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Lessons learned from using a donor skeleton in a 3 storey office building

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Abstract

During the last decade a lot of attention has been paid to sustainability of structures. Reuse of existing buildings, limiting environmental impact and reuse of elements were applied in practice. In general, reuse of elements, with for instance the use of a donor skeleton, was applied on a very limited scale, as this reuse often comes at a price. In 2018 there was an opportunity to apply a donor skeleton on a larger scale in an office building of 6200 m^2. This paper will describe the process of design and construction of this special project, and will derive lessons learned in order to increase application of upscaling of building elements in future projects.

Keywords: circularity, re-use and sustainability of structures

1 Introduction

The Brundtland report [1] defines sustainable development as: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

Within science a lot of attention has been paid to various frameworks for sustainable construction (e.g. shearing layers model Brand [2]), typologies and ways to measure sustainability. As the load bearing structure entails approximately 60% of the weight of a building, it is clear that the choices of structural engineers have a large influence on the environmental impact. Within practice, a huge number of initiatives of sustainable and less sustainable solutions have been launched. IMd Consulting engineers has been a frontrunner in the Netherlands in methodically thinking about sustainable structural engineering, in combination with practical application of the developed strategies.

In 2009 IMd published five principles of sustainable structural engineering, which were updated in 2020 [3].

These principles are:

1. Increase the lifetime of a building/structure
2. Reduce the use of materials
3. Use sustainable materials
4. Include the environmental impact of construction logistics and transport
5. Design for circular use in the future

The first principle entails that when a structure has a high level of adaptability, various types of future use are possible within the designed geometry, and the need for demolition and rebuilding will be reduced.

The second principle, is related to minimizing the amount of material needed for the structure.

This should be regarded in relation to the third principle: it is preferable to use sustainable materials, with the least environmental impact.

The focus should not be entirely on construction materials, the environmental impact of construction logistics and transport are of relevance too. It is preferable to apply materials that can be produced within a short distance from the construction site.

The fifth principle recommends focussing on the future possibilities of a structure by ensuring circular use of the structure itself, its elements and/or its materials. When designing a structure, already take reuse of the building or of building elements into account.

Literature shows several hierarchies of sustainable strategies. One of these typologies is the 10R model of Cramer [4]. Her hierarchy consists of 10 strategies: refuse, reduce, renew, re-use, repair, refurbish, remanufacture, re-purpose, recycle and recover (see also figure 1, with some adjustments).

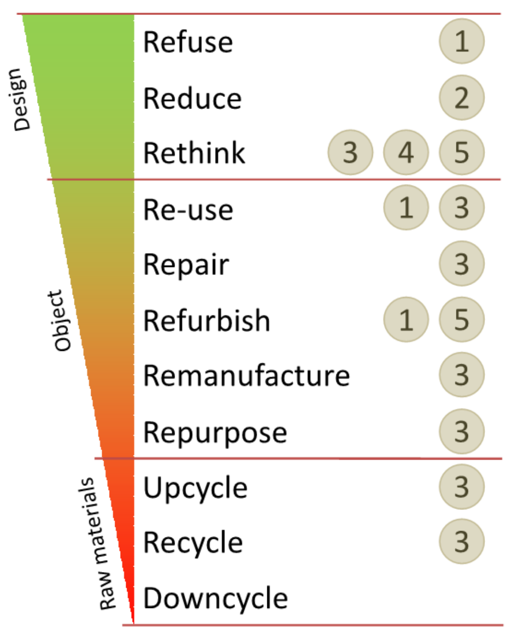

Figure 1: Adjusted 10R model and IMd's principles of sustainable structural engineering (after: [4]).

The first three strategies (refuse, reduce, rethink) are related to the design. The next five strategies to the object itself, and the final three strategies to raw building materials.

If we try to couple IMd's five principles to Cramer's strategies (figure 1), it becomes clear that in the design phase all of the five principles for sustainable structural engineering can be influenced.

During the last decades IMd and other companies have applied these principles in building projects. In particular many existing buildings were transformed to accommodate a new function, extending their lifetime. Furthermore, attention has been paid to the environmental impact of material and energy use in new buildings, approved by labels like BREAAM and LEED. In the seventies and eighties various types of modular construction were developed, especially in Scandinavia. However, until recently the reuse of building elements has not been applied on a large scale. Understandable fears like misfit of elements, inferior quality of deteriorated materials, and therefore additional risks and costs prevented this. With an increasing awareness of the necessity to change current building practice and to avoid depletion of raw materials, concepts like donor skeletons were developed. A donor skeleton is the situation where an existing structure is demounted and remounted at another location, usually with a different shape. Until recently, these concepts usually have been applied on a small scale in for instance residential buildings. Ways to increase the scale of application were explored with for instance Madaster (www.madaster.nl), which processes a database with building elements of existing buildings. When a building is going to be demolished, this database can be used to see if elements can be reused.

The project Biopartner 5, which will be delivered in 2021, is an example of an office building where several of the strategies were included. This paper will give a description of the design and construction of this building, and will provide an overview of lessons learned.

2 Background and initial design of the project

The Client's wish was to develop an incubator for biotech companies, close to Leiden's University. Several start-ups were already hosted in earlier developed buildings, and there was a growing demand for additional space. Client wanted to meet these spatial needs, but also wished to make an iconic building by creating a very sustainable design.

The preliminary structural design was a conventional steel structure, but with demountable connections, to enable reuse of elements in the future. The floor slabs were also designed in such a way that reuse of elements was possible. During technical design stage, the design team received information about an existing building on the university campus, that was to be demolished. An investigation was initiated to find out if elements of this building could be reused, and finally it was decided to reuse a large part of the steel structure of this building. By this decision the existing building was promoted to be a "donor skeleton". Furthermore, other elements from the existing building could be reused, like crushed masonry to be used in the green façade.

Figure 2: bird's eyes view of the design (image Popma Ter Steege)

Figure 3: view of the façade, with crushed masonry as part of the green façade (image Popma Ter Steege).

The design had to be checked to see if it would meet the possibilities of the donor skeleton. The gridlines of the initial design were set at 3,6m because this resulted in an efficient structure. The gridlines of the structure with use of donor skeleton were kept at 3,6m, which resulted in some useable overcapacity of the existing steel beams. It was decided to provide stability in one direction, with portal frame behavior, as the existing steel structure included moment resisting connections. In this way the overcapacity of the steel beams, could be used for stability.

3 Structural design

The structural design consists of hollow core slabs for the floors and a steel skeleton. A plan of the roof is presented in figure 4.

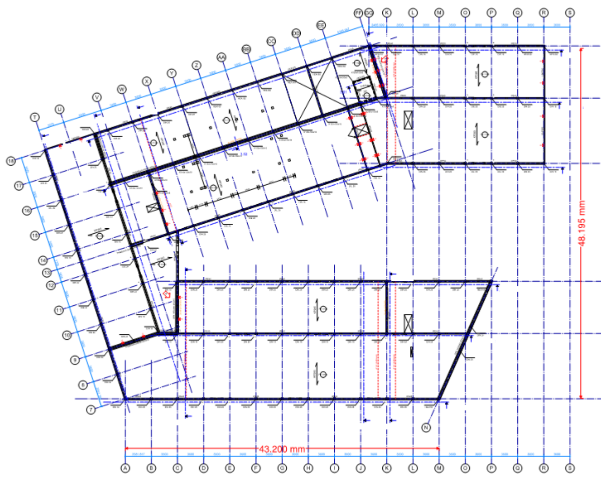

Figure 4: roof plan: hollow core slabs and steel beams

The steel structure consisted to a large extent of elements of the donor skeleton. At some points, for instance wind braces and a truss for a winter garden, new steel elements were included. In these situations it was decided that new steel would be more efficient in terms of labour and cost. However, the design strategy remained to reuse as much as possible.

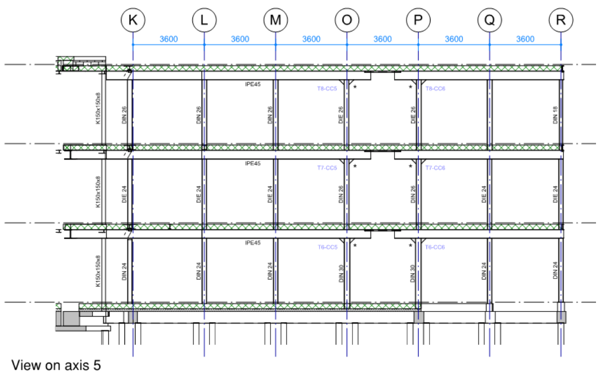

Figure 5. Section with donor steel elements and hollow core slabs

With the choice for existing steel the idea of making the building demountable was not abandoned. The design team soon realized that demountable, bolted connections would also have the benefit of reducing transportation cost. When the connections of the existing structure could be made with bolts, it could be avoided that the elements had to be transported to the factory to remove paint and apply welds.

The connection between hollow core slabs and steel beams is designed to be demountable. However, as they have a function in stability, careful design of these connections was needed, to ensure diaphragmatic behavior (see figure 6).

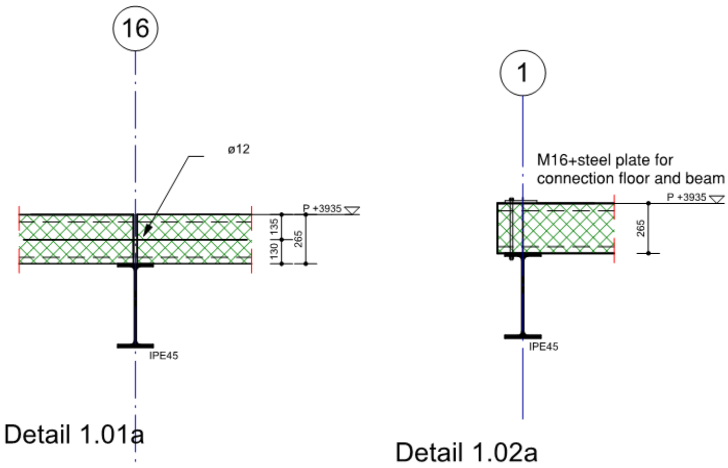

Figure 6: connections between steel beams and hollow core slabs that needed to be demountable, and to provide sufficient coherence for stability

The foundation was a traditional foundation with prefab concrete piles and cast in situ beams. It appeared hard to find donor elements that could be used for the foundation, or to include elements that would be demountable. This is a challenge for future projects.

4 Testing of materials and disassembly of existing structure

4.1 Testing of materials

To know what characteristics of the existing steel could be used for the calculations, various samples were taken, and destructive tests were performed. Chemical composition of the steel was analyzed, to check if it was suited for welding. However, only after removal of paint it appeared that the steel was galvanized, which would make welding harder. For several connections, detailing was changed in bolted alternatives.

A recalculation of the existing building was done to get a good understanding of the stresses that already had occurred in the existing steel members. In the end it was chosen to use a value of 180MPa for the yield strength of steel. This value was below the values of all tested elements. Furthermore, this value was conservative, related to the normally used steel in that era.

Finally, destructive testing of some welds was performed. It appeared that several welds of the moment resisting connections, didn't meet demands of proper welding. This type of connections needed to be strengthened with bolted connections in a later stage of the project.

Figure 7: steel elements in the existing building, during inspection

Figure 8: damaged donor steel after disassembly

4.2 Disassembly of existing building

The donor skeleton had to be demounted. Architect and structural engineer had to mark and code all elements that needed to be reused. A 3d BIM model of the existing building was made linking the coded elements from the old and the new building.

Furthermore, a protocol was set for the sizes of the elements and the allowable deviations. This appeared to be a challenge for the contractor. During disassembly, various elements were damaged to a larger extent than acceptable, and the disassembled elements were not properly stored, resulting in additional deformations of the elements.

Figure 9: improper storage of donor steel after demolition

After disassembly, it also appeared that several connections were different from the existing drawings, and reconsideration of these details was needed.

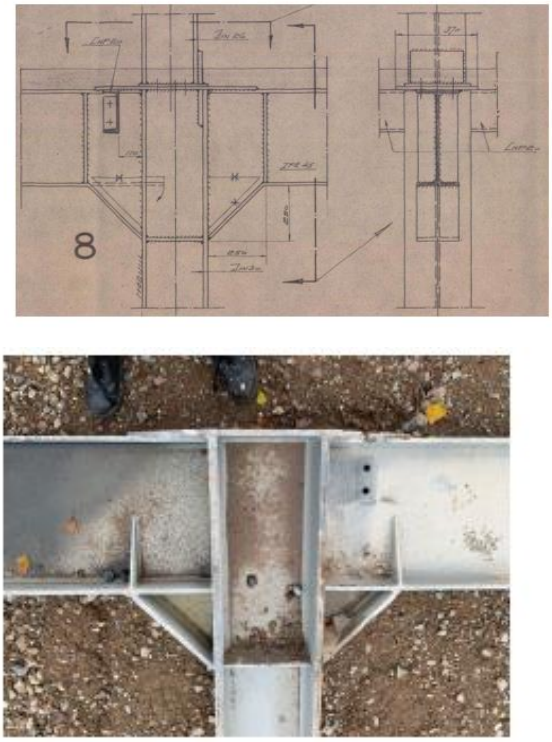

Figure 10: Difference between design of connections and actually constructed connections.

5 Construction stage

The construction of pile foundation and foundation beams with the ground floor, went without much difficulties. For the erection of the donor steel, all elements were measured before, and where necessary adjusted, to ensure that they would fit.

Figure 11: Assembly of steel elements (photo: De Vries en Verburg contractor, DVV)

Figure 12: side view of T-frame donor elements (photo: Rene de Wit)

As tests of existing welds were performed only during construction, some improvisation was needed to strengthen the connections, when appeared that weld quality was sometimes insufficient.

End of 2020 the façade was closed, and in spring 2021 the project was delivered.

6 Lessons learned

The design and construction of the project was evaluated in 2020, with input from project manager, main contractor, steel contractor, architect and structural engineer. The following lessons learned could be derived:

- The design should fit the available material, to reduce the number of actions needed to adjust the elements. In Biopartner 5, the chosen grid was suitable for the sizes of the available elements. Furthermore, stability in one direction could be provided by existing moment resistant connections.
- It should be carefully chosen what elements in the new building can be made with existing elements, and what elements need to be made out of new material.
- Reuse should not only be limited to elements, but where possible be extended to components. In Biopartner 5, T-frames where reused, which reduced the number of actions that were needed to make the connections. However, transport of these connected elements was harder.
- When it is clear that donor elements can be used, a testing program needs to be elaborated to determine characteristics and usability. It is of importance to determine the right number of samples, to be able to determine the allowable stresses. Recalculation of existing structure can be of aid, to make this decision. Furthermore, the composition and conservation of the existing steel needs to be determined. E.g. galvanizing of steel reduces the possibilities of welding and application of a fireproofing paint. Additionally, it needs to be known if Chrome 6 paint is used.
- Use of donor steel for execution class 3 projects might be hard, if the origin of the steel is not known.
- Demountable connections ask for special attention to robustness. In the design with hollow concrete slabs without structural topping, diaphragmatic behavior needed to be ensured with specially designed demountable connections.
- Disassembly of existing structures with the aim to reuse elements or components is very different from demolition of a structure. Communication and instruction about possibilities and needs between engineer and demolition contractor are essential.
- It needs to be determined what kind of deviations are acceptable and what measures are available to accommodate deviations in size and straightness. Furthermore, redundant amount of donor material is needed, as not all elements fulfil the requirements.
- To be successful, all building partners need to be committed. During the design and construction various challenges were faced that often took more time to solve than in traditional projects. This asks for a good collaboration and commitment of the various partners in design, as well as in disassembly and construction.

Figure 13: overview of building after construction (photo DVV)

7 Conclusion

The design and construction of Biopartner 5 was a challenging, although rewarding experience. Thanks to the commitment of all building partners, this project is an example of a double sustainable project: the design made use of a donor skeleton, and the connections were designed to be demountable, enabling future reuse.

Currently, the use of a donor skeleton in steel asks for more engineering time, and more construction attention, than a new steel structure. The costs can therefore be higher, but various potential users were attracted because of the sustainable character of the building. If in future, participants overcome the teething problems there should be enough margin between the price of used and new raw materials to make a sound business case. Furthermore if use of raw materials would be taxed by the government, than these kinds of sustainable initiatives will become more profitable.

8 Acknowledgements

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