

Construction principles of seismic and energy renovation systems for existing buildings

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Highlights

Prefabricated façade renovation system in combination with seismic retrofit of certain types of buildings.

Developing lightweight and adaptive construction system.

Improving thermal comfort, reduce energy demand in building operation.

Use the seismic frame and the façade panels to gain additional living space and integrate building service systems.

Abstract

Prefabricated “building systems” for the renovation of façades of existing buildings can achieve not only a physical building improvement of the envelope and thus result in lower energy consumption but also make an improvement in the resistance to seismic stress. To this end, the development of a combination of an exoskeleton and lightweight components as infill for the seismic truss system will be presented. Both a variability of the spatial appearance of the truss as well as the modularization of all construction components as a prerequisite for the prefabrication was examined and the system will be transferred into the real application by case studies as part of an H2020 research project.

Keywords

Deep renovation, Seismic retrofit, Nearly Zero Energy existing buildings, Modular prefabrication, Building technology

1. INTRODUCTION

Prefabricated “building systems” for the renovation of façades of existing buildings have been researched, developed and constructed for more than ten years now. Since then, numerous systems have been developed for energetic refurbishment mainly from research side and a few are established on the market but mainly as tailor made system, which however, only provide for a thermal improvement and architectural appearance of the shell. The complexity of the interface between the new and the existing structure, also due to the manifold requirements within the retrofit system, has to be structured. The differences between the existing typology and the retrofit layer typology should be as small as possible so that the interaction works functionally, technically and in



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a wider perspective also socially and economically.

The renovatoin construction system originally developed at the Technical University Munich and the associated refurbishment process for block of flats, originated in the 1950-70s, consists of large prefabricated panels in timber construction. [1] These panels are equally covered as a wrap around the existing building envelope. The panel system is particularly suitable for multi-storey buildings with a recurring façade grid and it is set up flat in front of the existing facades of load-bearing exterior walls or a load-bearing shear wall structure after dismantling an old curtain wall façade. It may happen that existing loggias or balconies are closed by the new wall elements but usually little or nothing is changed on the buildings spatial and functional properties. By a digitally captured geometric representation of the existing building the elements can be individually, quickly and inexpensively configured and with the use of modern prefabrication methods in timber construction produced in the sense of environmentally friendly, sustainable, solutions for facade renovation.

In seismically active areas, though, there is also a need for deep renovation methods, which strenghten weak structures of buildings and reduce the energy consumption. [2] The goal is an integrated building system consisting of a seismic effective exoskeleton with prefabricated filling elements for wall, ceiling and façade in a lightweight construction, which can be flexibly adapted to various existing building types and bring along new, efficient technical systems. The method contains the development of possible constructions and flexibility of design variants. These variants are adapted in existing structures with application to case studies. Another focus beside the spatial variability is the integration of building services systems and modularization for prefabrication as further tasks. The results move toward two types: flat and spatial exoskeleton as the carrier systems a) integrated subcomponents, b) a planar retrofit solution, c) a truss based spatial retrofit solution. The distinction between a 2D-system and a 3D-system definition is discussed. One of the solutions to the described challenges lies in modularization and the constructive separation of the various functions. Finally the discussion of differentiation to existing renovation building systems. Further investigation of spatial, seismic exoskeleton structures made of engineered wood products which are promising as building technology and thus from the perspective of overall life cycle assessment, life cycle costing and renewable resource goals offer an outlook on future tasks.

2. STATE OF THE ART

Existing structures – dimensions, grids and structural systems

In short, the existing structure with its dimension and the main grid develops out of functional requirements and follows with its spans the supporting walls and columns. It has usually been provided with an optimized support system for these pre-conditions.

Overlay and connection

The existing structure is to be strengthened against earthquake events. For this purpose, a new superstructure is created, the exoskeleton, which superimposes the existing structure and improves the longitudinal and transverse stiffening of the building. For optimal flow of forces, the exoskeleton must tie to the major axes of the existing structure, which are the existing load-bearing and stiffening walls, columns and ceilings in order to absorb the forces as directly as possible. The exoskeleton is attached to the outside of the building in front of the facade. It acts in the flat, 2-dimensional variant along the direction of the facades in order to improve their stiffening effect. The spatial, 3-dimensional variant of the exoskeleton extends the previous structure of the stiffening partition walls to the outside. This results in a reinforcement of the existing partition walls in the transverse direction of the building and the 3-dimensional exoskeleton thus re-acts orthogonal to the existing facade. The shear forces in partition walls are transferred in line with the exoskeleton. From a functional point of view the braced frames orthogonal with the facade repeat the principle of separation between the units or rooms.

Exoskeleton truss structure

The truss structure of the exoskeleton consists of building-high braced frames of steel or aluminum sections, while the existing structural elements are generally solid wall panels. Within the truss structure of the exoskeleton, with its multiple members, spatial units must be generated as a kind of infill. Due to the various uses of the spatial units, there are all sorts of expansion phases starting from the plain balcony to the winter garden to the thermal-controlled full room extension. Thus, panels must be added to the superstructure in order to have a space-forming effect and they are the second important construction component beside the exoskeleton. Together the truss and the panels are the entire renovation system. These panels are installed side by side in different combinations and create a variety of connections or even intersections between the panel and the exoskeleton. All of them must be thermally optimized, sealed,

and which are all vulnerabilities to potential quality problems and damage. A strategy has to be developed that reduces the number of connections between the components.

Objectives

The goal is to occupy the zones within the exoskeleton and form closed unit spaces inbetween the structural frame. There is a special case within the 2-dimensional exoskeleton, because here only a wall plate for additional thermal insulation of the facade is used, as it will be described below. Further panel components are developed for the 3-dimensional exoskeleton amongst a floor slab and ceiling combination, second wall panels, third façade or exterior wall panels and optionally as fourth element a façade insulation panel for direct mounting on the existing exterior wall.

The differences between the existing construction typology and the retrofit wrap around layer should be as small as possible so that the interaction works functionally, technically, and from the process side. Here the big challenge in the processual implementation is the coordination of different trades and their specific technical interfaces. The prefabrication goal requires a material and design selection that can meet the technical requirements and is suitable for automated production processes. Finally, the integration of technical components must be made possible.

3. METHODOLOGY

The complexity of the connection between the new super-structure, envelope and services and the existing substance and architecture but also due to the manifold requirements within a retrofit component have to be structured that lead to a problem-solving development. These include, among other things, the analysis and identification of the problems of the renovation process of existing buildings. Action research during these analyses uncovers particularly critical problem areas (a) dimensions – seismic grid; (b) overlay existing and seismic grid, (c) substructure inbetween the overlay of two grids,

Building	Type of use	Grid lateral span [m]	Grid transversal span [m]	Superstructure	Construction type	Floor slabs
A	4-storey dormitory	5.75	3.73-5.78	shear core + thin shear walls	Concrete with masonry partition	1-axial transversal
B	4-storey block of flats	2.95 – 3.98	2.9-3.8	RF-skeleton with shear core	Concrete, masonry infill	2-axial
C	5-storey dormitory	3.65	6.25	exterior walls + corridor walls	Masonry partition walls	1-axial lateral
D	Teraced-houses	6.30	3.25 – 4.00	section walls + exterior wall	Masonry walls	1-axial lateral

Table 1. Characteristics of existing structures.

(d) connections between different structures.

The design follows an iterative process that balances the different obligations arising from the usage requirements and higher-level regulatory requirements against each other and, based on the requirements criteria, allows informed decisions for alternative solutions. To this end, the influence of the following three objectives on the project-specific level is considered, because there is a highly complex geometry given by the exoskeleton structure and the existing structure. In addition, the technical functions of the building envelope must be taken into account in this constellation of existing building fabric and the seismic framework. As a final and most important requirement, the prefabrication of the renovation system and the necessary formation of smaller units, i.e. the so-called modularization must be included in the design process. This modularization allows decisions regarding the materials, component assemblies and assembly formation and last but not least opens up the possibility of integration of building services systems into the construction components.

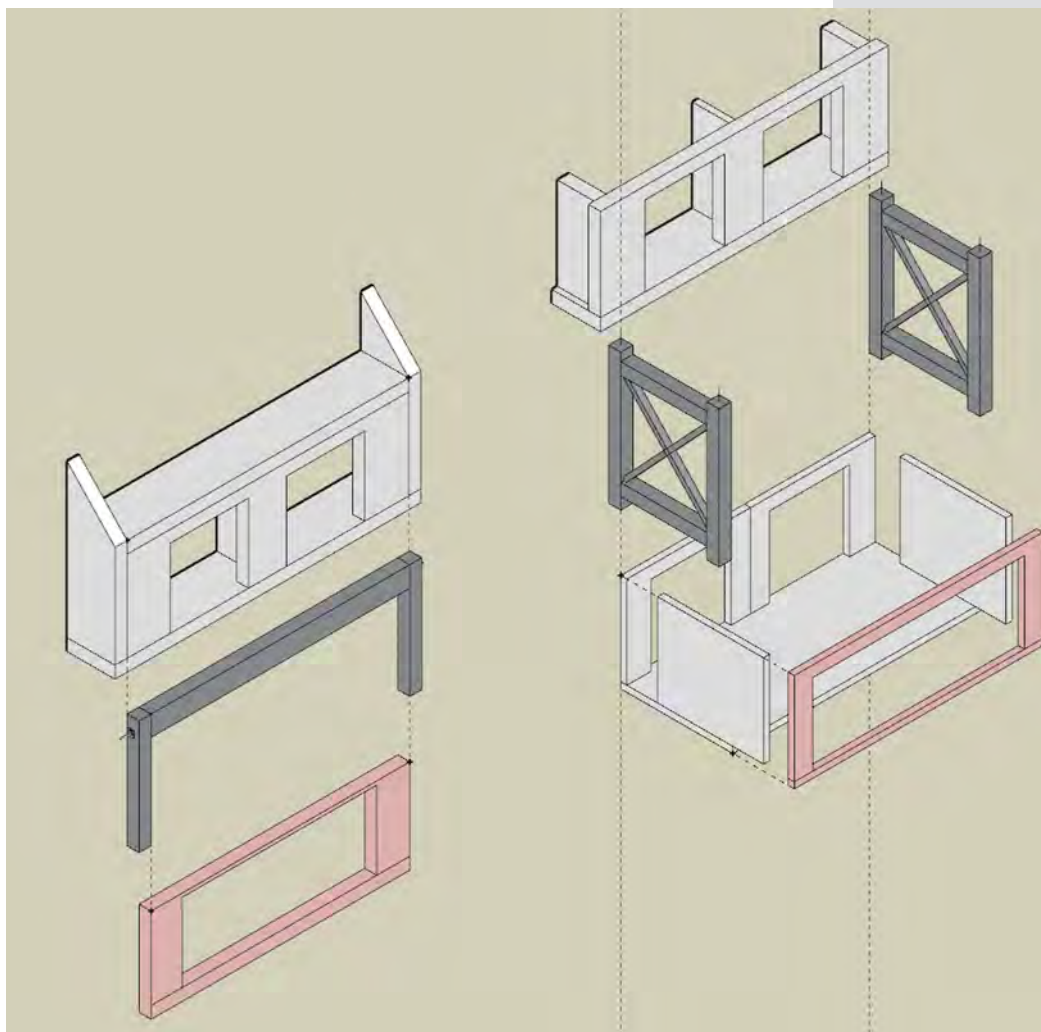


Figure 1. Synopsis of generic 2d- and 3d-system for seismic renovation.

4. RESULTS

4.1 EXOSKELETON (SEISMIC FRAME) AND SPATIAL ELEMENTS

The development of an integrated building system consisting of a seismically effective exoskeleton (two types - flat and - spatial) together with prefabricated infill elements for wall, ceiling and façade in lightweight construction (or with preassembled modules). All components of the system should be flexibly adaptable to the existing construction types of existing buildings, their grid, overall geometry and seismic requirements. Last but not least the development of alternative constructions and design variants to make possible different stages of the development of the retrofit measure.

Two fundamental different types of exoskeleton are examined, cp. Figure 1. The first one is two-dimensional and applied in parallel with existing weak lateral exterior walls in order to reinforce them. The 2D-frame is, to the moment, for small-scale application and for pure facade renovation without the achievement of extra space. The second variant is a three-dimensional, spatial frame, which runs parallel as well as it extends perpendicular to the existing façade. The 3D-frame is dedicated to multistory apartment buildings and with the strengthening it supplies an energy efficient facade that can also extend the living space of the existing flat. In both exoskeleton frames components should be inserted to enable an improved performance of the façade by an additional insulation layer and the frames should also be hidden by the façade panels.

Lightweight panel components

A lightweight panel component should fulfil various functions at the same time. Its main function is the building enclosure and insulation with a safe and durable structure; additionally it integrates windows and openings, carry Renewable Energy Source (RES) sub-components and, finally yet importantly, brings back a 'fresh' architectural appearance with renewed interior surfaces and exterior elevation. The components are designed according to the architectural features, safety and thermal requirements of the existing building. The decision to make the 'super-component' a lightweight structure is due to seismic reasons. The panel add-ons to existing building should not contribute to a substantial increase of physical mass, because this will require a higher strength of the exoskeleton.

The functional requirements come from the application of the timber

construction system as a lightweight but performant material and building technology for modern urban buildings. This particularly concerns the selection and correct combination of materials not only according to the requirements of the overall system but also at the level of the respective construction components. Thus, the functionality for the hygrothermal requirements has to comply as well as with the other safety requirements from sound or fire protection. The goal is to enable robust and durable construction components, which thus also meet the requirements of sustainability. For this purpose, the products must be selected on an environmental sound basis and be prepared efficiently within the production processes, without much processing effort and with little waste to prefabricated components. Additionally they need a sufficient lifetime, be easy to maintain, well to dismantle and environmentally friendly recyclable. This already makes it clear that the aforementioned considerations must always be reflected back to the production methods in order to implement the lean construction theory in practice.

Prefabrication of panels

Furthermore, the coordination of sub-components within a pre-made component is of the utmost importance, in order to enable the cost-effective assembly of parts, and to respond to neighbouring or even connecting components with cable routing or ductwork. This organizational approach will enable the use of components in different case studies and other types of buildings. In technical systems, maintenance and repair capability of subcomponents with different technical lifetime must be foreseen.

The prefabrication strategy took principles from off-site manufacturing based on the knowledge from prefab timber construction. The prefabrication makes assembly at the construction site more efficient and leaner in terms of time and organization. The processes for module production can take place completely in the factory, but the possibilities and advantages or disadvantages of a mobile field factory are also examined. Additionally analysing the assembly and mounting process in different case studies based on the background knowledge of the authors for the development of a generic process structure.

Principles of prefabrication strategy, use:

- standardized raw material and construction products;
- modular geometry and composition rules for the basic material;
- defined interfaces between the elements;
- industrial level production system of the panel system;
- standardized logistics and assembly processes;
- standardized connection of modular panels.

Integration of Building Services

As already mentioned above, there are several technical subsystems for RES, ventilation and for Information and Communication Technology (ICT), which should be part of new building envelopes. This follows the prerequisite of minimal invasive measures on the existing substance, to reduce affect on tenants, and contributes to better social sustainability. The correct combination of active (e.g. heat-pumps; ventilation units) and passive (e.g. ducts; switchboxes) sub-components integrated into the ‘super-component’ is a challenging task because of various geometry, power supply and optimal interface with the existing façade and interior layout. As this aspect of building services systems needs to be discussed extensively, it will be stopped here and continued pursuing in another publication related to building services in retrofit.

4.2 2D-SYSTEM EN DETAIL

Existing research and studies have shown that post-tensioned timber frames, used as seismic exoskeleton, allow for easy and fast mounting processes at the construction site, as Newcombe et al. and Smith et al. propose. [3, 4] Construction processes make up for an essential part of the overall costs of a building and should therefore be optimized. Due to its lightweight and modular nature, the post-tensioned timber frame can be mounted in multiple possible sequences.

The connections with internal metal sheets and dowels at the column bases, and seismic connectors with wood screws are also prefabricated and attached to the structural components. In order to enable transportation of the prefabricated seismic elements with standard-sized trucks, it is chosen to assemble the single elements of the frame at the construction site. With a length of over 37 m and a height of 5.20 m, heavy transport would be necessary to convey the preassembled frame. Each post-tensioned frame consists of seven columns and twelve beams. Both the upper and lower beams require a steel tendon and anchor plates for the posttensioning of the frame. Due to the lightweight of the timber exoskeleton, assembling at site is relatively easy. The exoskeleton components can be maneuvered into position manually and low capacity cranes are sufficient for lifting.

The post-tensioned timber frame and additional prefabricated façade elements are produced that intend to increase the energy efficiency of the existing buildings, cp. Figure 2, Figure 3 and Figure 4. The construction of the entire system is divided into two parts. In a first sequence, the post-tensioned timber frame is built, and in a second sequence the insulating façade elements are

attached to the structure. The evaluation of the post-tensioned timber frame as alternative solution is based on the work of Rödel. [5]

Before the frame is delivered to site, several preparations should be made. At first, the foundation for the columns is produced. Therefore, a concrete strip is poured in front of the existing foundation and grout pads are arranged at the position of the columns. Since the chosen insulation concept includes a layer of mineral wool and moisture barrier in front of the existing masonry walls, the installation of the panels also needs to be prepared. Afterwards, the frame elements are delivered to the site. Construction of the timber frame is then started with one of the outer columns.

After erection of the outer column at one end, each bay is constructed by moving to the other end of the frame structure. Thereby, construction of the lower and upper beams is separated. The upper beams are positioned only after the first story of the frame is set up.



Figure 2. Terraced house elevation.

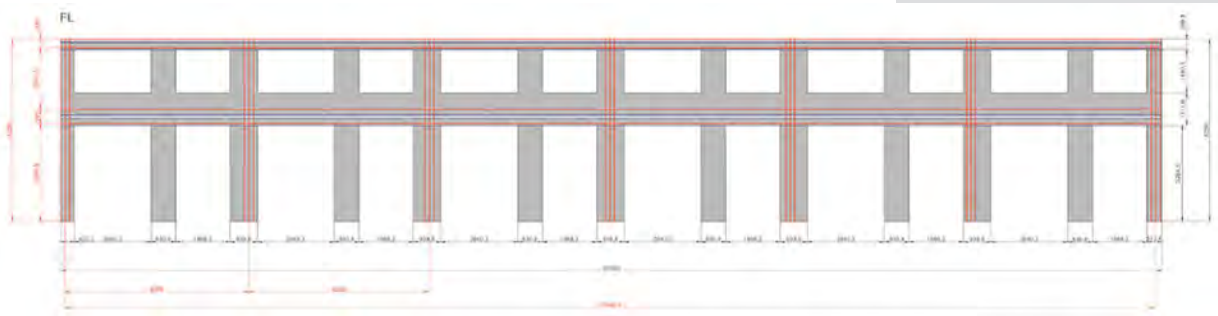


Figure 3. Available construction space and potential frame design.

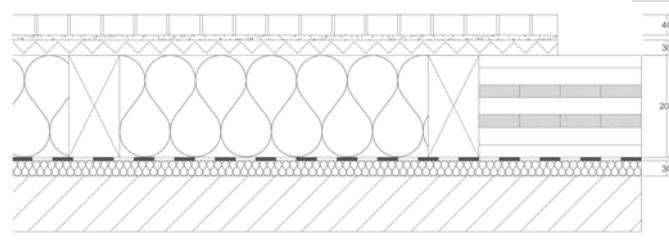


Figure 4. Horizontal section of facade element structure (frame column on right, existing exterior wall below).

4.3 3D-SYSTEM EN DETAIL WITH FOCUS ON ENCLOSURES

As already described for the 2D-frame, a foundation for the frame system is also created for the 3D-frame. Subsequently, the exoskeleton truss is set up and connected with the existing structure by seismic connectors. It contains the braced frame, which is oriented orthogonally to the façade to avoid buckling of the truss system small lateral beams are inserted in parallel with the existing facade. This combination formulates uniform cells next to and above each other. Ceiling, wall and facade panels can now be set in these cells. The cells each form their own modules, which can be assigned different spatial characteristics, from the simple balcony or wintergardens to the complete, temperature-controlled room extension. As further subcomponents on the third level, windows and the building services are integrated into the previous module level. This top-down organized product structure creates geometric entity or modules that clearly define the dependencies in a hierarchical manner. On top of this framework, further branches with variants can be developed which re-fit into the respective higher-level structure, cp. Figure 5.

During the next step of development, the above-mentioned chain of dependencies will be played through systematically and checked on the existing examples and demo projects. Due to the feedback, it is possible to check the robustness of the solutions found, e.g. for connections. The functional layers of the renovation system must be tailored to the requirements of the respective subcomponents in order to fulfil the functions of the overall component. For our renovation system this leads to the following three layers,

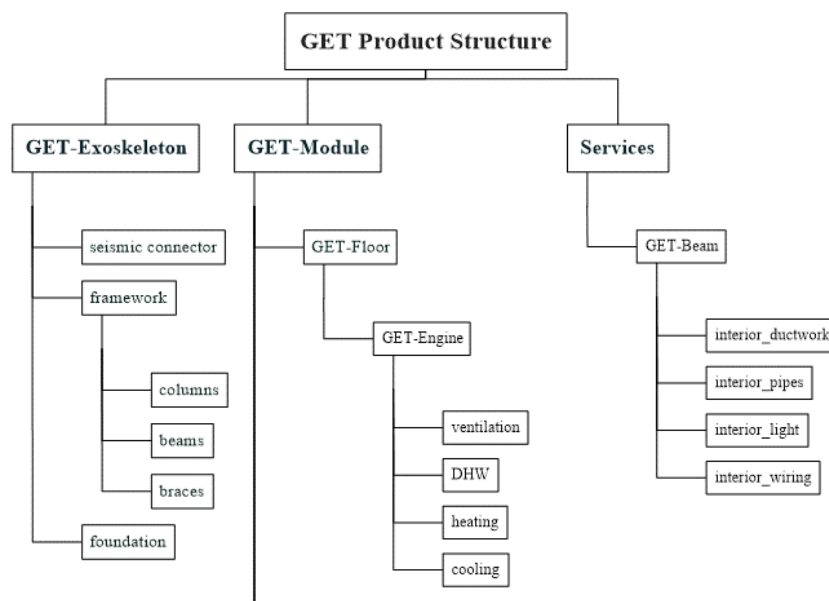


Figure 5. Product structure derived from the physical structure.

which are distinguished in the further course, cp. Figure 6 and Figure 7. The most important layer is the structure-forming layer that contains the primary seismic structure of the 3-dimensional exoskeleton and its subcomponents and is therefore called the primary layer. He is responsible for the necessary strength, he takes over the deadloads and payloads of the room expansion and stiffens the modules in the horizontal direction. The secondary layer is defined by the physical closure that it provides for the existing apartments or the extra room extensions. It also represents the thermal envelope of the renovated building. The tertiary layer is defined for the building services. He integrates the technologies for energy production from RES. It is within the renovation modules or, depending on the degree of miniaturization, also in the parts of the floor slabs, walls or as a separate sub-component connected to the superior component both geometrically, technically, and organizationally. In the structure of the renovation system, the 3-dimensional exoskeleton can be recognized as a dominant add-on structure to the existing building, cp. Figure 8.

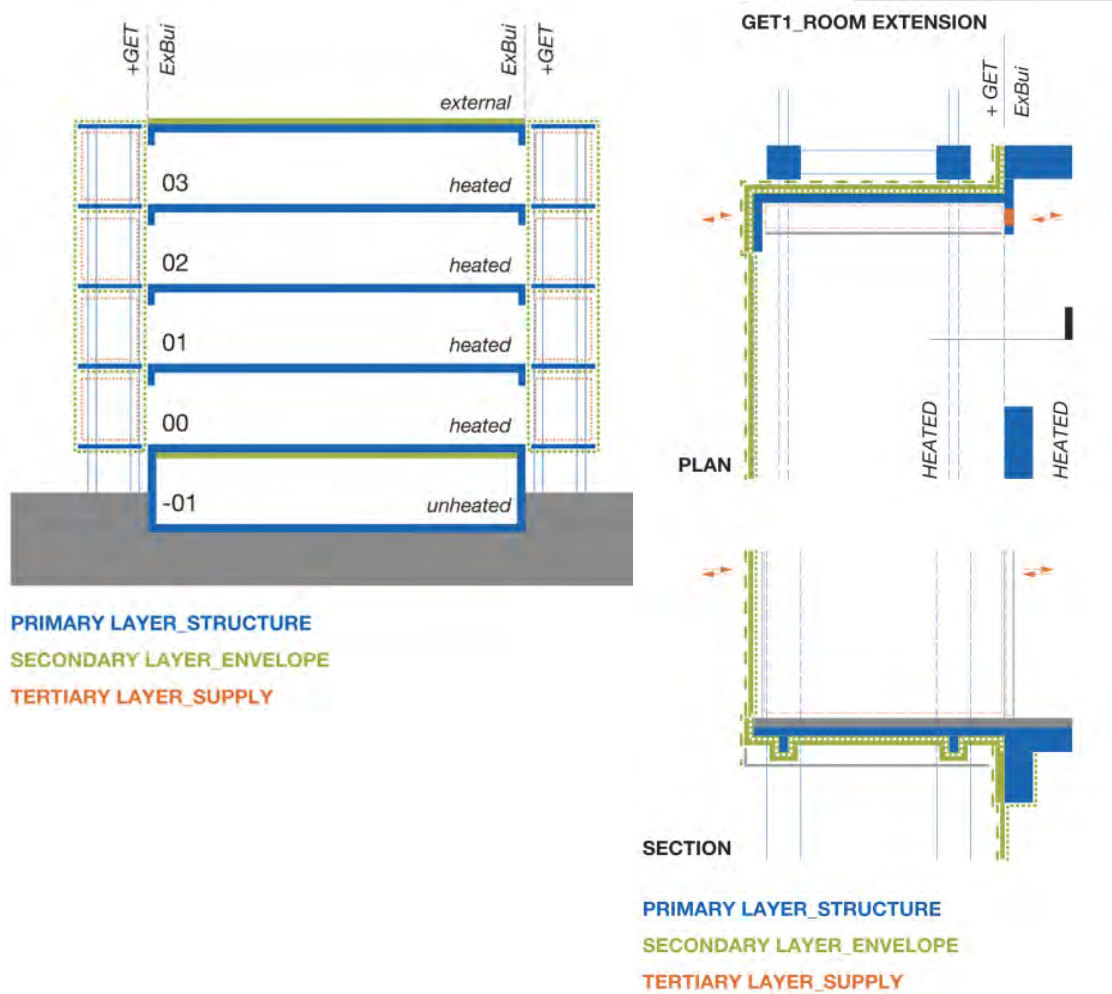


Figure 6. (On left) Cross section with system border definition on the renovation system application to of an existing building. Figure 7. (On right) Plan with layer principles for exemplary module with heated room extension.

4.4 DISCUSSION

The stated goal was to define a durable and robust system as infill into the two different exoskeleton variants. The 2-dimensional system variant, due to its limited functional requirements and simple geometry, is a solution that already meets all requirements in terms of stability, heat and moisture protection, modularity and buildability, and the simplicity for efficiency to a high degree. This is considerably more complex for the 3-dimensional system variant. These not only have to fulfil a stabilizing and thermal task, but additionally also vary spatially and climatically in their use. As a lightweight variant, the room extension have thermal advantages in winter, as it heats up quickly. However, it is sensitive to solar radiation what is advantageous in winter, but in summer in any case an additional, external sun protection must be added. Thermal-hygric protection of the envelope components, the room extension is built from, is especially important to consider for compounds. By avoiding the convection, an air-tight shell is made, for control of diffusion. Dry installation is required to prevent construction site related moisture damage. The fire protection must be considered differentiated for the room enclosure, the fire resistance and the fire propagation. The air-tightness avoids a passage of flue gas by the shell, thus ensuring the integrity of the room enclosure. Furthermore, at least a 30-minute fire resistance of the large-scale facade components must be ensured so that they do not collapse before the escape of tenants and do not fall down and thereby endanger the fire fighters during rescue and fire extinguishing. A delay in the spread of fire in façade cladding shall be provided by non-combustible cladding or by appropriate measures to delay the vertical or lateral fire propagation by fire stops. The sound insulation against external noise is to be ensured by appropriate wall and window structures. The important protection against transmission of

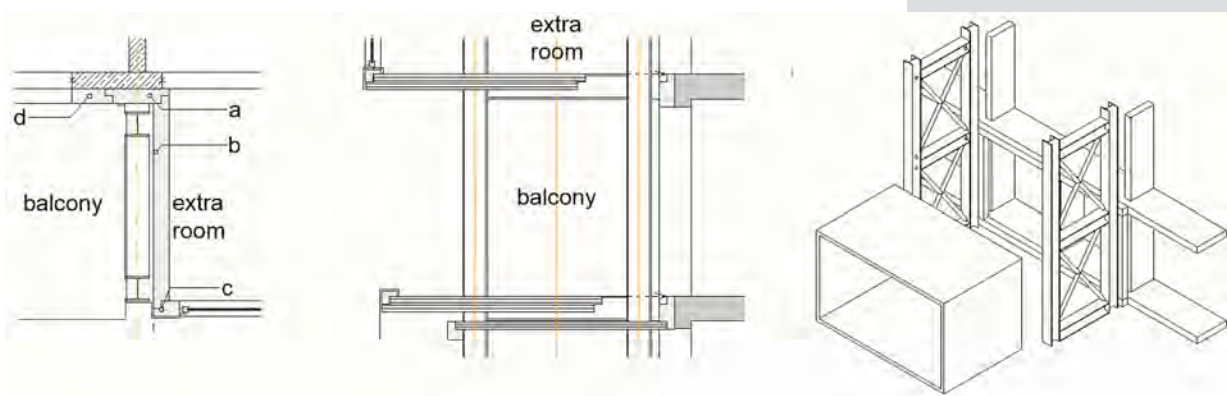


Figure 8. Plan (left), cross section (middle), perspective (right) of modular elements of renovation infill into 3d-system with (a) intermediate insulation panel, (b) partition wall panel, (c) exterior façade panel, (d) insulation panel.

sound from or to neighbouring units via ceilings or walls must be maintained by decoupling the flooring from the load-bearing ceiling and wall construction. All of the above show that the system has many detailed solutions thought through in advance to solve the various requirements, otherwise it can not be prefabricated. This pre-planning and prefabrication also helps to solve critical connections in a systematic manner and not by late decision on-site. These challenges can be solved by the strategy of modularization, ie. the creation of subsystems and their subsequent reunification and the constructive separation of the different functions.

The modular character is thus already given by the exoskeleton and then continued in the subcomponents. By creating spaces between the exoskeleton structure valuable floor area is lost and the room height might be reduced. The part of the structure that creates the space closure, carries vertical loads and introduces the wind loads into the main structure must be produced twice. These are additionally required material and financial resources. The assembly processes and prefabrication require additional interfaces due to the different materials. Additional interfaces mean extra planning and organizational effort as well as other possible sources of error.

5. CONCLUSIONS

In principle the 3-dimensional truss structure of the exoskeleton offers lots of advantages, not only a great openness for light, air and sun coming into the apartments, but also the light-weight of the reinforcement structure is a crucial issue required for high seismic performance. A way out of the above-described dilemma between the truss structure of the exoskeleton and the shear-wall structure of many existing buildings could consist in a structure of the exoskeleton of planar components, cp. Figure 9. This combines the space-creating elements and the structural function, as it already occurs in existing buildings. The wall elements of the “exoskeleton” should be as light as possible in order not to bring unnecessary loads into the building, because then even more resistant and therefore more complex structures would be required to improve seismic safety. This evolved exoskeleton could be implemented in the form of large-area cross-laminated timber elements. Because the material has a basis weight of only 480 kg/m³.

An exoskeleton approach means renovation from the outside with little intervention from the inside. Further discussion and analysis is necessary if this approach might be inefficient and perhaps even damaging for the overall system stability, because the stiffening functions are largely shifted to the new

superstructure outside of the existing structure. This strategy is seen as a valid approach to a single family or terraced house renovation, but does not appear to be effective in multi-storey buildings. Here are usually several structural parts available, e.g. corridor walls and shear cores, which are laterally effective and they should also be reinforced (Fibre Reinforced Polymer jackets). Whereby the overall system achieves increased redundancy and a better distribution of lateral loads on all parts of the building. This double stiffening approach, both on the level of the building envelope and in parts of the inner support structure is also used as state of the art method in modern superstructures of high-rise buildings, especially in seismic active zones, as it is described by Sarkisian. [6].

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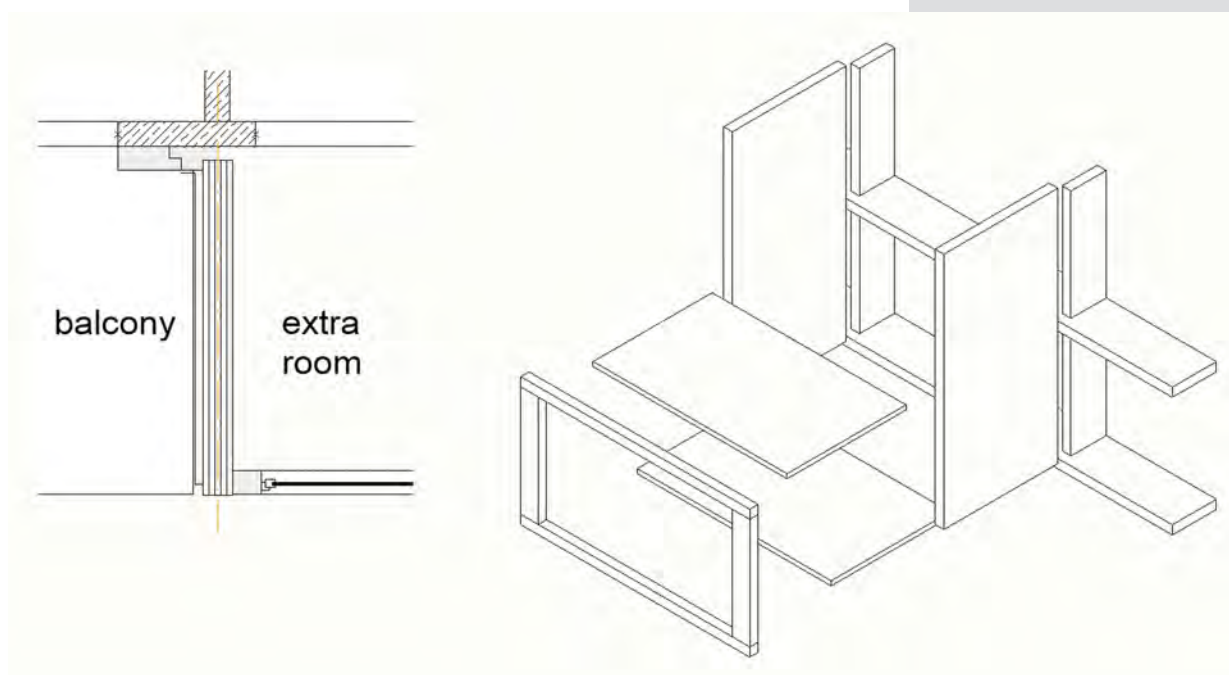


Figure 9. Plan (left) and perspective (right) of alternative exoskeleton solution made of lightweight, large-scale panels providing structure and space.

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