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Generic materializations for heightening of buildings and their effects on embodied carbon and costs

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Abstract. Targeting urban and sub-urban building archetypes, generic but practice-oriented materializations of basic construction elements (slabs and walls) and their combinations were conceived for heightening of existing buildings by two to four floors. The developed concepts considered numerous construction materials and requirements from architecture, structural engineering, building physics, and fire protection. Evaluations explored the effects on embodied carbon, weight and estimated cost per surface unit of market-oriented element combinations, to identify suitable (and inappropriate) materializations and to detect governing elements and materials. Globally, a heightening by four floors is better than by two, in terms of relative carbon and cost impacts, but some trade-offs in architectural floor plan layout may be required. Seeking cost reductions is generally disadvantageous for embodied carbon while an investment increase does not necessarily provide a reduced carbon footprint. Overall, timber construction results in the lowest embodied carbon (around 5 kg $CO_{2,eq}/m^2 \cdot a$) while being up to 10% more expensive than the cheapest and up to 15% heavier than the lightest materializations (which depend on the floor plan layout). Lightweight concrete construction can be the most economic materialization but is also up to 200% heavier than the lightest (which can possibly not be supported by the existing building), and results in up to 45% more embodied carbon than constructing with timber.

1. Introduction

As do many countries, Switzerland experienced an important population increase over the last decades, in general, which leads to more and more urban residents, in particular. From 1998 to 2023, the annual increase rate of total population amounted to 0.9% on average, varying by +/-0.5%. In the same period, the urban population ratio increased from 83.6% to 84.8%, being stable since 2017 [1]. This evolution results in the well-known problem of urban sprawl which ultimately triggered the legal requirement for densification of urban zones towards the interior.

To accommodate the increasing urban population, there are several options: reduced living space per inhabitant in new construction of multi-family houses, in particular (which saw annual increases of approx. 5% since 1960 to becoming stable since 2005 [2]); densified (re)construction in wasteland zones (which may provide more favorable societal services, e.g. recreation zones); demolition and densified reconstruction of existing buildings (resulting in huge amounts of waste and important cost); and heightening of existing buildings. Heightening seems the most promising option, as it does not consume wasteland, does not create demolition waste, and adds to the continuous use of existing buildings.

Today, heightenings are often built in lightweight timber or steel construction with one to three added floors, respecting requirements from thermal and acoustic insulation, and fire protection. Project development and tendering usually focus on construction cost, but neglect embodied carbon.

The latter and increasingly important aspect forms the core of the research presented here, baptized ConDensUrbEn (from "Construire la Densification Urbaine en Equilibre avec la Nature") [3]. It explores generic solutions for primary structure (i.e. load-bearing) and necessary finishings (i.e. secondary structure) of basic construction elements (i.e. slab and wall elements) and their combinations for constructing heightenings, considering traditional but also more recent construction materials.

Evaluations targeted the effects of construction element combinations on embodied carbon, weight and approximate construction cost per added surface unit. Ultimately, suitable (and inappropriate) materialization solutions for heightenings, governing construction elements and material layers, and possible trade-offs among the evaluated effects should be identified.

2. Case study buildings

Based on an earlier project on energetic retrofit [4], which also derived construction typologies of multi-family houses from 1900 to 1990, representative buildings were selected, targeting wide-spread archetypes from intense construction periods, in order to develop heightening materialization concepts.

2.1. Building archetypes

The first case study building represents (a part of) a typical Swiss urban dwelling block from the between-wars construction period, Figure 1. Above a basement and a commercial ground level, five residential floors with four apartments each, and a penthouse level with an attic are placed. Walls are made of cement bricks, while floor slabs consist of so-called "hourdis" slabs.

Figure 1. Typical pre-WW2 building in Swiss urban dwelling (1939).

Figure 2. Typical post-WW2 building as Swiss suburban standalone (1972).

The second case study reflects a typical (sub-)urban standalone building, Figure 2. Basement and parking compartments are situated at the ground level, above which four residential floors (with four apartments each) and an attic are placed. The multi-layer walls are made of clay bricks, and the floor slabs are made of normal-weight reinforced concrete.

3. Conceptual design of construction elements for heightening

Some aspects in conceiving the heightening were neglected, for example: effects on urbanistic quality (e.g. additional shading), local constraints for access and execution of the construction (with important effects on cost), and interaction of the heightening with an energetic retrofit of the existing envelope.

3.1. Structural evaluation and general heightening potential of the case study buildings

A first general targeted the structural capacities of the existing walls, to deduce approximate allowable surface weight and number of possible floors (the two interacting), having an effect on conception.

Results for wind design show that the pre-WW2 building (Figure 1) can accommodate up to four additional floors if the surface weight can be limited to 500 kg/m^2,which is feasible but excludes more massive materializations. The post-WW2 building (Figure 2), however, can only accommodate one additional floor of max. 200 kg/m^2, which is more than challenging to attain.

But, both buildings have insufficient earthquake safety already in the existing state, i.e. without heightening. Thus, a minimum strengthening of shear walls is required in any case, to be possibly complemented as a consequence of the selected materialization and number of added floors.

3.2. *Floor plan schemes and structural concepts*

The floor plans of the heightening and of the existing building strongly interact. Two options for the heightening were developed here: i) a restrained floor plan, very close to the existing one, with limited spans and minor changes in load paths, but leaving little freedom in apartment layout; and ii) an open floor plan with greatly increased freedom in apartment layout, but resulting in much larger spans and requiring deep beams (i.e. story-high walls) to assure load transfers.

3.3. *Materialization concepts for construction elements*

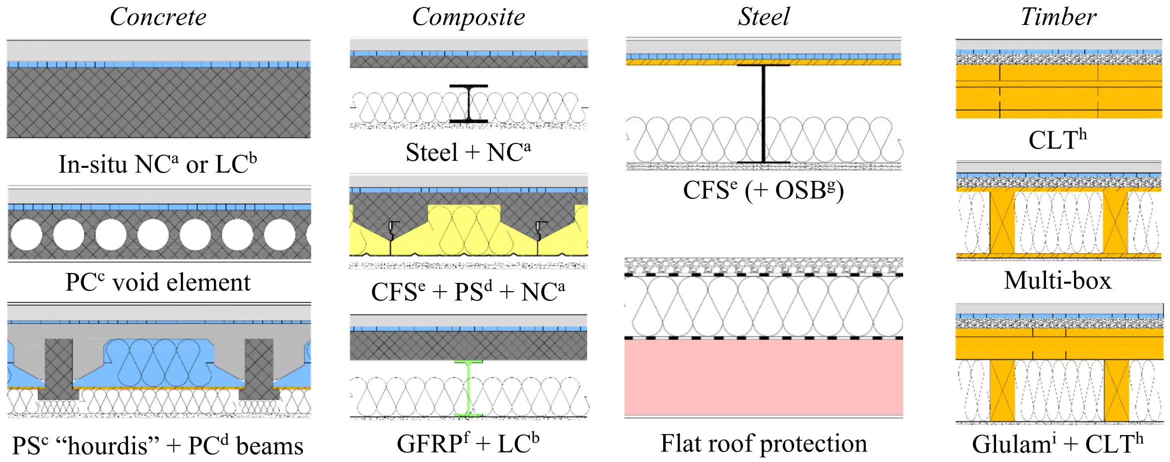
With a focus on generic materialization options for heightening elements, dimensioning of structural elements was limited to pre-design level and omitted profound analysis of construction details.

Thermal insulation requirements were considered by assuring a comparable U-value for envelope elements (max. 0.17 W/m^{2}K), admitted to result in comparable energy consumption (which is excluded in the evaluations). Openly accessible catalogue compositions for secondary structure were used to satisfy acoustic insulation requirements, considering variable but practical standards for finishings.

3.3.1. Floor and roof slabs. For several main construction material categories, a multitude of conceptual designs of slab elements were developed, Figure 3. They should span one-way only, pertinent for most of the materializations. For their structural design, a span interval of 7-11 m was derived from the floor plan layouts. More details (motivation, dimensions, secondary structure options) are given in [3].

The same concepts as for floors were considered for flat roof elements, adding thermal insulation made of rock wool of varying thickness (depending on the materialization of the slab concept), and protection (i.e. waterproofing, gravel layer).

Structural and building-physical designs of the slabs allowed to determine material volumes and surface weights, respectively, serving as a basis for subsequent evaluations.



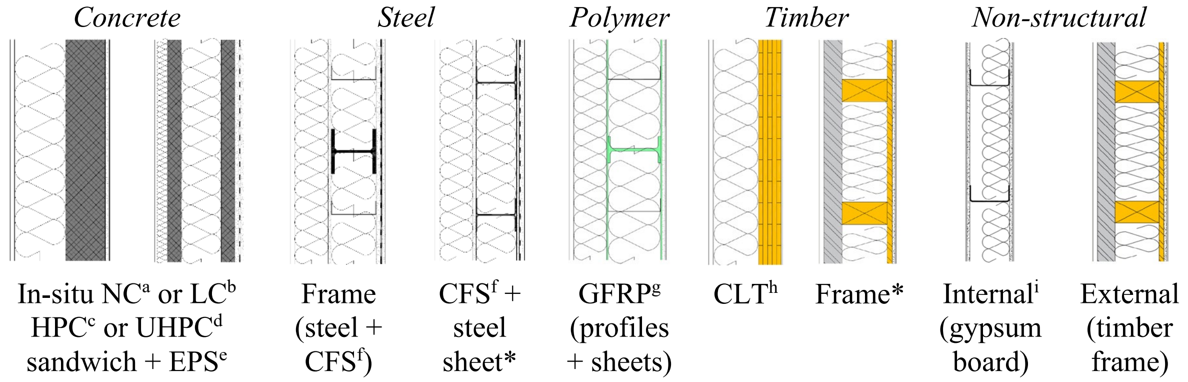
[a] Normal-weight (reinforced) concrete [b] Light-weight (reinforced) concrete [c] Polystyrene [d] Prestressed (prefabricated) concrete [e] Cold-formed steel [f] Glass-fiber reinforced polymer [g] Oriented strand board [h] Cross-laminated timber [i] Glued laminated timber (providing profiled CLT slab for large spans)

Figure 3. Materialization concepts for floor and roof elements (typical cross-section).

3.3.2. Walls. Considering different construction material categories again, several wall compositions were conceived, Figure 4. Their structural design has to consider the supported slab type (i.e. its surface weight) and the floor plan layout (i.e. need for deep beams or not, and associated slab spans) as well as execution and building-physical requirements.

For mainly compressed walls (i.e. in restrained floor plan), four heightening floors were considered to determine required thicknesses of the structural material. For the open floor plan, it was assumed that one deep beam carries one floor (which is also a result of construction sequence). Note that certain materialization concepts cannot be used as deep beam, as indicated in Figure 4.

In general, rock wool was considered as thermal insulation material, except for prefabricated concrete sandwich elements, where the use of EPS is more appropriate for durability and humidity reasons.



[a] Normal-weight (reinforced) concrete [b] Light-weight (reinforced) concrete [c] High-performance concrete [d] Ultra-high performance concrete [e] Expanded polystyrene [f] Cold-formed steel [g] Glass-fiber reinforced polymer [h] Cross-laminated timber [i] KNAUF® system * inappropriate concept for use as deep beam

Figure 4. Materialization concepts for wall elements (typical cross-section).

3.3.3. Strengthening of existing walls. Many existing walls require strengthening for earthquake or wind already in their current state (section 3.1). Adding loads from heightening tends to increase the shear resistance of the brick walls, thanks to the increased compression from the additional weight. As such, required strengthening again depends on the materialization and number of added floors.

Two strengthening options were considered: a "light" intervention, with epoxy-bonded carbon sheets, for modest structural deficits (60-75%); and a "heavy" intervention, with a new structural concrete wall concreted against the existing, for larger structural deficits (>75%). For structural deficits <60%, an intervention is generally disproportionate according to the Swiss code SIA269/8 (2017) on earthquake evaluation of existing structures. An equivalent approach was applied for wind loads.

4. Effects of materializations on embodied carbon and construction cost

4.1. Selection of element combinations and evaluation approach

Combining every slab concept with every wall concept would result in 90 possible combinations to be evaluated. To limit the efforts, practical aspects were considered in the selection of element combinations. As an example, it was not deemed very wise to combine a rather heavy concrete slab with a light-weight timber wall, as this results in an overly increased wall thickness. For a smooth planning process, a mix of too many different material disciplines should be avoided, too (e.g. no CLT slabs on GFRP walls). Doing so, about 25 reasonable combinations of slab and wall materializations remained, of which 13 were deemed the most promising and were evaluated.

Evaluations considered embodied carbon, construction cost, and associated surface weight. The first was determined from material volumes and official unit impacts, considering fabrication and disposal only. For unreported materials, specialists of the project team established impact estimations.

Construction cost, however, not only depend on material consumption, but are heavily influenced by local constraints for the execution of a heightening on a specific building (e.g. access, storage surfaces, space for lifting equipment). To allow qualitative comparisons, usual market prizes for material and mounting were considered, and the cost were normalized to a reference materialization.

Impact results presented hereafter refer to the energy reference area (ERA) of the heightening, which also includes the top floor of the existing building, and to usual amortization periods for structural and non-structural materials. They consider comparable (maximum) impacts from secondary structure.

4.2. Two heightening floors with restrained floor plan layout

Constructing the heightening in timber results in the lowest embodied carbon with 5.1 kg $CO_{2,eq}/(m^2 \cdot a)$, being virtually the same for timber multi-box slabs and frame walls or CLT combinations. Using box and frame elements results in a surface weight of 320 kg/m^2 while CLT adds some 80 kg/m^2.

CFS materializations for slabs and walls result in the lowest surface weight with approx. 290 kg/m^2 but in an embodied carbon increase to 6.0 kg $CO_{2,eq}/(m^2 \cdot a)$. Composite hollow block slabs (CFS+PS+NC) combined with steel or CFS frames yield a minor increase to 6.1 to 6.3 kg $CO_{2,eq}/(m^2 \cdot a)$ of embodied carbon with a major increase in surface weight to up to 580 kg/m^2.

"Hourdis" slabs (PS hollow block + PC beam) with UHPC sandwich walls provide a comparable surface weight of 610 kg/m^2 but increase embodied carbon to 7.0 kg $CO_{2,eq}/(m^2 \cdot a)$. That can be brought down again to 6.2 kg $CO_{2,eq}/(m^2 \cdot a)$ with traditional in-situ concrete (NC) in slabs and walls but would come with the maximum surface weight of 1'280 kg/m^2. Other concrete element combinations are situated between the two previously mentioned limits of surface weight and embodied carbon.

The highest embodied carbon of 9.2 kg $CO_{2,eq}/(m^2 \cdot a)$ is found with GFRP in slabs and walls, while the surface weight amounts to approx. 460 kg/m^2. By the way, this shows that there is no correlation between embodied carbon and surface weight or construction material density, respectively.

For all materialization concepts, embodied carbon impacts are first located in the flat roof, followed by the floor slab and internal wall elements. External wall elements and strengthening of existing walls contribute the least. All concepts require more heavy than light strengthening, with ratios ranging from about 4:1 for materializations with up to 680 kg/m^2 to 7:1 for the maximum (1'280 kg/m^2).

4.2.1. Correlation of embodied carbon and construction cost. Taking a traditional materialization with timber multi-box slabs and frame walls as a reference shows that using in-situ NC or LC elements can reduce construction cost by about 8% but at the expense of embodied carbon increase of 20% to 30%. Other concrete materializations have costs comparable to the reference or not more than 10% higher.

Choosing CLT accounts for a cost increase of 10% for the same embodied carbon. Steel solutions of any form increase cost by approx. 10% to 20% and embodied carbon by 20% to 25%. Applying GFRP not only yields the highest embodied carbon (+80%) but also the highest construction cost (+60%). Reducing requirements on the secondary structures, i.e. accepting "rawer" finishings, can result in reductions of embodied carbon and construction cost of up to 15%.

4.2.2. Changes with four floors. Total impacts in embodied carbon, additional weight and construction cost naturally increase with more floors. However, as the ERA of the heightening is also increased, the relative impact of the flat roof on embodied carbon decreases, and the floor slabs become the most important contributors, followed by the internal walls. External walls have a contribution lower or comparable to the roof. Embodied carbon from strengthening is reduced by 25% to 40% (above all, in heavy strengthening), showing the beneficial effect of increased load on brick walls loaded in shear.

Relatively, surface weights increase by max. 3% (timber) while embodied carbon is reduced by 5% to 6% for concrete, by 4% to 7% for any solution involving steel, and by 8% for timber materializations. Construction costs are also reduced by approximately 10% for concrete materializations, 8% for steel solutions, and by up to 10% for heightenings in timber. Reducing finishing standards results in even more pronounced reductions of embodied carbon and construction costs (up to 20% less).

4.3. Two heightening floors with open floor plan

Construction of the heightening in timber results (again) in the lowest embodied carbon of 5.0 kg $CO_{2,eq}/(m^2 \cdot a)$, using CLT deep beam walls combined with multi-box slabs. This construction element combination also results in the lowest surface weight of 360 kg/m^2. Using CLT instead of multi-box slabs increases embodied carbon to 5.3 kg $CO_{2,eq}/(m^2 \cdot a)$ and surface weight to 470 kg/m^2.

The GFRP combination results in almost the same surface weight (480 kg/m^2) but is again out of league in embodied carbon with 11.4 kg $CO_{2,eq}/(m^2 \cdot a)$. Pure CFS slabs are not feasible for the large spans of this floor plan layout (CFS profile heights being limited). However, composite hollow block slabs (CFS+PS+NC) combined with steel frame walls can, yielding 5.9 kg $CO_{2,eq}/(m^2 \cdot a)$ of embodied carbon and a surface weight of 580 kg/m^2. Virtually equivalent results are found if more traditional steel-concrete composite slabs (steel + NC) are combined with steel frame walls.

The concrete materialization with the lowest embodied carbon of 6.3 kg $CO_{2,eq}/(m^2 \cdot a)$ is found by combining PC void slabs with HPC sandwich walls, resulting in a surface weight of 800 kg/m^2. Using UHPC instead of HPC in walls reduces surface weight to 750 kg/m^2 but increases embodied carbon to 6.6 kg $CO_{2,eq}/(m^2 \cdot a)$. Replacing the PC void slabs with "hourdis" slabs (PS hollow blocks + PC beams), still combined with UHPC walls, yields a surface weight of 640 kg/m^2, but comes with an increase of embodied carbon to 6.7 kg $CO_{2,eq}/(m^2 \cdot a)$. The highest embodied carbon of 7.3 kg $CO_{2,eq}/(m^2 \cdot a)$ for a heightening in concrete is found by applying in-situ LC in slabs and walls, resulting in a surface weight of 1'040 kg/m^2. The heaviest concrete heightening, with 1'650 kg/m^2, results when using NC instead of LC, yielding embodied carbon of 6.9 kg $CO_{2,eq}/(m^2 \cdot a)$.

Floor and roof elements contribute similarly and the most to embodied carbon, due to the increased span, followed by the internal walls. Strengthening of existing walls is further reduced, as there are less walls to be strengthened and the additional load on the brick shear walls is further increased.

4.3.1. Embodied carbon and construction cost. Referring again to a timber solution (multi-box slabs with CLT walls), construction costs could be reduced by less than 4% (using in-situ LC again) if an embodied carbon increase of 45% is accepted. All other materializations (excluding the unsuitable use of GFRP in any construction element) have roughly the same or max. 10% higher cost and come along with an increase in embodied carbon of 20% to 40%.

4.3.2. Four floors. Relative changes in embodied carbon, surface weight, and construction cost show the same but generally less pronounced tendencies as for the restrained floor plan.

5. Conclusions

Overall, a heightening with four floors is more beneficial than with two floors, in terms of relative embodied carbon and construction cost, but some compromises in floor plan layout or element materializations may be required for the higher heightening.

Also, there is a target conflict between added weight, embodied carbon, and cost per surface unit when trying to identify the most appropriate construction material category. In general, for minimum embodied carbon, the mathematical sum of products of material volumes and unit impacts governs, above all in floor and roof elements (in structural and secondary layers).

The current practice of heightenings in timber or cold-formed steel (CFS) already does a good job. Timber is possibly a bit heavier than the lightest solution but provides the lowest embodied carbon. Cost increases are very modest, compared to the cheapest lightweight concrete (LC) construction. CFS results in the lightest heightening, but is only feasible for moderate floor spans and comes with rather important increases in cost and embodied carbon. For large floors spans, timber should be used. An LC heightening may be the cheapest but also provides very significant increases in added weight and embodied carbon.

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