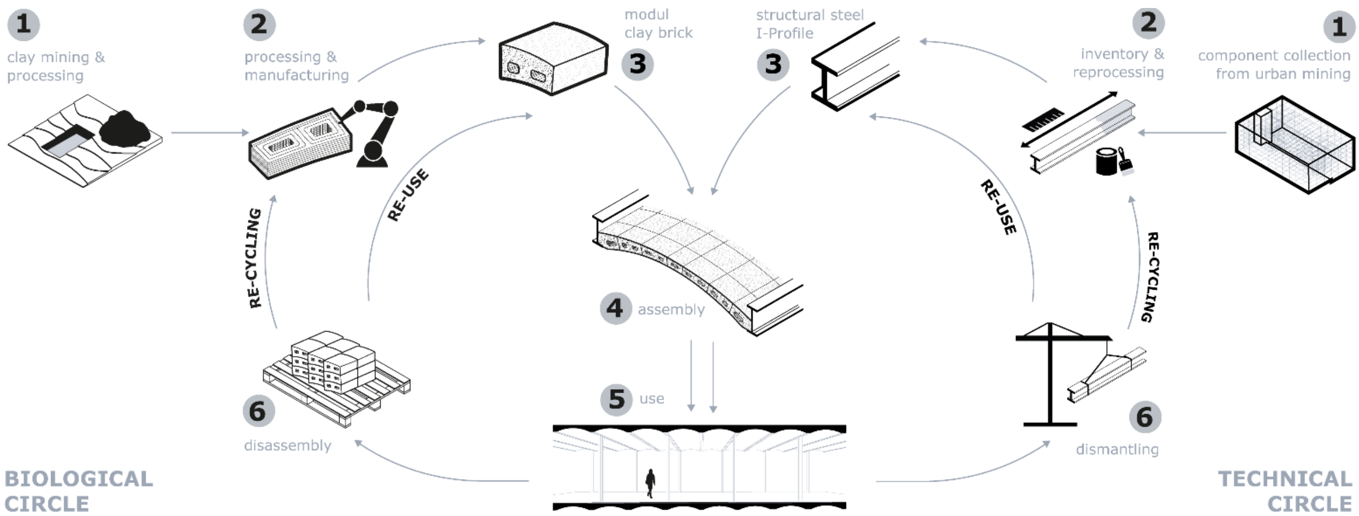

Figure 6 Circularity of clay and steel in hybrid construction systems

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