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Joining rammed earth and re-use elements in an urban context.

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The exploration of this thesis starts with two premises. The first one is the given task of designing a guest residence for researchers in the urban fabric of Munichs Maxvorstadt. The second is to use a new, still prototypical fabrication method for 3D printing rammed earth components, which promises to expand the current means for geometric freedom in earth architecture called ‚Intrusion Earth Additive Manufacturing'. This foundation is part of the overall aspiration to propose a building design, which tries not to contribute to the major challenges of the western building economy, which are an increasing waste occurrence as a result of demolition and drastic greenhouse gas emissions tracible back to the use of kiln-fired materials.
On the way towards this explorative goal, which ultimately aims to understand the possible advantages in the utilization of Intrusion Earth, the potential and limits of conventional rammed earth are analyzed. Beginning with the decline of loam materials in the west at the brim of the 20th century, despite their beneficial characteristics. Followed by the question why rammed earth experiences a renaissance, what is the current state of the art and why the use of the method still faces many limits today. The examination of another re-surfacing resource practice will be discussed, especially how the irregular shapes of re-purposed materials of demolished buildings can provide a prototypical application for a rammed earth fabrication process, that enables broad geometric freedom. The case study design is based on the findings of this research journey and will focus on the spatial requirements for a guest house, the implementation of irregular shaped re-used building elements and the bond in a structural frame of earth, with particular focus on the connection and architectural reception of Intrusion Earth components together with conventional materials and rammed earth.

preface

„almost 8% of the global Co2 emissions are back tracible to the cement industry“

introduction

Introduction

The search for ways of sustainable construction in an urban context has diverse aspects and is a moving target. The discussion often starts with focusing on the villain, the use of cementous materials such as concrete. In fact, it is true, that almost 8% of the global Co2 emissions are back tracible to the cement industry [1] and have to be reduced but comparing it with other kiln fired or „warm“ produced materials such as Bricks or Steel, it appears as a comparatively energy efficient construction material. Considering those aspect, it can be concluded that not the use of concrete in principle is the problem, but the quantity and intensity of its application. This leads to the assumption, that to reduce the construction sectors emissions, a multilayered approach is advisable, by focusing on reducing the clinker content in cement, one of its high energy intensive ingredients, the cement content in concrete and finally reducing the concrete content in structures. [2] As this thesis focuses among other aspects on urban earth construction, it will be in the realm of the third layer. But it will also challenge it by putting the simplicity of its premises in question.

Earth?

Ignored in the western hemisphere for a long time, it is nevertheless one of the oldest building materials utilized by humans. Early examples date back to the settling down phase of the neolithic period, making it an around 10.000 years old cultural asset [3] and it is still one of the most used building materials today. A fourth of the world’s population lives in structures constructed out of or with clay-based materials, with an even higher ratio in developing countries. [4] But its use is not limited to those regions. In fact, earth as a building material is, as well as traces of historical earth structures, available on all five inhabited continents, making it a worldwide phenomenon. [5] This leads to the first of different promising reasons to use the material, it is not only accessible, but indeed abundant almost everywhere. [6] Often recognized as waste during the excavation phase of construction projects, it has to be transported and landfilled, but could instead be used for the construction of the building itself. [5] This aspect already can avoid a significant part of the transport emissions caused during a buildings construction phase. [7]
When taking a closer look, another compelling second argument becomes evident. In contrast to cement, which gains it compressional

strength in an irreversible exotherm reaction called ‚hydration' when exposed to water after being kiln-fired at over 1450° Celsius, [8] the solidification of clay-based materials does not need primary energy implementation, rather than water as a liquefying agent, and different mechanisms of cohesion, solidifying the material with a significant strength when dried. [9] This also means, that pure earth materials are reversible and reusable by exposing it to water. Its hydrophilic state and capillary action results in a third strong argument, it absorbs and emits moisture in its surrounding environment, fostering a comfortable building climate by naturally regulating humidity. [10]

But why was earth lost as a building material, when considering those compelling arguments? One part of the answer is, that those advantages come at a proverbial price.
As mentioned earlier, pure earth is water soluble. This means that a long water exposure leads to the disintegration of earth structures, especially in the case of water intake from above. As a result, they must be sheltered accordingly, always shielding them from the elements. This is achieved by implementing physical protection measures such as wide roof overhangs or erosion brakers, thin horizontal lime or ceramic barriers in the face of the wall to slow down dripping water, reducing the erosion. [11] Equally important as the provision of those measures, is the knowledge of how to plan, build and prepare this comparatively fragile material, a significant bottle for the use in contemporary architecture caused by the displacement of the material in the west. [12]
Another advantage, the onsite use of excavated earth, turns out to have negative aspects. Nevertheless, enabling the reduction of material transport, does this method indicate, that the material is „produced" at the building site, not manufactured in a normed process, which complicates the use under contemporary building codes. A legal framework for onsite material tests and evaluations or earth structure per se is not available in every country, such as Belgium, were some actors use German building code norms and try to implement them into the state's legislature. [13]

But this is not all, when looking at the different earth techniques that evolved in its long history of application in a general overview, (Fig. 1) it is evident, that a large portion of those methods require manual labor, thus containing a time intensive process in their entirety, rendering them less affordable in times, where the material is significant cheaper than the manual labor arranging it.

Left behind by industrialization

Those three mitigating factors, the need for specialized knowledge, the more complex standardization and a mainly manual and laborious process of an in contrast healthy, sustainable and available material, came into the fairway of the industrial revolution of the 19. century's Europe. In this time of a significant population explosion and the therefore emerging need for living space, resulted in the industrialization of the building industry. [14] During comparable historical developments, the industry tends to focus on mass producible materials, that are cheap and easy applicable. [15] In Germany, this was particularly the case for cement. With an annual production volume of 500.000 tons in 1880, a 14 times increase in contrast to the beginning of the first world war in 1914. [16]
In those times of shifting focus, the earth building culture got lost in the western hemisphere in favor of the industrialization of conventional, high embodied but less complicated materials. Even though an increasing interest for earth as a building material emerges, the disadvantages mentioned earlier still represent a challenge today.

Strategies to escape the niche

To circumvent those, mainly two procedures evolved, to ‚advance' the material application, both inspired by methods the conventional building industry. The first one is an obvious one, adding hydraulic binders such as cement or lime to the earth mix, the material is stabilized chemically. This method makes the mix easier to handle, reduces the knowledge threshold and prevents the water solubility, aiming at a high stability and reducing cost. Though one could argue that by using onsite earth and aggregate does reduce transport emissions, this approach fails the goal of reducing the cement content in the material itself, thus does not present a significant better solution then using concrete in the first place. [15] This impression is strengthened by the fact, that stabilized earth, together with its ability to be water soluble, loses the opportunity to be reused and to regulate a buildings climate permanently, [10] at the cost of a larger amount of cement that must be used, to achieve the same strength as conventional concrete. [17] Realizing that the stabilization manages the obstacles of earth application only by surrendering the higher goal of reducing the quantity of used cement. In contrast, the second procedure is a promising one, the industrialization of earth construction products. Inspired by the advancements of the concrete production, [15] does this process incorporate two aspects, which are described more in detail later. However, it can already be said, that only a fragment of earth methods is utilized for industrialization, most of them seem to be non applicable.

This applies particularly to methods that involve stacking, molding and shaping by hand. Although some of them are transferrable to industrialized processes, different brick formats in particular, but their ability to reduce costs to balance other material shortcomings are reduced by their labor-intensive application on site due to their small size. Focusing on large load-bearing elements, the most promising candidate for industrialization is rammed earth.

„the solidification of clay-based materials does not need primary energy implementation“

[Damp earth composition used for vertical load-bearing structures by pouring and compacting layer by layer into a formwork. Mixed with large to medium sized aggregates such as gravel and coarse sand.]

Rammed Earth

Rammed Earth

Being part of the compacted earth realm, one of the twelve main earth building methods defined by CRAterre, rammed earth is one of the three monolithic methods and one of the most sophisticated earth techniques in general. [20]. In Europe, a lot of historical examples can be found in an area spanning between the Iberian Peninsula and the central southeast of France. [21] Despite the knowledge loss and missing public reception of the technique, there is a long history of rammed earth architectures in Europe. An extensive use took place in France, especially in the late 18th century, with estimations of up to 15% of all historical rural buildings in the country being made from rammed earth. [22] It is used for vertical load-bearing structures by pouring a damp earth composition mixed with large to medium aggregates such as gravel and coarse sand, layer by layer into a formwork compacting it and therefore forming a wall step by step. [23] (Fig. 1) By mentioning the use for vertical load-bearing structures, a fundamental characteristic of pure earth structures is that the material can withstand considerable compressional forces on the one hand, but almost no tensile forces on the other. [24] To achieve this compressional strength, which lies between 2-6 N/mm2 at a mass of 1700 -2200 kg/m3, [25] compared to concrete (C20/25) with a value of 28 N/mm2 [26] the preparation of the material has to be performed carefully.

Traditional Ramming Method

A historical formwork setup consisted out of two mould walls and a supporting structure. This structure consisted out of two or more timber beams perpendicular to the wall at the bottom of the segment, which functioned as turnbuckles for the supporting columns of the formwork walls. At the top, the columns were tightened together with a rope. This setup guaranteed the slip molds structural integrity during the ramming process. (Fig. 2) The work was done by using hand-held rammers, a stick with a ramming weight at the bottom, either standing next to, or in the formwork to compact the material. After ramming the material to the top of the mould, the slipform and the beam tendons were be removed immediately to be placed elsewhere leaving the characteristic beam holes behind. (Fig. 3) This method is still in limited use today, but with a contemporary formwork setup, using smaller steel tendons instead. [27] (Fig. 4) Martin Rauch untilized this system for building his own house in Schlins, Austria, often referred to as Haus Rauch. [28] (Fig. 5)

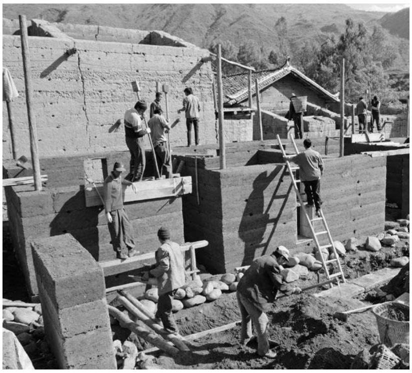

Fig. 1: Traditional rammed earth application.

Fig. 2: Traditional rammed earth mould.

Fig. 3: Rammed earth building with beam holes.

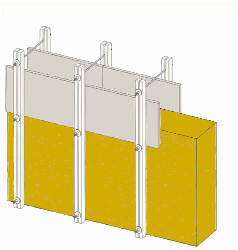

Fig. 4: Contemporary mould setup.

To fasten the manual process, which normally takes 28-30h per square meter, a first step towards mechanization was taken by using pneumatic hand rams, which have a higher ram frequency, in earlier projects a stroke count of around 160 hits per minutes is described, increasing the work speed. [29] (Fig. 6)

The project served as a case study and demonstrator for Rauch's findings in loam structure, who implemented, together with the Architect Roger Boltshauser, different techniques of rammed earth applications in the building. An interesting aspect are the earlier mentioned erosion brakers, in this case ceramic tiles that are rammed horizontally into the faces of the walls in a specific distance, to slow down the water flow during rain. At Haus Rauch, they are not only part of the concept ‚controlled erosion‘, conceived by Rauch himself, a method that anticipates the expected wall decimation caused by the weather conditions and adds that to the dimension of the structure beforehand, but also serve as a design element by varying in their distance. [30] (Fig. 5) This project not only showed the durability in the harsh climate conditions of the central European alps by considering the erosion as a subtractive aspect of the design, but also that pure rammed earth walls in a contemporary building are realizable and can be improved by developing the method further. Although there must have been a time advantage and reduction of manual labor compared to the traditional method, but the erection of this building still precents a mainly artisan procedure, that resulted in corresponding construction costs. [28]1.2 million € for a two story house) As this presents a significant threshold for a widespread application after all, it nevertheless expanded the view towards a further industrialization of rammed earth, which already occurs today.

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Fig. 5: Haus Rauch, Schlins Austria

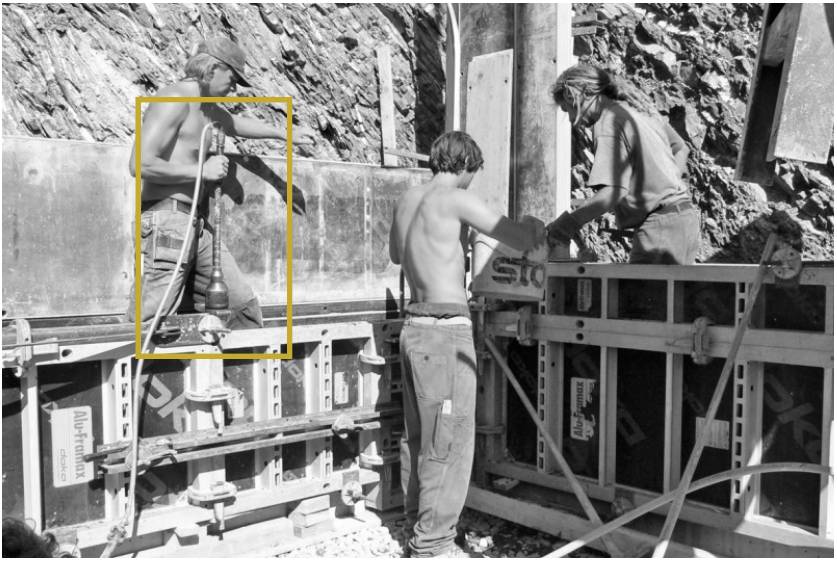

Fig. 6: Hand held pneumatic rams during construction.

Steps Towards Industrialization

Looking at the previously described advancement as a way to reduce cost, a fundamental industrialization seems promising. On the way towards that goal, two aspects of the same are of interest.

The first, prefabrication of construction components reduces the onsite efforts by producing the parts offsite prior to assembly, in a controlled in-door situation. This measure can accelerate the production and reduce costs by avoiding onsite logistic challenges. For rammed earth components, that have to dry 4-6 weeks before implementation [11], is this of advantage to reduce onsite fabrication and storage needs. [18][19] At the Ricola Kräuterzentrum, an herb processing center for the Swiss company Ricola which will be part of the investigation later on, those advantages were tested by Lehm Ton Erde Gmbh, with on of the first semi-industrialized manufacturing line for a large-scale loam construction project.

Automation on the other hand presents a viable opportunity to minimize the required amount of physical labor by using digitally controlled automated tools. [18] Based on his findings and experience in loam building, Martin Rauch developed a semi-industrialized production line for his production hall in Schlins, especially for rammed earth walls. By using an ‚endless mould‘ of over 50 meters, a reduction of required form work was achieved which simplifies the ramming process and saves time. On the complete length, a pneumatic ramming machine (called ROBERTA) (Fig. 7) with a digital-controlled feeding system rams the material and accelerates the process in addition. After finishing the complete length, the wall is cut down into wall segments using a vertical circular saw and rearranged for drying and preparations. Those preparations contain the tonge - groove connection for the later wall assembly, which are prepared by using a circular saw and sledgehammer to carve out groove’s channels at the end and top face of the components. [31]

It is evident that the offsite prefabrication and progressing automation are enabling the rammed earth production to increase their productivity and quality while simultaneously reducing the need for physical labor, thus reducing the cost. Nevertheless, there are still large portions of manual applications, such as the preparation of the component connection, which is not possible with the current means of production.

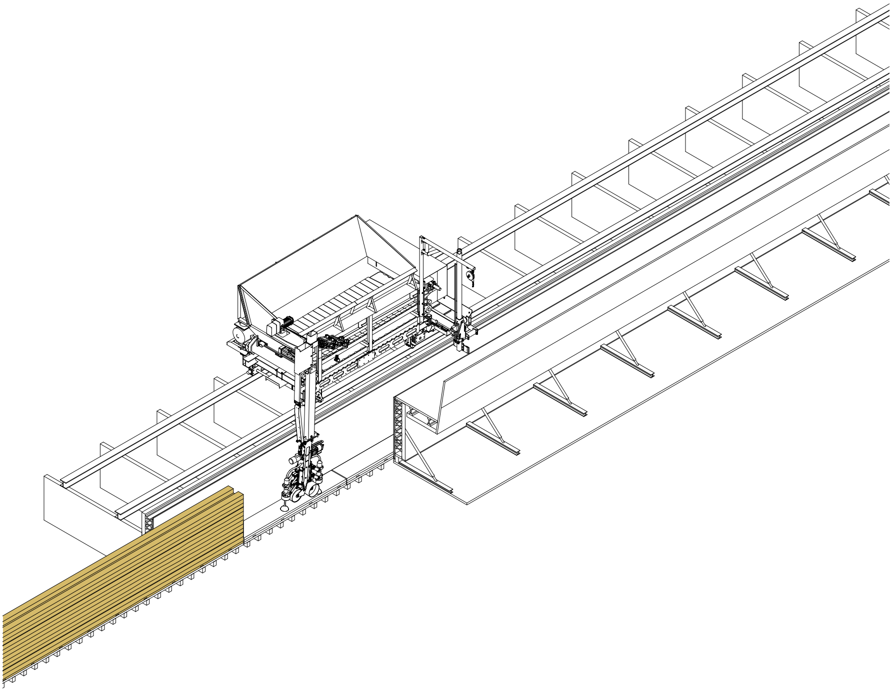

Fig. 7: Ramming Machine ‚Roberta' with endless mould (50m)

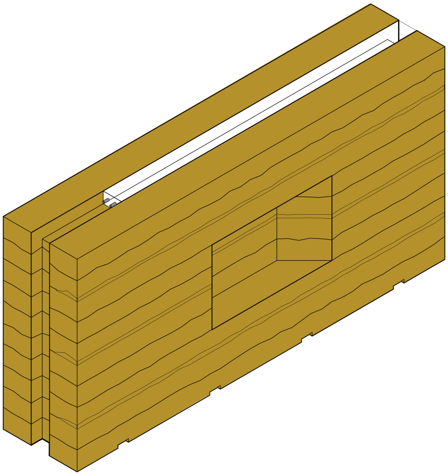

Fig. 8: Wall components.

Rammed Earth Components

Structural wall. The focus lies on load bearing elements, the tallest sized group of pure rammed earth are wall systems. With a size of around 350 by 120 by 25-80 cm, they placed like large bricks in an offset on top of each other. [11] Connected by a groove tongue connection system, as earlier mentioned prepared by hand, they transfer the load vertically on compression. On the exterior, the erosion brakers are always necessary when walls are exposed to weathering. The insulation can either be implemented into the core of the wall, an example is the glass foam insulation rammed into the walls of the Alnatura headquater, [7] (Fig. 8) or can be applied in a conventional way on the exterior or interior of the wall. All those functions are implemented during the ramming process in a linear mould. In addition, it is possible to implement niches and other forms into the face of the wall, [32] how this is realized is part of the later discussion. The general form for load-bearing walls that are produced with some degree of industrialization seem to be limited to a straight linear orientation. The most obvious reason is the production process using linear forms and machines, that operate in a linear alignment such as the ROBERTA machine at LEHM TON ERDE GmbH. A higher degree of form modification is possible but complicates the production process.

Interior Lining. Not a load-bearing element but also interesting are insulated interior lining walls segments. They are smaller than structural wall components with a length of 140 by 120 cm height and a thickness between 7 and 12 cm without insulation. They can contain a higher degree of integrated installation such as water feeding tubes for thermal activation. The opportunity to plan and implement electronics and other installations into the wall segments beforehand persists as well, probably by either using place holders during the fabrication or subtract the required volume afterwards. [33]

To summarize, the figural opportunities are quite similar to those of load-bearing walls, but in contrast, it is possible to produce even curved walls. Martin Rauch’s company promotes this option on their website, it is likely that other manufactures provide this opportunity as well. Considering the means of production of the company, it is likely that this customized solution would be performed by using an individually made form and pneumatic hand rams.
Slab elements. A hybrid application of rammed earth components are ‚Hourdisböden‘. The german term describes a horizontal filling between parallel beams.

Either available as a vaulted or shaped system. A well cited project using this application with rammed earth is the HORTUS project by Herzog de Meuron. (Fig. 9) This office building, based on a wooden skeleton structure contains ready-made earth slab modules. They consist out of a CNC produced wooden frame and several secondary beams, which are the bearing for rammed earth linear vault fillings. (Fig. 10) The fabrication of this element also includes machine supported material application, however the vaulted shape is compacted using mainly hand held pneumatic rams. After the preparation, the module is turned upside down and placed inside of the building. [34]

Even though the fabrication process itself is quite manually, a portion of the process is automized. This is especially important to apply the right amount of material at the sides, to be able to form the sloped form of the linear vault, observable in the process video of HdM. But in summation it is this a geometrically limited approach. The rectangular module can easily be scaled in different directions, but needs to function in a rectagular grid, because when leaving the orthogonal domain, the production process is complicated and more labor intensive, considering that the electronic vibration machines seem to be optimized for a specific radius and a specific width of the segement. Even though the loam floor is not load-bearing, the cross section of the vaults must be symmetrical with the current setup. This would also be the case for press manufactured arch blocks such as the TERRADEK-system of TERRABLOC. It is a system for a similar application, a vault shaped element (Fig.11), which is clamped between two A-shaped wooden beams. [35] This shaped form can either be produced in 90 degree turned form with pneumatic hand rams, but more feasible appears a modified concrete brick press.

In general, systems such as TERRADEK, are produced in an industrialized manner as described by the producer, however that the module has a specific width that must be met with corresponding wooden or steel beams, that are optimized to be used in the frame of a construction grid, similar to the HORTUS project. This means that its application and form is quite determined.

An example for its application is a Villa by ‚Rudaz Architekten‘ in Volketswil in Switzerland. In this house with a steel frame structure, the Terrabloc system is clamped in-between steel I-beams to function as floor filling, but also as roof filling and facade element. In this case, the elements are rectangular instead of arched, so a load-bearing function is not obligatory. [36] (Fig.12)

Fig. 9: HORTUS project by Herzog de Meuron.

Fig. 10: HORTUS slab modules

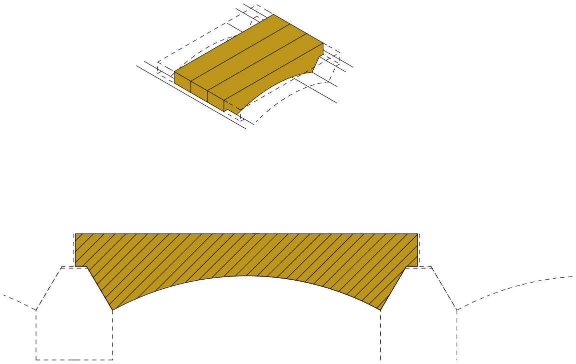

Fig. 11: TERRADEK

Fig. 12: EFH by RUDAZ Architekten

Large brick formats. Component systems, such as TERRAPAD also by terrabloc, are significantly smaller than wall components but with a length of 80 cm, a height of 15 cm and varying width still bigger than conventional bricks. Also does this product, also the earlier mentioned TERRADEK, leave the realm of pure rammed earth, as it is stabilized with 4% of its volume with cement, the negative aspects of this action were already mentioned before, nevertheless having a reduced cement content in contrast to conventional concrete. [37] (Fig. 13) With its smaller size, it offers a wider range of geometric applications, compared with the earlier discussed wall systems, despite a high degree of industrialization. However, with its shrinking size, the required manual manpower for its implementation should still be considerately better than for small bricks, which are left out of the consideration for the same reason.

The comparison of different component types and sizes leads to the following assumption. It appears that the degree of geometric freedom of prefabricated rammed earth elements increases with the reduction of the component size. This should increases the required amount of manual labor and therefore the construction cost. This could presents an obstacle for rammed earth applications today when the necessity of geometric flexibility meets the wish of using a sustainable but still affordable material.

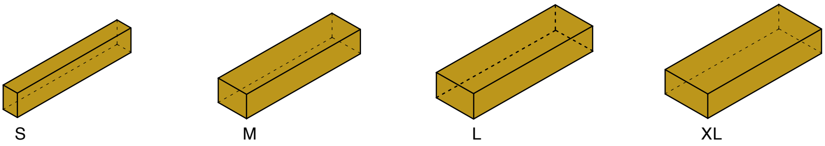

Fig. 13: TERRAPAD brick

Rammed Earth in the Urban Environment

Considering that the scope of this thesis entails the exploration and case study of rammed earth construction in a residential project in Munich, the focus of building typology tends to lean towards urban architecture, especially when realizing, that all previously shown examples are freestanding projects in a loose building fabric. And there is a reason for that. Examples that are built in a dense city fabric and prefabricated seem to be an exploration gap. However, historical precedent in the urban environment is available, especially in the old strongholds of the Pisé-technique in the region around Lyon in central southeast France. Also in the German city of Weilburg are different examples still part of the cities landscape. One example is the ‚highest Pisé building worldwide‘, (Fig. 14) built by the Wilhelm Jacob Wimpf between 1826-1828. [38]

As this building again stands freely at a slope, other examples of the builder in denser parts of the city are more conclusive. The building in Limburger Straße 13 is also a Pisé example and is especially interesting because of its appearance and floorplan shape. From the outside, covered by plaster, is the rammed earth structure not even guessable. (Fig. 15) When looking at the floorplan, the thick walls give an impression, that a conventional building method is unlikely, would it mean that a lot of redundant material would have been applied. (pic) Even more interesting however is the irregular shape of the building. Its portraits a typical patched plot, which occurs in grown cityscapes regularly. (Fig. 16) This aspect is always of importance during the consideration of architectural approaches in dense cities, especially when looking at big cities in Europa, who in their layout often follow a rather historical and thus organic development, than a grid like expenditure, especially when approaching the city centers. As mentioned, due to missing contemporary built examples of rammed earth architecture in a cityscape, a conceptional project in a prototypical state will be looked at closer, the ‚case study steel house‘, planned by Roger Boltshauser Architects. (Fig. 17)

This concept emphasizes the problems of earth architecture in highly developed and dense cities of central Europe. The prefabricated rammed earth components are produced offsite and are assembled in the city to minimize the efforts onsite. A reduction of the wall’s needed thickness was achieved by tensioning them vertically from the buildings top to foundation in order to maximize the usable space and still comply with building codes, especially adding to its earthquake resilience. [39] A characteristic aspect of the project is the utilization of re-purposed Larssen sheet piling covert with earth filling as floor slabs. With this measure BA AG circumvents one given characteristic of clay, its missing tensile strength.

Fig. 14: ‚Highest‘ Pisé building in Europe, Weilburg.

Fig. 15: Pisé building in Weilburg, Limburger Straße 13

Fig. 16: floor plan, Limburger Straße 13

Fig. 17: Case study steel house, Boltshauser Architekten

Knowingly or unknowingly, he even goes on first step further by introducing the aspect of material re-use, to circumvent the utilization of conventional materials with tensile strength abilities, but instead high embodied greenhouse gases. For this approach a simple rule seems to be applicable: “vertical structure -> rammed earth, horizontal structure -> repurposed construction element”. The reflection on prefabricated rammed earth architecture in dense urban environments sheds light on important observations. The first one is its obvious lack of use. The given historical examples are mainly from the 19th century and were done with manual techniques according to the time. Another observation is, that there is more than one main construction material or resource to consider. In contrast to the first one, the earth on site, which is abundantly available, the second one, the available space in the city, is a limited one. This is the reason, why concept proposes to optimize the structural dimensions of rammed earth by adding compression to the walls by tensioning them vertically from above to the foundation. But that is not all, the reflection opens the scope of the discussion towards another available material in the city, re-usable elements. Considering this a potential third and possibly redundant resource in the city, its application will be investigated further in the following.

„for the city of Munich alone, a construction waste occurrence [..] of approximately 172.000 cubic meters can be estimated for the year of 2023“

[Re-use, re-purposing or urban mining describes a process of dismantling still intact buidling materials or elements and their re-use in new structures. In this chapter, additional focus lies on those sourceable materials, their current implementation and the intersection of those (not neccesarily as re-used) with rammed earth. The aim is to understand the challenges of their combination, exemplary illustrated by current geometric limits of rammed earth in built projects.]

Re-use(,) Materials with Rammed Earth

Re-use(,) Materials with Rammed Earth

Approaching the topic, one of the first aspects is a brief historical review. In the long construction practice of humanity, the dismantling of still intact material and its *re-use in new structures* (Fig. 18) was always practiced and often occurred in times of demographic or economic crisis when lots of structures lost their use and eventually functioned as urban quarries. [40] This method can also be seen in combination with rammed earth, a material that itself often experiences a renaissance in times of crisis. Its increasing use in mid-eval France can be interpretated as a countermeasure against urban fires in growing cities built out of wood [41], in parts of Germany in the 19th century an action against an appearing wood scarcity. [38] The building on rue du Lion d´Or 21 in La Côte-Saint-André (Fig. 19) in central France. Showcased in Roger Boltshausers book ‚Pisé' as an example, it shows rectangular areas of its outer wall constructed in a *combination of brick and stone*, containing all openings with arched lintels, such as windows and doors. [42] The varying quantity of used bricks and stones in these clearly defined areas indicate the use of at least partly scavenged materials. The larger portion of the wall without openings is done out of *rammed earth*, considering its free availability an obvious way to avoid buying expansive or not available building material. Considering its probable age of over 150 years, it provides an early proof for the combination of re-purposed material and rammed earth. However, his ‚physical re-use , practice lost its dynamic with the large application of concrete beginning in the late 19th century. [40]

Going forward in time to today, the facts support this observation, seeing that a significant portion of the worlds waste occurrence is back traceable to the construction industry. In Germany this is the case for almost 50 percent of all solid waste and excavation materials. [43] Even though an exact waste volume is not specified, for the city of Munich alone a construction waste occurrence (without excavation, assumed 3m story hight) of approximately 172.000 cubic meters can be estimated for the year of 2023. [44]

Moving on form the symptoms to the cause, a significant waste inheritance was produced at the same time. In 2023, 9837 residential units were built in Munich. [45] The volume of the load-bearing structure, the portion of the construction that incorporates 50-70% of a buildings grey energy, [46] (without interior lining, installations or facade) exceeds a value of estimated of 446.000 m3 (in solid construction, assuming an average story hight of 3m) in this year alone. [45] Considering that currently the use of recyclable or separatable materials is limited, this means that this portion offers a high degree of sustainable optimization in reverse, especially when many building components of that soon considered waste can still be functionally intact and repurposed, even though statistics for that are hard to provide in a situation of varying built in materials with uncertain conditions and limited means to test them. Nevertheless, the attempt of an overview will be provided, describing to be considered materials, an example for their reuse and a general outlook for a connection between the material and rammed earth.

Fig. 18: Spolia in Greece.

Fig. 19: Pisé building with fragments out of brick.

Steel Re-Use

33 percent of the German annual steel product is produced for the construction industry, cumulating to 10,73 million tons for the year 2022 alone. [47], not considering steel imports. Nevertheless, a high degree of re-use is already in place, with a recycling quota of 80-90%, were a 75% reduction of needed primary energy can be achieved. [48] An applied example, the project K.118 in Winterthur, (Fig. 20) Switzerland by the practice ‚in situ Baubüro' showed, that the use of gathered and re-assembled steel elements, in this case different kinds of beams formed the main load-bearing structure and the stairwell, (Fig. 21) which led to a save of up to 91% in greenhouse gases in comparison to newly fabricated parts. [49]

Steel and Rammed Earth. In combination with earthen materials, both groups profit from each other considering their specific characteristics. Metals can handle tensile loads very well, but are quite threatened by fire hazards, leading normally to a carefully covering process of the same. [50] Rammed earth on the other hand cannot withstand tension but performs under compression quite well and instead of being damaged during a fire, it tends to sinter and thus effectively provides cover for encapsulated materials. [51] But for rammed earth to function together with metal elements in one system, certain measures must be taken. Earth, in contrast to concrete, does not enter a bond when being combined with uncured material.

To achieve a similar stability, physical methods are applicable. At the Ricola Kräuterzentrum, the connection of the round steel frames of the windows and the rammed earth facade, steel swords in orientation of the bed joints were implemented into the window frames. They prevent a horizontal tilt of the walls. [52]

Another application of steel as a horizontal slab element is proposed in the earlier mentioned Case Study Steel House. In this case the repurposing of *Larssen steel sheets* normally used to for the stabilization of excavation walls. (Fig. 22) Filled with rammed earth and covered with regular flooring, contemporary living standards and fireproofing can be achieved, but as the project is not realized yet, a built proof of concept is still pending. [39] Obstacles in the fabrication of this combination are discussed later.

Fig. 20: Project K.118 by in situ Baubüro

Fig. 21: Project K.118 re-used stair case

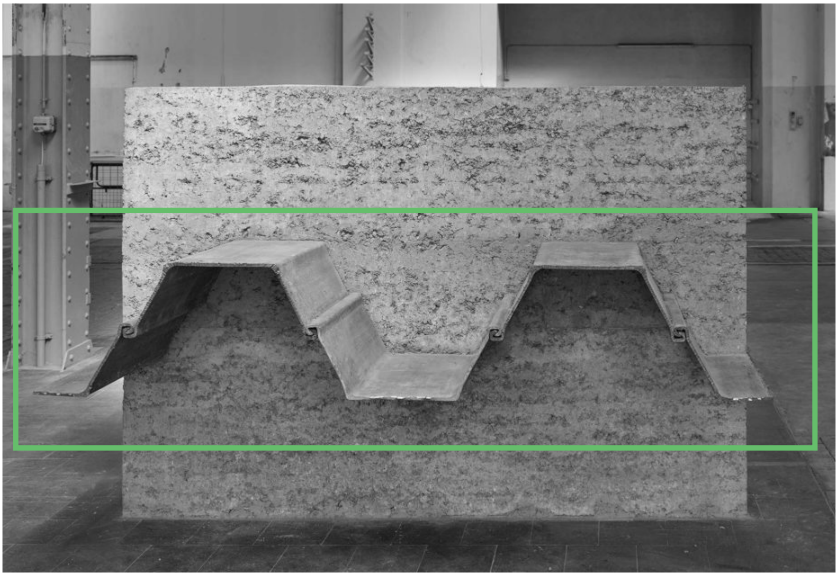

Fig. 22: Larssen steel sheet joint, Boltshauser Architekten

Concrete Re-Use

In contrast to that with much less predictable numbers for a possible degree of re-use of reinforced concrete is provided, the numbers for the concrete applications easier available. The cumulated concrete usage in 2021 exceeds 100 million tons in Germany, calculation of the ‚Transportbeton' organization estimating of up to 150 million tons. [53] To counteract the implying consequences of this production volume, re-purposing complete wall and slab segments are an effective way of saving greenhouse gas emissions. This potential already has been demonstrated in applied projects, which show an emission saving potential of up to 95%. [48] The project thoravej 29 (Fig.23) by ‚philmann' architects transformed a reinforced concrete skeleton with ribbed slabs, from the appearance of an industrial structure into a community hub by refurbishing and rearranging the building, but also its former elements. They re-purposed *disassembled slabs to function as stair structure* by using specifically for their use made steel connecters. [54] (Fig. 24)

concrete and rammed earth. The combination of concrete or similar materials such as reinforced trass lime and rammed earth are quite well known. A common interface is the elevated concrete foundation plinth, that prevents the contact of the earth structure with wet soil standing on top. (Fig. 25) [11]

Another application is that of a concrete ring beam in its regular function. The anchoring between the earth wall and concrete ring beam functions either with an anchor rod, (Fig. 26) or similar to the connection of reinforced concrete or trass lime lintels, which are described in Martin Rauchs book ‚Gestampfte Erde'. Poured into a recess of the top face bottom of the wall, small screws, that are applied into the rammed earth, create a connection between both materials. [55] (Fig. 27)

However, since re-used elements and particularly concrete components in this case will be connected in an already solid state, a small-scale bond, which develops during the curing of the concrete in connection with the small anchor screw seems neglectable. But there is precedent for the anchoring of solid elements in rammed earth walls. One way is to secure a beam to an anchor plate, that is rammed into the wall several layers beneath the element itself and screw tension both parts together. [56] In theory, this method should be applicable to other horizontal elements, that need vertical anchoring in a rammed earth wall. This possibility among others will be considered later.

Fig. 23: project T29 philmann architects

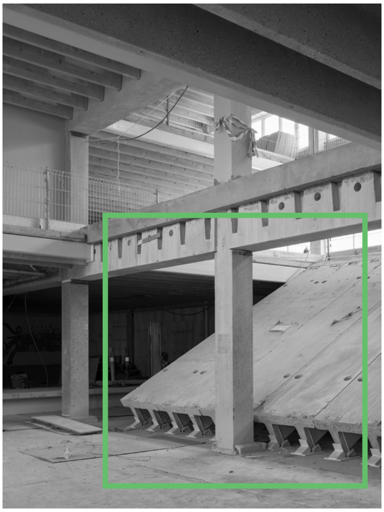

Fig. 24: Stair structure out of ribbed slabs.

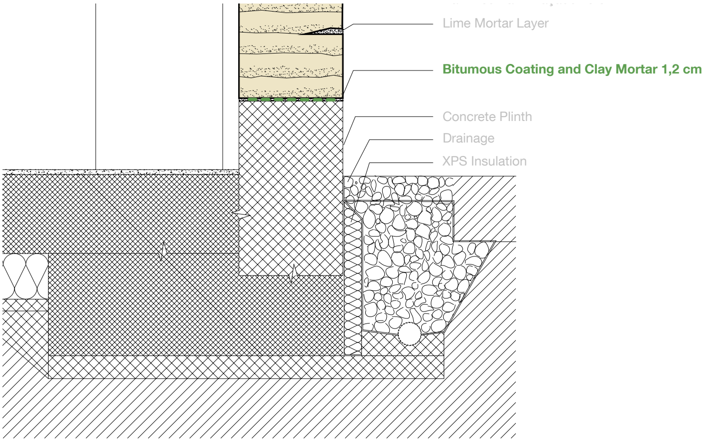

Fig. 25: Plinth, Ricola Kräuterzentrum

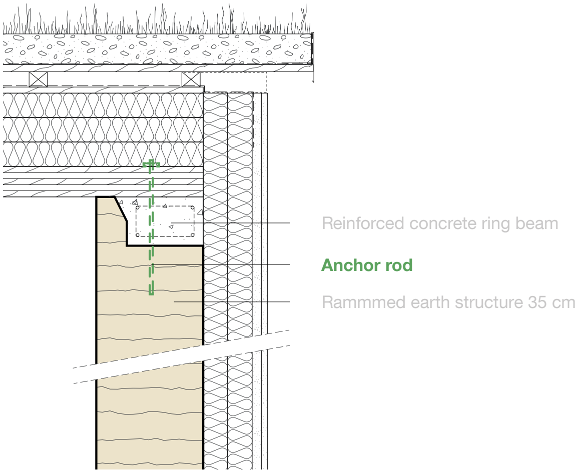

Fig. 26: Anchor rod, ERDEN Design Guide.

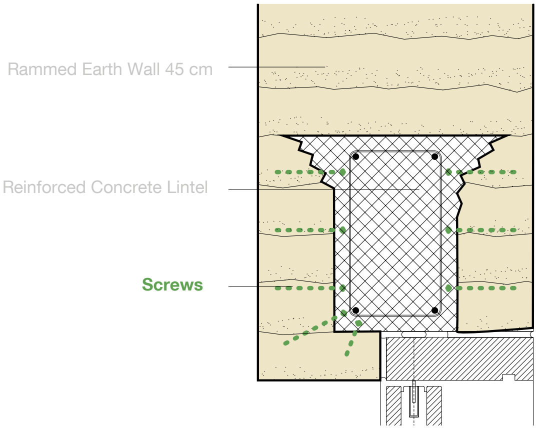

Fig. 27: Reinforced Lime lintel.

Re-use of Façade Elements

One often available domain is the realm of facade elements, especially elements of curtain walls are easy to dismantle and re-purpose. This includes a variety of materials, for the earlier mentioned project K118 where corrugated aluminum sheets used and also especially expansive materials such as marble can easily be converted. An especially interesting domain are windows. Even though the removal is quite simple, their reapplication is rare, the conversion to contemporary standards is often named as an obstacle. [48]
Nevertheless are several successful projects incorporating re-used windows available. On is the ‚ELYA Kultur- und Gewerbehaus' by in situ, which *incoprorates different window sizes* in vertical fields on the outside face of the facade, and also to the courtyard. [57] (Fig. 28)
The windows are *installed* in an *offsite* prefabricated wooden frame component, which reduces the individual installation onsite. (Fig. 29)
This implementation reveals the main problem of using different window sizes. Their diverging formats are requiring a framework, in which they can be implemented in a cost-effective way. In a conventional massive construction project, this would mean to plan a lot of different lintels and openings in onsite erected walls, complicating the construction process. For rammed earth wall components, this also represents an obstacle, it after all means to create a variety of different elements for individual situations.

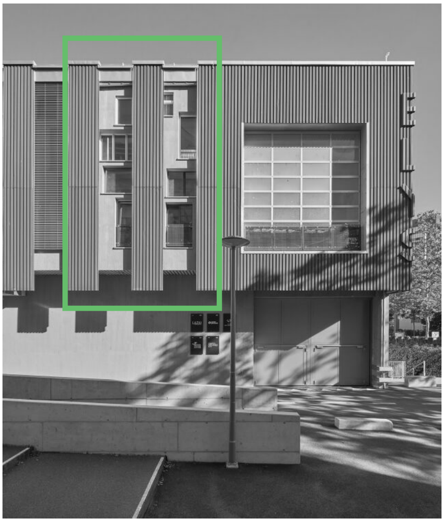
Fig. 28: ELYS project, in situ


Fig. 29: Pre-mounted re-use windows.

Façade elements and rammed earth. The technical details of windows in rammed earth are overlapping with those of ring beams and lintels and can be seen at the earlier described point. Nevertheless, it’s important to mention, windows are an elementary part of the water protection scheme of an earth wall, which means that its edges should also function as measures to slow down the water flow on the surface but also should divert the water intake away from the wall and provide drainage.

In an example detail, this is exemplary shown by integrating a window reveal stone upstand to prevent moisture clogging in area of the windowsill. (Fig. 30) In the design guide of ‚ERDEN‘, a company of Martin Rauch this method is called ‚protection by design‘ [11]

As mentioned earlier it is also possible to combine rammed earth walls and conventional insulation systems, even using conventional horizontal anchor connections and the resulting surface finish. [32] This implies that a general application of re-used facade elements should be possible. Still emphasis must be put on an appropriate combination considering the material characteristics of earthen materials and the need for protection of trapped moisture exposure.

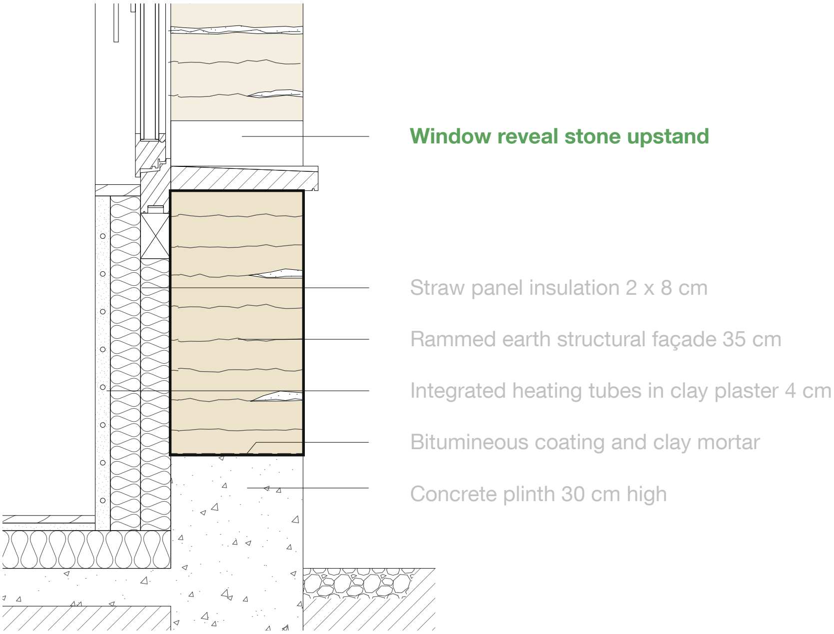

Fig. 30: Water protection window.

As a material that reappeared often in states of crisis, even before in ecological ones, rammed earth experiences it renaissance today not in a situation of material scarcity but oversupply. This oversupply of energy intensive materials occurs in contrast to the past not in a situation of demographic and economic decline, but in a situation of growth, consequently damaging the environment in its course. Considering the large numbers of material applications together with the waste volume associated with the construction industry, the non-destructive disassembly and reimplementation of material seems only to be in its infancy state. But there seems to be a perspective that an urban pool of re-appropriable materials could be considered again as one of the abundantly available resources of the urban environment, next to the earthen materials beneath the ground.

Different material combinations with rammed earth are already known from historical precedents. The construction process however was different than today, where the planning of an earth building starts with the earth aspect itself, followed by all substituting materials, making it an initially earth centered design process. The historical process however followed another play book. As seen in the example from France, the design process started with the parts of the building that are not realizable using the onsite loam and the material sourcing for those missing elements, which were later glued together by rammed earth.

The contemporary re-usable practice works in the same way as shown before. The material sourcing comes first, then its combination and application. [58] As those materials are already in their finished state, in the case of concrete this means cured and solid, not pourable in a wall cavity or something alike, the earth portion needs to be designed afterwards when trying to bring both domains together. This reverses the design process, the rammed earth must react on the already available materials, not the other way around. The advantage is, that applications such as horizontal load-bearing elements which are hard or not realizable using earth are viable without creating a large ecological footprint.

And earth can be a relevant mediator between different geometries, considering that the material is formable and a limited larger material application to simplify joints is acceptable given its low grey energy content, abundance and positive effects on the interior condition.

But to function as that mediator, it still faces limits which are mainly back tracible to the need of manifold geometrical abilities to be able to connect sourced elements with different characteristics, currently not realizable due to the material's unchangeable material characteristics (except stabilization) on the one hand and the available fabrication principles on the other.
To understand the currently available scope of geometric freedom and its limits, contemporary examples of unstabilized rammed earth component with unconventional forms will be looked at more closely.

Challenging Geometries and Rammed Earth

Window joint, Ricola Kräuterzentrum. At the ‚Ricola Kräuterzentrum project' for example, a specific part of the wall offers an opportunity for that, as adjacent elements of the round windows provide a glance of complex geometry. Taking a closer look at the components during the construction phase, one shows a changing layer direction when approaching to the window frame and a slight change in surface quality. (Fig. 31) This indicates that a different tool, presumable a handheld pneumatic ram was used to fill and compact the blind spot of this mould area with an acute angle, to create the circular shape, which could not be reached or executed with industrial machines. (Fig. 32)
Also interesting is a part further down to the bottom of the window frame. At the steeper part of the window circle the layers are more horizontal than at the component described before. But at the lower part of the element, the earth layers tend to an arc like form, which occures when an equal amount of material is placed and rammed over a curved surface. (Fig. 31) This indicates that the component was rammed upside down. In contrast to the earlier element, the round shape is in that case not a problem, feasible flat angle when being rammed in a rotated orientation, but surely includes also a portion of manual work at the curved edges.
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Fig. 31: RIcola Kräuterzentrum during construction.

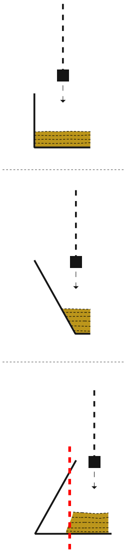


Fig. 32 Ramming blind spot.

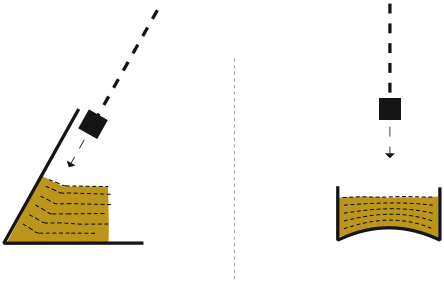


Fig. 33 Ramming curved surface.

was rammed upside down. In contrast to the earlier element, the round shape is in that case not a problem, feasible flat angle when being rammed in a rotated orientation, but surely includes also a portion of manual work at the curved edges.
In comparison to a fully machine-made wall component, the fabrication process of those parts contains a longer fabrication time considering the manual work portion, but also an additional mould part must be implemented to realize the arched form. (Fig. 34) Briefly summarized will that, in addition to the manual retouching of the joints, [51] will have had a significant impact on the cost of the building's construction.

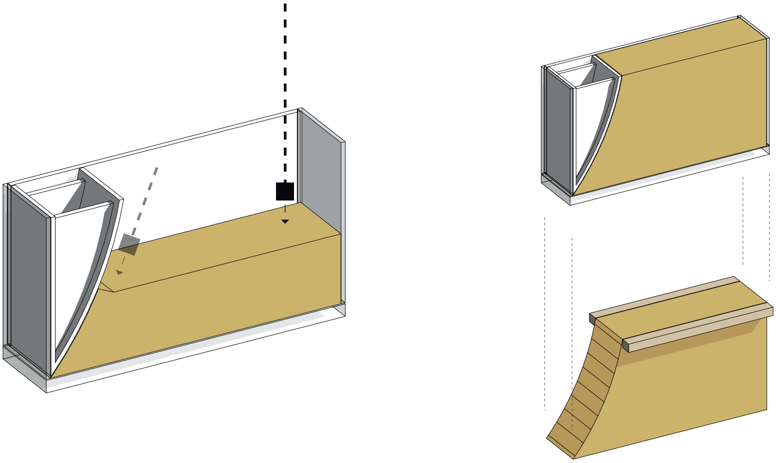


Fig. 34 Additional mould part.

Larrsen Sheet Joint, Case Study Steel House. When taking a look at a reoccurring connection point of the Case Study Steel House by Boltshauser Architekten AG, the walls components, (Fig. 35) that later hold the sheet pilings together, are rammed, they cannot be formed exactly to its shape. This is a result of the current production state of the art, which is a ramming machine working perpendicular to the layer or bottom orientation of the mould. (Fig. 32)
That leaves among other two solutions to produce and place the component. The first one is to ram it upside down in a mold template of the sheet pilings, flip it and then place it on the wall according to its

corresponding position. This results in a significant amount of maneuvering when the component must be lifted and rotated, as well as a risk of damaging the brittle material in the process. (Fig. 36)

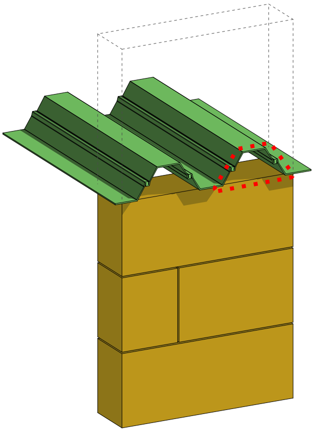
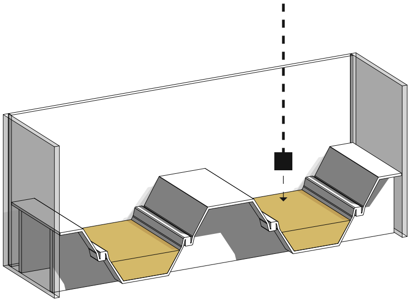


Fig. 35 Larssen Sheet Joint problem.



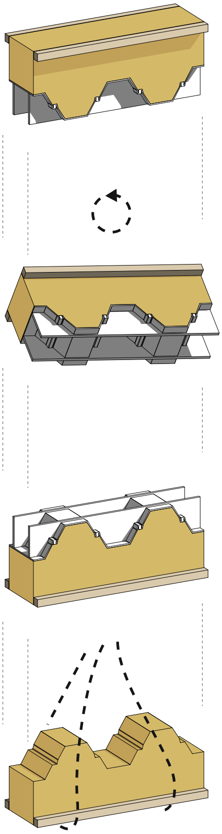


Fig. 36 Ramming upside down.

The second and more feasible solution is to produce a regular component and subtract the irregular shape afterwards by using a circular saw to define the edges and than hammer away the excess material with a jackhammer. (Fig. 37)
In a picture of the 1:1 prototype assembly indicator for that method is identifiable. The flat finish at near the edges indicates the use of a saw, were the rough texture in the middle of the surface makes the use of a pneumatic chisel expectable. (Fig. 38)
Both methods have disadvantages in comparison to the fabrication of regular rectangular elements. The first one requires complex form work and maneuvering of heavy elements and seems in general not very feasible. The second approach contains the ramming of redundant parts of a component, just to chisel them away manually afterwards. Although the excess material can be reused without any disadvantage, it still means, that the method includes machine ramming, which is the part of the process with the highest energy consumption, of volume parts that are later already considered excess. The result is a component that should incorporate a greater portion of manual processing and embodied grey energy.

Fig. 38 Preparation marks.

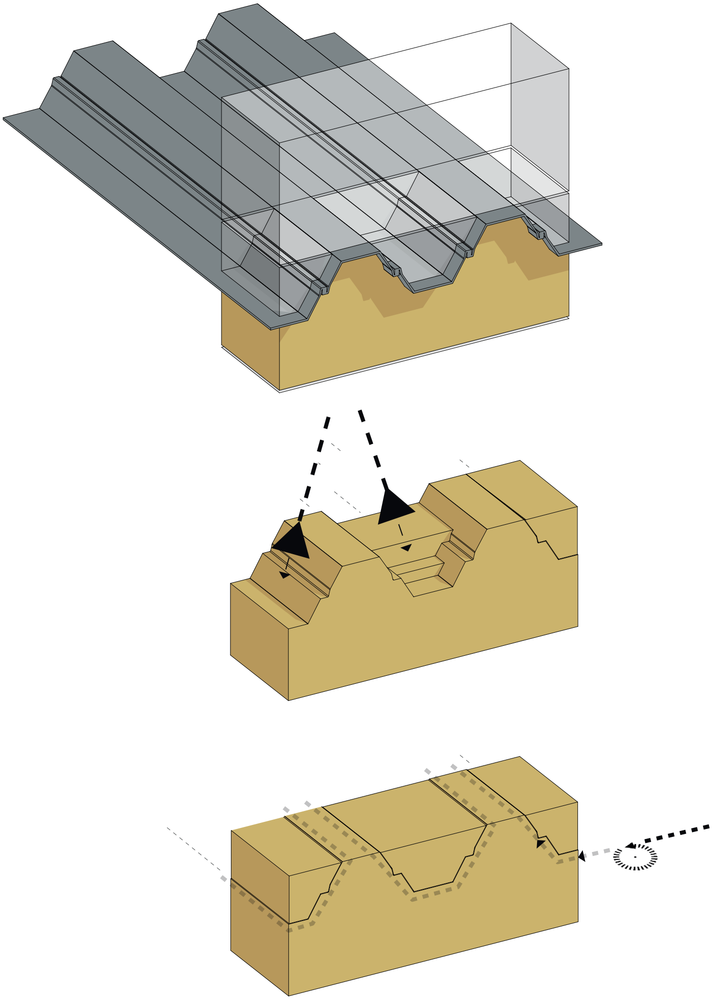


Fig. 37 Regular component with subtractive joint preperation.

Slab fillings. Floor filling systems such as the ‚HORTUS‘ module or the component based TERRADEK in an irregular grid system as a reference could not be found, also not in another material application such as kiln-fired brick, or flat brick fillings with concrete covering. On reason for that is that when different component width in the field between non-parallel beams, the apex of the arch segments would sit different heights to be structurally sound, next to other emerging problems, such as different horizontal forces that are led towards the beams. (Fig. 39)

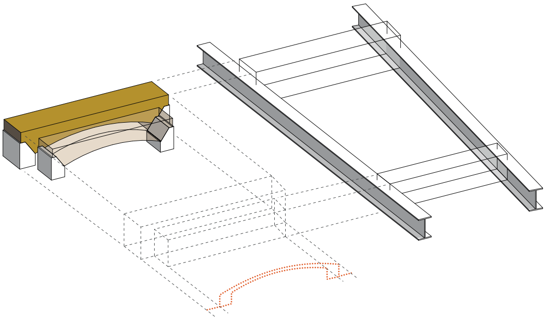


Fig. 39 Irregular hybrid slab filling limits.

But as established before and when assuming that the fillings are non-loadbearing, still would the current prefabricating production state of the art not be able to create irregular shaped components with its contemporary means. (Fig. 40) The result would be manual post-processing on site comparable with the handling of brick and only would be possible with rectangular horizontal elements that are not load-bearing, the bearing capabilities of structural arched elements would be disintegrated by changing the geometry.

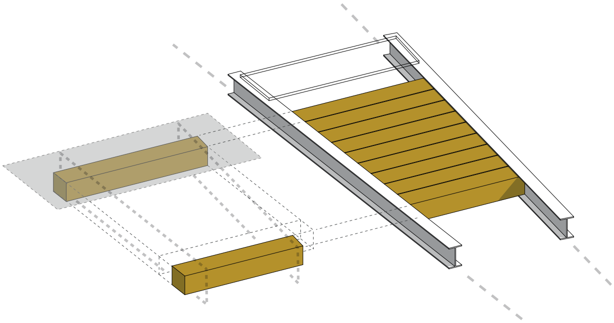


Fig. 40 Irregular hybrid slab filling.

It is evident that currently geometric limits are defined by the material characteristics but especially because of the production process of rammed earth. For the moment, this is only circumventable by either decreasing the element size towards brick format which leads to a high demand of manual workforce, or to produce and prepare the prefabricated components in a more artisanal process in the first place, leading to the same ends. Large rectangular wall elements are increasingly easy produceable in a mechanized production process, but when already containing niches and preinstalled installation space, additional form work is required, meaning more material and also leading to higher cost. Some geometric requirements such as irregular edges or grooves at the top and side faces require even a subtractive preparation process, which consists of sawing and hammering away parts of the newly made walls, increasing redundant material fabrication in the first place and again an increase in manual processing. This work-load increase adds to a still quite manual process of the erection of rammed earth buildings in the first place, whose surface joint retouching alone is estimated to represent 20% of all the work effort. [51] When re-used elements are included in the consideration, it's getting even more complicated. The opening challenge is, as mentioned before, a multi-layered one. The unsure quantity of prosecutable materials is a factor, which is increasing the use of different shaped elements in a state of already wide-ranging element thus geometric variety, including straight, diagonal or curved and even completely irregular surfaces and connections. Summarizing all the factors, the following picture emerges. Similar forms as the ones needed to combine a diverse re-use practice with rammed earth construction are probable realizable, when considering that similar shapes already have been implemented. However, to do so, an incomparable high degree of manual work is necessary, which represents a backward step in the efforts of making earth architecture more accessible in the western hemisphere through industrialization, to oppose the challenges imposed by climate change and the consequences of linear material circles, in whose creation the construction industry is largely co-responsible.

A further development of rammed earth techniques with focus on achieving a higher degree of geometric freedom without compromising a high degree of industrialization is indispensable to leave not only the current state of geometric rigidity, but also to create possibility of a future implementation of unconventional methods to reduce the content of ‚new concrete' among other new materials with lots of incorporated primary energy. One development focusing on achieving that goal will be introduced in the following.

[Additive manufacturing process for rammed earth. An alternation of selectively applying earth paste and compacting aggregate, allowing to ‚ram-print‘ complex geometries step by step.]

Intrusion Earth

Intrusion Earth Additive Manufacturing

3D printing rammed earth. This mentioned development is an additive manufacturing technique in a still prototypical state, called ‚Intrusion Earth‘ (IEAM, Intrusion Earth Additive Manufacturing). This method aims to achieve advantages seen in other particle bed print techniques such as ‚Selective Paste Intrusion‘, where loose aggregates are bound together by selectively applying cement, done layer by layer, enabling the printing of objects with large geometric variety. [59] Functioning as an inspiration, but by utilizing clay in a different application process instead of hydraulic binders, this new approach works in a scope of considerately lower compressive strength, [4] but incorporates all the advantages that were mentioned before for the use of loam and the extension of the geometric scope, including its reutilization capabilities and low carbon footprint that cement on the other site is lacking.

Method overview. The printing process is an alternation of applying and compacting aggregate, which can be stone grit or similar material, and the application of a clay-based binder, consisting of clay, sand and straw, and works as follows.
In a framed work-bed an initial layer of aggregate is applied, whose diameter defines the layer height. The prepared aggregate surface is the process starting point of every layer, followed by the application of a seam of earth paste (Fig. 41), done by a robot. The application area of the seam defines the area where the binding, thus the solidification of the element will occur. When the next portion of aggregate is placed (Fig. 42), the surface is rammed to guarantee a sufficient bond of paste and aggregate, which presents the finish of a layer cycle, and the preparation for the next one. In this way, complex geometries are ‚ram-printed‘ step by step. (Fig.43) [59]
Categorization. Considering the different aspects of this technique, it appears to combine different earth building domains into one automated method. The material properties, or better those of the binder paste are configured by adding straw to the mix, which strengthens the material against shrinkage caused cracking, which progressively occurs when the water content of the material rises. [59] This reinforcement was often used for very wet clay or loam applications, for load-bearing techniques this explicitly applied for *COB*. A method where earth-straw lumps where stacked and layered to form walls and later trimmed to create an even finish. [60]

Fig. 41 Clay extruding.

Fig. 42 Aggregate laying.

Fig. 43 Automated ram.

Another similarity appears referring to the method of extruding. The binder application is done by extruding the paste trough a nozzle, which is fed by a material pump, providing the material. [59] A similarity appears in the domain of conventional earth extruding, where an industrialized fabrication process ejects earth bricks by extruding almost pure clay through a mouth piece defining the length and width, resulting in an endless clay cuboid, which is then cut into right size for the wanted bricks. [61]

And as already mentioned, there are strong similarities to the process and the finished pro-cess of the rammed earth domain. In contrast to conventional rammed earth, the material is applied in a separated state, first the aggregates and then the clay binder, different than having a course ready-made mix which is the case for rammed earth.

So, when trying to categorizing Intrusion Earth, one could conclude it is a mixture of the three methods, an extruded stacked rammed earth technique, but this is not the case.

Only having similarities with cob in relation to one material characteristic and only one fab-rication aspect of ‚conventional extruded earth‘ on the one hand, the material matrix (large aggregates) and characteristics (a theoretical compressive strength similar to compacted earth), the additive fabrication process (layer-based cycle of material application and ram-ming) and the component type of the product defines the manufacturing process clearly as a rammed earth technique in the realm of 3D printing.

Intrusion Earth and conventional Rammed Earth

Having established the relation of rammed earth and its automated counterpart, the question of the connection of both occurs out of a specific reason. The process of linear shaped rammed earth components is already a sophisticated and compared to its staring point a fast thus efficient one. Using a 3D printing technique to fabricate regular shaped components does not present an advancement when its advantage lies in the geometric manifoldness of its product. In addition are some hypothetical questions still unanswered, one that the setup could be a more complex, thus more expensive to create and control, and two, there is no data for production speed yet. This means that the use case for the technique probably lies in the delta of geometric freedom that with the current rammed earth fabrication

process with manual work portions is more cost intensive than a more expensive fabrication process providing this freedom.
This means that in a project where IEAM will play a role, all regular rectangular components will probably be produced in a conventional way, comparable to the mechanized setup discussed before. Assuming both techniques have similar material characteristics and considering the observation that rammed earth works quite well even with considerably stronger and stiffer materials such as brick walls as seen in the historical example in France, the question of joining both is more a structural and visual one than one of connection different materials.

Structural Connection. Based on that, the assumption is that the joints can be executed according to rammed earth practice guides mentioned earlier, which among other requirements includes planning the joints of the components to form an overlapping orientation comparable to masonry bonds, to ensure the walls structural integrity. [11] However, this should only apply to level bed joint plains with a 0° orientation, since in contemporary rammed earth applications different angled horizontal joints do not occur. When using IEAM, especially with the aim of incorporating irregular shaped re-use elements, which could include arched formed components where the joints are aligned perpendicular to the forces at work, the likeliness for inclined angled joints is rising.
As apparently there is no precedent for rammed earth components that are bigger than brick format, that are applied in this way, the joining of natural stone, also a material with an immense disbalance between compressional and tensile strength but still a lot stronger than rammed earth, [62] will be source of loose inspiration and function as a design tool for the component and joint design occurring in the following case study.

Architectural Implementation. Another question is the visual connection of both materials. Mould produced rammed earth has a, often irregular, distinctive layer structured face, which is caused by tiny differences in the layered raw material and also shallow spalling on the surface, induced by ripped off clay parts when removing the mold. (Fig. 44)

Nevertheless is the surface finish of those brown-ochre-colored parts very smooth, with sharp edges. Quite in contrast to the current surface finish of Intrusion earth components. As a result of the fabrication process are the vertical corners always chamfered, and the texture is rougher. However, as a result of the ramming process of similar sized but different shaped aggregates in a more liquid clay mix, a fusion of the layers does occur, creating a consistent surface appearance.
(Fig. 45) This effect leads to an interesting opportunity, which is already imaginable when looking at the results of the demonstrator fabrication during the student project. For this application, brick chippings were used as aggregates, creating a very specific surface appearance of alternating ochre clay and pale red chippings, fusing when increasing the distance.
But there is another aspect, the brown-ochre and regular shaped mould-rammed earth components, and the rougher appearing IE components in a warm pale red with blunt edges do in a way assemble the material combination of Hans Döllgasts repair of the ‚Alte Pinakothek‘ in the city center of Munich, where sharp ochre bricks and natural stone encounter worn out red bricks.
After a direct bomb hit during the second world war, a large portion of the building, especially the southern facade was destroyed. (Fig. 46) The damage was repaired by using re-purposed bricks of other damaged or destroyed buildings.
Reimagining and filling the structures wound in a different way, and yet following the historical ductus of the facade, it was completed again. [63] (Fig. 47) Transferred back to the earth domain, this indicates that differing edge appearance and a selectable color choice of the aggregate can play a role in the buildings design, even or especially in contrast to the appearance of other earth components, re-used elements or already existing structure.
Transferred back to the earth domain, this indicates that differing edge appearance and a selectable color choice of the aggregate can play a role in the buildings design, even or especially in contrast to the appearance of other earth components, re-used elements or already existing structure.

Bringing all those new aspects together, it appears that by going a further step towards industrialization, especially automation the figural limitation of rammed earth can be reduced in future. Nevertheless, the IE-technology is still in its infancy, but prototypical applications are promising. In combination with mould-rammed earth, new challenges emerge especially in the connection of angled bed joints, but in contrast to that, the architectural opportunities, such as new forms, material combinations and applications are moving within reach. Those opportunities will prototypically applied in the following case study, to deepen the understanding of what could be possible and open questions for future discussions.

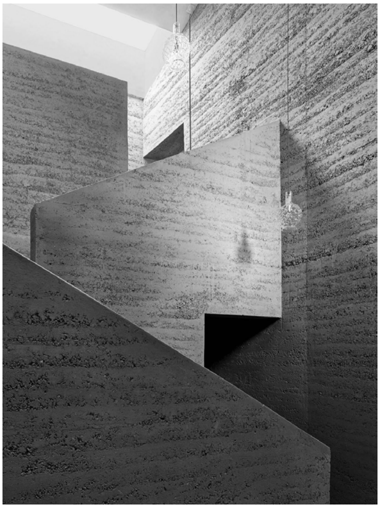


Fig. 44 Rammed earth surface.

Fig. 45 Intrusion earth surface.

Fig. 46 Alte Pinakothek.

Fig. 47 Alte Pinakothek Detail.

Design Rule

Design Rule

1. Defining regular Component Segmentation for Rammed Earth.

2. Placing irregular Re-Use Element.

3. Identifying Area out of Scope for regular RE Segmentation.

4. Defining IE components that correspond between irregular shape and regular grid.

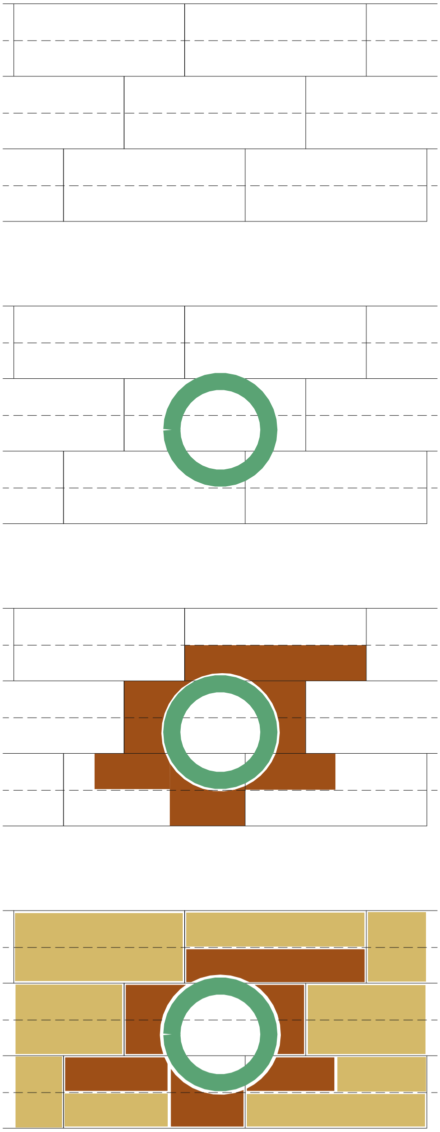


Fig. 48 IE Design Algorithm.

[Additive manufacturing process for rammed earth. An alternation of selectively applying earth paste and compacting aggregate, allowing to ‚ram-print‘ complex geometries step by step.]

Case Study Objects

Ribbed Slab

For the horizontal floor development, parts of ripped slab structures, made of reinforced concrete, are of interest. Occurring in different demolished or threatened buildings in Munich, especially car park structures such as the ‚City Parkhaus am Färbergraben‘ or the ‚Alpina-Parkhaus am Stachus‘ (https://abriss-atlas.de/map/), a general availability and quantity is expected. For this project, elements of 6.4 m length and 1.3 m width are presumed and thus had an influence on the structural layout of the case study.

Normally bedded in a negative formed concrete beam, the slab parts are now placed on the walls top face. When segmenting the rammed earth walls, the irregular shaped connecting surface of the slab bottom indicates an irregular earth component form according to the observations of the Larssen Sheet Joint at the ‚Boltshauser Case study‘. Instead of ramming a regular component and saw and chisel it to its final shape, the bed joint form can already be considered during the printing process, in addition to the conventional grooves to connect the individual wall elements.

Fig. 49 Ribbed slab concept model 1:20.

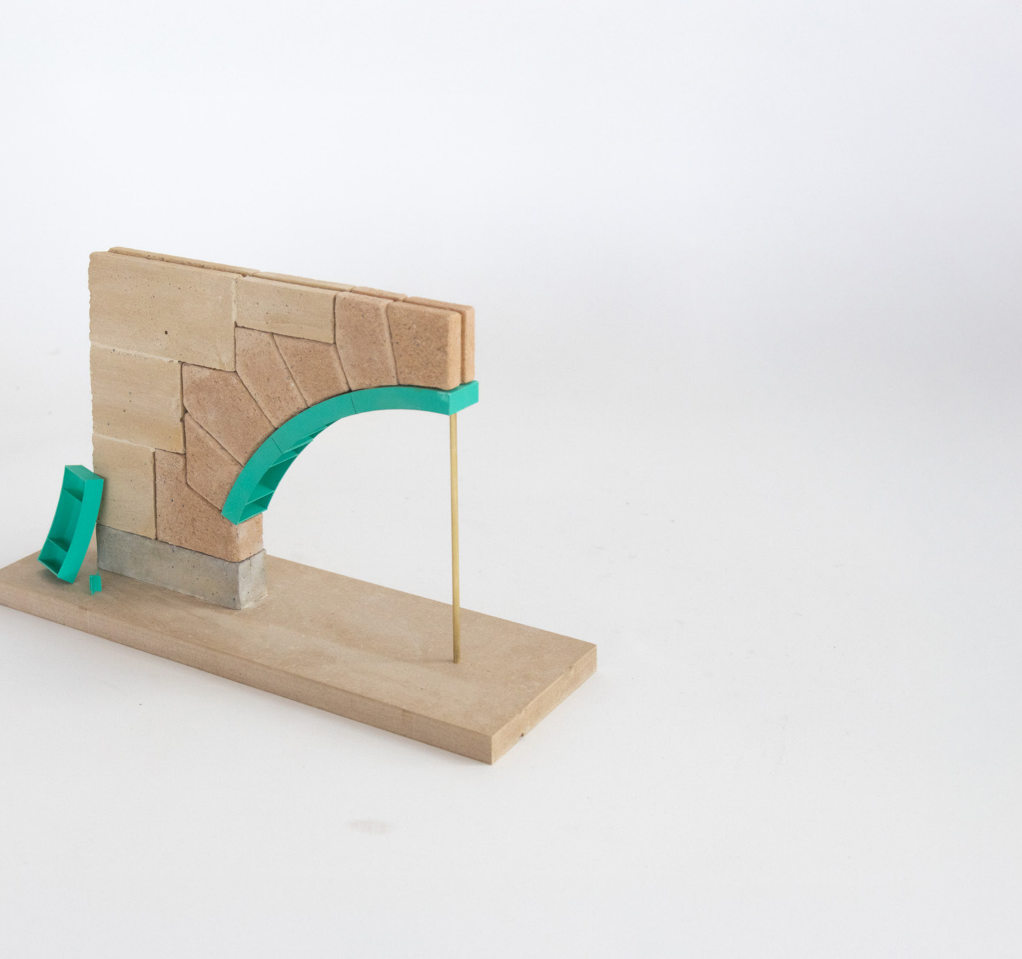
Ribbed Slab

Tunnel Construction Segment (ger. ‚Tübbing‘)

Used for the construction of the ‚Zweite Stammstrecke‘, a main trainline beneath the city of Munich, reinforced concrete ‚Tübbinge‘ (german expression) are used. [65] At challenging portions of tunnel construction, steel segments are used, which contrast with the concrete pendants, comparatively easy to dismantle, to replace and are available in different sizes and qualities. [67]
When placing segments of the mentioned as arch structure into the walls, certain challenges become evident. The first one is the anchoring to the wall, which is in the case of rammed earth difficult, also the horizontal forces of the arch and the weight from above could spread the segments and the wall.
To circumvent that, a foundation of IE shell components is printed, to function as a ‚lost formwork‘, for the reinforcement and a lime concrete mixture, which is the connection point of the arch segment, leading the forces towards the foundation. The imposts are connected in a conventional reinforced lime grove with the adjacent walls.

When now designing the rammed earth components according to the conventional overlapping and horizontal bed joint requirements, certain component forms emerge, which provide the same challenges as curved elements that were used or for the ‚Ricola‘ project. Considering now the geometric freedom in the IE process, the problematic segments can be divided and printed according to structural favorably aspects, such as force distribution and architectural aspects, such as layer orientation.

Fig. 51 Tunnel construction segment, concept model 1:20.

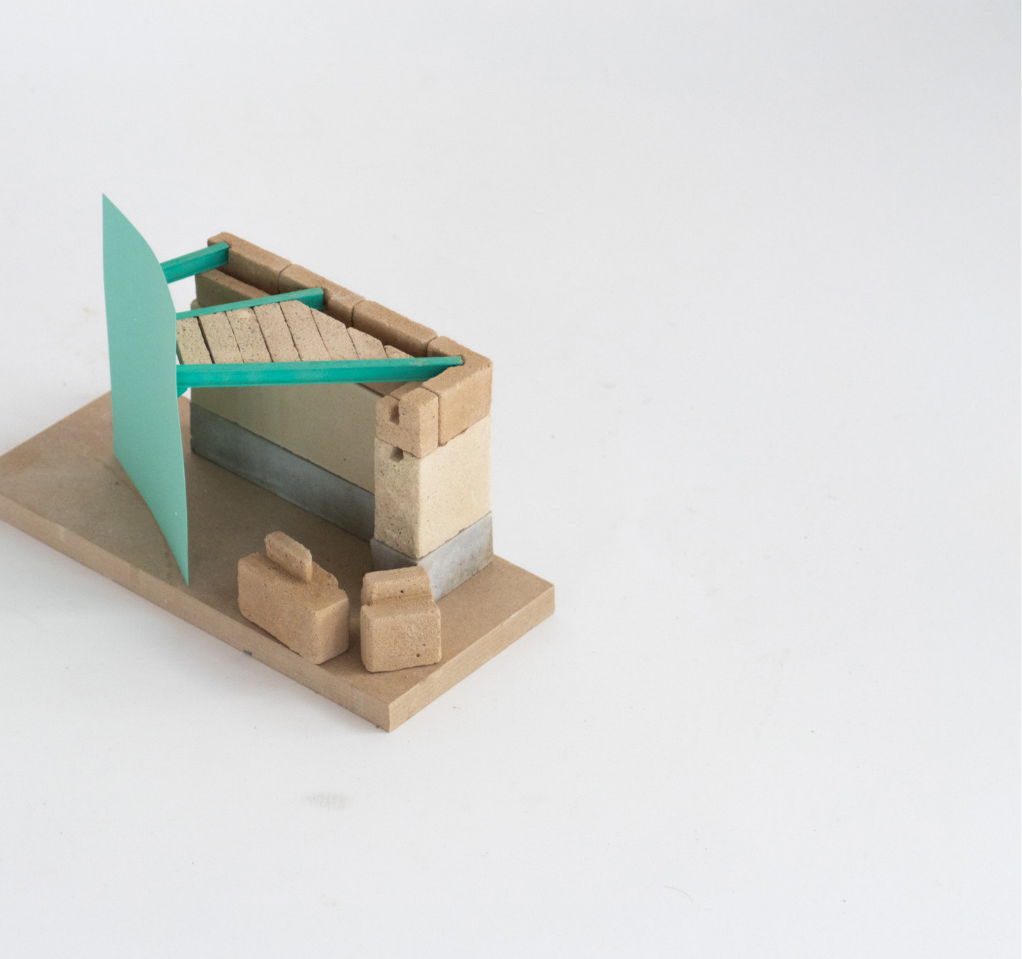


‚Hourdis'-Floor

The round wall formation of the elevator shaft provides another interesting situation, the slab design of the floor segment surrounding and touching the curved wall. (Grafik) The earlier mentioned ripped slab elements are not usable for that situation, it would include an unreasonable amount of cutting and the connection point would still be not feasible. The inspiration for a solution of the situation are the hybrid floors of the TERRADEK -system, using beams and non-load bearing rammed earth fillings. As described earlier are irregular situations not feasible due to structural and fabrication limits, but when having the opportunity to use free formed rammed earth, at least irregular fillings are of interest, also from an architectural design aspect. When now placing re-acquired I-beams for the purpose, a perpendicular orientation to the curve can simplify the steel-concrete joint (Grafik), the steel earth includes the bolt anchoring of the beam into the ring-beam of the wall. As the perpendicularity towards the curved shaft creates an irregular orientation towards the earth wall, the sheathing wall segments are printed as well. After the filling, of the beam yokes, the beams are planked and a regular floor setup can be established on top.

Fig. 53 Irregular hybrid floor filling, concept model 1:20.

‚Hourdis'-floor

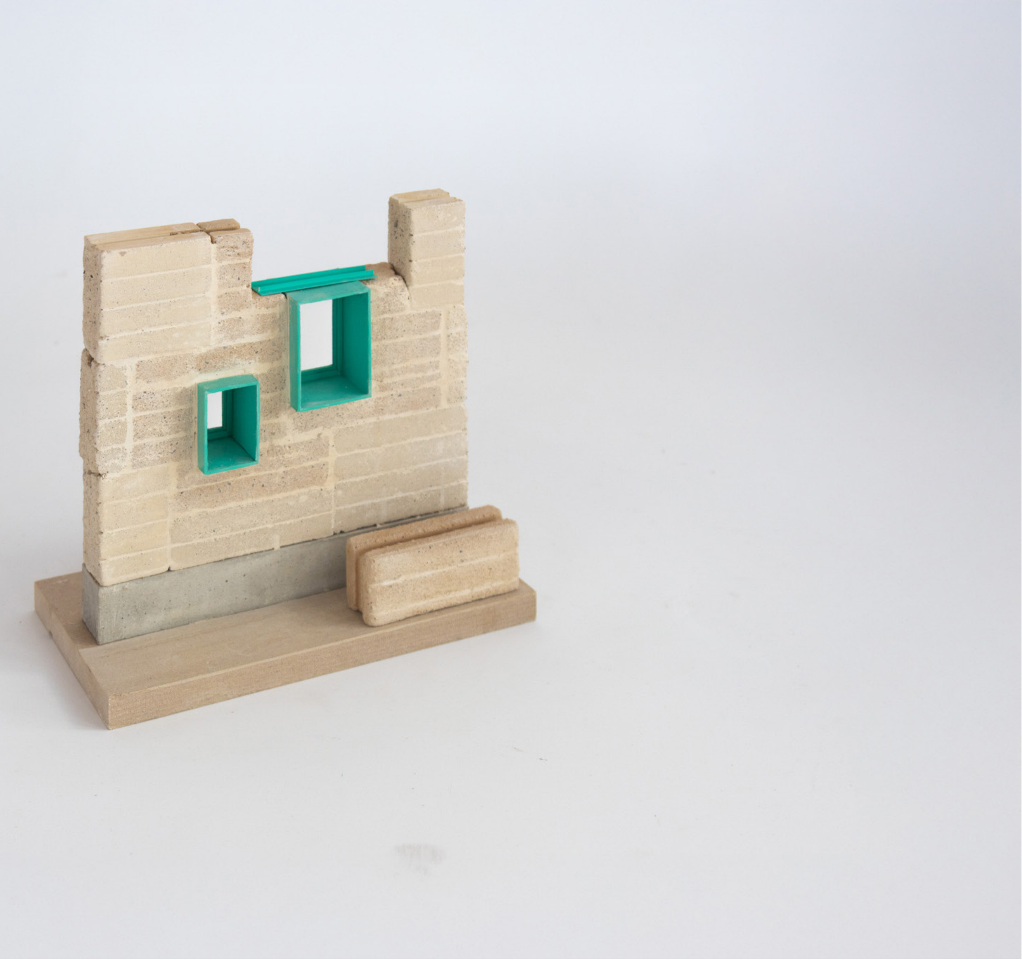


Façade

Mentioned earlier as an interesting and often occurring but complex re-use element due to their varying sizes and quantities are windows. They appear in almost every demolition case in Munich and are quite available as a result. [67] For the case stud, they will be used as part of the visual barrier between the street and the intimate living spaces. This barrier is established by a massive wall, perforated with small re-purposed windows, which are freely positioned to create different spatial atmospheres in the rooms behind the wall. Considering the placement of the windows before the joint segmentation of the rammed earth components can lead to certain irregularities, which can either be avoided by placing the windows as far as possible in a grid, which is still of limited use due to their different sizes in comparison to a regular grid and has a reverse dependency towards the architectural design. Accepting irregular component shapes as result is in consideration of the possible additive manufacturing capabilities the more feasible method. Printed in their different sizes and arrangement, allowing the implementation of a lintel, the parts can be produced in their final shape.

Fig. 55 Façade, concept model 1:20.

Façade



[A residence for guest researchers, situated in Maxvorstadt, Munich. The plot is between Arcisstraße 47 and Neureutherstraße 15.]

Case Study Design

Theoretic Space Exploration

This case study started with a quite loose frame. The task was to design a residential house for guest researchers on a plot in Munich’s Maxvorstadt, a few meters north the ‚Nordfriedhof‘, utilizing the new additive manufactured rammed earth technique, not knowing at the start, that this task formulation already included the formula framework for this case study design, which was later occurred also during the research for this thesis.
When using earth as a building material, which kind whatsoever, it is indispensable to put emphasis on the resource. To achieve specific results, it is important to know where the material comes from and to be aware of its availableness. Understanding the composition of the material to enable certain strength and mass properties and what measures have to be taken to protect the material while storing and process it.
Those are important question that must be considered, and they are always connected with space. The space to source, store, to operate and to build, a limited resource in the city.
As a result, a specifically resource focused approach developed for this design, focusing on earth and space. But as mentioned earlier, because of the structurally limiting characteristics of rammed earth, the missing tensile strength in particular, the search for a substituting resource led to another abundant one in the city, re-use elements of demolished or condemned buildings, an emerging topic in the architectural realm.
Combining this with the observations made beforehand, a logical design order would start with the designation of the plot and the spatial needs of the building, followed by gathering the (substituting thus mostly horizontal) re-use elements and placing them according to their structural and atmospheric capabilities. Then identifying the following (vertical) structural needs, leading to the definition of the load-bearing earth structure which bonds everything together. By implication this means that all the functions, are framed in earth.
This defines the framework for the design proposal as followed:

space + re-use + earth = architecture

This is just a preliminary and simplified formular, it will be used and adjusted on the way.

Urban Space

Urban fabric and space. Situated in between Neureutherstraße 15 and Arcisstraße 47, the plot is still part of the Maxvorstadts dense rectangular layout. The typical fabric consists of closed or almost closed perimeter blocks with buildings of approximately 15m heave and up to 20 m roof height. The perimeters are regularly perforated by entrances perpendicular to the streets, prompting the buildings to bending inwards, which creates small courtyards or more intimate niches in bigger courtyards. (Fig. 58) The ‚block‘ in which the case study site is located consists of single standing buildings, but is perceived in a similar way, a regular linear perforation towards ‚Nordfriedhof‘ and one towards an informal street in the west, small niches and a long courtyard axis, parallel to Neureutherstraße. This perception however is damaged in the area of the case study plot. Here the block breaks open towards Arcisstraße and prevents the conclusion of the encapsulated space. To finish this ensemble, the case study design will act as earthen glue, filling the gap between the structures, connected by a now re-attached interface, the firewalls of the existing buildings, which had no function until today. (Fig. 59)

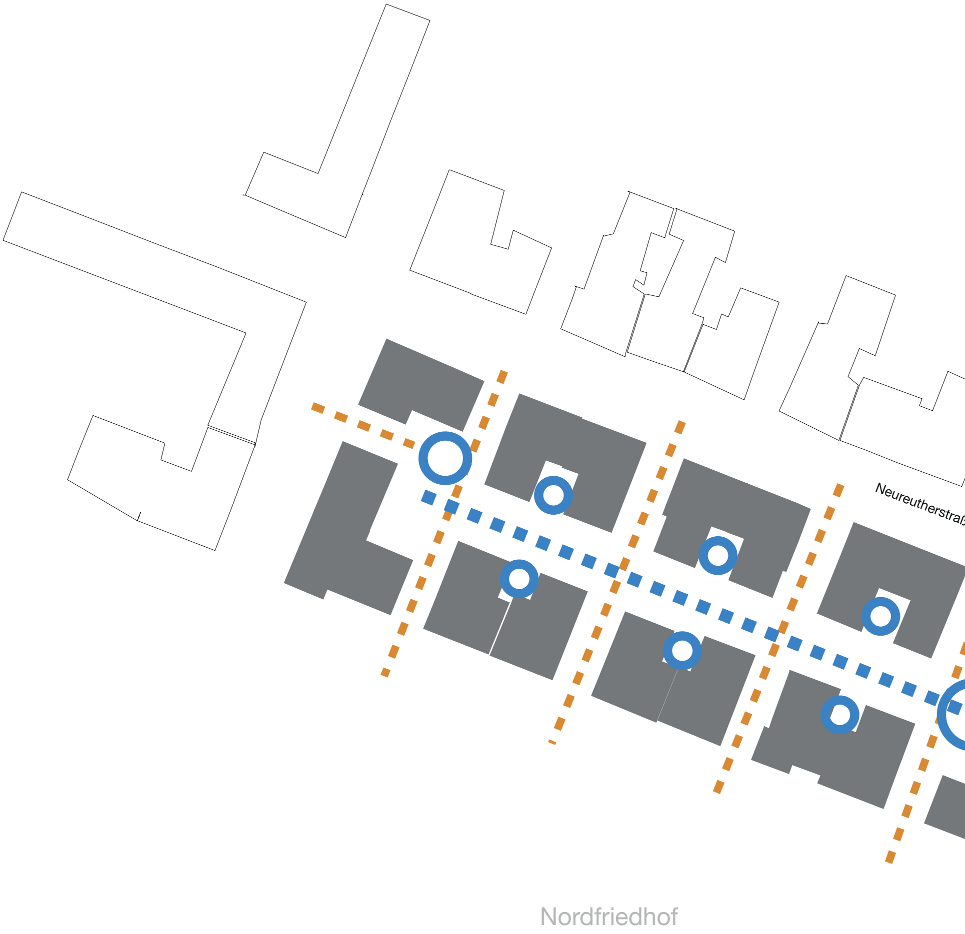
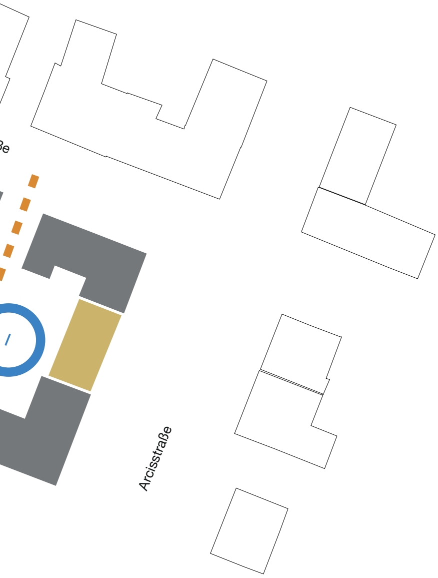


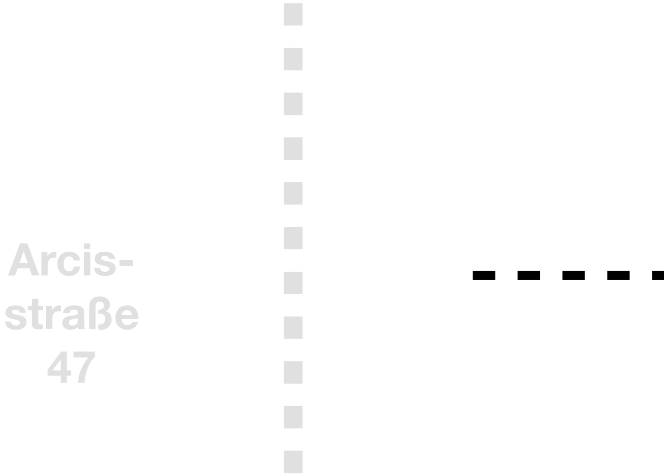
Fig. 58 Urban fabric Block, 1:2000 (scaled)

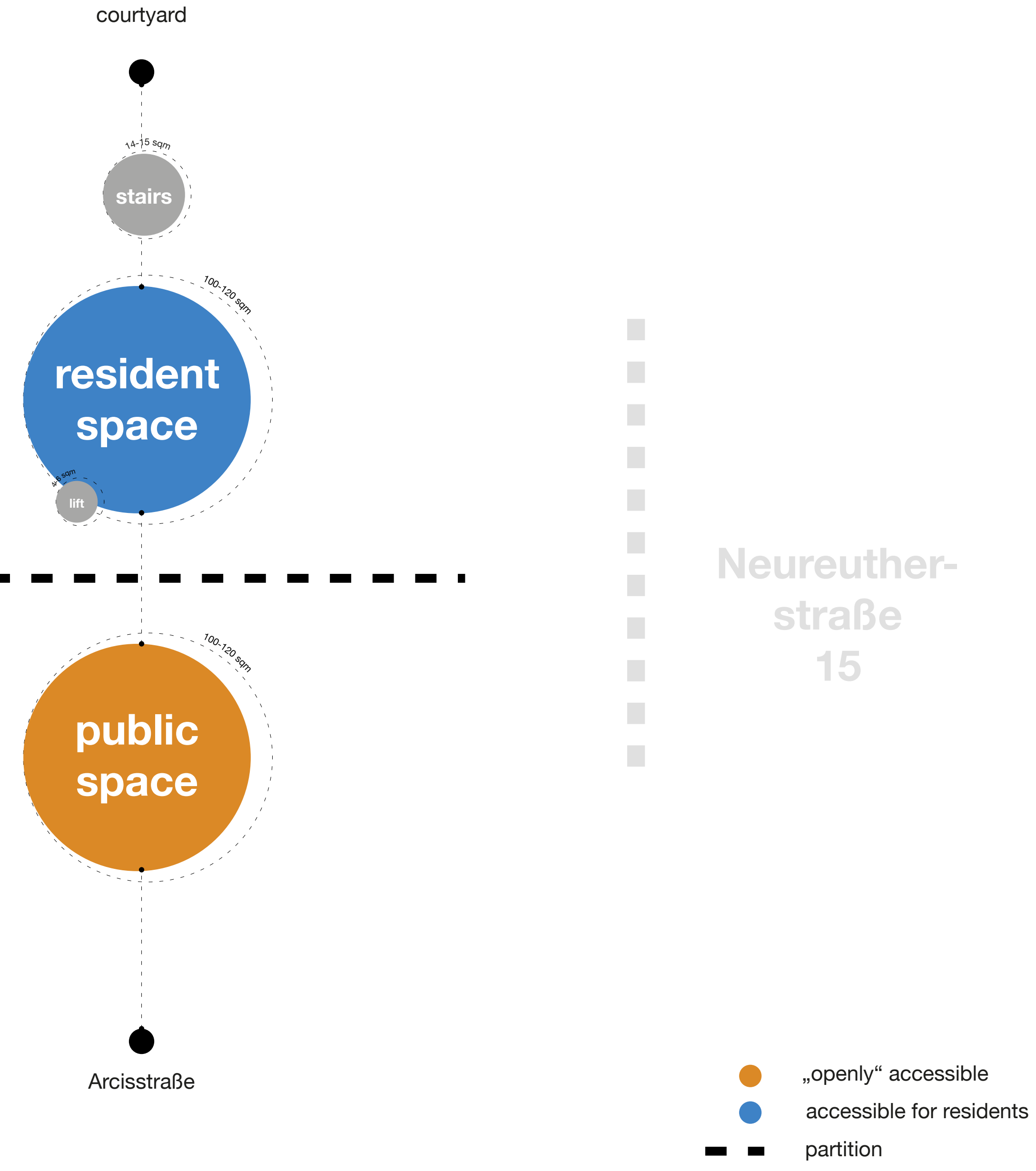
Fig. 57 Urban fabric Neureutherstraße, 1:5000 (scaled)



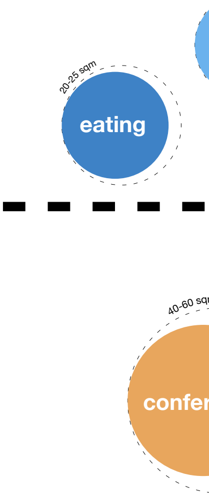
Ground Floor Space

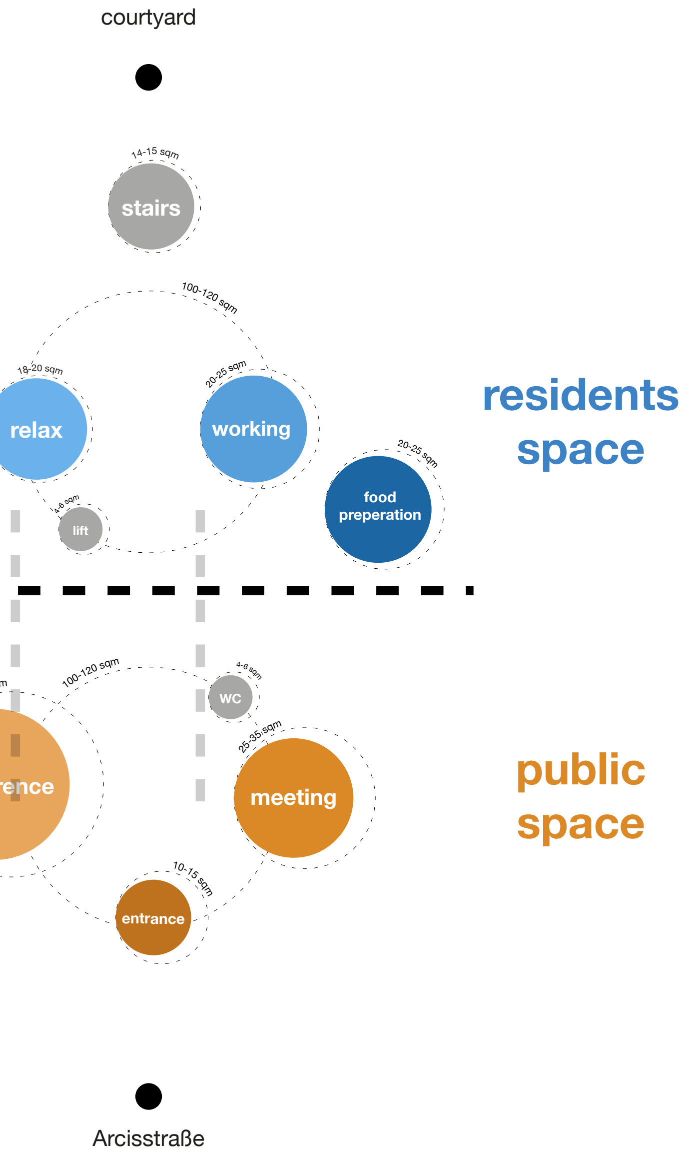
The ground floor with the main entrance towards Arcisstraße will be segmented into two parts, an ‚openly' accessible area for public use, and a communal space for the residents towards the courtyard.




courtyard
14-15 sqm
stairs
100-120 sqm
resident space
4-6 sqm
lift
Neureuther-
straße
15
100-120 sqm
public space
Arcisstraße
● „openly“ accessible
● accessible for residents
▬ ▬ partition

The public use is intended to host a conference hall, usable for presentations and other events, an offer that is not only open for residents, but for the interested public. A smaller meeting space can either be used separately, or function with its partitioned kitchen/bar installments as catering area.
Surpassing the threshold towards the courtyard, a linear room layout provides different offers for the residents, such as spaces for a collective kitchen and eating, but also for working or relaxation. This offer intends to provide an interface for the guests that far varying backgrounds, to bring them together in everyday life activities and thus foster a network, but also to offer a community in a new city during the short stay of 6 to 12 months. (T64)





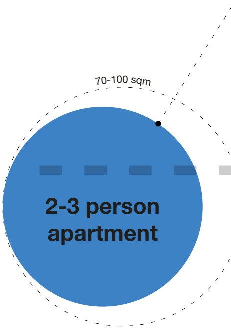
● „openly“ accessible

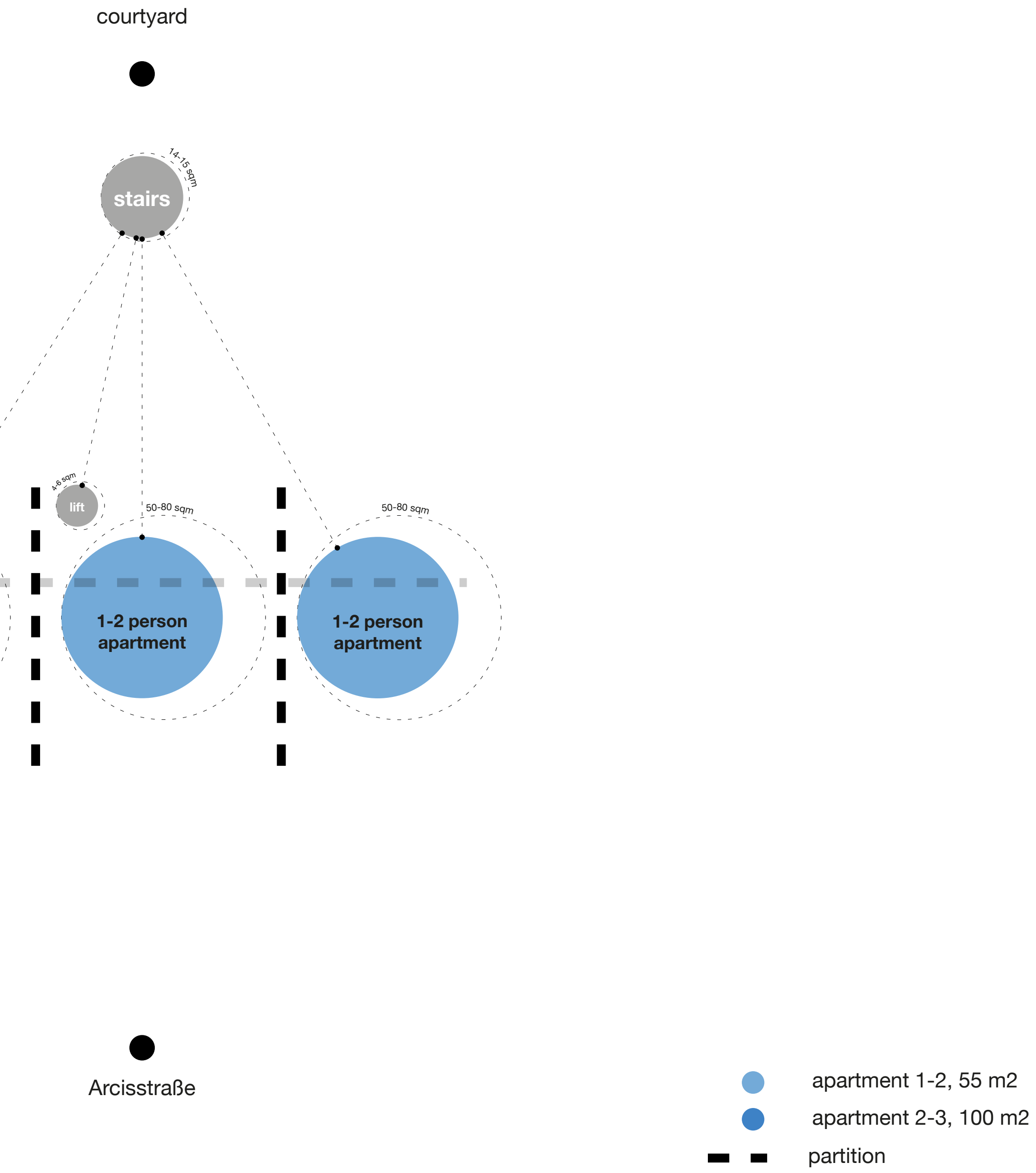
● accessible for residents

▬ ▬ partition

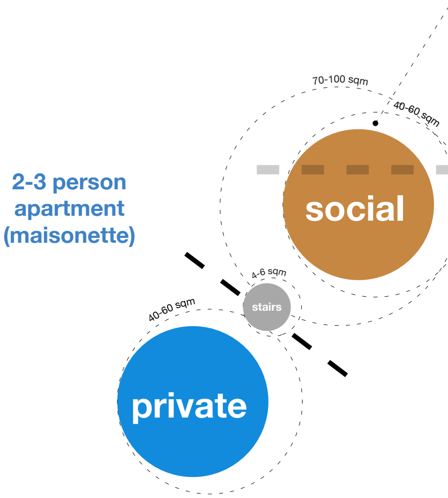
Regular Floor Space

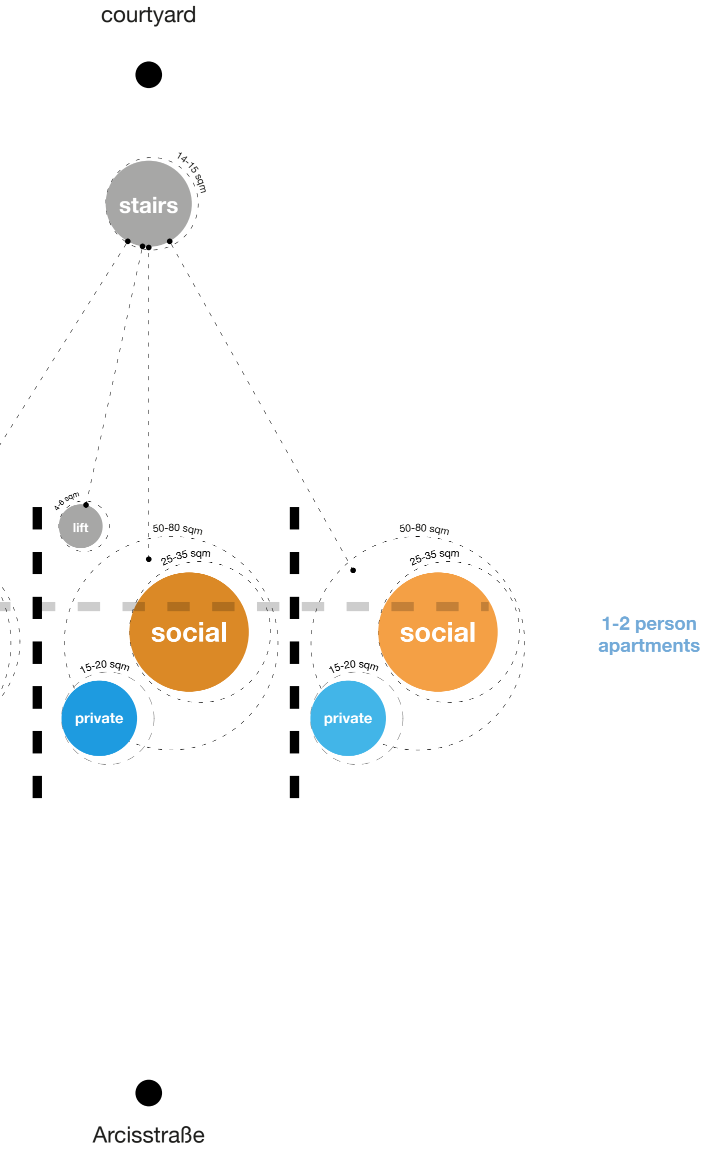
The first floor, functioning as a regular floor plan layout, is accessible either through the free-standing staircase in the courtyard or an elevator. The space contains the access to three apartments, here two for 1/2-person(s) with a floor size of 55 m2, and on for 2-3 individuals with 100 m2, organized as a maisonette.




courtyard
stairs
14-15 sqm
4-6 sqm
lift
50-80 sqm
1-2 person apartment
50-80 sqm
1-2 person apartment
Arcisstraße
apartment 1-2, 55 m2
apartment 2-3, 100 m2
partition

The layout of the apartments can be separated in social functions, which will be architecturally more exposed, and intimate funtions, that will be of a more enclosed nature, nevertheless being oriented towards the street side.





🟧 „extroverted“ living space

🟦 „intimate“ private space

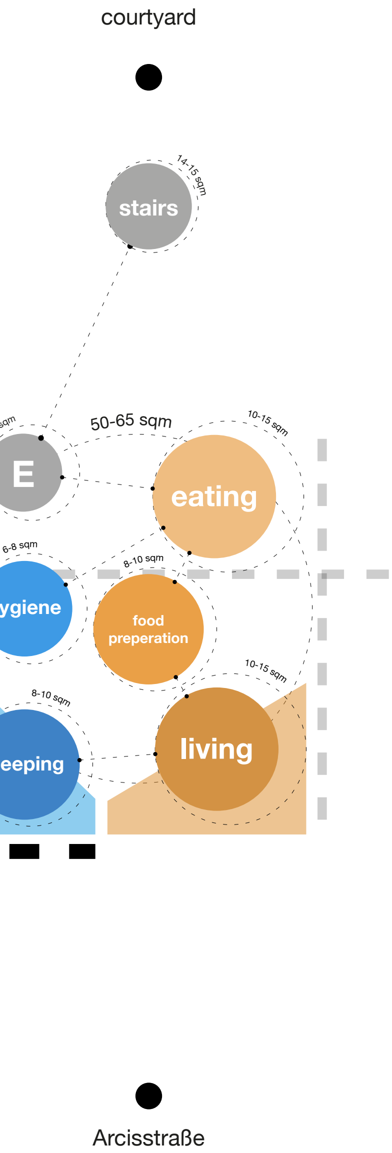
▬ ▬ apartment seperation

Apartment Space

The smaller apartment is accessible by the stairs and an arcade in the courtyard. The living space is pinned though the building, with the most extroverted function, the eating area, oriented towards the arcade and living towards the street side with large facade openings. More „intimate“ functions are arranged in a niche axis, enclosed with a ‚visual barrier‘ towards Arcisstraße, which will be provided by the structure with small openings. The separation between sleeping and living area will not be of a structural nature, but of an ephemeral interior installation, to open the sleeping area towards the bright living space.

1-2 person apartments

space apartment type 1

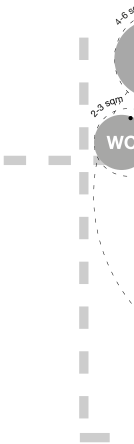


🟧 „extroverted“ living space

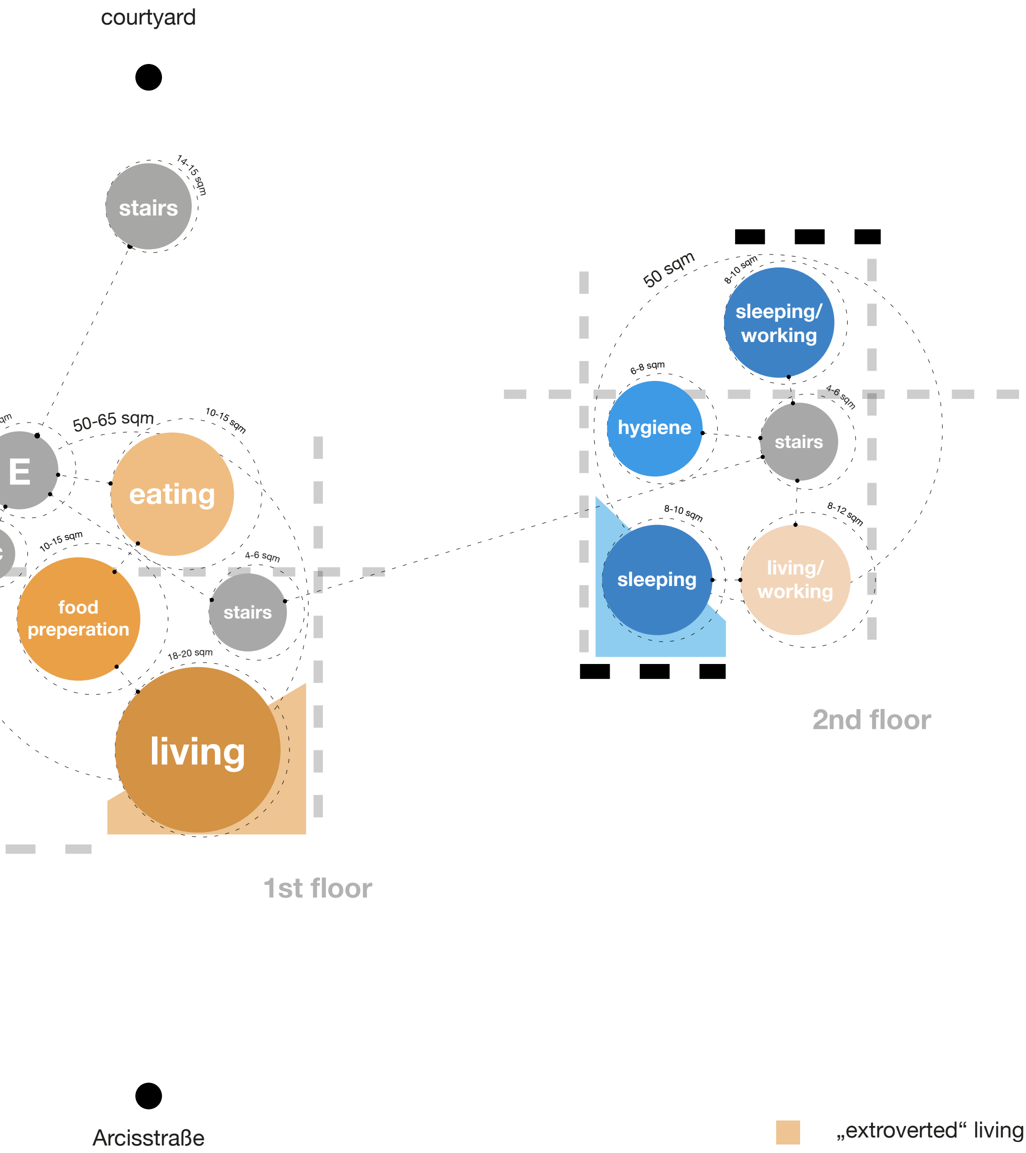
🟦 „intimate“ private space

▬ ▮ visual barrier

The second apartment type, accessed in the same way, is functionally separated by the floor level. Organized as a maisonette is the extroverted usage on the first apartment floor and the intimate ones on the second level, however the with general arrangements function the same way.



2-3 person apartment (maisonette)



🟧 „extroverted“ living space

🟦 „intimate“ private space

▬ ▮ visual barrier

Physical Design Exploration

Fig. 65 1:1000 model.

1:1000 Model, surroundings

Fig. 66 1:200 model.

1:200 Model, perimeter

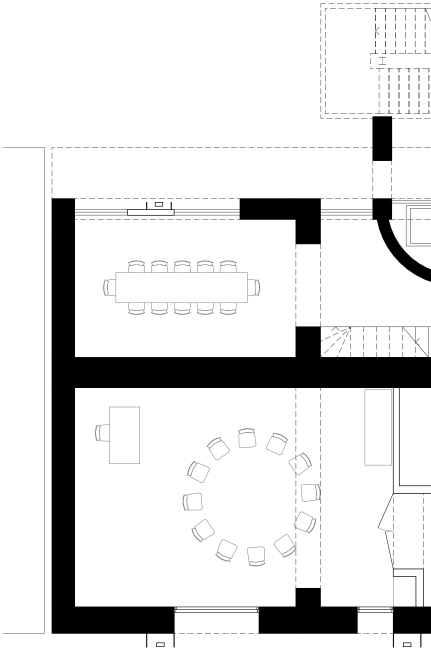


Fig. 67 1:100 plan ground floor.

1:100 plan, ground floor

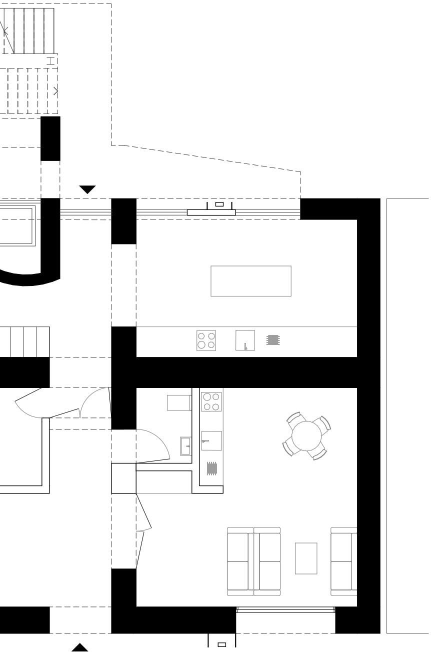


Fig. 68 View conference hall.

rendering, conference hall

rendering, residents space

Fig. 69 View residents sp

ace.

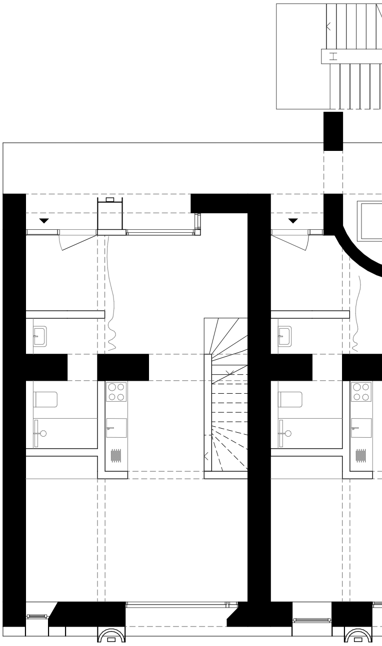
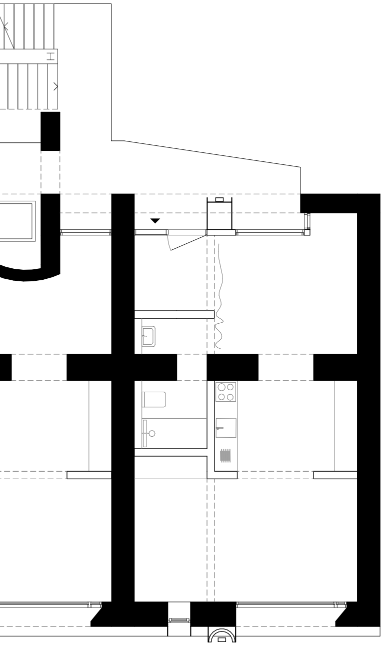


Fig. 70 1:100 plan regular floor.

1:100 plan, regular floor plan



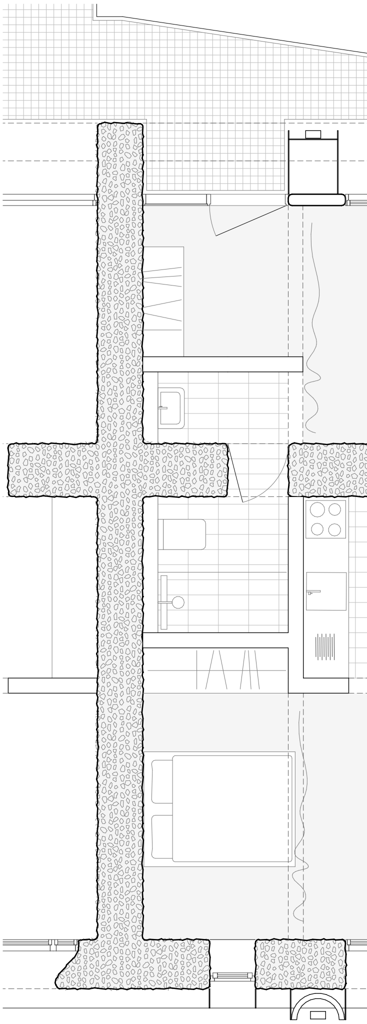
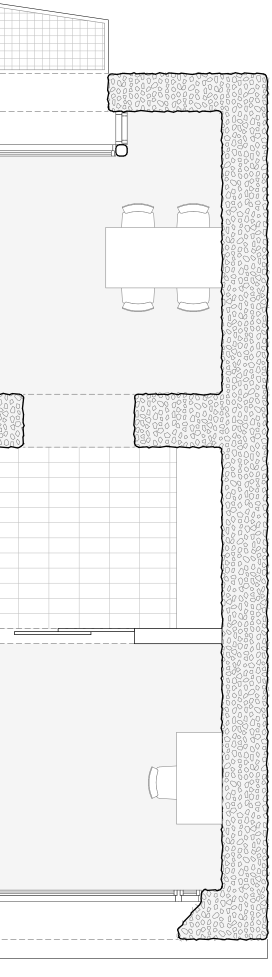


Fig. 71 1:50 plan apartment 1.

1:50 plan, apartment 1-2



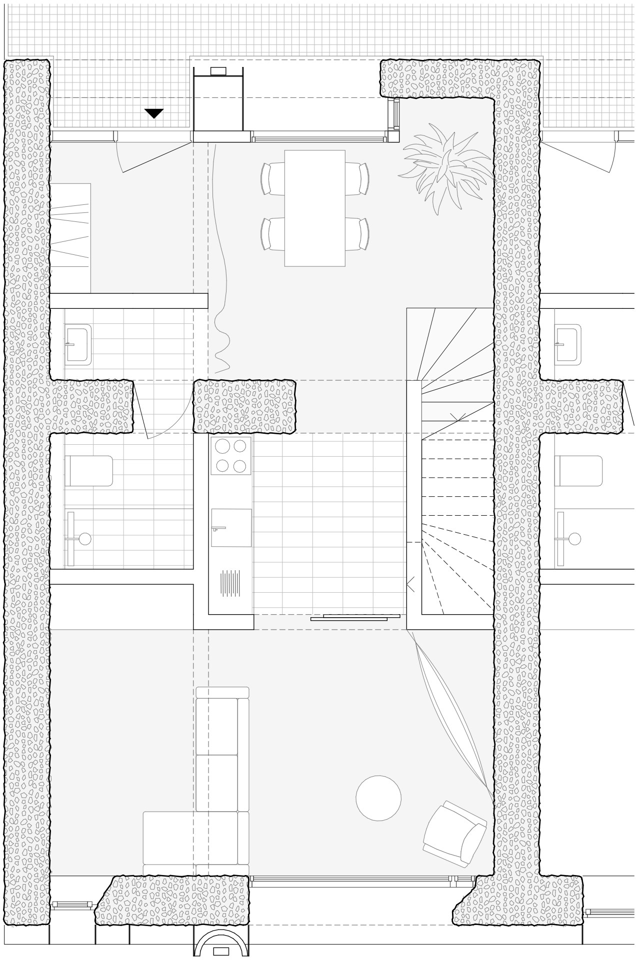


Fig. 72 1:50 plan apartment 2.

1:50 plan, apartment 2-3, maisonette

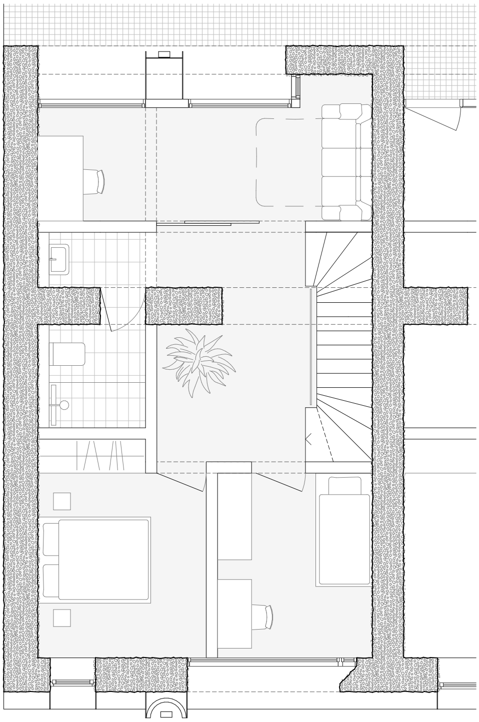


Fig. 73 View apartment 2.

rendering, apartment 2-3

Fig. 74 Model 1:50 section back.

Fig. 75 Model 1:50 section front.

1:50 model, section

1:10 detail, indoor wall

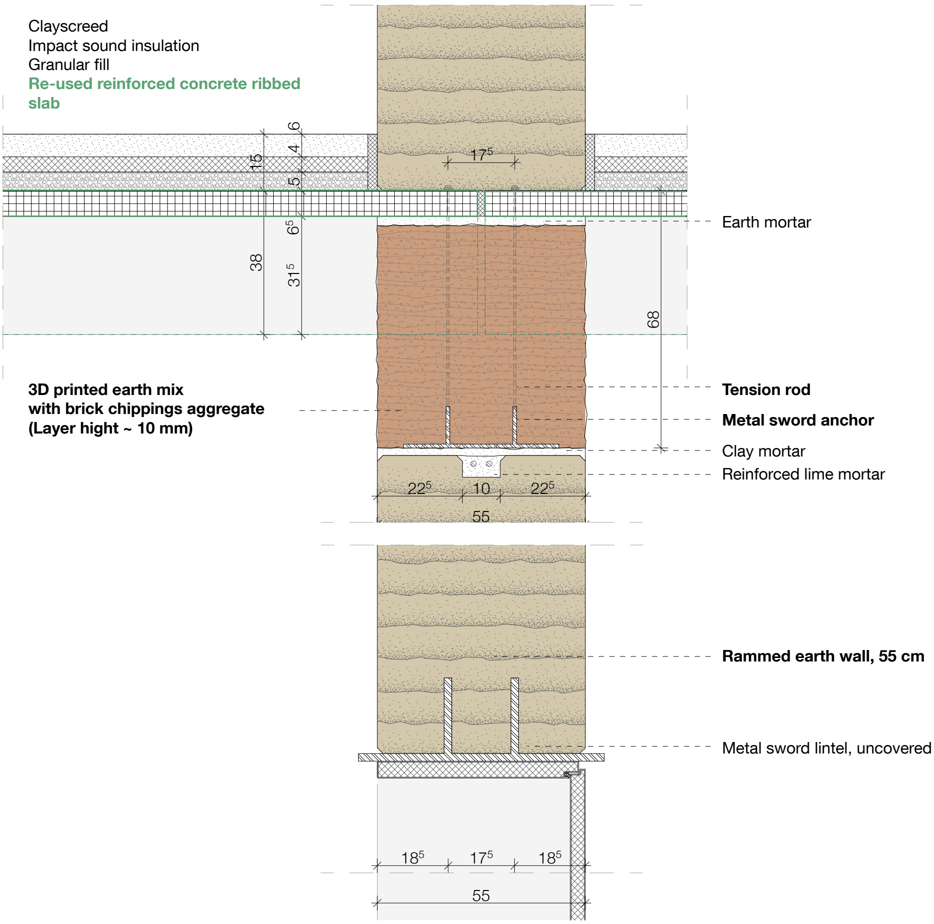


Fig. 76 Detail lintel 1:10

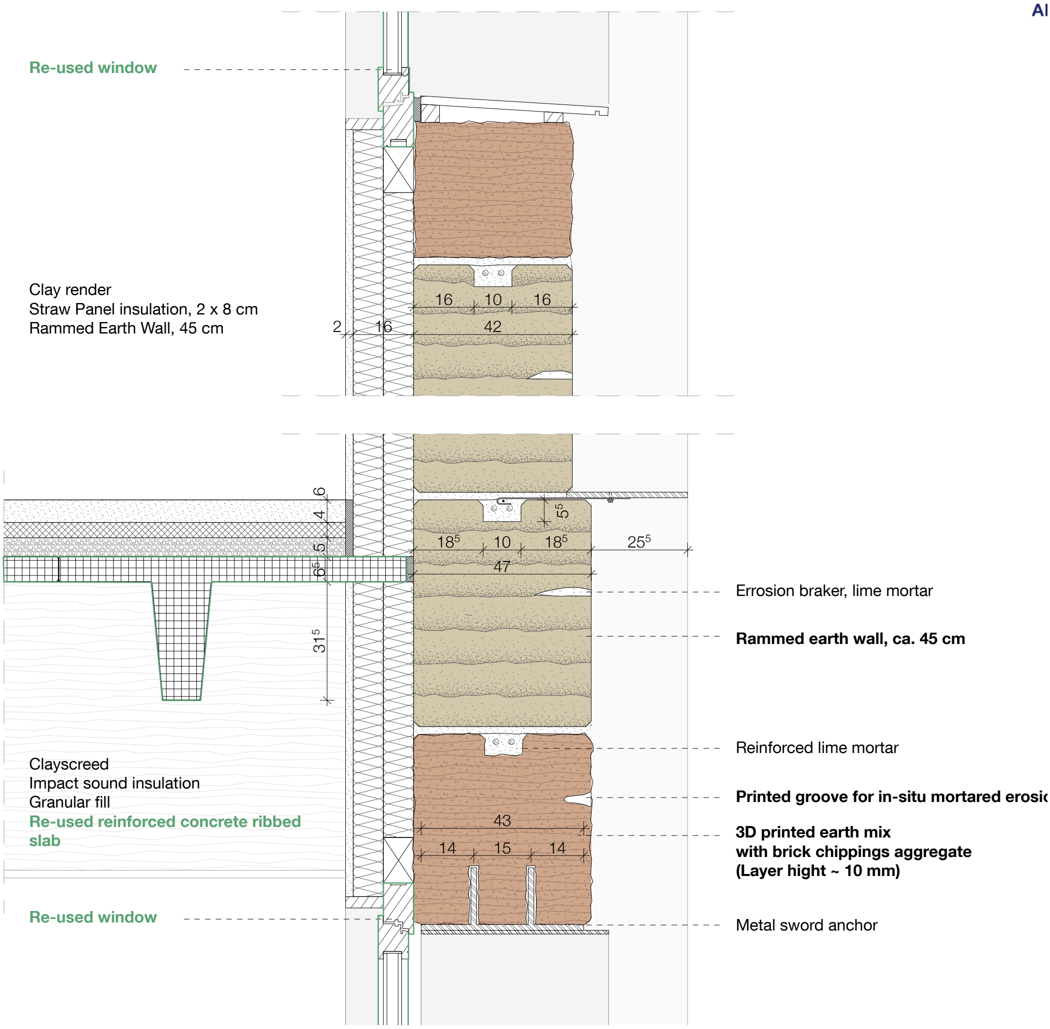


Fig. 77 Detail lintel, façade 1:10

1:10 detail, exterior wall

Demonstrator Object

„..this new [..]method stimulates a reassessment of what is possible with rammed earth.“

conclusion

Earth is the connecting aspect of this design. It's a core characteristic of the same, connecting the ecosystem that we live in by the soil we stand on. SInce its long time of utilization, it was always used to connect elements, as doub on posts to fill gaps and create contained spaces, or as mortar or as structure rammed in place to either build new or to complete structures out of different material.
Nevertheless, is its application seeming limited, many methods are either forgotten completely in the west or only used in an artisanal way for the maintenance of heritage buildings, in a time were uncomplicated and mass-produced materials have the highest market share, bought at the cost of high energy consumption and limited recycling capabilities. The efforts to utilize locally, unfired and healthy clay-based materials again, is gaining momentum, but is nevertheless limited by a large development gradient between conventional industrialized materials such as concrete and earth products, who in addition require a higher degree of material knowledge, considering its lower strength and need for weather protection.
For the case of rammed earth, one of the materials that offers and already sees a degree of industrialization, this gradient is shrinking. In a linear mechanized ramming process, rectangular components can be produced in large quantities. However, the fabrication state of the art is still limited, especially considering geometric freedom. By analyzing different case studies, it becomes evident that figural challenging shapes generally include a considerable amount of manual processing or secondary structure during the fabrication process. This consequential indicates, that the application of rammed earth in contemporary building projects is limited to regular orthogonal shapes, assuming that an artisanal construction process would like to be avoided. This limits its today´s utilization especially in the urban environment with its often-appearing irregular configurations, quite in contrast to the 19th century's southeast of France, when the manual method was regularly applied in cities, possible because of low wage-levels in contrast to high material costs or to bypass the use of unavailable material, using free material from the ground.
Not only the fabrication process, but also the space requirements for earth walls present an obstacle when building in cities. Seeing prototypical proposals to reduce this need and to optimize space usage in a situation of its limited availability, sharpen the discussion not necessarily towards a general solution for the problem, rather than to

cleverly highlight the dependence of rammed earth structure and the resource of well-considered space.
Since rammed earth is often used in combination with other materials, supporting the few unfavorable characteristics, the scope of observation opens towards another yet abundant resource in the city, re-usable elements from demolished buildings. Practiced at almost point in time of human-made architecture is this method today especially perceivable in buildings that are erected in times after crisis or demographic shift but was always relevant until the advanced building industry created states of saturation were using new material is cheaper than re-purposing the existing In times of demographic growth together with a material overproduction is a state of overexploitation inevitable, plundering the earth resources and polluting at the same time. To escape this state especially in the overconsuming western hemisphere, actors of the architectural society are exploring the re-integration of disassembled building elements to reduce the material demand and waste simultaneously.

To understand the re-use practice of different materials, example projects and the general material combinations with rammed earth were investigated, to act as a guideline for a possible connection of earth and re-use. It shows that interface solutions for different materials and rammed earth already have precedent, providing a framework for a further investigation, nevertheless are challenging geometric requirements expectable. Those requirements and the limits of the state-of-the-art automation are investigated by looking at the geometric range of different components, that were either produced for built different project or are available on the market. Even though a figural variety exists, the research indicates that an increasing degree of geometric freedom comes at the cost of an increase of manual labor and production redundancy.
Further developments such as the prototypical ‚Intrusion Earth Additive Manufacturing‘ strives to circumvent this state and offers new architectural opportunities and geometric freedom by abandoning the mould-based ramming process in favor of an aggregate bed-based intrusion process, were aggregate and earth paste are applied separately before being rammed. In a case study design with the goal of designing a residence for researchers for the ‚Technical University‘ in Munichs Maxvorstadt, all those assumptions serve as a framework.

It shows different applications of minable materials of the city, how they are arranged according to the spatial requirements, between the urban and the small scale, visualizing the geometric constraints of rammed earth and a proposed escape from those constraints, using ‚intrusion earth' as a mediating agent.
The focus of investigation lies on different structural elements, such as slabs, but also facade parts such as windows, in conclusion a very narrow frame of what seems to be possible with this new technique. Starting from large load-bearing re-use elements, towards smaller components, the investigation leaves out smaller and often appearing secondhand elements, such as sinks, radiators and other interior parts that are easy to dismantle. When zooming in even more, the use of different aggregates seems promising from an architectural standing point, either in changing the color of the material, or to experiment with translucent aggregates, comparable to translucent concrete. Also, the opportunity of overbuilding structure using rammed earth could be an interesting domain to save material and work effort, an example with brick and one using earth was described earlier, showing the general feasibility, and the promise of low labor demand and cost efficiency, considering the opportunity of producing customized rammed earth components in an automated process.

All in all, this new ‚intrusion earth' method stimulates a reassessment of what is possible with rammed earth. Moreover, a new yet old approach to use digitally fabricated earth as an interface to combine what's already there. Taking up the assumption that was mentioned in the beginning, the reduction of the concrete content in buildings is not necessarily the only way, it depends on its kind.

Or to use the words of Brandon Clifford in his ‚Cannibalist Manifesto':
‚We intend to build with rubble. This pursuit for cannibalized material applications begins with the thrash heaps of our ancestors [..], our remedy is [..] cyclopean masonry.' [69]
Let's provide the cyclopean glue.

Appendix

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cyclopean_ glue:

Joining rammed earth and re-use elements in an urban context.

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