Prefabricated Retrofit Facade System – a Systemized Building Construction Detailing

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Short Summary

In comparison to a demolition of existing buildings with severe technical deficits, usually the retrofitting of buildings is more effective in order to prepare them for low energy consumption and new necessities as communication and media connection or HVAC-installation (Heat, Ventilation and Air-Conditioning). Prefabricated retrofit solutions are developed throughout Europe to enable higher levels of industrialization in building envelope modernization and hence additionally improvements in energy efficiency. Five years of experience and a reasonable number of demonstrations done with timber-based element system (TES) facades show tendencies for best-practice building construction.

This paper focuses on the jointing between single façade elements and the connection of those elements to the existing building. Being a crucial construction detail within the TES-facade, the joint area shall meet various requirements and challenges, from load bearing over hygro-thermal to fire safety functionality. The results of in-depth construction detailing lay out the requirements and principles of the TES joint.

Keywords: Energy efficiency, refurbishment, façade construction, timber construction, prefabrication, fire safety, building envelope.

1. Introduction

Prefabrication – a well-known concept in new timber construction – still needs the implementation of proper detailing considering the different circumstances and assembly methods in refurbishment in order to apply it for retrofit projects. TES EnergyFacade and the follow-up smartTES, two international research consortia, work on this idea since 2008 [1]. Since then the TES facade elements for energy efficient retrofit of the building envelope with prefabricated timber based elements are demonstrated in several projects. A first milestone was the definition of an integrated work process starting from planning, digital survey, prefabrication and assembly [2]. A key feature was the development of horizontal and vertical joints of façade elements for certain assembly routines and structural properties. Further findings are dealing with fire safety, ecologic properties, thermal and moisture behaviour in specific climate conditions. This article shows the development of principles of detailing timber framework in refurbishment; analogy to existing systematics in timber construction, the requirements, and generic solutions.

2. Retrofit with prefabricated façades

Modern, prefabricated timber frame construction is highly developed as a building system for new construction. There is also no limit for small series or so-called pilot prefabrication [3][2]. Because

of the flexibility in the production planning and manufacturing, custom timber framed components can be produced without overhead [4]. This fact makes timber framed façade elements very interesting for the refurbishment of existing buildings, because individual elements are required for almost each building and project. Numerous pilot projects and demonstrators in the context of research projects have shown that the transferability of the principles of the timber framed building on a conceptual level is possible and useful [5][6][7]. But at the detail level numerous new developments and adjustments are necessary to meet the requirements of a reliable and economically feasible design.
The accurate measurement of the façade is a prerequisite for precise prefabrication and mounting Geometry data have to be combined with a thorough survey of the existing façade construction, assessing materials, detailing, load bearing capacity and if necessary building services und further in depth information from the existing substance [2].

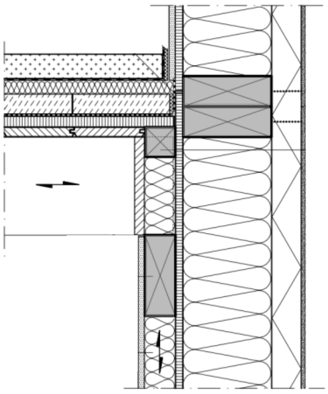

Figure 1: Vertical section of typical semi-balloon frame construction [9].

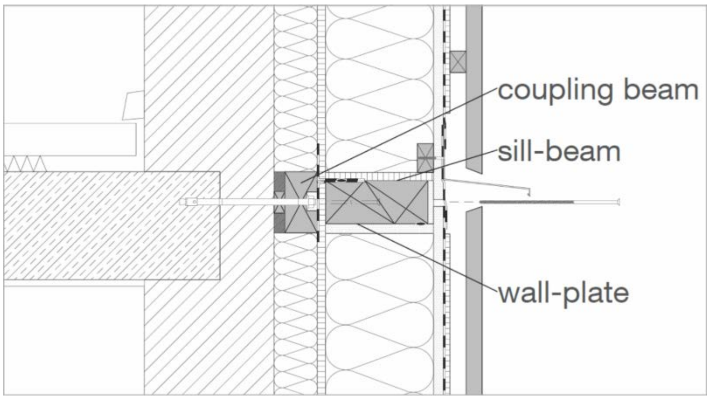

Figure 2: TES horizontal joint Vertical

3. Timber framed construction in refurbishment

3.1 Systematics of new-built timber framework and analogy

The three principles of timber frame construction are the platform frame construction, balloon frame, and the semi or virtual balloon-frame [8].
The virtual balloon-frame construction is the most suitable type as an analogy for a TES EnergyFacade element. The elements have storey-high size and are horizontally oriented; they can be produced in original upright position, put on the truck and handled on site the same way without changing orientation. All elements are stacked on top of each other and the dominant joint is the horizontal one. This has the advantage of a continuous façade layer or building skin, without interruptions and unbroken functional layers for air tightness, insulation or fire safety. In analogy to the ceiling support edge beam a so called coupling beam is introduced as a connection between the existing ceiling and the timber-framed wall. The coupling beam is adjusted exactly in height and depth. It has the additional advantage to assist horizontal alignment of TES elements. In contrast to new building in virtual retrofitting balloon-frame, no vertical forces are transferred to the coupling beam. The vertical loads are transferred only through the timber framed wall. The horizontal loads have to be induced into the existing ceiling plate. Hygrothermal exposure and wood protection of such a detailing solution can be solved in analogy to new building. The fire safety must be examined in depth because facades have a certain risk in the spread of fire and fire safety has always observed in relation with the boundary conditions of the existing building.

3.2 Definition of requirements

The number of parameters affecting the TES element and its details is large. Most influential are apart from structural issues, planning building physics of timber construction, correct production of multilayered elements and assembly on existing exterior walls. The main parameters about strengths and fixtures are derived from the load-bearing structure of the elements. As a result, they are at the same time in conjunction with the materiality, manufacture, structural arrangement, aka. tectonics, and the assembly process. The other group of influences originates from building physics. They affect TES elements on the main inner and outer protection functions and therefore define the requirements for layering and details. In addition to the production, they are in interaction to the assembly, economy, ecology and technical building equipment and must be linked to the static requirements. These interactions take place not only within the TES system, but and above all, they are in interaction with the existing building. Some protective functions of the existing exterior wall are partially replaced by the TES, such as the thermal protection; they are fulfilled primarily by the TES envelope.

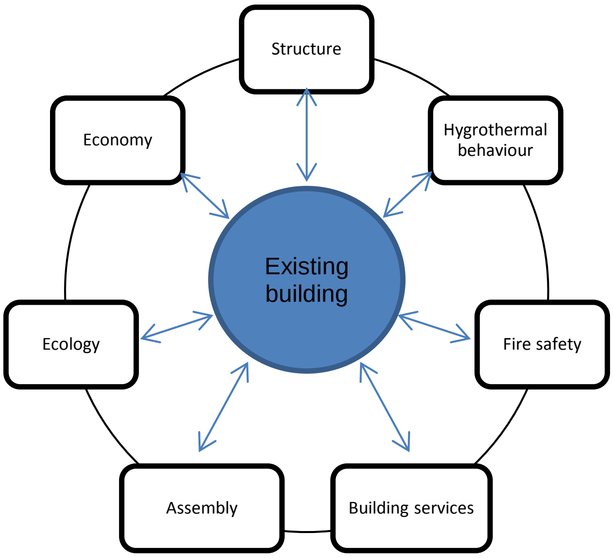

Figure 3: Parameters of a TES façade system.

3.3 Limitations of the analogy

The development of the retrofit construction system starts from the main structural influences and the appropriate way of tectonics of parts. The focus is on the area of the horizontal element joint. It is the connection of the existing exterior walls with the existing ceiling. The horizontal joint is the most relevant detail to solve from the technical and economic perspective, because it is the most frequent joint of a virtual balloon-frame. A 1950ies multi-story house with 8 apartments on four floors has a total length of basement and roof eaves joint line between circa 80 and 130 m. All other horizontal joints between the floors have a total length of approximately 240 and 390 m. The complete vertical joint length is around 65 to 75 m. It matches a ratio between vertical and horizontal joints from 1:5 to 1:7. The high deviation in this ratio clearly shows how important detailing of the horizontal joint has to be done. It influences assembly effort and costs to a large extent. The technical requirements and the effort in this area of the element have to be adjusted very carefully to avoid high costs or unforeseeable risk. The developed solutions have to be in line with the condition of efficiency. A robust solution of butt jointing two elements will reduce the risk of the construction system for failures. The detailed analysis of the construction principles on the applicability and specialties of the construction process with large-format element in refurbishment results in clear advantages for the balloon-frame principle. The requirements of the continuity of the insulation layer and the uninterrupted surface with defined axis of fixing, as alignment, and mounting aid for the façade elements are established as significant characteristics.
A further invention is the adaption layer between the uneven surface of the existing exterior wall and the plane back side of the TES element. The gap should be at least fifty millimetres wide for further filling with blown-in insulation material, preferably cellulose fibre. The process of blowing thermal insulation material in the gap has the advantage of adapting the thickness, where it is needed. Around penetrations of the exterior wall and the elements like windows, the gap should be stuffed with non-combustible mineral wool.

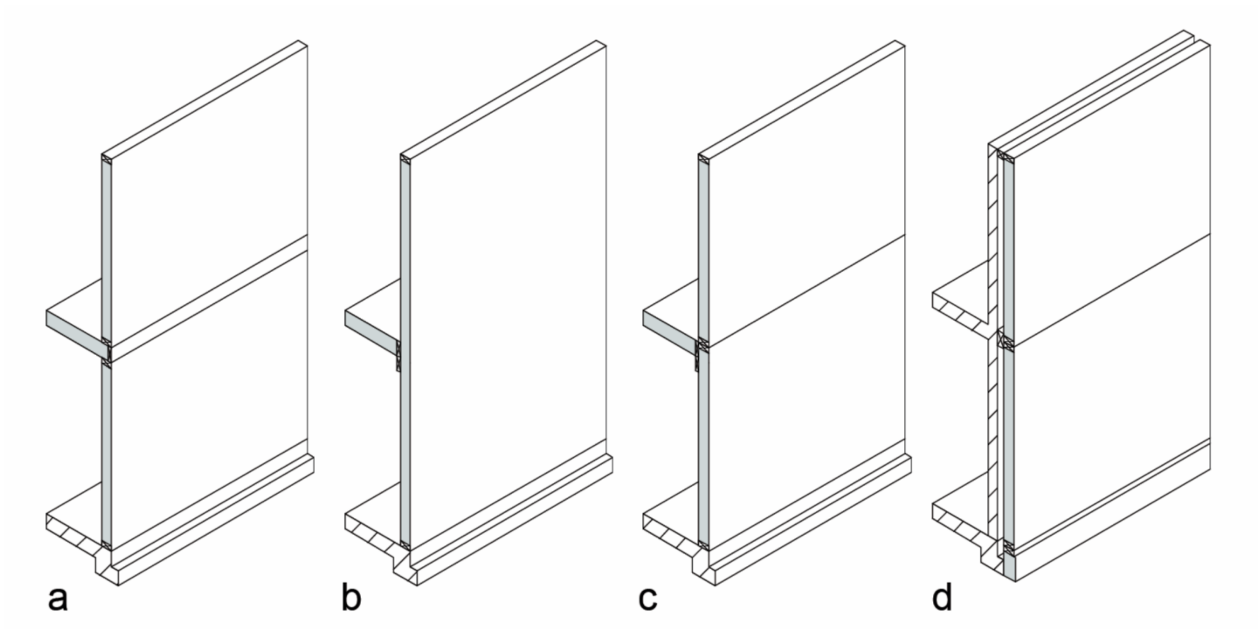

Figure 4: Development of platform frame, (a) balloon-, and semi balloon-frame (b-c) to TES (d) in analogy to (c).

4. Results in timber framework for refurbishment

4.1 Development of the horizontal construction joint

4.1.1 Principles of timber framing for refurbishment existing buildings

As in classic timber frame construction the solid wood studs are positioned in a span of 625 mm and butt-jointed perpendicular to sill-beam and wall-plate. On the element inside an OSB is applied and on the outside a gypsum fiber board. The cavities are filled with thermal insulation, e.g. cellulose fiber. Usually a timber-frame element measures about 12,0 x 3,2 m², limited by production facilities and transportation. [5]

Figure 5: Mounting a TES-Element [gumpp&maier]

While the TES-facade is built with a tolerance of +/-2 mm, the existing exterior wall deviates +/-40 mm in depth. This unevenness is leveled by the coupling beam, which is anchored into the existing wall and runs around the entire building horizontally on each floor level. Thus, while mounting, it's possible to align the façade elements to the coupling beam and fix it with self-drilling timber screws. The assembly of the elements happens horizontally row by row. The design of the element joint was inspired by the simple joining method of a tongue-and-groove connection and enhances the common butt-joint known from classic timber-frame constructions. The tongue consists of the upper element's sill-beam. The groove consists of wall-plate and the overlapping gypsum fiber board of the lower element. That way the upper element is fitting precisely into the lower element, without any larger alignment work necessary and still guaranteeing a force-fitting connection. [5] The vertical connection is a butt-joint of two members without any further connection.

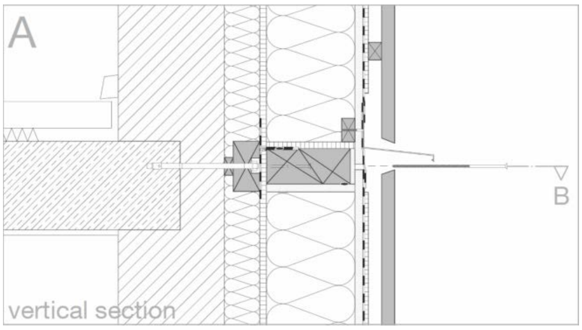

Figure 6: TES horizontal joint Vertical

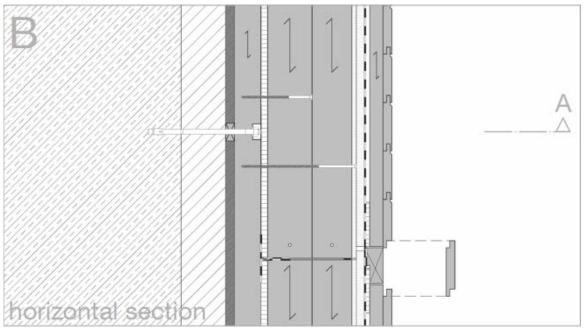

Figure 7: TES horizontal joint Horizontal

All facade components such as the window generally are integrated in the TES element, see Figure 7. This has the advantage of better manufacturing control and simplified construction site operations. The new window can be installed in different configurations as a replacement for the existing one. It can be integrated only as a supplementary window in the TES, which enhances the existing window and improves its thermal and acoustic properties. This solution is an important option for upgrading existing components of good quality, speeds up the construction process significantly and reduces disturbances of the residents.

The variety of applicable cladding materials is analog to new timber-frame buildings; however, retrofitting a larger multi-storey building, the options are strongly limited by fire safety requirements. In this paper the construction is given with a rear ventilated wooden façade.

4.1.2 Structural joint

Essentially there are two main loads (actions) on the TES-façade that have to be taken in to account constructing the loadbearing system: Self-weight and wind-load.
The self-weight of the given construction is with about 80 kg/m² (varying by thickness, thermal insulation material and cladding) comparably high. This is due to the extended timber loadbearing structure, the necessary fire safety boards, and a dense cellulose fibre thermal insulation. The vertical force caused by self-weight conducts all the way through the timber frame into a foundation system at the foot of the façade. As the vertical force accumulates over the building height, the horizontal joint between the elements is built as full form fit contact connector. (Fig. 8 No. 1)

The horizontal forces from the wind-load are induced shortest way into the next ceiling. To prevent unnecessary eccentricities the element joint is placed exactly at the height of the ceiling. So the element fixation with self-drilling screws should be horizontally in line with the ceiling anchorage. To connect both elements with the coupling beam, sill-beam of the top element and the wall-plate of the bottom element need to be on same height. This requirement is fulfilled by the tongue-and-groove connection. (Fig. 8 No. 2)

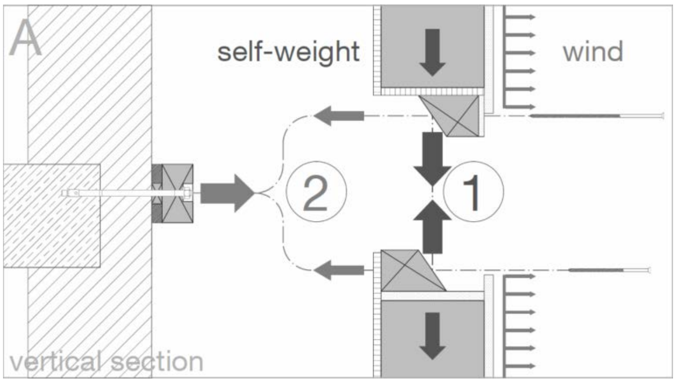

Figure 8: Force conduction

Another advantage of organising the connections in one spot is, in regard to high level prefabrication, a minimal necessary intervention from outside, which reduces onsite finish work on the cladding and thereby keeps the visual surface intact.

4.1.3 Hygrothermal behaviour of TES elements

The requirements, measures and design principles for moisture behaviour and safety of timber framed walls consist of three basic principles:

- No thermal bridges
- No convection
- Moisture management

The avoidance of thermal bridges is the first principle in detail development as no high heat-conductive material from the hot to the cold side goes through so that conduction of heat is minimised. Thus, the impact of material-related thermal bridges can be largely reduced by the use of wood or wood-based materials in the joint area. Geometry-related thermal bridges are not available on that part of the element; they are slightly more relevant at corners. They can be solved when the principle of an external insulation layer and sufficient layer thickness are taken into consideration. A flexible variation of the insulation layer thickness can be achieved by the adaptation of the depth of studs.

Moisture management also has to deal with diffusion safety of the TES layer. The back panelling of the element has to be vapour retardant. Diffusion open (to the outside) regular cross section of the element with a low $s_d < 0,5m$ on the outside of the element and an s_d at least six times higher on the inside of the element is recommended.
Air and wind tightness of timber framed elements are one of the most important measures to stop convection of warm and moist air to the cold side of wooden parts. There are basic rules like the reduction of joints, airtight back panelling and sealing of clamped joints. Further all element joints have to be sealed with elastic rubber sealants. A proper airtight construction also improves fire safety and sound protection by overcoming leakages.
Airtightness is even more important than good diffusion properties, because through joints there is a higher risk for leakages. The horizontal and vertical TES joints have to be sealed for airtightness reasons to ensure the moisture performance and avoid heat conductivity through wet wood or insulation materials in the joint area.

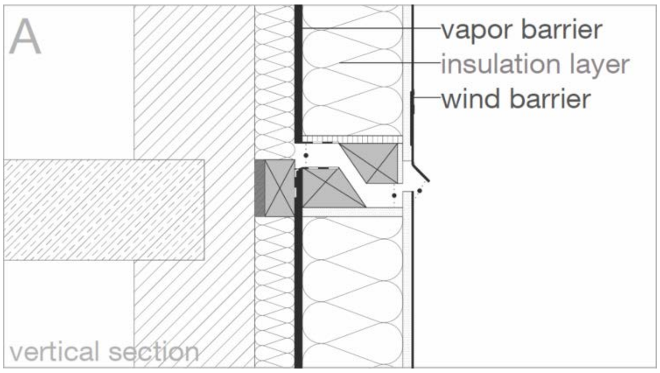

Figure 9: Hygrothermal Detail

Special attention is needed for window assembly. Penetrations offer a path for additional moisture intake into timber framework. Moisture protection from flanking/penetrating materials with high capillarity like brick wall could be a problem. An airtight closure of these penetrations is necessary. Window penetration in existing walls and TES elements requires the connection of window frame to airtight layer of the TES. Furthermore the airtightness of the gap has to be ensured especially for fire safety reasons. A closure with an airtight and fire proof box frame and sealing of the butt-joint between box frame and window frame is necessary. A window position in the existing wall is not allowed according the rules of thermal protection.
Wind tightness is provided by a wind barrier as an outer panelling or membrane of the closed TES element. The wind barrier has to be sealed at connection by tapes or clamped joints.
Besides construction material has to be dry, and elements are protected during construction by closed cavities and heavy weathering to minimize moisture intake. Diffusion open layering supports the drying capacity of elements. Hollow spaces between TES and existing walls have to be avoided and reduce the risk of uncontrolled convection. An appropriate measure is the filling of cavities with soft and dense insulation material during the assembly process. There is a good experience with blown-in cellulose fibre that has a sorption quality that can buffer the moisture from the existing exterior walls and reduces the moisture load on the wooden parts of TES.

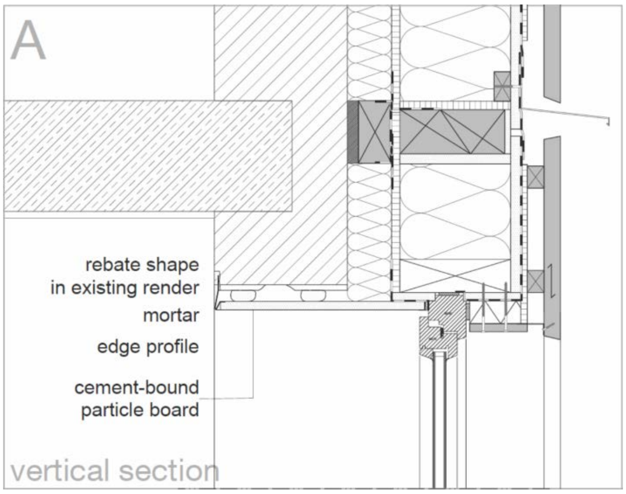

Figure 10: Detail Window

The existing wall and the window connection is very often permeable, warm and moist air is leaky into the gap, the coupling beam sits behind the insulation on the warm side and will not be damaged. See here the interrelation to other topics of building physics: hot pyrolysis gas, smoke, odors and airborne sound use same leaky paths. They will be stopped at TES element back side and at the coupling beam functioning as interruption at each floor. The window joint does not have to be fully closed, due to the second safety line described above.

The joints at the base and roof eaves as well as vertical edges are taped and sealed air-tight, what is non-trivial, since the ground from existing plaster or masonry will not show the best conditions. The elements and element joints are made air-tight with sealing stripes positioned between the elements and all paneling joints, thereby it is important that the inner sealing stripe is connected air-tightly with the OSB by sealing tape, see figure 9. This means, no warm and moist air can penetrate into the insulated compartments and reach the low-temperature side. There is no risk of condensation and moisture intake into the wood.

4.1.4 Wood protection and durability

The built-in wood and wood-based materials are sufficiently protected through compliance with the previously mentioned hygrothermal requirements and moisture management in closed timber frame components. Thus the TES elements fulfill the requirements of use class 0 [11].

4.1.5 Fire safety

Normally, the existing structure already fulfills the fire safety objectives. However the condition of the existing building has to be verified by a fire safety survey. [1] The TES-façade layer has to fulfill the requirements of the relevant building classes. In building classes 4 / 5, in which most of the potential TES-retrofitting objects are classified, or building ≥ 3 storeys, non-loadbearing exterior walls have to be at least fire-retardant (Fig. 11 No. 1) and difficult combustible cladding and insulation material of at least class C- or B-s2,d0 is required. Timber or other combustible façade materials are possible but need special construction and additional approval. Where combustible material and ventilated gaps are used the cladding must have a storey wise separation either by suitable fire stops or with a floor wise horizontal separating construction. (Fig. 11 No. 2) [1][13][14] The component requirements for the ceiling have to be taken in account especially if the existing wall is removed or quite thin. The spread of fire and smoke into the next storey in detour over the TES-façade has to be prevented. If the existing wall is removed, by definition, the TES-joint becomes part of the existing ceiling. (Fig. 11 No. 3)

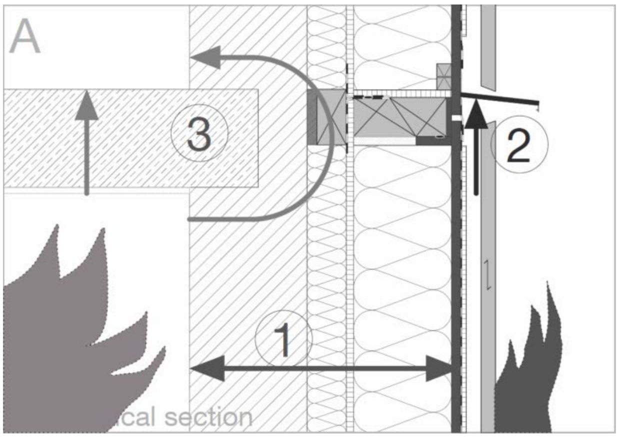

Figure 11: Fire safety detail

At the element joint closing the gypsum board layer is solved by backing the board with an additional stripe of gypsum fiber board and horizontally with another gypsum fiber board below the wall-plate.
(The fire barrier metal sheet is disposed slightly above the joint area in order not to obstruct the screwing of the sill-beam to the horizontal coupling beam.)

4.1.6 Mounting

An important difference to new building is the accessibility of the elements while mounting, because one side is blocked by the existing wall. The higher the prefabrication level the less work needs to be done on site. But, connection points will be harder to access this way. Especially if a visible cladding has been prefabricated, necessary works shall not leave any signs of destruction.

Pilot projects have shown that by sloping the cut between upper sill-beam and lower wall-plate and building a tough-and-groove connection the mounting of the elements is simplified a lot.
The screwing of the elements to the coupling beam offers a simple and uncomplicated solution.
(Before the prefabricated TES-Elements are mounted to the building, it’s necessary to set the foot foundation, remove existing windows and building up surrounding scaffolding, if no elevating platform is used.)

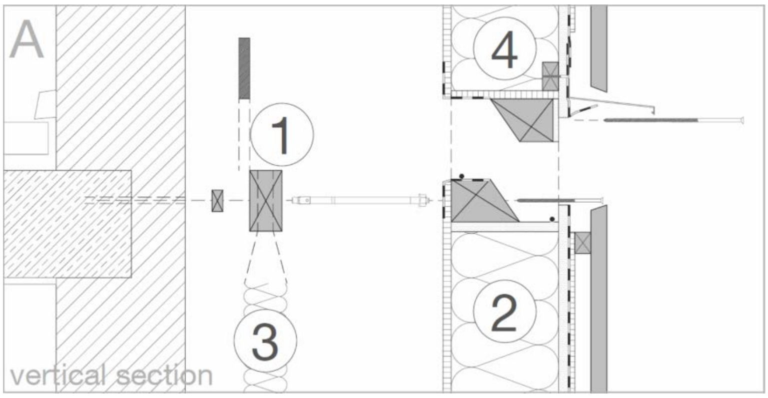

Figure 12: Mounting process

The mounting process is divided in four steps (Fig. 12):
(1) Fixing the coupling beam to the wall: For a fast mounting process and a clean plane stop for the elements the coupling beam is positioned by using a laser-assisted positioning system. The position points were taken during site measuring in the survey phase. With the help of computer-aided design a leveled plane is calculated onto the uneven surface of the existing building. The gap between existing wall and coupling beam is filled with swelling mortar.
(2) Placing the lower element, butting the wall-plate against the coupling beam, and fixing the connection with screws.
(3) Filling the adaption layer by blowing cellulose fiber through an opening in the coupling beam. (After the window reveal was made in a combination of out-run gypsum fiber board, foil and filler from the inside out)
(4) Placing the upper element into the lower element, screwing the sill-beam to the coupling beam, and closing the wind-barrier.

4.2 Principles of timber framed jointing in retrofit

For the structural connection of the TES-Façade to an existing building, the construction of the existing ceiling needs to be examined closely regarding stability and positioning. The pull-out strength of anchoring in to the floor slab needs to be determined. In some cases parts of the masonry work pass in front of the ceiling, this has an influence on the anchorage length. The self-weight of the façade needs be carried by the existing foundation. For the foundation system of the TES-Façade various solutions are available and should be chosen according to the existing laod-bearing capabilities.

The moisture management has to be dealt with like in new building. The claims for hygrothermal protection are airtightness of timber framed elements back-panelling and horizontal air stops in the vertical gap zone at each storey. The airtight sealing of the window remains a critical point. Convection and airborne sound might find also horizontal ways to neighbouring units through leakages around the box frame. Then this construction detailing can be improved from the inside after there are faults during assembly.

By adding the TES-Façade as wall part not only the fire safety of the wall as such has to be taken into account, but also the fire and smoke spread though gaps between new TES-Façade and existing structure.

5. Conclusion

Generally spoken the interface of the existing building envelope and the new timber-framed wrap around has to be planned very carefully. The building survey has to examine all types of exterior walls and junctions of existing ceilings with exterior walls. These are evident for structural jointing and critical routes for air, moisture, sound and fire propagation. In the early planning process it is prerequisite for risk mitigation. Timber framed elements for façade retrofit have no high risks as shown in the proposed robust solutions.

5.1 Outlook

The other principle details are examined in the further course of the project and published shortly in a final project report. Moreover, other variants to the positioning and improvement of the airtight layers and their connections in combination with sorptive insulation layers are tested. Another interesting issue is the capability of TES elements to provide the building envelope multifunctional properties with the integration of building service systems or dynamic energy saving concepts.
The timber-frame-system enables a self-bearing façade. Additionally loadbearing components like balconies, spatial extensions, or roof-top extensions can be built and integrated in the same system. Also HVAC-Systems can be included into TES. Research to potential topology and detailing is ongoing.

6. Acknowledgements

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