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ORIGINAL ARTICLE

Design for disassembling, reuse, and the circular economy: a demonstration building, "Petite Maison"

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Abstract

For sustainability purposes, steel reuse at the material, structural element, and structure levels has been proposed and encouraged in recent years. Designing for deconstruction or disassembly is identified as one key strategy. A recent RFCS (Research Fund for Coal and Steel) project – REDUCE – has investigated the methodology and opportunities to design and facilitate the reuse of composite structures in steel frames. Furthermore, a demonstration building – the Pavilion "Petite Maison" – has been constructed using the solutions developed within REDUCE. The "Petite Maison" is located in Esch-sur-Alzette, Luxembourg, and it contributes to Esch2022, European Capital of Culture, by promoting circularity, reuse, and sustainability. It is open to public visits and is planned to be deconstructed with elements being tracked for reuse. This paper presents the design concept of the structural system of the "Petite Maison", proposals of standard and modular elements and kits, and the analyzing methods for adaptable steel connections and demountable shear connections that are applied in the system.

Keywords

Circular economy, Design for deconstruction or disassembling, Steel reuse, Demonstration building

1 Introduction

In alignment with the Green Deal [1] and Circular Economy Action Plan [2], design for deconstruction and reuse has been proposed in recent years for resource efficiency, reduction in both carbon emissions and construction waste, and for a Circular Economy. Considering innovations and promotions in using low carbon materials, for example, low carbon concrete [3], XCarb® steel [4], Cross-Laminated Timber and Laminated Veneer Lumber, reuse on elements and structure levels will potentially provide added value for sustainability and the economy.

The EU Horizon 2020 – BAMB project [5] started in 2015 has initiated circular solutions and tools to enable a more sustainable value chain for general building materials. The EU RFCS (Research Fund for Coal and Steel) PROGRESS project (2017 – 2020) [6] has targeted design for deconstruction and reuse of elements in single-storey buildings framed in steel. Following this project, the Steel Construction Institute, London, published a guide [7] for using reclaimed structural steel. The RFCS REDUCE project (2016 – 2019) [8] has focused on providing methodology for demountable multi-storey composite structures. A guide [9] on demountable composite structural systems has also been published based on the findings in REDUCE. Since 2021, the "Petite Maison" project [10] has been developed for the theme of circularity, with objectives such as demonstrating the phases of construction, use, and deconstruction, and showcasing the demountability of the systems proposed in REDUCE.

2 The REDUCE project

Composite structures have been widely used thanks to their improved structural behaviour resulting from composite actions between elements. However, traditionally, they are unable to be disassembled due to the permanent links, such as those between concrete slabs and their supporting steel beams via welded studs. This means that, at the end of the design life, the composite construction has to be demolished with steel sent for recycling and concrete downcycled or landfilled. The REDUCE project targeted composite structures and explored methodologies, tools, and guidance to facilitate design for deconstruction and reuse for these composite structures. Opportunities for greater standardisation, the quantification of whole-life benefits of the developed systems, and the use of Building Information Modelling were also investigated to encourage demountable design and reuse.

Experimental, numerical, and analytical studies have been performed, providing better insight into the behaviour and design approaches of composite structures in demountable systems. The developed systems are robust, modular, demountable, and potentially standardized and reusable in either in their entirety or partially. Adaptable steel connections between beams and columns, and bolted connections between slabs and beams have been used in the "Petite Maison" project.

3 Structure of the "Petite Maison"

Figure 1 shows part of the steel skeleton and exterior features of the "Petite Maison" building. The design concept is to form the main structure using a set of modular, standardized, prefabricated structural kits and make the structure fully demountable. As a demonstration building, three phases planned: construction, use, and deconstruction phases. The main aim is to demonstrate the circularity of building structures to engineers, architects, researchers, students, policymakers, and the public. To facilitate the reuse of elements of this building, each element will be linked to virtual databases to track use history, but this is out of the scope of this paper.

The structural system of the "Petite Maison" comprises a steel frame with adaptable steel connections between steel beams and steel columns, prefabricated concrete slabs connected to beams by bolts, and bracings providing lateral stability. Composite action of beams by bolted shear connections were investigated in the REDUCE project but the performance and design of such composite beams in reuse scenarios remains unfamiliar. Further experimental investigations are necessary. Therefore, the calculations for the "Petite Maison" were based on rules for steel structures. It should be noted that the weight of the steel beams and columns were reduced about 24%, from 17.39 tons to 13.25 tons, by using a higher grade of steel (S355 to S460). The embodied carbon is therefore reduced.

The steel frame is 10.8 meters (m) × 8.1 meters between the centrelines of the corner columns. These dimensions are defined based on a structural grid size of 1.35 m, which will be described in Section 3.3. Standardized structural kits are proposed and described in Sections 3.1 and 3.2. For complex joints where members meet in multiple directions, special care is taken to ensure that theses members are bolted to columns in predefined bolts holes. More information about the structural system used in the "Petite Maison" can be found in the related reference [11].

Figure 1 Photo shows the "Petite Maison"

3.1 The kit of slab and shear connection

As a demonstration for steel-framed composite structure, the composite action between the concrete slab and steel beam is established using bolted shear connections. Figure 2 illustrates how a bolt is used as a shear connector. The bolt will be inserted through the holes of the welded plates of the steel tube, all of which are all embedded in a prefabricated concrete slab, and then tightened from either the top or the bottom. The slab and shear connection are offered as a single kit for use and reuse.

Figure 2 Photo shows a cross-sectional view of a prefabricated concrete slab, embedded steel tube with welded plates

3.2 The kit of beam and steel connections

To promote greater standardisation, the nominal beam length is designed as a standard value that respects a module of 1.35 m in a structural grid. Adaptable steel connections are therefore designed to bridge the beam to a wide range of supporting elements, such as primary beams or columns, within a planning grid. The beam and adaptable steel connections are then offered as a single kit. This means that each beam element is paired with connections at two beam ends, as shown in Figure 3. The L-shaped element is formed with one end plate with bolt holes in normal sizes (for example, a 26mm clearance hole for M24 bolts) connecting the supporting members and one fin plate with long slotted holes connecting the web of the beam. With the fin plate and long holes, the beam in a standard length can connect with primary beams or columns in different sizes at flange or web. The kit includes one beam element and other elements like the two L-shaped steel plates, bolts, washers/washer plates, and nuts.

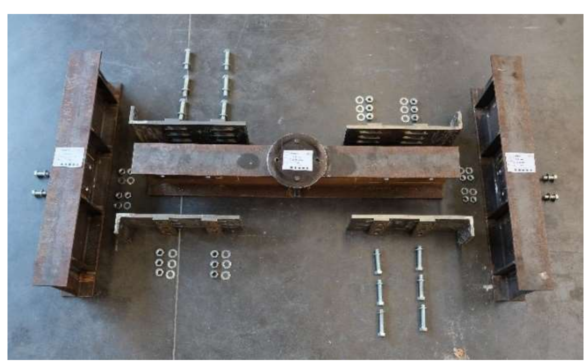

Figure 3 Photo shows a kit consisting of a steel beam and connecting elements (the two primary beams are excluded in the kit)

3.3 Proposed standard grid axes

A reference system is proposed for grid axes to define the positions of columns, bolts/bolt holes and shear connectors, and nominal beam length.

3.3.1 Maxi-Grid, Vertical Axis of 1.35 m

The Maxi-Grid, the usual structural grid, is proposed as 1.35 meter spacing which is commonly used in Europe. Columns and other vertical elements can be arranged at the intersection points of the grid lines, but it is preferable to avoid other positions to maintain a standard layout and geometry for elements such as beams and slabs. Figure 4 illustrates that the spacing between columns is a multiple of the basic module size of 1.35 meters, resulting in 5.4 meters or 8.1 meters in the “Petite Maison”.

Figure 4 Photo shows the axis of columns following a proposed standard grid

3.3.2 Midi-Grid B: position for beam end

Figure 5 illustrates a column connected to beams in two directions. When the size of the column varies, the length of the beams must typically be adjusted accordingly. Additionally, when a beam end is coped to fit its supporting member, such as a column or primary beam, it results in additional processing costs and may reduce the chances for reuse of the beam without remanufacturing.

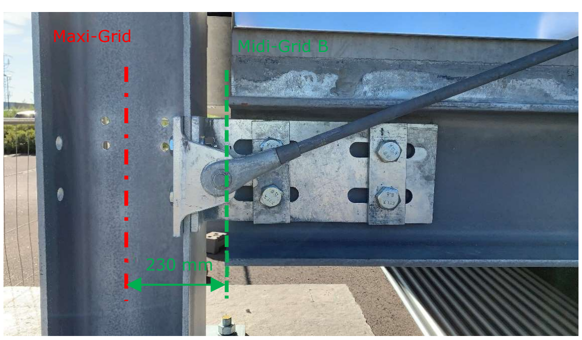

Figure 5 Photo displays the proposed standard distance between the centreline of a column and the end of a beam

With the use of adaptable steel connections, the nominal beam length can be standardized as $L = n \times 1.35 - 2 \times 0.23$ m, when the distance between the centreline of a column and the end of an adjacent beam is set to a value of 230 mm. This approach allows for a wide range of column profiles up to a width of, for example, 450 mm, to be selected. This simplifies the process of sorting elements on site and avoids issues related to coping. As a result, A Midi-Grid for the position of beam ends is defined.

3.3.3 Midi-Grid V1, V2 and H1, H2: positions for bolts

Connection details in steel structures are often standardised to minimize fabrication costs, which can have a significant impact on the overall cost of the structure.

To standardise the positions of bolts in the L-shaped element, Midi-Grids are proposed in both the horizontal and vertical directions. Figure 6 illustrates the bolt grids on the beam side.

In the horizontal grids, the top fibre of the top flange of the steel beam serves as the reference line. The distance from this line to the first row of bolts (at Midi-Grid H1) is 105 mm, followed by a bolt spacing of 75mm in subsequent rows.

In the vertical grids, the centreline of the column serves as the reference line. The distance from this line to the first column of bolts (at Midi-Grid V1) is 280 mm (230 mm to the beam end + 50 mm edge distance), followed by a bolt spacing of 250 mm in subsequent columns.

These grids are applied to the bolts in both the fin plate and the end plate of the L-shaped element. However, the horizontal spacing of bolts in the end plate is not yet defined, as it depends on the width or depth of columns and web thickness of the beam.

Further work on Midi-Grids for the position of bolts and various connection configurations will continue in a following project.

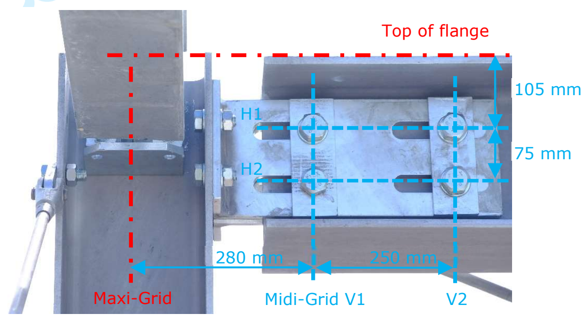

Figure 6 Photo displays the proposed Midi-Grids for bolt positions

3.3.4 Midi-Grid D: Positions of shear connectors between slab and steel beam

To achieve greater standardisation in the structural system, the bolts between the concrete slab and its supporting steel beam are also arranged at a standard spacing. For example, the spacing may be half of the grid module of 1.35 m, which is 675 mm, or a quarter of the module, which is 337.5 mm. Figure 7 illustrates the grids for bolts between the concrete slab and the steel beam.

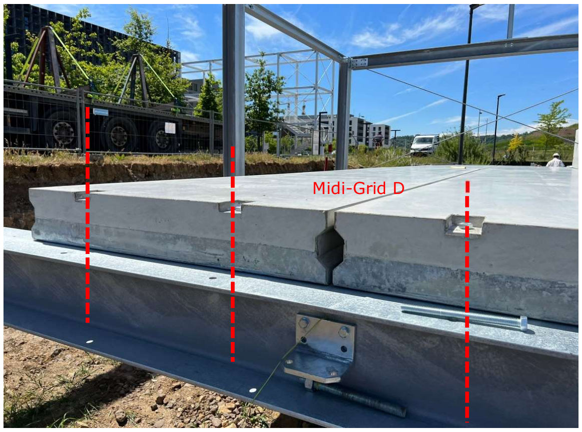

Figure 7 Photo illustrates the grids for bolts between the concrete slab and its supporting steel beam

3.4 Complex joints

To maximise the potential for reuse of the system, it is important to avoid welding and remanufacturing, such as cutting or drilling, as much as possible. This can be achieved through a fully demountable design, standardised dimensions of elements.

Figure 8 illustrates complex joints at a middle column where beams, bracings, and a steel post supporting a timber roof structure meet from multiple directions. Each column member has a standard configuration with bolt holes in both the flanges and web. Some of these bolt holes may appear redundant when connecting columns to their supported beams, but they are used for connecting bracings and the steel post. Pre-welded L-shaped plates are designed to bridge the distance from the elements to the bolt holes.

Figure 8 Photo shows complex joints where members meet in multiple directions

4 Analysis of the adaptable steel connections

The adaptable steel connection discussed can be designed as either a pinned or semi-rigid connection, utilizing the component method of EN 1993-1-8 [12]. It is similar to a double cleat connection, commonly used in steel construction, but with long slotted holes in the fin plate of the L-shaped element.

Figure 9 provides an example where a pin is assumed to be the centreline of the column, and the end plate and fin plate should resistance a combination of bending moment and shear force. Alternatively, the adaptable steel connection can be designed like flexible end plate connections, assuming the pin is at the end plate, in which case, eccentricity needs to be considered for the column design. In both scenarios, the beam's web needs to have sufficient resistance to transfer forces and moments. The bolt holes in the beam web are round, normal holes, rather than long-slotted like those in the fin plate of the L-shaped element.

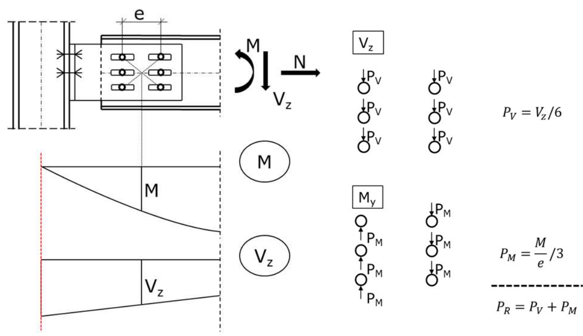

Figure 9 One scenario where a pinned connection is assumed as the centreline of the column

5 Resistance of demountable shear connections in composite beams

The shear resistance of the demountable shear connections applied between the concrete slabs and steel beams has been evaluated through standard push tests, composite beam tests in bending, and respective numerical simulations. Relevant information can be found in Kozma's doctoral thesis [13].

Based on experimental tests, the shear connections have sufficient slip capacity to allow for the development of plastic resistance of the composite section. However, the design rules for these types of connections are not yet covered by the current version of EN 1994-1-1 [14]. An effective shear resistance and an algorithm have been proposed [15] to extend the scope of EN 1994-1-1. The rules may remain applicable for the plastic bending resistance of composite beams with partial shear connection.

6 Conclusions

This paper presents the design concept of a demonstration building – "Petite Maison" – aimed at promoting circularity and design for deconstruction and reuse. A steel frame was designed with newly developed adaptable steel connections and demountable shear connectors within an RFCS project – REDUCE. Standardized and modularized elements were considered, and structural kits were proposed to facilitate reuse.

The "Petite Maison" has demonstrated the possibility of designing structures that are demountable, potentially reusable, and made with standardised elements and detailing. However, work on assessment procedures and certification of reclaimed structural materials or elements is still ongoing. The respective environmental benefits implied by the design of the "Petite Maison" have been quantified and will be presented in a parallel paper.

Acknowledgement

We would like to acknowledge the contributions of all the partners of the "Petite Maison" project, without whom the project would not have been successful. The project was initiated in the frame of the European Capital of Culture Esch2022, and was supported by the University of Luxembourg, Le Fonds Belval, the City of Esch-sur-Alzette, etc. It was coordinated by Prof. Carole Schmit with the support of Mr. Dragos Ghioca. The steel profiles were provided by ArcelorMittal. A full list of supporting partners is available at the following weblink: https://petitemaison.lu/partners.

The underlying scientific research leading to this project was part of the research project "REDUCE", which was funded by the European Commission, Research Fund for Coal and Steel, under grant agreement No. 710040. The projects had partners including the Steel Construction Institute, University of Luxembourg, University of Bradford, Lindab, Tata Steel, Bouwen met Staal, Delft University of Technology, and AEC3.

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Figure 1 Photo shows the “Petite Maison”

1422x1066mm (72 x 72 DPI)

Figure 2 Photo shows a cross-sectional view of a prefabricated concrete slab, embedded steel tube with welded plates

1422x1066mm (72 x 72 DPI)

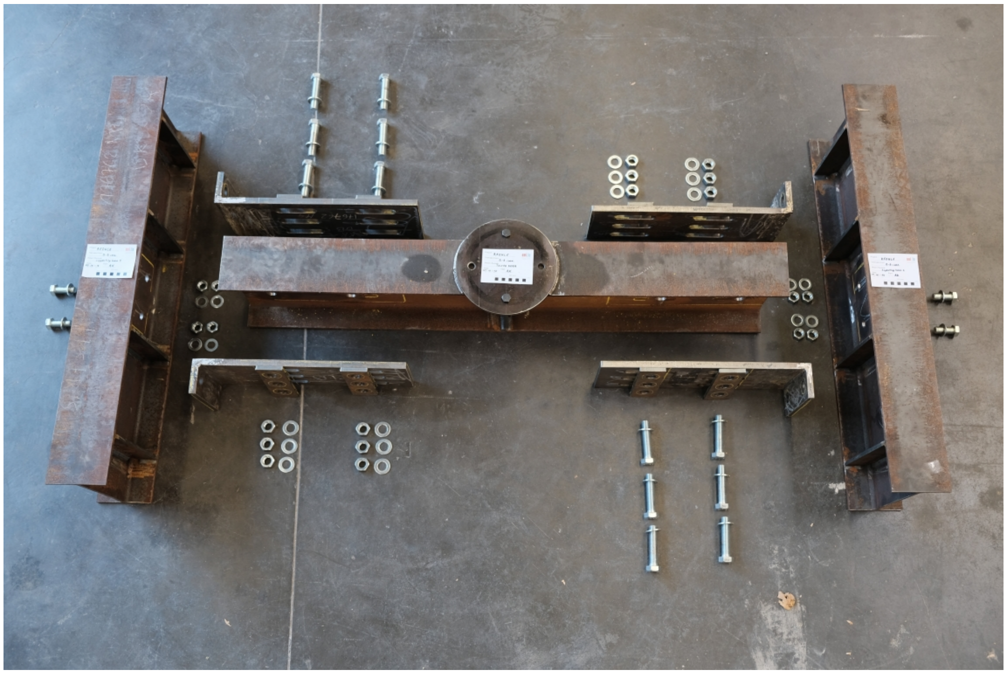


Figure 3 Photo shows a kit consisting of a steel beam and connecting elements (the two primary beams are excluded in the kit)

2116x1411mm (72 x 72 DPI)

Figure 4 Photo shows the axis of columns following a proposed standard grid

1422x800mm (72 x 72 DPI)


6×1.35m = 8.1m
4×1.35m = 5.4m
5.4m

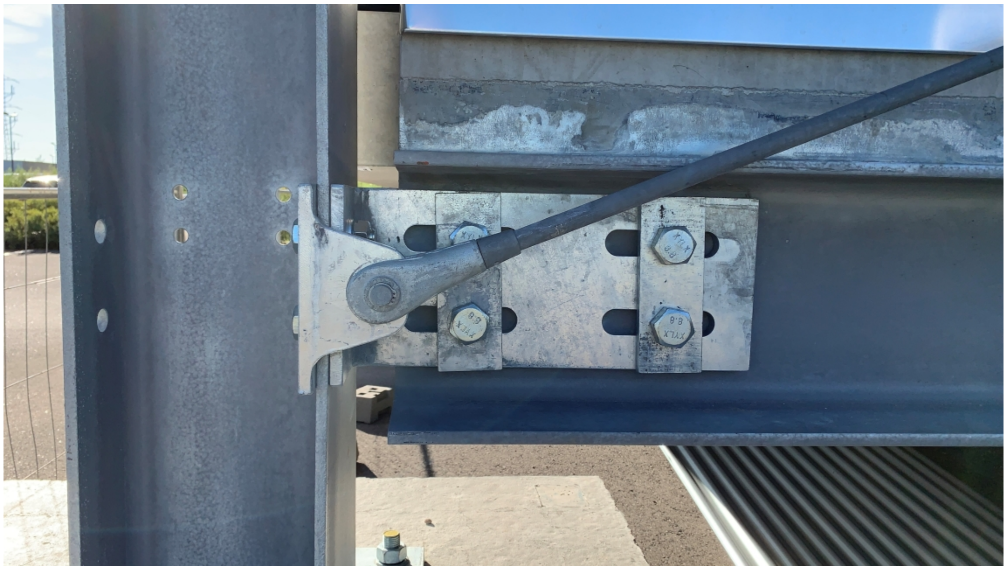
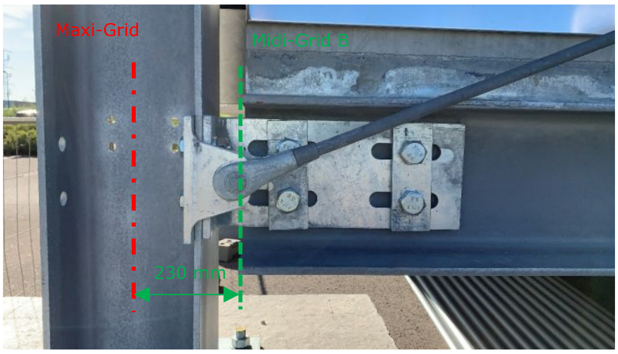


Figure 5 Photo displays the proposed standard distance between the centreline of a column and the end of a beam

1422x800mm (72 x 72 DPI)


Maxi-Grid
Midi-Grid B
230 mm

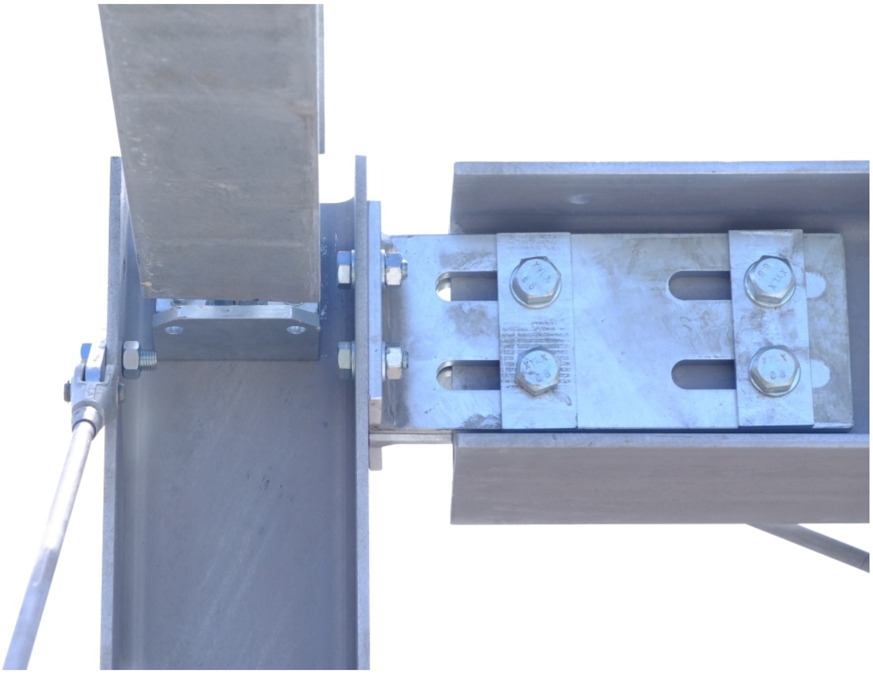


Figure 6 Photo displays the proposed Midi-Grids for bolt positions

1727x1151mm (72 x 72 DPI)

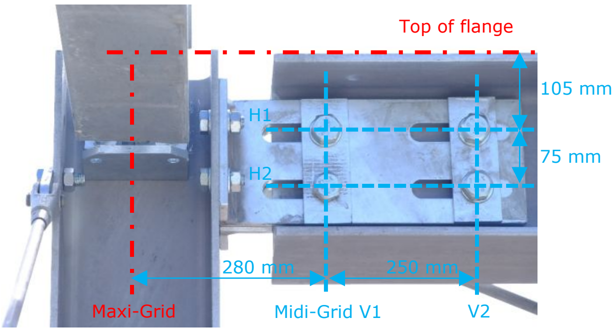

Top of flange
105 mm
75 mm
H1
H2
280 mm
250 mm
Maxi-Grid
Midi-Grid V1
V2

Figure 7 Photo illustrates the grids for bolts between the concrete slab and its supporting steel beam

722x541mm (72 x 72 DPI)

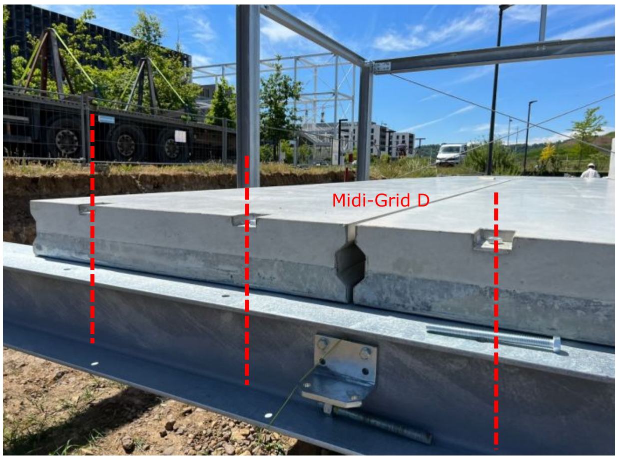
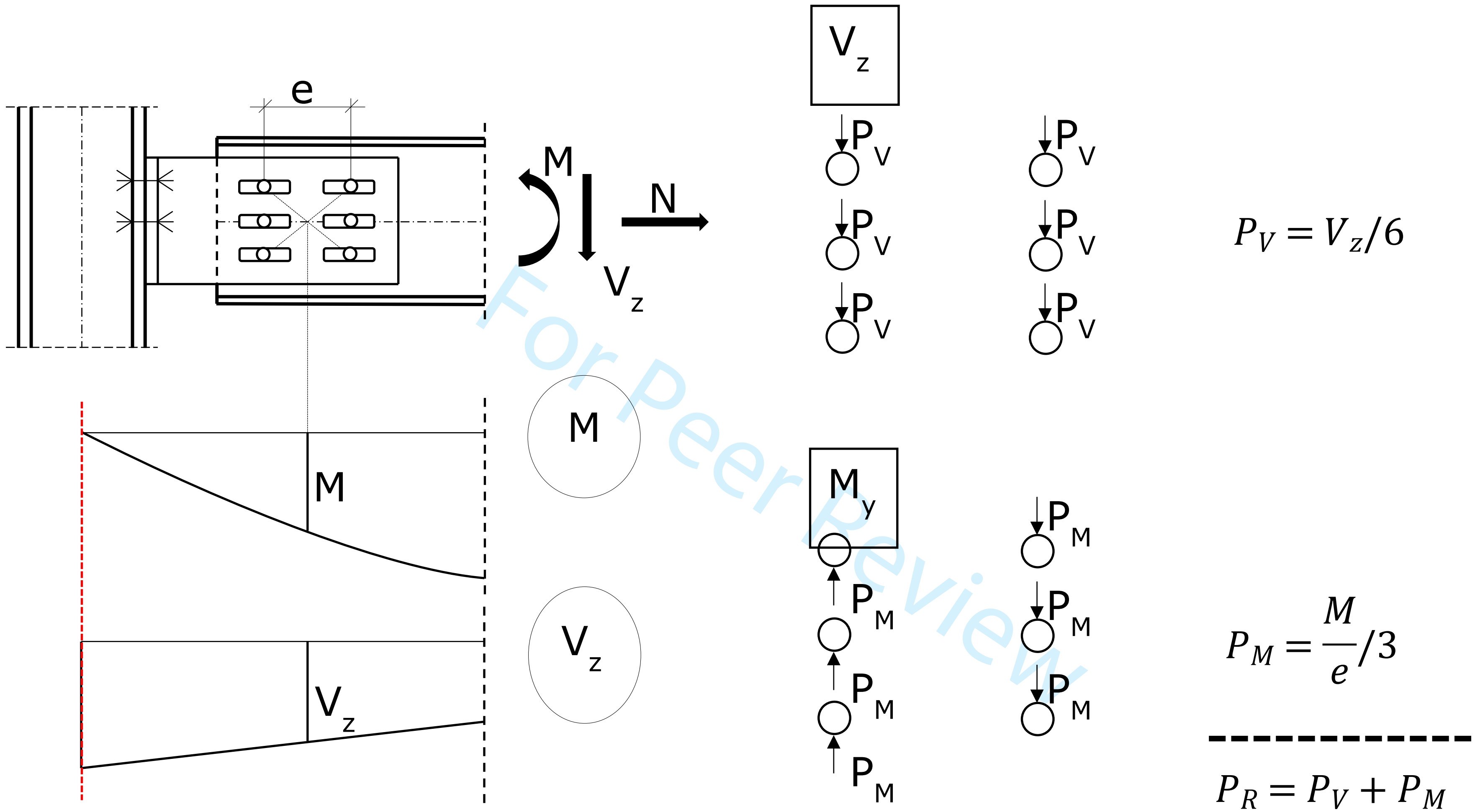

Midi-Grid D

Figure 8 Photo shows complex joints where members meet in multiple directions

1727x1151mm (72 x 72 DPI)


e
M
N
V z
V z
P V
M
M y
P M
V z
P_V = V_z/6
P_M = M/e /3
P_R = P_V + P_M